750 GeV diphoton resonance from singlets in an exceptional supersymmetric standard model

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Abstract: The 750–760 GeV diphoton resonance may be identified as one or two scalars and/or one or two pseudoscalars contained in the two singlet superfields $S_1, S_2$ arising from the three 27-dimensional representations of $E_6$. The three 27s also contain three copies of colour-triplet charge $\pm 1/3$ vector-like fermions $D, \bar{D}$ and two copies of charged inert Higgsinos $\tilde{H}^+, \tilde{H}^-$ to which the singlets $S_{1,2}$ may couple. We propose a variant of the $E_6$SSM where the third singlet $S_3$ breaks a gauged $U(1)_N$ above the TeV scale, predicting $Z_N, D, \bar{D}, \tilde{H}^+, \tilde{H}^-$ at LHC Run 2, leaving the two lighter singlets $S_{1,2}$ with masses around 750 GeV. We calculate the branching ratios and cross-sections for the two scalar and two pseudoscalar states associated with the $S_{1,2}$ singlets, including possible degeneracies and maximal mixing, subject to the constraint that their couplings remain perturbative up to the unification scale.

Keywords: Supersymmetry Phenomenology

ArXiv ePrint: 1601.07242
1 Introduction

Recently ATLAS and CMS experiments have reported an excess of diphoton events at an invariant mass around 750 GeV and 760 GeV from LHC Run-2 with pp collisions at the center of mass energy of 13 TeV [1, 2]. The local significance of the excess ATLAS events is $3.9\sigma$ while that of the excess CMS events is $2.6\sigma$, corresponding to the respective cross sections $\sigma(pp \rightarrow \gamma\gamma) = 10.6\,\text{fb}$ and $\sigma(pp \rightarrow \gamma\gamma) = 6.3\,\text{fb}$. ATLAS favours a broad width of $\Gamma \sim 45\,\text{GeV}$, while CMS, although not excluding a broad resonance, actually prefers a narrow width. The diphoton excesses observed by ATLAS and CMS at this mass scale may be partially understood by the factor of 5 gain in cross-section due to gluon production. However there is no evidence for any coupling of the resonance into anything except gluons and photons (no final states such as $f\bar{f}$, $VV$ ($f$ being a fermion and $V$ being $W, Z$) since no missing $E_T$ or jets have been observed.

This may be the first indication of new physics at the TeV scale. It could even be the tip of an iceberg of many future discoveries. Several interpretations have been suggested based on extensions of the Standard Model spectrum [3–158]. Many of these papers suggest a spinless singlet coupled to vector-like fermions [3, 9, 10, 12, 14, 21, 22, 34, 37, 55, 61, 63, 83, 84, 98, 104, 107, 109, 121, 125, 131, 158]. Indeed, the observed resonance could be interpreted as a Standard Model scalar or pseudoscalar singlet state $X$ with mass $m_X \sim 750 - 760\,\text{GeV}$. Moreover, because it decays into two photons, its spin is consistent with $s = 0$. The process of generating the two photons can take place by the gluon-gluon fusion mechanism according to the process $gg \rightarrow X \rightarrow \gamma\gamma$ hence it requires production and decay of the particle $X$. In a renormalisable theory this interaction can be realised assuming vector-like fermions at the TeV scale, which carry electric charge and colour. Such vector-like pairs have not been observed at LHC, hence the mass of the fermion pair should be around or above the TeV scale. For example, in F-theory models based on $E_6$, low energy singlets coupling to extra vector-like matter is predicted and may be responsible for
the 750 GeV diphoton resonance [158]. Such models motivate the phenomenological study of $E_6$ as being the origin of the new physics.

An example of a model with singlets and extra vector-like matter is the Exceptional Supersymmetric (SUSY) Standard Model ($E_6$SSM) [159, 160], where the spectrum of the MSSM is extended to fill out three complete 27-dimensional representations of the gauge group $E_6$ which is broken at the unification scale down to the SM gauge group plus an additional gauged $U(1)_N$ symmetry at low energies under which right-handed neutrinos are neutral, allowing them to get large masses. The three 27-plet families (labelled by $i = 1, 2, 3$) contain the usual quarks and leptons plus the following extra states: SM-singlet fields, $S_i$; up- and down-type Higgs doublets, $H_{ui}$ and $H_{di}$; and charged $\pm 1/3$ coloured, exotics $D_i$ and $\bar{D}_i$. The extra matter ensures anomaly cancellation, however the model also contains two extra SU(2) doublets, $H'$ and $H''$, which are required for gauge coupling unification [161]. To evade rapid proton decay a $Z_2$ symmetry, either $Z^S_2$ or $Z^D_2$, is introduced and to evade large flavour changing neutral currents an approximate $Z^H_N$ symmetry is introduced where only the third family of Higgs doublets $H_{u3}$ and $H_{d3}$ and singlets $S_3$ are even under it and hence couple to fermions and get vacuum expectation values (VEVs). In particular, the third family singlet $S_3$ gets a VEV, $\langle S_3 \rangle = s/\sqrt{2}$, which is responsible for the effective $\mu$ term, inert Higgsino and D-fermion and $Z^H_N$ masses, while the first and second families of Higgs doublets and SM-singlets do not get VEVs and are called “inert”. Further aspects of the theory and phenomenology of this SUSY extension of the SM have been extensively studied in [162–193].

In this paper we take all three singlets to be even under the approximate $Z^H_N$, which allows them all to couple to $\tilde{H}_{ui}$ and $\tilde{H}_{di}$ as well as $\tilde{D}_i$ and $\tilde{D}_i$. We shall assume that the third singlet $S_3$ has appreciable couplings to the three families of $H_{ui}, H_{di}$ and $D_i$, $\tilde{D}_i$, so that its large VEV generates effective mass terms for all these states, as well a $Z^H_N$, above the TeV scale but possibly within the reach of LHC Run 2. However the first and second singlets $S_{1, 2}$ may have relatively small couplings to the third pair of Higgs doublets $H_{u3}$ and $H_{d3}$, which are the only Higgs doublets to acquire VEVs. In addition, we shall suppose that the value of the third singlet $S_3$ VEV $s$ is above the TeV scale, while the other singlets $S_{1, 2}$ at most develop small VEVs. This is different from the modified $E_6$SSM in [125], where two of the singlets were assigned even under the approximate $Z^H_2$ and both were allowed to develop VEVs and couple to all three families of $H_{ui}, H_{di}$ and $D_i, \bar{D}_i$. In the version of the $E_6$SSM here, we suppose that, after the third singlet $S_3$ with large large $s$ VEV is integrated out, only the first and second singlets $S_{1, 2}$ appear in the low energy effective theory and provide candidates for the 750-760 GeV resonance which may be identified as one or two scalars and/or one or two pseudoscalars contained in $S_{1, 2}$. The assumed smallness of the coupling of $S_{1, 2}$ to $H_{u3}$ and $H_{d3}$ means that the observed resonance will not easily decay into pairs of top quarks or W bosons.

Many of the features of the considered model would be common to other SUSY $E_6$ models where the low energy spectrum consists of complete 27-plets. The present model is a variant of the $E_6$SSM and like that model is distinguished by the choice of surviving gauged $U(1)_N$ under which right-handed neutrinos have zero charge and may acquire large Majorana masses, corresponding to a high scale seesaw mechanism. For earlier literature
on other SUSY $E_6$ models based on different surviving gauged $U(1)$ symmetries under which right-handed neutrinos are charged see [159].

The layout of the remainder of the paper is as follows. In section 2 we discuss the variant of the $E_6$SSM that we shall study, and discuss the renormalisation group equations which constrain the Yukawa couplings to be perturbative up to the unification scale. In section 3 we apply this model to the 750 GeV diphoton resonance, calculating the branching ratios and cross-sections for the two scalar and two pseudoscalar states associated with the $S_{1,2}$ singlets, including possible degeneracies and mixing. Section 4 concludes the paper.

2 A variant of the $E_6$SSM

We first recall that the $E_6$SSM [159, 160] may be derived from an $E_6$ GUT group broken via the following symmetry breaking chain:

$$
E_6 \rightarrow SO(10) \otimes U(1)_\psi \\
\rightarrow SU(5) \otimes U(1)_X \otimes U(1)_\psi \\
\rightarrow SU(3) \otimes SU(2) \otimes U(1)_Y \times U(1)_X \otimes U(1)_\psi \\
\rightarrow SU(3) \otimes SU(2) \otimes U(1)_Y \otimes U(1)_N.
$$

(2.1)

We assume that the above symmetry breaking chain occurs at a single GUT scale $M_X$ in one step, due to some unspecified symmetry breaking sector,

$$
E_6 \rightarrow SU(3) \otimes SU(2) \otimes U(1)_Y \otimes U(1)_N,
$$

(2.2)

where

$$
U(1)_N = \cos(\vartheta)U(1)_X + \sin(\vartheta)U(1)_\psi
$$

(2.3)

and $\tan(\vartheta) = \sqrt{15}$ such that the right-handed neutrinos that appear in the model are completely neutral and may get large intermediate scale masses. However the $U(1)_N$ gauge group remains unbroken down to the few TeV energy scale where its breaking results in an observable $Z'_N$. Three complete 27 representations of $E_6$ then also must survive down to this scale in order to ensure anomaly cancellation. These 27s decompose under the $SU(5) \otimes U(1)_N$ subgroup as follows:

$$
27_i \rightarrow (10, 1)_i + (\bar{5}, 2)_i + (\bar{\bar{5}}, -3)_i + (5, -2)_i + (1, 5)_i + (1, 0)_i,
$$

(2.4)

where the $U(1)_N$ charges must be GUT normalised by a factor of $1/\sqrt{40}$. The first two terms contain the usual quarks and leptons, and the final term, which is a singlet under the entire low energy gauge group, contains the (CP conjugated) right-handed neutrinos $N_f$. The last-but-one term, which is charged only under $U(1)_N$, contains the SM-singlet fields $S_i$. The remaining terms $(\bar{5}, -3)_i$ and $(5, -2)_i$ contain three families of up- and down-type Higgs doublets, $H_{ui}$ and $H_{di}$, and charged $\pm 1/3$ coloured exotics, $D_i$ and $\bar{D}_i$. These are all superfields and are written with hats in the following.

The low energy gauge invariant superpotential can be written

$$
W^{E_6SSM} = W_0 + W_{1,2},
$$

(2.5)
where $W_{0,1,2}$ are given by

\[ W_0 = \lambda_{jkli} \hat{H}_{dji} \hat{H}_{uik} \hat{S}_i + \kappa_{jkli} \hat{D}_{jL} \hat{D}_{kL} \hat{S}_i + h^N_{ijk} \hat{N}^c_i \hat{H}_{uj} \hat{L}_{kj}, \]
\[ + h^U_{ijk} \hat{H}_{ui} \hat{Q}_{Lj} \hat{u}_{Rk} + h^D_{ijk} \hat{H}_{di} \hat{Q}_{Lj} \hat{d}_{Rk} + h^E_{ijk} \hat{H}_{di} \hat{L}_{Lj} \hat{e}_{Rk}, \]
\[ (2.6) \]
\[ W_1 = g^{Q}_{ijk} \hat{D}_{Lj} \hat{Q}_{Lj} \hat{L}_{kj} + g^{a}_{ijk} \hat{D}_{Lj} \hat{Q}_{Lj} \hat{u}_{Rk}, \]
\[ (2.7) \]
\[ W_2 = g^{N}_{ijk} \hat{N}^c_i \hat{D}_{Lj} \hat{d}_{Rk} + g^{E}_{ijk} \hat{D}_{Lj} \hat{d}_{Rk} \hat{e}_{Rk} + g^{D}_{ijk} \hat{D}_{Lj} \hat{Q}_{Lj} \hat{L}_{kj}, \]
\[ (2.8) \]

with $W_{1,2}$ referring to either $W_1$ or $W_2$ (but not both together which would result in excessive proton decay unless the associated Yukawa couplings were very small).

At the renormalisable level the gauge invariance ensures matter parity and hence LSP stability. All lepton and quark superfields are defined to be odd under matter parity $Z_2^M$, while $\hat{H}_{ui}$, $\hat{H}_{dji}$, $\hat{D}_{Lj}$, $\hat{D}_{Lj}$, and $\hat{S}_i$ are even. This means that the fermions associated with $\hat{D}_{Lj}$, $\hat{D}_{Lj}$ superfields are taken to be even, apart from the active $\hat{S}_3$, $\hat{H}_{d3}$, and $\hat{H}_{a3}$ which are taken to be even. The inert fields then have small couplings to matter and do not radiatively acquire VEVs or lead to large flavour changing neutral currents. The active fields can have large couplings to matter and radiative electroweak symmetry breaking (EWSB) occurs with these fields. In particular the VEV $\langle S_3 \rangle = s/\sqrt{2}$ is responsible for breaking the U(1)$_N$ gauge group and generating the effective $\mu$ term and D-fermion masses. In particular we must have $s > 5$ TeV in order to satisfy $M_{Z^* N} > 2.5$ TeV, which is the current LHC Run 2 experimental limit [194].

We now propose a variant of the E6SSM in which we allow all three singlets $\hat{S}_i$ (as well as $\hat{H}_{d3}$ and $\hat{H}_{u3}$) to be even under the $Z_2^H$. This allows all three singlets $\hat{S}_i$ to couple to $\hat{H}_{ui}$ and $\hat{H}_{di}$ as well as $\hat{D}_{Lj}$ and $\hat{D}_{Lj}$. If for simplicity we take the couplings in eq. (2.6) to have the diagonal form, $\lambda_{ijkl} \propto \lambda_{ij} \delta_{jk}$ and $\kappa_{ijkl} \propto \kappa_{ji} \delta_{jk}$, then the $Z_2^H$ symmetry allows to reduce the structure of the Yukawa interactions in the superpotential to:

\[ W_{E6SSM} \simeq \lambda_{ij} \hat{H}_{dji} \hat{H}_{uik} \hat{S}_i + \kappa_{ij} \hat{D}_{jL} \hat{D}_{kL} \hat{S}_i + W_{MSSM}(\mu = 0). \]
\[ (2.9) \]

The superfield $\hat{S}_3$ is assumed to acquire a rather large VEV ($\langle S_3 \rangle = s/\sqrt{2}$) giving rise to the effective $\mu$ term, masses of exotic quarks and inert Higgsino states which are given by

\[ \mu = \frac{\lambda_{33}s}{\sqrt{2}}, \quad \mu_{H_u} = \frac{\lambda_{i3}s}{\sqrt{2}}, \quad \mu_{D_{Lj}} = \frac{\kappa_{i3}s}{\sqrt{2}}. \]
In our analysis here we restrict our consideration to the case when exotic quarks and inert Higgsinos are sufficiently light compared to the VEV $s > 5$ TeV, but are heavier than half the mass of the 750 GeV resonance, so that they appear in loop diagrams for the singlet decays. It means that the Yukawa couplings of $\tilde{S}_3$ to all exotic states should be quite small. Throughout this paper we are going to assume that some scalar components of the first and second singlets $\tilde{S}_a$, with $\alpha = 1, 2$, can be identified with the resonances which give rise to the excess of diphoton events at an invariant mass around 750 GeV recently reported by the LHC experiments. ATLAS and CMS measurements indicate that the branching ratios of the decays of such resonances into SM fermions have to be sufficiently small. This implies that the mixing between the scalar components of $\tilde{S}_a$ and the neutral scalar components of the third pair of Higgs doublets $H_u$ and $H_d$, which are the ones that give rise to the EWSB, should be strongly suppressed. In order to ensure the suppression of the corresponding mixing we impose the further requirement, namely that the SM singlets $\tilde{S}_a$, with $\alpha = 1, 2$, have rather small couplings to the third pair of Higgs doublets $H_u$ and $H_d$, i.e. $\lambda_{3\alpha} \approx 0$. This guarantees that $\tilde{S}_a$ develop rather small VEVs and the mixing between the neutral scalar components of $\tilde{S}_a$, $H_u$ and $H_d$ can be negligibly small so that it can be even ignored in the leading approximation. In this context it is worth pointing out that if couplings $\kappa_{3i}$, $\lambda_{3\alpha}$, $\lambda_{33}$ and $\lambda_{33}$ are set to be small at the scale $M_X$ then they will remain small at any scale below $M_X$.

Neglecting the Yukawa couplings $\lambda_{3\alpha}$ the low energy effective superpotential of the modified E$_6$SSM below the scale $\langle \tilde{S}_3 \rangle$ can be written as

\begin{equation}
W_{\text{eff}} \simeq \lambda_{a1} \tilde{S}_1 (\bar{H}^d_\alpha \tilde{H}^u_\alpha) + \kappa_{i1} \tilde{S}_1 (\bar{D}_i \tilde{D}_i) + \lambda_{a2} \tilde{S}_2 (\bar{H}^d_\alpha \tilde{H}^u_\alpha) + \kappa_{i2} \tilde{S}_2 (\bar{D}_i \tilde{D}_i) + \mu_{H_u} (\bar{H}^u_\alpha \tilde{H}^u_\alpha) + \mu_{D_i} (\bar{D}_i \tilde{D}_i) + W_{\text{MSSM}} (\mu \neq 0) .
\end{equation}

where $\alpha = 1, 2$ and $i = 1, 2, 3$. The superpotential (2.10) does not contain any mass terms that involve superfields $\tilde{S}_a$. This implies that the fermion components of $\tilde{S}_a$ can be very light. In particular, the corresponding states can be lighter than 0.1 eV forming hot dark matter in the Universe. Such fermion states have negligible couplings to $Z$ boson as well as other SM particles and therefore would not have been observed at earlier collider experiments. These states also do not change the branching ratios of the $Z$ boson and Higgs decays.\footnote{The presence of very light neutral fermions in the particle spectrum might have interesting implications for the neutrino physics (see, for example [195]).} Moreover if $Z'$ boson is sufficiently heavy the presence of such light fermion states does not affect Big Bang Nucleosynthesis [181–183].

The superpotential (2.10) contains ten new Yukawa couplings $\lambda_{a1}$, $\lambda_{a2}$, $\kappa_{i1}$ and $\kappa_{i2}$. The running of these Yukawa couplings obey the following system of the renormalization
group (RG) equations:

\[
\frac{d\lambda_1}{dt} = \frac{\lambda_1}{(4\pi)^2} \left[ 2\lambda_1^2 + 2\lambda_2^2 + 2 \left( \sum_\beta \lambda_\beta^2 \right) + 3 \left( \sum_j \kappa_j^2 \right) - 3g_2^2 \\
- \frac{3}{5}g_1^2 - \frac{19}{10}g_1^2 \right] + \frac{\lambda_2}{(4\pi)^2} \left[ 2 \left( \sum_\beta \lambda_\beta \lambda_\beta \right) + 3 \left( \sum_j \kappa_j \kappa_j \right) \right],
\]

\[
\frac{d\lambda_2}{dt} = \frac{\lambda_2}{(4\pi)^2} \left[ 2\lambda_1^2 + 2\lambda_2^2 + 2 \left( \sum_\beta \lambda_\beta^2 \right) + 3 \left( \sum_j \kappa_j^2 \right) - 3g_2^2 \\
- \frac{3}{5}g_1^2 - \frac{19}{10}g_1^2 \right] + \frac{\lambda_1}{(4\pi)^2} \left[ 2 \left( \sum_\beta \lambda_\beta \lambda_\beta \right) + 3 \left( \sum_j \kappa_j \kappa_j \right) \right],
\]

\[
\frac{d\kappa_1}{dt} = \frac{\kappa_1}{(4\pi)^2} \left[ 2\kappa_1^2 + 2\kappa_2^2 + 2 \left( \sum_\beta \lambda_\beta^2 \right) + 3 \left( \sum_j \kappa_j^2 \right) - \frac{16}{3}g_3^2 \\
- \frac{4}{15}g_1^2 - \frac{19}{10}g_1^2 \right] + \frac{\kappa_2}{(4\pi)^2} \left[ 2 \left( \sum_\beta \lambda_\beta \lambda_\beta \right) + 3 \left( \sum_j \kappa_j \kappa_j \right) \right],
\]

\[
\frac{d\kappa_2}{dt} = \frac{\kappa_2}{(4\pi)^2} \left[ 2\kappa_1^2 + 2\kappa_2^2 + 2 \left( \sum_\beta \lambda_\beta^2 \right) + 3 \left( \sum_j \kappa_j^2 \right) - \frac{16}{3}g_3^2 \\
- \frac{4}{15}g_1^2 - \frac{19}{10}g_1^2 \right] + \frac{\kappa_1}{(4\pi)^2} \left[ 2 \left( \sum_\beta \lambda_\beta \lambda_\beta \right) + 3 \left( \sum_j \kappa_j \kappa_j \right) \right].
\]

The requirement of validity of perturbation theory up to the Grand Unification scale $M_X$ restricts the interval of variations of these Yukawa couplings at low-energies. In our analysis here we use a set of one-loop RG equations (2.11) while the evolution of gauge couplings is calculated in the two-loop approximation.

3 750 GeV diphoton excess in the variant E₆SSM

Turning now to a discussion of the 750 GeV diphoton excess recently observed by ATLAS and CMS in the framework of the variant of the E₆SSM discussed in the previous section, whose effective superpotential is given by eq. (2.10). This SUSY model involves two SM singlet superfields $\hat{S}_{1,2}$ plus a set of extra vector-like supermultiplets beyond the MSSM, including two pairs of inert Higgs doublets ($\hat{H}_d^1$ and $\hat{H}_d^2$), as well as three generations of exotic quarks $\hat{D}_i$ and $\hat{D}_i$ with electric charges $\mp 1/3$.

The scenario discussed in this section is that the 750-760 GeV diphoton resonance may be identified as one or two scalars denoted $N_{1,2}$ and/or one or two pseudoscalars denoted $A_{1,2}$ contained in the two singlet superfields $\hat{S}_{1,2}$. The masses of these scalars and pseudoscalars arises from the soft SUSY breaking sector. However, to simplify our analysis, we assume that all other sparticles are sufficiently heavy so that their contributions
to the production and decay rates of states with masses around 750 GeV can be ignored. Moreover the scenario under consideration implies that almost all exotic vector-like fermion mass states are heavier than 375 GeV so that the on-shell decays of \( N_\alpha \) and \( A_\alpha \) into the corresponding particles are not kinematically allowed.

Integrating out the heavy fermions corresponding to two pairs of inert Higgsino doublets \( \tilde{H}_d \) and \( \tilde{H}_u \) and three generations of vector-like \( D_i \) and \( \bar{D}_i \) fermions, which appear in the usual triangle loop diagrams, one obtains the effective Lagrangian which describes the interactions of \( N_\alpha \) and \( A_\alpha \) with the SM gauge bosons,

\[
\mathcal{L}_{\text{eff}} = \sum_\alpha \left( c_{1\alpha} N_\alpha B_{\mu\nu} B^{\mu\nu} + c_{2\alpha} N_\alpha W_{\mu\nu}^a W^{a\mu\nu} + c_{3\alpha} N_\alpha G_{\mu\nu}^a G^{a\mu\nu} + \tilde{c}_{1\alpha} A_\alpha \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu} + \tilde{c}_{2\alpha} A_\alpha W_{\mu\nu}^a \tilde{W}^{a\mu\nu} + \tilde{c}_{3\alpha} A_\alpha G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \right),
\]

where

\[
\begin{align*}
c_{1\alpha} &= \frac{\alpha_Y}{16\pi} \left[ \sum_i \frac{2\kappa_{i\alpha}}{3\sqrt{2}\mu_{D_i}} A(x_D_i) + \sum_\beta \frac{\lambda_{i\beta\alpha}}{\sqrt{2}\mu_{H_\beta}} A(x_{H_\beta}) \right], \\
c_{2\alpha} &= \frac{\alpha_2}{16\pi} \left[ \sum_\beta \frac{\lambda_{i\beta\alpha}}{\sqrt{2}\mu_{H_\beta}} A(x_{H_\beta}) \right], \\
c_{3\alpha} &= \frac{\alpha_3}{16\pi} \left[ \sum_i \frac{\kappa_{i\alpha}}{\sqrt{2}\mu_{D_i}} A(x_D_i) \right],
\end{align*}
\]

\[
A(x) = 2x(1 + (1 - x) \arcsin^2[1/\sqrt{x}]), \quad \text{for} \quad x \geq 1.
\]

In eq. (3.1) \( B_{\mu\nu} \), \( W_{\mu\nu}^a \), \( G_{\mu\nu}^a \) are field strengths for the U(1)\(_Y\), SU(2)\(_W\) and SU(3)\(_C\) gauge interactions respectively while \( \tilde{G}^{a\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\lambda\rho} G_\lambda^a \) etc. In eqs. (3.2) \( x_{D_i} = 4\mu_{D_i}/M_X^2 \), \( x_{H_\alpha} = 4\mu_{H_\alpha}/M_X^2 \) and \( \alpha_Y = 3\alpha_1/5 \) whereas \( \alpha_1 \), \( \alpha_2 \) and \( \alpha_3 \) are (GUT normalised) gauge couplings of U(1)\(_Y\), SU(2)\(_W\) and SU(3)\(_C\) interactions. In order to obtain analytic expressions for \( \tilde{c}_{i\alpha} \) one should replace in eqs. (3.2) \( c_{i\alpha} \) by \( \tilde{c}_{i\alpha} \) and substitute function \( B(x) \) instead of \( A(x) \), where

\[
B(x) = 2x \arcsin^2[1/\sqrt{x}].
\]

Because in our analysis we focus on the diphoton decays of \( N_\alpha \) and \( A_\alpha \) that may lead to the 750 GeV diphoton excess it is convenient to use the effective Lagrangian that describes the interactions of these fields with the electromagnetic one. Using eq. (3.1) one obtains

\[
\mathcal{L}_{\text{eff}}^{\gamma\gamma} = \sum_\alpha \left( c_\gamma^\alpha N_\alpha F_{\mu\nu} F^{\mu\nu} + \tilde{c}_\gamma^\alpha A_\alpha F_{\mu\nu} \tilde{F}^{\mu\nu} \right),
\]

where \( c_\gamma^\alpha = c_{1\alpha}\cos^2\theta_W + c_{2\alpha}\sin^2\theta_W \), \( \tilde{c}_\gamma^\alpha = \tilde{c}_{1\alpha}\cos^2\theta_W + \tilde{c}_{2\alpha}\sin^2\theta_W \) and \( F_{\mu\nu} \) is a field strength associated with the electromagnetic interaction.

At the LHC the exotic states \( N_\alpha \) and \( A_\alpha \) can be predominantly produced through gluon fusion. When exotic quarks have masses below 1 TeV the corresponding production cross
section is rather large and determined by the effective couplings $|c_{3\alpha}|^2$ and $|\tilde{c}_{3\alpha}|^2$. However such states mainly decay into a pair of gluons which is very problematic to detect at the LHC. Therefore possible collider signatures of these exotic states are associated with their decays into $WW$, $ZZ$, $\gamma Z$ and $\gamma\gamma$. Since $W$ and $Z$ decay mostly into quarks the process $pp \to N_\alpha(A_\alpha) \to \gamma\gamma$ tends to be one of the most promising channels to search for such resonances. In the limit when exotic states decay predominantly into a pair of gluons the branching ratios of $N_\alpha \to \gamma\gamma$ and $A_\alpha \to \gamma\gamma$ are proportional to $|c_{3\alpha}|^2/|c_{3\alpha}|^2$ and $|\tilde{c}_{3\alpha}|^2/|\tilde{c}_{3\alpha}|^2$ respectively. As a consequence cross sections $\sigma(pp \to N_\alpha(A_\alpha) \to \gamma\gamma)$ do not depend on $|c_{3\alpha}|^2$ and $|\tilde{c}_{3\alpha}|^2$. The corresponding signal strengths are basically defined by the partial decay widths ($N_\alpha \to \gamma\gamma$) and ($A_\alpha \to \gamma\gamma$).

The cross sections of the processes that may result in the 750 GeV diphoton excess can be written as

$$\sigma(pp \to X_\alpha \to \gamma\gamma) \simeq \frac{C_{gg}}{M_{X_\alpha} s \Gamma_{X_\alpha}} \Gamma(X_\alpha \to gg) \Gamma(X_\alpha \to \gamma\gamma),$$

(3.5)

where $X_\alpha$ is either $N_\alpha$ or $A_\alpha$ exotic states, $\Gamma_{X_\alpha}$ is a total decay width of the resonance $X_\alpha$ while $C_{gg} \simeq 3163$, $\sqrt{s} \simeq 13$ TeV and $M_{X_\alpha}$ is the mass of the appropriate exotic state which should be somewhat around 750 GeV. The partial decay widths of the corresponding resonances are given by

$$\Gamma(N_\alpha \to gg) = \frac{2}{\pi} M_{N_\alpha}^3 |c_{3\alpha}|^2, \quad \Gamma(A_\alpha \to gg) = \frac{2}{\pi} M_{A_\alpha}^3 |\tilde{c}_{3\alpha}|^2,$$

$$\Gamma(N_\alpha \to \gamma\gamma) = \frac{M_{N_\alpha}^3}{4\pi} |c_{3\alpha}|^2, \quad \Gamma(A_\alpha \to \gamma\gamma) = \frac{M_{A_\alpha}^3}{4\pi} |\tilde{c}_{3\alpha}|^2.$$

(3.6)

In the limit when $\Gamma_{X_\alpha} \approx \Gamma(X_\alpha \to gg)$ the dependence of the cross section (3.5) on $\Gamma(X_\alpha \to gg)$ disappear and its value is determined by the partial decay width $\Gamma(X_\alpha \to \gamma\gamma)$ as one could naively expect. In this case, as it was pointed out in [10], one can obtain $\sigma(pp \to \gamma\gamma) \approx 8$ fb at the 13 TeV LHC if

$$\frac{\Gamma(X_\alpha \to \gamma\gamma)}{M_{X_\alpha}} = 1.1 \times 10^{-6}.$$

(3.7)

Then the cross section $\sigma_{\gamma\gamma} \approx \sigma(pp \to \gamma\gamma)$ for arbitrary partial decay widths of $X_\alpha \to \gamma\gamma$ can be approximately estimated as

$$\sigma_{\gamma\gamma} \simeq 7.3$ fb $\times \text{BR}(X_\alpha \to gg) \times \left(\frac{\Gamma(X_\alpha \to \gamma\gamma)}{M_{X_\alpha}} \times 10^6\right).$$

(3.8)

where the branching ratios associated with the decays of exotic states into gluons $g$ and vector bosons $V$ ($V = \gamma$, $W^\pm$, $Z$) are given by

$$\text{BR}(X_\alpha \to gg) = \frac{\Gamma(X_\alpha \to gg)}{\Gamma_{X_\alpha}}, \quad \text{BR}(X_\alpha \to VV) = \frac{\Gamma(X_\alpha \to VV)}{\Gamma_{X_\alpha}}.$$

(3.9)

In eqs. (3.9) $\Gamma(X_\alpha \to gg)$ and $\Gamma(X_\alpha \to VV)$ are partial decay widths that correspond to the exotic state decays into a pair of gluons and a pair of vector bosons respectively whereas $\Gamma_{X_\alpha}$ is a total decay width of this state.
3.1 One scalar/pseudoscalar case

Let us now consider the scenario when one of the scalar/pseudoscalar exotic states \( N_1 \) or \( A_1 \) has a mass which is rather close to 750 GeV. From eqs. (3.2)–(3.4) and (3.6) it follows that the diphoton decay rates of these new bosons and the corresponding signal strength depend very strongly on the values of the Yukawa couplings \( \lambda_{a1} \) and \( \kappa_{i1} \). On the other hand the growth of these Yukawa couplings at low energies entails the increase of their values at the Grand Unification scale \( M_X \) resulting in the appearance of the Landau pole that spoils the applicability of perturbation theory at high energies (see, for example [196–198]). The requirement of validity of perturbation theory up to the scale \( M_X \) sets an upper bound on the low energy value of \( \lambda_{a1} \) and \( \kappa_{i1} \). In our analysis we use two-loop SM RG equations to compute the values of the gauge couplings at the scale \( Q = 2 \) TeV. Above this scale we use two-loop RG equations for the gauge couplings and one-loop RG equations for the Yukawa couplings including the ones given by eq. (2.11) to analyse the RG flow of these couplings. In the simplest case when \( \lambda_{a1} = \kappa_{i1} \) our numerical analysis indicates that the values of these couplings at the scale \( Q = 2 \) TeV should not exceed 0.6.

The upper bound on the coupling \( \lambda_{a1} \) becomes less stringent when \( \kappa_{i1} \) are small. In the limit when all \( \kappa_{i1} \) vanish the value of \( \lambda_{11} = \lambda_{21} \) has to remain smaller than 0.81 to ensure the applicability of perturbation theory up to the GUT scale. Although in this case \( \Gamma(A_1 \to \gamma\gamma) \) and \( \Gamma(N_1 \to \gamma\gamma) \) attain their maximal value the production cross sections of exotic states \( N_1 \) or \( A_1 \) are negligibly small since they are determined by the low-energy values of \( \kappa_{i1} \). The upper bounds on \( \kappa_{i1} \) can be also significantly relaxed when \( \lambda_{11} = \lambda_{21} = 0 \). If this is a case then the requirement of the validity of perturbation theory implies that \( \kappa_{11} = \kappa_{21} = \kappa_{31} \lesssim 0.79 \). However in this limit the diphoton production rate associated with the presence \( A_1 \) or \( N_1 \) is again negligibly small because the corresponding partial decay width vanish. Thus in this section we focus on the scenario with \( \lambda_{a1} = \kappa_{i1} = 0.6 \). This choice of parameters guarantees that the production cross sections of \( N_1 \) and \( A_1 \) as well as their partial decay width can be sufficiently large.

In figures 1a and 1b the dependence of the branching ratios of the exotic pseudoscalar and scalar states on the masses of exotic quarks is examined. To simplify our analysis the masses of all exotic quarks are set to be equal while the masses of all inert Higgsinos are assumed to be around 400 GeV. From figure 1a and 1b it follows that the exotic pseudoscalar and scalar states decay predominantly into a pair of gluons when the masses of exotic quarks \( \mu_D \) are below 1 TeV. Moreover if \( \mu_D \) is close to 400 – 500 GeV all other branching ratios are negligibly small. With increasing \( \mu_D \) the branching ratio of the exotic pseudoscalar (scalar) state decays into gluons decreases whereas the branching ratios of the decays of this state into \( W^+W^−, ZZ, \gamma\gamma \) and \( \gamma Z \) increase. The branching ratios of \( A_1(N_1) \to WW \) and \( A_1(N_1) \to ZZ \) are the second and third largest ones. The branching ratio of \( A_1(N_1) \to \gamma\gamma \) is considerably smaller but still larger than \( A_1(N_1) \to \gamma Z \). Although the branching ratios of \( A_1(N_1) \to WW \) and \( A_1(N_1) \to ZZ \) can be a substantially bigger than the branching ratio \( A_1(N_1) \to \gamma\gamma \) their experimental detection is more problematic because \( W \) and \( Z \) decays mainly into quarks. When \( \mu_D \) is around 1 TeV the branching ratio of \( A_1(N_1) \to gg \) is still the largest one and constitutes about 75%(80%) while for \( \mu_D \simeq 2 \) TeV the branching ratios of \( A_1(N_1) \to gg \) and \( A_1(N_1) \to WW \) become comparable.
Figure 1. Predictions for the one pseudoscalar (left panels) or one scalar (right panels) case. In all cases the masses of vector-like quarks are set to be equal, i.e. $\mu_D = \mu_{\tilde{D}}$, whereas $\lambda_{\alpha 1} = \kappa_{\alpha 1} = 0.6$, $\lambda_{\alpha 2} = \kappa_{\alpha 2} = 0$. In (a) the branching ratios of the decays of $A_1$ into $\gamma Z$ (lowest solid line), $\gamma \gamma$ (second lowest solid line), $ZZ$ (third lowest solid line), $WW$ (second highest solid line) and $gg$ (highest solid line) as a function of exotic quark masses $\mu_D$ for $M_{A_1} \approx 750$ GeV. In (b) the branching ratios of the decays of $N_1$ into $\gamma Z$ (lowest dashed line), $\gamma \gamma$ (second lowest dashed line), $ZZ$ (third lowest dashed line), $WW$ (second highest dashed line) and $gg$ (highest dashed line) as a function of $\mu_D$ for $M_{N_1} \approx 750$ GeV. In (c) the ratios $\Gamma(A_1 \to \gamma \gamma)/M_X$ as a function of $\mu_D$ for $M_{A_1} \approx 750$ GeV. The upper and lower solid lines correspond to the scenarios with $\mu_{H_{\alpha}} = 400$ GeV and $\mu_{H_{\alpha}} = 500$ GeV. In (d) the ratios $\Gamma(N_1 \to \gamma \gamma)/M_X$ as a function of $\mu_D$ for $M_{N_1} \approx 750$ GeV. The upper and lower dashed lines correspond to the scenarios with $\mu_{H_{\alpha}} = 400$ GeV and $\mu_{H_{\alpha}} = 500$ GeV. In (e) the cross sections $\sigma(pp \to A_1 \to \gamma \gamma)$ in fb as a function of $\mu_D$ for $M_{A_1} \approx 750$ GeV. The upper and lower solid lines represent the scenarios with $\mu_{H_{\alpha}} = 400$ GeV and $\mu_{H_{\alpha}} = 500$ GeV. In (f) the cross sections $\sigma(pp \to N_1 \to \gamma \gamma)$ in fb as a function of $\mu_D$ for $M_{N_1} \approx 750$ GeV. The upper and lower dashed lines represent the scenarios with $\mu_{H_{\alpha}} = 400$ GeV and $\mu_{H_{\alpha}} = 500$ GeV.
In figure 1c and 1d we explore the dependence of the partial decay widths associated with the decays of the exotic pseudoscalar and scalar states into a pair of photons on the masses of exotic quarks and inert Higgsinos $\mu_{H_a}$. One can see that these decay widths decrease very rapidly with increasing $\mu_{H_a}$. The dependence on the masses of exotic quarks is weaker because these states carry small electric charges $\pm 1/3$. Since here we assume that $\kappa_{i1}/\mu_{D_i}$ and $\lambda_{a1}/\mu_{H_a}$ have the same sign the growth of either exotic quark masses or $\mu_{H_a}$ results in the reduction of the corresponding decay rate. When $\mu_D$ is larger than 1.5 TeV the dependence of the partial decay widths under consideration becomes rather weak. From figure 1c and 1d it is easy to see that the partial width of the decays $A_1 \to \gamma \gamma$ is substantially larger than the one associated with $N_1 \to \gamma \gamma$ leading to the larger value of the cross sections $\sigma(pp \to A_1 \to \gamma \gamma)$ as compared with $\sigma(pp \to N_1 \to \gamma \gamma)$.

In our analysis we use eq. (3.8) to estimate the values of the cross sections $\sigma(pp \to A_1 \to \gamma \gamma)$ and $\sigma(pp \to N_1 \to \gamma \gamma)$ at the 13 TeV LHC. The results of our investigation are shown in figures 1e and 1f. In the case of scalar exotic states with mass 750 GeV this cross section tends to be substantially smaller than 1 fb. The presence of 750 GeV exotic pseudoscalar can lead to the considerably stronger signal in the diphoton channel. When all exotic quarks have masses around 400–500 GeV the corresponding cross section can reach 2–3 fb. Somewhat stronger signal can be obtained if we assume that both scalar and pseudoscalar exotic states have masses which are close to 750 GeV. The existence of two nearly degenerate resonances may also explain why the analysis performed by the ATLAS collaboration leads to the relatively large best-fit width which is about 45 GeV. Unfortunately, the cross sections mentioned above decrease substantially with increasing exotic quark masses. Indeed, if $\mu_D \gtrsim 1$ TeV the sum of the cross sections $\sigma(pp \to A_1 \to \gamma \gamma) + \sigma(pp \to N_1 \to \gamma \gamma)$ does not exceed 2 fb. These cross sections continue to fall even for $\mu_D \gtrsim 1.5$ TeV when the corresponding partial decay widths are rather close to their lower saturation limits because the branching ratios associated with the decays of $A_1$ and $N_1$ into a pair of gluons decrease with increasing $\mu_D$.

3.2 Two degenerate scalar/pseudoscalar case

Now let us assume that there are two superfields $\hat{S}_1$ and $\hat{S}_2$ that have sufficiently large Yukawa couplings to the exotic quark and inert Higgsino states and can contribute to the measured cross section $pp \to \gamma \gamma$. In other words we assume that scalar and pseudoscalar components of both superfields can have masses around 750 GeV. Naively one may expect that this could allow to enhance the theoretical prediction for the cross section $pp \to \gamma \gamma$. Again we start from the simplest case when all Yukawa couplings are the same. Then the numerical analysis indicates that in this case the requirement of the validity of perturbation theory up to the scale $M_X$ sets even more stringent upper bound on the low energy value of the Yukawa couplings as compared with the one scalar/pseudoscalar case. Indeed, using the one-loop RG equations (2.11) and two-loop RG equations for the gauge couplings one obtains that $\lambda_{a1} = \kappa_{i1} = \lambda_{a2} = \kappa_{i2} = \lambda_0 \lesssim 0.43$. Smaller values of the Yukawa couplings do not affect the branching ratios of $A_1$ and $N_1$. Moreover $A_2$ and $A_1$ as well as $N_2$ and $N_1$ have basically the same branching ratios. This is because partial decay widths of $A_{1,2}$ and
Figure 2. Predictions for two degenerate pseudoscalars (left panels) or two degenerate scalars (right panels) case. In all cases $\mu_D = \mu_D$, while $\mu_{H,c} = 400\text{ GeV}$, $\lambda_{a1} = \kappa_{i1} = 0.43$ and $\lambda_{a2} = \kappa_{i2} = 0.41$. In (a) the branching ratios of the decays of $A_{1,2}$ into $\gamma Z$ (lowest solid line), $\gamma\gamma$ (second lowest solid line), $ZZ$ (third lowest solid line), $WW$ (second highest solid line) and $gg$ (highest solid line) as a function of exotic quark masses $\mu_D$ for $M_{A_{1,2}} \simeq 750\text{ GeV}$. In (b) the branching ratios of the decays of $N_{1,2}$ into $\gamma Z$ (lowest dashed line), $\gamma\gamma$ (second lowest dashed line), $ZZ$ (third lowest dashed line), $WW$ (second highest dashed line) and $gg$ (highest dashed line) as a function of $\mu_D$ for $M_{N_{1,2}} \simeq 750\text{ GeV}$. In (c) the ratios $\Gamma(A_1 \to \gamma\gamma)/M_X$ (upper solid line) and $\Gamma(A_2 \to \gamma\gamma)/M_X$ (lower solid line) as a function of $\mu_D$ for $M_{A_{1,2}} \simeq 750\text{ GeV}$. In (d) the ratios $\Gamma(N_1 \to \gamma\gamma)/M_X$ (upper dashed line) and $\Gamma(N_2 \to \gamma\gamma)/M_X$ (lower dashed line) as a function of $\mu_D$ for $M_{N_{1,2}} \simeq 750\text{ GeV}$. In (e) the cross sections (fb) $\sigma(pp \to A_{1,2} \to \gamma\gamma)$ (upper solid line) and $\sigma(pp \to A_2 \to \gamma\gamma)$ (lower solid line) as a function of $\mu_D$ for $M_{A_{1,2}} \simeq 750\text{ GeV}$. The dashed-dotted line correspond to the sum of these cross sections. In (f) the cross sections (fb) $\sigma(pp \to N_{1,2} \to \gamma\gamma)$ (upper dashed line) and $\sigma(pp \to N_2 \to \gamma\gamma)$ (lower dashed line) as a function of $\mu_D$ for $M_{N_{1,2}} \simeq 750\text{ GeV}$. The dashed-dotted line correspond to the sum of these cross sections.
$N_{1,2}$ as well as the corresponding total widths are proportional to $\lambda_0^2$. As a consequence in the leading approximation branching ratios do not depend on $\lambda_0$ (see figure 2a and 2b). On the other hand as one can see from figure 1c, 1d, 1e and 1f the partial decay widths of $A_{1,2} \to \gamma\gamma$ and $N_{1,2} \to \gamma\gamma$ as well as the cross sections $\sigma(pp \to A_{1,2} \to \gamma\gamma)$ and $\sigma(pp \to N_{1,2} \to \gamma\gamma)$ are reduced by factor 2 because of the smaller values of the Yukawa couplings. If all exotic states $A_1$ and $A_2$ as well as $N_1$ and $N_2$ are nearly degenerate around 750 GeV so that their distinction is not possible within present experimental accuracy, then the superpositions of rates from these bosons basically reproduces the corresponding rates in the one scalar/pseudoscalar case (see figures 1e, 1f, 2e and 2f). Thus, it seems rather problematic to achieve any enhancement of the signal in the diphoton channel in the scenario when all Yukawa couplings are equal or reasonably close to each other.

### 3.3 Maximal mixing scenario

Following on from the discussion in the previous subsection, there is one case when a modest enhancement of the signal in the diphoton channel can be achieved. This happens in the so-called maximal mixing scenario when the masses of exotic scalars as well as the masses of exotic pseudoscalars are rather close to 750 GeV and the breakdown of SUSY gives rise to the mixing of these states preserving CP conservation. In this case one can expect that the mixing angles between CP-odd exotic states and CP-even exotic states tend to be rather large, i.e. about $\pm \pi/4$, because these bosons are nearly degenerate. To simplify our analysis here we set these angles to be equal to $\pi/4$. Then the scalar components of the superfields $S_1$ and $S_2$ can be expressed in terms of the mass eigenstates $N_1$, $N_2$, $A_1$ and $A_2$ as follows

$$S_1 = \frac{1}{2} (N_1 + N_2 + i(A_1 + A_2)) , \quad S_2 = \frac{1}{2} (N_1 - N_2 + i(A_1 - A_2)) . \quad (3.10)$$

In addition we assume that only superfield $S_1$ couples to the inert Higgsino states, i.e. $\lambda_{i2} = 0$, and only superfield $S_2$ couples to the exotic quarks, i.e. $\kappa_{i1} = 0$. In this limit the requirement of the validity of perturbation theory up to the scale $M_X$ implies that $\lambda_{i1} = \lambda_0 \lesssim 0.8$ and $\kappa_{i2} = \kappa_0 \lesssim 0.79$.

Setting $\mu_{H_\alpha} = \mu_H$, $\mu_{D_i} = \mu_D$ and $M_{N_1} \simeq M_{N_2} \simeq M_{A_1} \simeq M_{A_2} \simeq M_X = 750$ GeV one can obtain simple analytical expressions for the partial decay widths of $N_1$, $A_1$, $N_2$ and $A_2$ into a pair of photons

$$\Gamma(N_1 \to \gamma\gamma) = \frac{\alpha^2 M_X^3}{256\pi^3} \left| \frac{\lambda_0}{\mu_H} A(x_H) + \frac{\kappa_0}{2\mu_D} A(x_D) \right|^2 , \quad (3.11)$$

$$\Gamma(A_1 \to \gamma\gamma) = \frac{\alpha^2 M_X^3}{256\pi^3} \left| \frac{\lambda_0}{\mu_H} B(x_H) + \frac{\kappa_0}{2\mu_D} B(x_D) \right|^2 , \quad (3.12)$$

$$\Gamma(N_2 \to \gamma\gamma) = \frac{\alpha^2 M_X^3}{256\pi^3} \left| \frac{\lambda_0}{\mu_H} A(x_H) - \frac{\kappa_0}{2\mu_D} A(x_D) \right|^2 , \quad (3.13)$$

$$\Gamma(A_2 \to \gamma\gamma) = \frac{\alpha^2 M_X^3}{256\pi^3} \left| \frac{\lambda_0}{\mu_H} B(x_H) - \frac{\kappa_0}{2\mu_D} B(x_D) \right|^2 , \quad (3.14)$$
Figure 3. Predictions for the branching ratios in the maximal mixing scenario for two maximally mixed pseudoscalars (left panels) or two maximally mixed scalars (right panels) case. In all cases the masses of exotic quarks are set to be equal, i.e. \( \mu_D = \mu_D \), while \( \mu_{H_u} = 400 \text{ GeV} \), \( \lambda_{\alpha_1} = 0.8 \), \( \kappa_{i_2} = 0.79 \) and \( \kappa_{i_1} = \lambda_{\alpha_2} = 0 \). In (a) the branching ratios of the decays of \( A_1 \) into \( \gamma Z \) (lowest solid line), \( \gamma \gamma \) (second lowest solid line), \( ZZ \) (third lowest solid line), \( WW \) (second highest solid line) and \( gg \) (highest solid line) as a function of exotic quark masses for \( M_{A_1} \simeq 750 \text{ GeV} \). In (b) the branching ratios of the decays of \( N_1 \) into \( \gamma Z \) (lowest dashed line), \( \gamma \gamma \) (second lowest dashed line), \( ZZ \) (third lowest dashed line), \( WW \) (second highest dashed line) and \( gg \) (highest dashed line) as a function of exotic quark masses for \( M_{N_1} \simeq 750 \text{ GeV} \). In (c) the branching ratios of the decays of \( A_2 \) into \( \gamma \gamma \) (lowest solid line), \( \gamma Z \) (second lowest solid line), \( ZZ \) (second lowest solid line), \( WW \) (second highest solid line) and \( gg \) (highest solid line) as a function of exotic quark masses for \( M_{A_1} \simeq 750 \text{ GeV} \). In (d) the branching ratios of the decays of \( N_2 \) into \( \gamma \gamma \) (lowest dashed line), \( \gamma Z \) (second lowest dashed line), \( ZZ \) (third lowest dashed line), \( WW \) (second highest dashed line) and \( gg \) (highest dashed line) as a function of exotic quark masses for \( M_{N_1} \simeq 750 \text{ GeV} \).

where \( x_D = 4\mu_D^2/M_X^2 \) and \( x_H = 4\mu_H^2/M_X^2 \). Assuming, that \( \kappa_0/\mu_D \) and \( \lambda_0/\mu_D \) have the same sign, eqs. (3.11) and (3.12) are very similar to the ones which was used before for the calculation of the corresponding partial decay widths in one scalar/pseudoscalar case. Because the expressions for other partial decay widths are also very similar the branching ratios shown in figures 3a and 3b are almost the same as in figures 1a and 1b. At the same time in the case of \( N_2 \) and \( A_2 \) destructive interference between the contributions of exotic quarks and inert Higgsinos occurs. This leads to the suppression of the diphoton partial decay width. As a consequence when exotic quarks are lighter than 1 TeV the branching ratios of the decays \( N_2 \to \gamma \gamma \) and \( A_2 \to \gamma \gamma \) are the lowest ones (see figures 3c and 3d).
As before from figure 3 it follows that all exotic states $N_1$, $A_1$, $N_2$ and $A_2$ decay mainly into a pair of gluons. The corresponding branching ratio decreases with increasing $\mu_D$ because $c_{3a}$ and $\tilde{c}_{3a}$ diminish. The branching ratios of the decay of these states into $WW$ and $ZZ$ are the second largest and third largest ones. These branching ratios are substantially larger than the ones associated with the decays of exotic states into $\gamma\gamma$ and $\gamma Z$. In the case of $N_2$ and $A_2$ the branching ratios of the decay of these states into $WW$ can be an order of magnitude larger than the branching ratios of $N_2 \to \gamma\gamma$ and $A_2 \to \gamma\gamma$. Nevertheless the observation of the decays of $N_\alpha$ and $A_\alpha$ into pairs of WW and ZZ tend to be more problematic since $W$ and $Z$ decay mostly into quarks. All branching ratios of the exotic scalar and pseudoscalar decays except the largest one grow with increasing $\mu_D$. As a result for $\mu_D \simeq 2$ TeV the branching ratios of $A_\alpha(N_\alpha) \to gg$ and $A_\alpha(N_\alpha) \to WW$ become sufficiently close.

The dependence of the partial decay widths and the corresponding cross sections at the 13 TeV LHC associated with the decays of the exotic pseudoscalar and scalar states into a pair of photons on the exotic quark masses is shown in figure 4. The results of our calculations for $N_1$ and $A_1$ are very similar to the ones obtained in the one scalar/pseudoscalar case (see figure 2e and 2f). The partial decay widths and the cross sections $\sigma(pp \to A_1(N_1) \to \gamma\gamma)$ are just a bit smaller since the Yukawa couplings of $A_1$ and $N_1$ to the exotic quarks and inert Higgsino states are slightly smaller. They decrease with increasing the masses of exotic quarks $\mu_D$ as before. On the contrary, the partial decay widths of $N_2 \to \gamma\gamma$ and $A_2 \to \gamma\gamma$ increase with increasing the exotic quark masses for fixed values of inert Higgsino masses because of the destructive interference mentioned above. They attain their maximal values for $\mu_D \gg 1$ TeV when the contribution of the exotic quarks to the partial decay widths become vanishingly small. The cross sections $\sigma(pp \to A_2(N_2) \to \gamma\gamma)$ also increase with increasing exotic quark masses when $\mu_D \lesssim 700$ GeV. However if exotic quarks are considerably heavier than 1 TeV then these cross sections become smaller for larger $\mu_D$ since the branching ratios of $A_2(N_2) \to gg$ diminish.

The sums of the cross sections $\sigma(pp \to N_1 \to \gamma\gamma) + \sigma(pp \to N_2 \to \gamma\gamma)$ and $\sigma(pp \to A_1 \to \gamma\gamma) + \sigma(pp \to A_2 \to \gamma\gamma)$ that correspond to the case when all exotic scalar and pseudoscalar states have masses around 750 GeV decreases with increasing $\mu_D$ (see figures 4c and 4d). At large values of the exotic quark masses these cross sections are bigger than the ones in the one scalar/pseudoscalar case shown in figure 1e and 1f. This is because the requirement of the validity of perturbation theory up to the scale $M_X$ allows for larger values of $\lambda_{a1}$ in the maximal mixing scenario as compared with the one scalar/pseudoscalar case. From figures 4c and 4d one can see that the sum of all cross section that includes contributions of all scalar and pseudoscalar states with masses around 750 GeV decreases from 4.5 fb to 3 fb when the exotic quark masses vary from 400 GeV to 1 TeV. The presence of such nearly degenerate states in the particle spectrum may also provide an explanation why the value of the best-fit width of the resonance obtained by ATLAS collaboration is so large.

4 Conclusions

In this paper we have proposed a variant of the $E_6$SSM in which the third singlet $S_3$ breaks the gauged $U(1)_N$ above the TeV scale, which predicts a $Z'_N$, vector-like colour triplet.
Figure 4. Predictions for the maximal mixing scenario for two maximally mixed pseudoscalars (left panels) or two maximally mixed scalars (right panels) case. In all cases $\mu_{H_u} = 400$ GeV, $\lambda_{\alpha 1} = 0.8$, $\kappa_{\alpha 2} = 0.79$, $\lambda_{\alpha 2} = \kappa_{\alpha 1} = 0$ and the masses of exotic quarks are set to be equal, i.e. $\mu_{D_1} = \mu_D$. In (a) the ratios $\Gamma(A_1 \to \gamma\gamma)/M_X$ (upper solid line) and $\Gamma(A_2 \to \gamma\gamma)/M_X$ (lower solid line) as a function of exotic quark masses in the maximal mixing scenario for $M_{A_1} \simeq 750$ GeV. In (b) the ratios $\Gamma(N_1 \to \gamma\gamma)/M_X$ (upper dashed line) and $\Gamma(N_2 \to \gamma\gamma)/M_X$ (lower dashed line) as a function of exotic quark masses in the maximal mixing scenario for $M_{N_1} \simeq 750$ GeV. In (c) the cross sections in fb $\sigma(pp \to A_1 \to \gamma\gamma)$ (upper solid line) and $\sigma(pp \to A_2 \to \gamma\gamma)$ (lower solid line) as a function of exotic quark masses for $M_{A_1,2} \simeq 750$ GeV. The dashed-dotted line correspond to the sum of these cross sections. In (d) the cross sections in fb $\sigma(pp \to N_1 \to \gamma\gamma)$ (upper dashed line) and $\sigma(pp \to N_2 \to \gamma\gamma)$ (lower dashed line) as a function of exotic quark masses for $M_{N_1,2} \simeq 750$ GeV. The dashed-dotted line correspond to the sum of these cross sections.

and charge $\mp 1/3$ quarks $D, \bar{D}$, and two families of inert Higgsinos, all of which should be observed at LHC Run 2, plus the two lighter singlets $\tilde{S}_1$ with masses around 750 GeV which are candidates for the recently observed diphoton excess. We have calculated the branching ratios and cross-sections for the two scalars $N_{1,2}$ and two pseudoscalars $A_{1,2}$ associated with $\tilde{S}_{1,2}$, including possible degeneracies and maximal mixing, subject to the constraint that their couplings remain perturbative up to the unification scale.

Our results show that this variant of the E6SSM with two nearly degenerate pseudoscalars $A_{1,2}$ with masses around 750 GeV, may give rise to cross sections of $pp \to \gamma\gamma$ that can be as large as about 3 fb providing that the inert Higgsino states have masses around 400 GeV, while the three generations of $D, \bar{D}$ are lighter than about 1 TeV. If the two
nearly degenerate scalars $N_{1,2}$ also have masses around 750 GeV, then these cross-sections may be further boosted by about 1 fb, assuming that they are at present unresolvable. The existence of nearly degenerate spinless singlets provides an explanation for why the best-fit width of the 750 GeV resonance obtained by the ATLAS collaboration is apparently so large, i.e. about 45 GeV. However further data from Run 2 should begin to resolve the two separate pseudoscalar states $A_{1,2}$ (plus perhaps the two scalar states $N_{1,2}$).

Finally we emphasise that the three families of light vector-like D-quarks around 1 TeV and two families of inert Higgsinos around 400 GeV, although not currently ruled out because of their non-standard decay patterns, should be observable in dedicated searches at Run 2 of the LHC. The $Z_N^0$ gauge boson also remains a prediction of the $E_6$ SSM. In addition, the proposed variant $E_6$ SSM also predicts further decay modes of the 750 GeV resonance into $WW$, $ZZ$ and $\gamma Z$ that might be possible to observe in the Run 2 at the LHC.

Acknowledgments

RN is grateful to P. Athron, P. Jackson, J. Li, M. Mühlleitner, P. Sharma, R. Young and J. Zanotti for helpful discussions. RN also thanks E. Boos, X. Tata and A. W. Thomas for useful comments and remarks. The work of R.N. was supported by the University of Adelaide and the Australian Research Council through the ARC Center of Excellence in Particle Physics at the Terascale. SFK acknowledges partial support from the STFC Consolidated ST/J000396/1 grant and the European Union FP7 ITN-INVISIBLES (Marie Curie Actions, PITN- GA-2011-289442).

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References

[1] ATLAS collaboration, Search for resonances decaying to photon pairs in 3.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, ATLAS-CONF-2015-081, CERN, Geneva Switzerland (2015).
[2] CMS collaboration, Search for new physics in high mass diphoton events in proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS-PAS-EXO-15-004, CERN, Geneva Switzerland (2015).
[3] K. Harigaya and Y. Nomura, Composite models for the 750 GeV diphoton excess, Phys. Lett. B 754 (2016) 151 [arXiv:1512.04850] [insPIRE].
[4] Y. Mambrini, G. Arcadi and A. Djouadi, The LHC diphoton resonance and dark matter, Phys. Lett. B 755 (2016) 426 [arXiv:1512.04913] [insPIRE].
[5] M. Backovic, A. Mariotti and D. Redigolo, Di-photon excess illuminates dark matter, arXiv:1512.04917 [insPIRE].
[6] A. Angelescu, A. Djouadi and G. Moreau, Scenarii for interpretations of the LHC diphoton excess: two Higgs doublets and vector-like quarks and leptons, arXiv:1512.04921 [insPIRE].
[7] Y. Nakai, R. Sato and K. Tobioka, Footprints of new strong dynamics via anomaly, arXiv:1512.04924 [insPIRE].

– 17 –
[8] S. Knapen, T. Melia, M. Papucci and K. Zurek, *Rays of light from the LHC*, arXiv:1512.04928 [inSPIRE].

[9] A. Pilaftsis, *Diphoton signatures from heavy axion decays at the CERN Large Hadron Collider*, Phys. Rev. D 93 (2016) 015017 [arXiv:1512.04931] [inSPIRE].

[10] R. Franceschini et al., *What is the $\gamma\gamma$ resonance at 750 GeV?*, arXiv:1512.04933 [inSPIRE].

[11] S. Di Chiara, L. Marzola and M. Raidal, *First interpretation of the 750 GeV di-photon resonance at the LHC*, arXiv:1512.04939 [inSPIRE].

[12] J. Ellis, S.A.R. Ellis, J. Quevillon, V. Sanz and T. You, *On the interpretation of a possible $\sim 750$ GeV particle decaying into $\gamma\gamma$*, arXiv:1512.05327 [inSPIRE].

[13] B. Bellazzini, R. Franceschini, F. Sala and J. Serra, *Goldstones in diphotons*, arXiv:1512.05330 [inSPIRE].

[14] R.S. Gupta, S. Jäger, Y. Kats, G. Perez and E. Stamou, *Interpreting a 750 GeV diphoton resonance*, arXiv:1512.05332 [inSPIRE].

[15] T. Higaki, K.S. Jeong, N. Kitajima and F. Takahashi, *The QCD axion from aligned axions and diphoton excess*, Phys. Lett. B 755 (2016) 13 [arXiv:1512.05295] [inSPIRE].

[16] S.D. McDermott, P. Meade and H. Ramani, *Singlet scalar resonances and the diphoton excess*, Phys. Lett. B 755 (2016) 353 [arXiv:1512.05326] [inSPIRE].

[17] M. Low, A. Tesi and L.-T. Wang, *A pseudoscalar decaying to photon pairs in the early LHC Run 2 data*, arXiv:1512.05328 [inSPIRE].

[18] C. Petersson and R. Torre, *The 750 GeV diphoton excess from the goldstino superpartner*, arXiv:1512.05333 [inSPIRE].

[19] E. Molinaro, F. Sannino and N. Vignaroli, *Minimal composite dynamics versus axion origin of the diphoton excess*, arXiv:1512.05334 [inSPIRE].

[20] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze and T. Li, *Interpretation of the diphoton excess at CMS and ATLAS*, arXiv:1512.05439 [inSPIRE].

[21] 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 [inSPIRE].

[22] 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 [inSPIRE].

[23] D. Becirevic, E. Bertuzzo, O. Sumensari and R.Z. Funchal, *Can the new resonance at LHC be a CP-odd Higgs boson?*, arXiv:1512.05623 [inSPIRE].

[24] J.M. No, V. Sanz and J. Setford, *See-saw composite Higgses at the LHC: linking naturalness to the 750 GeV di-photon resonance*, arXiv:1512.05700 [inSPIRE].

[25] S.V. Demidov and D.S. Gorbunov, *On goldstino interpretation of the diphoton excess*, arXiv:1512.05723 [inSPIRE].

[26] W. Chao, R. Huo and J.-H. Yu, *The minimal scalar-stealth top interpretation of the diphoton excess*, arXiv:1512.05738 [inSPIRE].
[29] S. Fichet, G. von Gersdorff and C. Royon, Scattering light by light at 750 GeV at the LHC, arXiv:1512.05751 [asPIRE].

[30] D. Curtin and C.B. Verhaaren, Quirky explanations for the diphoton excess, Phys. Rev. D 93 (2016) 055011 [arXiv:1512.05753] [asPIRE].

[31] L. Bian, N. Chen, D. Liu and J. Shu, A hidden confining world on the 750 GeV diphoton excess, arXiv:1512.05759 [asPIRE].

[32] 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 [asPIRE].

[33] C. Csáki, J. Hubisz and J. Terning, Minimal model of a diphoton resonance: production without gluon couplings, Phys. Rev. D 93 (2016) 035002 [arXiv:1512.05776] [asPIRE].

[34] A. Falkowski, O. Slone and T. Volansky, Phenomenology of a 750 GeV singlet, JHEP 02 (2016) 152 [arXiv:1512.05777] [asPIRE].

[35] Y. Bai, J. Berger and R. Lu, A 750 GeV dark pion: cousin of a dark G-parity-odd WIMP, arXiv:1512.05779 [asPIRE].

[36] R. Benbrik, C.-H. Chen and T. Nomura, Higgs singlet as a diphoton resonance in a vector-like quark model, arXiv:1512.06028 [asPIRE].

[37] 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 (2016) 403 [arXiv:1512.06083] [asPIRE].

[38] E. Gabrielli, K. Kannike, B. Mele, M. Raidal, C. Spethmann and H. Veermäe, A SUSY inspired simplified model for the 750 GeV diphoton excess, arXiv:1512.05961 [asPIRE].

[39] A. Alves, A.G. Dias and K. Sinha, The 750 GeV S-cion: where else should we look for it?, arXiv:1512.06091 [asPIRE].

[40] E. Megias, O. Pujolàs and M. Quiró, On dilatons and the LHC diphoton excess, arXiv:1512.06106 [asPIRE].

[41] L.M. Carpenter, R. Colburn and J. Goodman, Supersoft SUSY models and the 750 GeV diphoton excess, beyond effective operators, arXiv:1512.06107 [asPIRE].

[42] J. Bernon and C. Smith, Could the width of the diphoton anomaly signal a three-body decay?, arXiv:1512.06113 [asPIRE].

[43] W. Chao, Symmetries behind the 750 GeV diphoton excess, arXiv:1512.06297 [asPIRE].

[44] C. Han, H.M. Lee, M. Park and V. Sanz, The diphoton resonance as a gravity mediator of dark matter, Phys. Lett. B 755 (2016) 371 [arXiv:1512.06376] [asPIRE].

[45] S. Chang, A simple U(1) gauge theory explanation of the diphoton excess, Phys. Rev. D 93 (2016) 055016 [arXiv:1512.06426] [asPIRE].

[46] M. Dhuria and G. Goswami, Perturbativity, vacuum stability and inflation in the light of 750 GeV diphoton excess, arXiv:1512.06782 [asPIRE].

[47] H. Han, S. Wang and S. Zheng, Scalar explanation of diphoton excess at LHC, arXiv:1512.06562 [asPIRE].

[48] M.-X. Luo, K. Wang, T. Xu, L. Zhang and G. Zhu, Squarkonium/disquarkonium and the di-photon excess, arXiv:1512.06670 [asPIRE].
[49] J. Chang, K. Cheung and C.-T. Lu, *Interpreting the 750 GeV di-photon resonance using photon-jets in hidden-valley-like models*, arXiv:1512.06671 [inSPIRE].

[50] D. Bardhan, D. Bhatia, A. Chakraborty, U. Maitra, S. Raychaudhuri and T. Samui, *Radion candidate for the LHC diphoton resonance*, arXiv:1512.06674 [inSPIRE].

[51] 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 [inSPIRE].

[52] W. Liao and H.-Q. Zheng, *Scalar resonance at 750 GeV as composite of heavy vector-like fermions*, arXiv:1512.06741 [inSPIRE].

[53] W.S. Cho et al., *The 750 GeV diphoton excess may not imply a 750 GeV resonance*, arXiv:1512.06824 [inSPIRE].

[54] 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*, arXiv:1512.06842 [inSPIRE].

[55] R. Ding, L. Huang, T. Li and B. Zhu, *Interpreting 750 GeV diphoton excess with R-parity violation supersymmetry*, arXiv:1512.06560 [inSPIRE].

[56] X.-F. Han and L. Wang, *Implication of the 750 GeV diphoton resonance on two-Higgs-doublet model and its extensions with Higgs field*, arXiv:1512.06587 [inSPIRE].

[57] O. Antipin, M. Mojaza and F. Sannino, *A natural Coleman-Weinberg theory explains the diphoton excess*, arXiv:1512.06708 [inSPIRE].

[58] F. Wang, L. Wu, J.M. Yang and M. Zhang, *750 GeV diphoton resonance, 125 GeV Higgs and muon g-2 anomaly in delected anomaly mediation SUSY breaking scenario*, arXiv:1512.06715 [inSPIRE].

[59] 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 (2016) 456 [arXiv:1512.06728] [inSPIRE].

[60] F.P. Huang, C.S. Li, Z.L. Liu and Y. Wang, *750 GeV diphoton excess from cascade decay*, arXiv:1512.06732 [inSPIRE].

[61] J.J. Heckman, *750 GeV diphotons from a D3-brane*, arXiv:1512.06773 [inSPIRE].

[62] 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*, arXiv:1512.06787 [inSPIRE].

[63] J.S. Kim, K. Robiecki and R.R. de Austri, *Model-independent combination of diphoton constraints at 750 GeV*, arXiv:1512.06797 [inSPIRE].

[64] L. Berthier, J.M. Cline, W. Shepherd and M. Trott, *Effective interpretations of a diphoton excess*, arXiv:1512.06799 [inSPIRE].

[65] J.M. Cline and Z. Liu, *LHC diphotons from electroweakly pair-produced composite pseudoscalars*, arXiv:1512.06827 [inSPIRE].

[66] M. Bauer and M. Neubert, *Flavor anomalies, the diphoton excess and a dark matter candidate*, arXiv:1512.06828 [inSPIRE].

[67] 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 (2016) 145 [arXiv:1512.06833] [inSPIRE].
[68] S.M. Boucenna, S. Morisi and A. Vicente, The LHC diphoton resonance from gauge symmetry, arXiv:1512.06878 [hep-ph].
[69] P.S.B. Dev and D. Teresi, Asymmetric dark matter in the sun and the diphoton excess at the LHC, arXiv:1512.07243 [hep-ph].
[70] J. de Blas, J. Santiago and R. Vega-Morales, New vector bosons and the diphoton excess, arXiv:1512.07229 [hep-ph].
[71] C.W. Murphy, Vector leptoquarks and the 750 GeV diphoton resonance at the LHC, arXiv:1512.06976 [hep-ph].
[72] A.E.C. Hernández and I. Nisandzic, LHC diphoton 750 GeV resonance as an indication of SU(3)$_C$ × SU(3)$_L$ × U(1)$_X$ gauge symmetry, arXiv:1512.07165 [hep-ph].
[73] U.K. Dey, S. Mohanty and G. Tomar, 750 GeV resonance in the dark left-right model, arXiv:1512.07212 [hep-ph].
[74] G.M. Pelaggi, A. Strumia and E. Vigiani, Trinification can explain the di-photon and di-boson LHC anomalies, JHEP 03 (2016) 025 [arXiv:1512.07225] [hep-ph].
[75] A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, A. Parolini and H. Servidio, Singlets in composite Higgs models in light of the LHC di-photon searches, arXiv:1512.07242 [hep-ph].
[76] W.-C. Huang, Y.-L.S. Tsai and T.-C. Yuan, Gauged two Higgs doublet model confronts the LHC 750 GeV di-photon anomaly, arXiv:1512.07268 [hep-ph].
[77] Q.-H. Cao, S.-L. Chen and P.-H. Gu, Strong CP problem, neutrino masses and the 750 GeV diphoton resonance, arXiv:1512.07541 [hep-ph].
[78] J. Gu and Z. Liu, Running after diphoton, arXiv:1512.07624 [hep-ph].
[79] K.M. Patel and P. Sharma, Interpreting 750 GeV diphoton excess in SU(5) grand unified theory, arXiv:1512.07468 [hep-ph].
[80] M. Badziak, Interpreting the 750 GeV diphoton excess in minimal extensions of two-Higgs-doublet models, arXiv:1512.07497 [hep-ph].
[81] S. Chakraborty, A. Chakraborty and S. Raychaudhuri, Diphoton resonance at 750 GeV in the broken MRSSM, arXiv:1512.07527 [hep-ph].
[82] W. Altmannshofer, J. Galloway, S. Gori, A.L. Kagan, A. Martin and J. Zupan, On the 750 GeV di-photon excess, arXiv:1512.07616 [hep-ph].
[83] M. Cvetič, J. Halverson and P. Langacker, String consistency, heavy exotics and the 750 GeV diphoton excess at the LHC, arXiv:1512.07622 [hep-ph].
[84] B.C. Allanach, P.S.B. Dev, S.A. Renner and K. Sakurai, Di-photon excess explained by a resonant sneutrino in R-parity violating supersymmetry, arXiv:1512.07645 [hep-ph].
[85] H. Davoudiasl and C. Zhang, 750 GeV messenger of dark conformal symmetry breaking, Phys. Rev. D 93 (2016) 055006 [arXiv:1512.07672] [hep-ph].
[86] K. Das and S.K. Rai, The 750 GeV diphoton excess in a U(1) hidden symmetry model, arXiv:1512.07789 [hep-ph].
[87] K. Cheung, P. Ko, J.S. Lee, J. Park and P.-Y. Tseng, A Higgcision study on the 750 GeV di-photon resonance and 125 GeV SM Higgs boson with the Higgs-singlet mixing, arXiv:1512.07853 [hep-ph].
[88] N. Craig, P. Draper, C. Kilic and S. Thomas, How the $\gamma\gamma$ resonance stole christmas, arXiv:1512.07733 [INSPIRE].

[89] J. Liu, X.-P. Wang and W. Xue, LHC diphoton excess from colorful resonances, arXiv:1512.07885 [INSPIRE].

[90] J. Zhang and S. Zhou, Electroweak vacuum stability and diphoton excess at 750 GeV, arXiv:1512.07889 [INSPIRE].

[91] J.A. Casas, J.R. Espinosa and J.M. Moreno, The 750 GeV diphoton excess as a first light on supersymmetry breaking, arXiv:1512.07895 [INSPIRE].

[92] L.J. Hall, K. Harigaya and Y. Nomura, 750 GeV diphotons: implications for supersymmetric unification, JHEP 03 (2016) 017 [arXiv:1512.07904] [INSPIRE].

[93] J.-C. Park and S.C. Park, Indirect signature of dark matter with the diphoton resonance at 750 GeV, arXiv:1512.08117 [INSPIRE].

[94] A. Salvio and A. Mazumdar, Higgs stability and the 750 GeV diphoton excess, arXiv:1512.08184 [INSPIRE].

[95] G. Li, Y.-N. Mao, Y.-L. Tang, C. Zhang, Y. Zhou and S.-H. Zhu, A loop-philic pseudoscalar, arXiv:1512.08255 [INSPIRE].

[96] M. Son and A. Urbano, A new scalar resonance at 750 GeV: towards a proof of concept in favor of strongly interacting theories, arXiv:1512.08307 [INSPIRE].

[97] H. An, C. Cheung and Y. Zhang, Broad diphotons from narrow states, arXiv:1512.08378 [INSPIRE].

[98] F. Wang, W. Wang, L. Wu, J.M. Yang and M. Zhang, Interpreting 750 GeV diphoton resonance in the NMSSM with vector-like particles, arXiv:1512.08434 [INSPIRE].

[99] Q.-H. Cao, Y. Liu, K.-P. Xie, B. Yan and D.-M. Zhang, The diphoton excess, low energy theorem and the 331 model, arXiv:1512.08441 [INSPIRE].

[100] J. Gao, H. Zhang and H.X. Zhu, Diphoton excess at 750 GeV: gluon-gluon fusion or quark-antiquark annihilation?, arXiv:1512.08478 [INSPIRE].

[101] F. Goertz, J.F. Kamenik, A. Katz and M. Nardecchia, Indirect constraints on the scalar di-photon resonance at the LHC, arXiv:1512.08500 [INSPIRE].

[102] P.S.B. Dev, R.N. Mohapatra and Y. Zhang, Quark seesaw, vectorlike fermions and diphoton excess, arXiv:1512.08507 [INSPIRE].

[103] J. Cao, F. Wang and Y. Zhang, Interpreting the 750 GeV diphoton excess within topflavor seesaw model, arXiv:1512.08392 [INSPIRE].

[104] C. Cai, Z.-H. Yu and H.-H. Zhu, The 750 GeV diphoton resonance as a singlet scalar in an extra dimensional model, arXiv:1512.08440 [INSPIRE].

[105] J.E. Kim, Is an axizilla possible for di-photon resonance?, Phys. Lett. B 755 (2016) 190 [arXiv:1512.08467] [INSPIRE].

[106] W. Chao, Neutrino catalyzed diphoton excess, arXiv:1512.08484 [INSPIRE].

[107] L.A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lüst and T.R. Taylor, 750 GeV diphotons from closed string states, Phys. Lett. B 755 (2016) 312 [arXiv:1512.08502] [INSPIRE].
[108] N. Bizot, S. Davidson, M. Frigerio and J.-L. Kneur, *Two Higgs doublets to explain the excesses pp → γγ(750 GeV) and h → τ±μ∓*, arXiv:1512.08508 [INSPIRE].

[109] L.E. Ibáñez and V. Martín-Lozano, *A megaxion at 750 GeV as a first hint of low scale string theory*, arXiv:1512.08777 [INSPIRE].

[110] X.-J. Huang, W.-H. Zhang and Y.-F. Zhou, *A 750 GeV dark matter messenger at the galactic center*, arXiv:1512.08992 [INSPIRE].

[111] C.-W. Chiang, M. Ibe and T.T. Yanagida, *Revisiting scalar quark hidden sector in light of 750 GeV diphoton resonance*, arXiv:1512.08895 [INSPIRE].

[112] S.K. Kang and J. Song, *Top-phobic heavy Higgs boson as the 750 GeV diphoton resonance*, arXiv:1512.08963 [INSPIRE].

[113] S. Kanemura, K. Nishiwaki, H. Okada, Y. Orikasa, S.C. Park and R. Watanabe, *LHC 750 GeV diphoton excess in a radiative seesaw model*, arXiv:1512.09048 [INSPIRE].

[114] I. Low and J. Lykken, *Implications of gauge invariance on a heavy diphoton resonance*, arXiv:1512.09089 [INSPIRE].

[115] A.E.C. Hernández, *The 750 GeV diphoton resonance can cause the SM fermion mass and mixing pattern*, arXiv:1512.09092 [INSPIRE].

[116] K. Kaneta, S. Kang and H.-S. Lee, *Diphoton excess at the LHC Run 2 and its implications for a new heavy gauge boson*, arXiv:1512.09129 [INSPIRE].

[117] A. Dasgupta, M. Mitra and D. Borah, *Minimal left-right symmetry confronted with the 750 GeV di-photon excess at LHC*, arXiv:1512.09202 [INSPIRE].

[118] A. Berlin, *The diphoton and diboson excesses in a left-right symmetric theory of dark matter*, Phys. Rev. D 93 (2016) 055015 [arXiv:1601.01381] [INSPIRE].

[119] H. Zhang, *The 750 GeV diphoton excess: who introduces it?*, arXiv:1601.01355 [INSPIRE].

[120] F.F. Deppisch, C. Hati, S. Patra, P. Pritimita and U. Sarkar, *Implications of the diphoton excess on left-right models and gauge unification*, arXiv:1601.00952 [INSPIRE].

[121] B. Dutta et al., *Diphoton excess in consistent supersymmetric SU(5) models with vector-like particles*, arXiv:1601.00666 [INSPIRE].

[122] T. Modak, S. Sadhukhan and R. Srivastava, *750 GeV diphoton excess from gauged B-L symmetry*, arXiv:1601.00836 [INSPIRE].

[123] A.E.C. Hernández, I.d.M. Varzielas and E. Schumacher, *The 750 GeV diphoton resonance in the light of a 2HDM with S3 flavour symmetry*, arXiv:1601.00661 [INSPIRE].

[124] C. Csáki, J. Hubisz, S. Lombardo and J. Terning, *Gluon vs. photon production of a 750 GeV diphoton resonance*, arXiv:1601.00638 [INSPIRE].

[125] W. Chao, *The diphoton excess from an exceptional supersymmetric standard model*, arXiv:1601.00633 [INSPIRE].

[126] 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 [INSPIRE].

[127] K. Ghorbani and H. Ghorbani, *The 750 GeV diphoton excess from a pseudoscalar in fermionic dark matter scenario*, arXiv:1601.00602 [INSPIRE].
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*, arXiv:1601.00534 [inSPIRE].

P. Ko, Y. Omura and C. Yu, *Diphoton excess at 750 GeV in leptonphobic U(1)\(_Y\)* model inspired by Eq. GUT, arXiv:1601.00586 [inSPIRE].

T. Nomura and H. Okada, *Four-loop neutrino model inspired by diphoton excess at 750 GeV*, Phys. Lett. B 755 (2016) 306 [arXiv:1601.00386] [inSPIRE].

E. Palti, *Vector-like exotics in F-theory and 750 GeV diphotons*, arXiv:1601.00285 [inSPIRE].

C.T. Potter, *Pseudoscalar gluinonia to diphotons at the LHC*, arXiv:1601.00240 [inSPIRE].

S. Bhattacharya, S. Patra, N. Sahoo and N. Sahu, *750 GeV di-photon excess at CERN LHC from a dark sector assisted scalar decay*, arXiv:1601.00386 [inSPIRE].

D. Borah, S. Patra and S. Sahoo, *Subdominant left-right scalar dark matter as origin of the 750 GeV di-photon excess at LHC*, arXiv:1601.01828 [inSPIRE].

P. Ko and T. Nomura, *Dark sector shining through 750 GeV dark Higgs boson at the LHC*, arXiv:1601.02490 [inSPIRE].

J. Cao, L. Shang, W. Su, Y. Zhang and J. Zhu, *Interpreting the 750 GeV diphoton excess in the minimal dilaton model*, arXiv:1601.02570 [inSPIRE].

M. Fabbrichesi and A. Urbano, *The breaking of the SU(2)\(_L\) \times U(1)\(_Y\) symmetry: the 750 GeV resonance at the LHC and perturbative unitarity*, arXiv:1601.02447 [inSPIRE].

C. Hati, *Explaining the diphoton excess in alternative left-right symmetric model*, arXiv:1601.02457 [inSPIRE].

J.-H. Yu, *Hidden gauged U(1)\(_{\tau}\) model: unifying scotogenic neutrino and flavor dark matter*, arXiv:1601.02609 [inSPIRE].

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*, arXiv:1601.02714 [inSPIRE].

I. Dorsner, S. Fa\'ijer and N. Kosnik, *Is symmetry breaking of SU(5) theory responsible for the diphoton excess?*, arXiv:1601.03267 [inSPIRE].

A. Djouadi, J. Ellis, R. Godbole and J. Quevillon, *Future collider signatures of the possible 750 GeV state*, arXiv:1601.03696 [inSPIRE].

A.E. Faraggi and J. Rizos, *The 750 GeV diphoton LHC excess and extra Z’s in heterotic-string derived models*, arXiv:1601.03604 [inSPIRE].

A. Ghoshal, *On electroweak phase transition and di-photon excess with a 750 GeV scalar resonance*, arXiv:1601.04291 [inSPIRE].

T. Nomura and H. Okada, *Four-loop radiative seesaw model with 750 GeV diphoton resonance*, arXiv:1601.04516 [inSPIRE].

W. Chao, *The diphoton excess inspired electroweak baryogenesis*, arXiv:1601.04678 [inSPIRE].

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 \(\rightarrow \mu\tau\)*, arXiv:1601.04954 [inSPIRE].
[148] H. Okada and K. Yagyu, *Renormalizable model for neutrino mass, dark matter, muon g-2 and 750 GeV diphoton excess*, arXiv:1601.05038 [inSPIRE].

[149] D.B. Franzosi and M.T. Frandsen, *Symmetries and composite dynamics for the 750 GeV diphoton excess*, arXiv:1601.05357 [inSPIRE].

[150] A. Martini, K. Mawatari and D. Sengupta, *Diphoton excess in phenomenological spin-2 resonance scenarios*, arXiv:1601.05729 [inSPIRE].

[151] 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*, arXiv:1601.06374 [inSPIRE].

[152] C.-W. Chiang and A.-L. Kuo, *Can the 750 GeV diphoton resonance be the singlet Higgs boson of custodial Higgs triplet model?*, arXiv:1601.06394 [inSPIRE].

[153] U. Aydemir and T. Mandal, *Interpretation of the 750 GeV diphoton excess with colored scalars in SO(10) grand unification*, arXiv:1512.09136 [inSPIRE].

[154] S.F. King, S. Moretti and R. Nevzorov, *Spectrum of Higgs particles in the ESSM*, hep-ph/0601269 [inSPIRE].

[155] P. Athron, S.F. King, D.J. Miller, S. Moretti and R. Nevzorov, *Predictions of the constrained exceptional supersymmetric standard model*, Phys. Lett. B 681 (2009) 035009 [arXiv:0901.1192] [inSPIRE].

[156] P. Athron, S.F. King, D.J. Miller, S. Moretti and R. Nevzorov, *LHC signatures of the constrained exceptional supersymmetric standard model*, Phys. Rev. D 84 (2011) 055006 [arXiv:1102.4363] [inSPIRE].

[157] S.F. King, S. Moretti and R. Nevzorov, *Spectrum of Higgs particles in the ESSM*, hep-ph/0601269 [inSPIRE].
[166] S.F. King, S. Moretti and R. Nevzorov, $E_6$SSM, *AIP Conf. Proc.* **881** (2007) 138 [hep-ph/0610002] [SPIRE].

[167] P. Athron et al., *The constrained $E_6$SSM*, arXiv:0810.0617 [SPIRE].

[168] P. Athron et al., *Aspects of the exceptional supersymmetric standard model*, Nucl. Phys. Proc. Suppl. B **200-202** (2010) 120 [SPIRE].

[169] S.F. King, R. Luo, D.J. Miller and R. Nevzorov, *Leptogenesis in the exceptional supersymmetric standard model: flavour dependent lepton asymmetries*, JHEP **12** (2008) 042 [arXiv:0806.0330] [SPIRE].

[170] J.P. Hall et al., *Novel Higgs decays and dark matter in the $E_6$SSM*, Phys. Rev. D **83** (2011) 075013 [arXiv:1012.5114] [SPIRE].

[171] R. Nevzorov, *$E_6$ inspired supersymmetric models with exact custodial symmetry*, Phys. Rev. D **87** (2013) 015029 [arXiv:1205.5967] [SPIRE].

[172] P. Athron, M. Binjonaïd and S.F. King, *Fine tuning in the constrained exceptional supersymmetric standard model*, Phys. Rev. D **87** (2013) 115023 [arXiv:1302.5291] [SPIRE].

[173] J.P. Hall and S.F. King, *Bino dark matter and big bang nucleosynthesis in the constrained $E_6$SSM with massless inert singlinos*, JHEP **06** (2011) 006 [arXiv:1104.2259] [SPIRE].

[174] J.P. Hall and S.F. King, *Neutralino dark matter with inert higgsinos and singlinos*, JHEP **08** (2009) 088 [arXiv:0905.2696] [SPIRE].

[175] P. Athron, M. Mühlleitner, R. Nevzorov and A.G. Williams, *Non-standard Higgs decays in U(1) extensions of the MSSM*, JHEP **01** (2015) 153 [arXiv:1410.6288] [SPIRE].

[176] P. Athron, D. Harries, R. Nevzorov and A.G. Williams, *$E_6$ inspired SUSY benchmarks, dark matter relic density and a 125 GeV Higgs*, arXiv:1512.07040 [SPIRE].

[177] R. Howl and S.F. King, *Minimal $E_6$ supersymmetric standard model*, JHEP **01** (2008) 030 [arXiv:0708.1451] [SPIRE].
[185] R. Howl and S.F. King, *Planck scale unification in a supersymmetric standard model*, Phys. Lett. B 652 (2007) 331 [arXiv:0705.0301] [nSPIRE].

[186] R. Howl and S.F. King, *Exceptional supersymmetric standard models with non-Abelian discrete family symmetry*, JHEP 05 (2008) 008 [arXiv:0802.1909] [nSPIRE].

[187] R. Howl and S.F. King, *Solving the flavour problem in supersymmetric standard models with three Higgs families*, Phys. Lett. B 687 (2010) 355 [arXiv:0908.2067] [nSPIRE].

[188] J.C. Callaghan, S.F. King, G.K. Leontaris and G.G. Ross, *Towards a realistic F-theory GUT*, JHEP 04 (2012) 094 [arXiv:1109.1399] [nSPIRE].

[189] J.C. Callaghan and S.F. King, *E6 models from F-theory*, JHEP 04 (2013) 034 [arXiv:1210.6913] [nSPIRE].

[190] J.C. Callaghan, S.F. King and G.K. Leontaris, *Gauge coupling unification in E6 F-theory GUTs with matter and bulk exotics from flux breaking*, JHEP 12 (2013) 037 [arXiv:1307.4593] [nSPIRE].

[191] A. Belyaev, J.P. Hall, S.F. King and P. Svantesson, *Discovering E6 supersymmetric models in gluino cascade decays at the LHC*, Phys. Rev. D 87 (2013) 035019 [arXiv:1211.1962] [nSPIRE].

[192] A. Belyaev, J.P. Hall, S.F. King and P. Svantesson, *Novel gluino cascade decays in E6 inspired models*, Phys. Rev. D 86 (2012) 031702 [arXiv:1203.2495] [nSPIRE].

[193] A. Belyaev, J.P. Hall, S.F. King and P. Svantesson, *Novel gluino cascade decays in E6 inspired models*, Phys. Rev. D 86 (2012) 031702 [arXiv:1203.2495] [nSPIRE].

[194] CMS collaboration, *Search for a narrow resonance produced in 13 TeV pp collisions decaying to electron pair or muon pair final states*, CMS-PAS-EXO-15-005, CERN, Geneva Switzerland (2015).

[195] J.M. Frere, R.B. Nevzorov and M.I. Vysotsky, *Stimulated neutrino conversion and bounds on neutrino magnetic moments*, Phys. Lett. B 394 (1997) 127 [hep-ph/9608266] [nSPIRE].

[196] R.B. Nevzorov and M.A. Trusov, *Infrared quasi fixed solutions in the NMSSM*, Phys. Atom. Nucl. 64 (2001) 1299 [Yad. Fiz. 64 (2001) 1375] [hep-ph/0110363] [nSPIRE].

[197] R.B. Nevzorov and M.A. Trusov, *Quasi fixed point scenario in the modified NMSSM*, Phys. Atom. Nucl. 65 (2002) 335 [Yad. Fiz. 65 (2002) 359] [hep-ph/0301179] [nSPIRE].

[198] R.B. Nevzorov and M.A. Trusov, *Renormalization of the soft SUSY breaking terms in the strong Yukawa coupling limit in the NMSSM*, Phys. Atom. Nucl. 64 (2001) 1513 [Yad. Fiz. 64 (2001) 1589] [hep-ph/0112301] [nSPIRE].