Diphoton resonance at 750 GeV in the broken MRSSM

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Non-observation of superpartners of the Standard Model particles at the early runs of the LHC provide strong motivation for an $R$-symmetric minimal supersymmetric Standard Model, or MRSSM. This model also comes with a pair of extra scalars which couple only to superpartners at the tree level. We demonstrate that in the limit when the $U(1)_R$ symmetry is broken, one of these scalars develops all the properties necessary to explain the 750 GeV diphoton resonance recently observed at the LHC, as well as the non-observation of associated signals in other channels. Some confirmatory tests in the upcoming LHC runs are proposed.

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I. INTRODUCTION

In many ways, supersymmetric models remain the best option for new physics beyond the Standard Model (SM) of electroweak and strong interactions. The discovery of a light, probably elementary, scalar in 2012 [1] has made this motivation, if anything, stronger than ever. However, this must be coupled with the somewhat disappointing fact that the early runs of the Large Hadron Collider (LHC) at CERN, Geneva, have not found any of the promised signals for supersymmetry (SUSY) [2, 3]. Moreover, the decay modes of the 125 GeV scalar found in 2012 appear increasingly to resemble those of the SM Higgs boson [4]. Though all this does not invalidate the idea of SUSY per se, it has made it increasingly difficult to fit the observed results with popular models of SUSY, such as the so-called minimal supersymmetric SM, or MSSM.

To add to this tension, we have the recent announcement that both the ATLAS and CMS Collaborations seem to have observed [5, 6] an excess of diphoton events in the 13 TeV run, which commenced earlier this year. The excess events appear to arise from a resonant production of an intermediate scalar particle of mass around 750 GeV and a width which is best-fitted as 45 GeV. At the same time, both the experimental collaborations have announced that searches for deviations from the SM prediction in all other channels have produced null results. Their principal results on the diphoton excess are summarised below.

- The ATLAS Collaboration has observed [5] an excess of 14 events, with a peak at 750 GeV and a best-fit width of 45 GeV, in 3.2 fb$^{-1}$ of data at $\sqrt{s} = 13$ TeV. The local significance of this excess is 3.9$\sigma$, but it reduces to about 2.6$\sigma$ if the look Elsewhere effect is included. Taking into account the experimental acceptance value of about 0.4, this corresponds to an excess signal of 10 ± 3 fb.

- The CMS Collaboration has observed [6] an excess of 10 events, with a peak at 760 GeV, in 2.6 fb$^{-1}$ of data at $\sqrt{s} = 13$ TeV. The local significance of this excess is 2.3$\sigma$, but it reduces to about 2.0$\sigma$ if the width is assumed to be around 45 GeV. Taking into account the experimental acceptance value of about 40%, this corresponds to an excess signal of 6 ± 3 fb.

While there is a strong probability that this excess is only a statistical fluctuation in the data, there is always the exciting possibility that this may be the first observed manifestation of new physics at the LHC – or, for that matter, any other collider experiment. Undoubtedly, this announcement has stirred the theoretical mind, for several new physics interpretations of this excess have already appeared in the literature. For example, models with vector-like fermions and extended scalar sectors [7–13], SUSY [7, 14], extra dimensions [10, 15], axions and composite scalars [16, 17], vector resonances [18], leptoquarks [19], dark matter candidates [12, 20], minimal gauge extensions of the SM and MSSM [21] have been studied. Some have proposed model-independent tests of the signal [16, 22], and others have constructed scenarios in which the presence of a diphoton excess and the absence of any other signals arises in a natural way [23]. In addition, electroweak vacuum stability and inflation in the presence of this new resonance has been analysed in Refs. [24]. However, it is probably a fair statement to say that an explanation of the current results is rather difficult to obtain in any of the popular ‘minimal’ models which have hitherto been the mainstay of phenomenological studies of physics beyond the SM. Quite naturally, therefore, many of the proposed scenarios invoke exotic options, which are barely permitted by the experimental data and do not conform to the choices commonly seen earlier in the literature [25]. It is interesting, therefore, to ask, if there can be found a well-motivated model, where...
a specific scenario in the parameter choices could explain the observed facts in this regard.

In this article, we consider the minimal $R$-symmetric supersymmetric SM, or MRSSM [26], which – apart from the usual virtues of a SUSY model – can explain in a natural way, the non-observance of SUSY-specific signals at the LHC in the present and previous runs. These models generally contain Dirac gauginos in their spectra as opposed to Majorana gauginos in MSSM. The presence of a Dirac gluino reduces the production cross-section for squarks considerably, explaining their absence in LHC data. Multiple versions of models with Dirac gauginos can be found in the literature on SUSY [27]. In these, flavor and CP-violation constraints are suppressed [28] and issues pertaining to neutrino mass generation and dark matter can also be addressed [29, 30]. To cut a long story short, once we have Dirac gauginos in a $R$-symmetric model, it becomes necessary to incorporate two additional $SU(2)_L$-doublet chiral superfields $\hat{R}_u$ and $\hat{R}_d$ carrying nonzero $R$-charges. To avoid spontaneous $R$-breaking and the emergence of $R$-axions, the scalar components of $\hat{R}_u$ and $\hat{R}_d$ do not receive any nonzero vacuum expectation value (vev). Hence they are dubbed ‘inert’ doublets. It is one of these ‘inert’ scalars which we propose as a candidate for the 750 GeV resonance.

The plan of this paper is as follows. In Section II, we describe the $R$-symmetric version of the MSSM, illustrating the role of the ‘inert’ doublets mentioned above. We then go on, in Section III, to explain how $R$-symmetry requires to be broken in order to obtain a left-right mixing in the top-squark sector, which is vital to get a diphoton signal. Section IV is devoted to an explanation of how the diphoton excess arises in this model. In Section V, we summarise our results and mention some tests which may falsify this scenario in future runs of the LHC.

II. MRSSM – THE FRAMEWORK

In $R$-symmetric models, one adds to the symmetries of the SM an extra $U(1)_R$ global symmetry, under which the superpartner fields transform, but the SM fields do not. This $R$-symmetry prohibits Majorana gaugino masses, trilinear scalar couplings and forces us to set the Higgsino mass parameter $\mu = 0$. Hence, the gauginos need to be Dirac fermions, to construct which one needs to introduce additional superfields, such as a color and $SU(2)_L$ singlet $\hat{S}$, a colorless $SU(2)_L$ triplet $\hat{T}$ and another $SU(2)_L$ triplet $\hat{\phi}$ which transforms as an octet under $SU(3)_c$. An immediate consequence of this is that squarks coupling to quarks and a Dirac gluino have much lower production cross-sections at the LHC than they would have had in the usual case of a Majorana gluino. This significantly weakens the rather tight constraints on light squarks which have already been obtained at the LHC. To ensure, however, that the lighter chargino $\tilde{\chi}^{-1}_1$ does not become massless, we require to generate a $\mu$ term by adding two new superfields $\tilde{R}_u$ and $\tilde{R}_d$ carrying nonzero $R$-charges. The SM gauge quantum numbers and $U(1)_R$ charges of all the chiral superfields in the model are shown in Table I. It is important to note that the scalars $\tilde{R}_u$ and $\tilde{R}_d$ have the same $R$-charge as the superfields $\tilde{R}_u$ and $\tilde{R}_d$ whereas the $R$-charges of the fermions $\tilde{R}_u$ and $\tilde{R}_d$ are less by one unit. In addition, to have an invariant action, the superpotential has to have charge assignments of $SU(2)_L \times SU(3)_c \times U(1)_Y$ as well as their $U(1)_R$ charge assignments.

### Table I: The chiral superfields in the MRSSM, showing their $SU(2)_L \times SU(3)_c \times U(1)_Y$ and $U(1)_R$ charges.

| Superfields | SM rep | $U(1)_R$ |
|-------------|--------|----------|
| $Q_i$       | $(3, 2, \frac{1}{6})$ | 1        |
| $U^c_i$     | $(3, 1, -\frac{2}{3})$ | 1        |
| $D^c_i$     | $(3, 1, \frac{2}{3})$ | 1        |
| $L_i$       | $(1, 2, -1)$ | 1        |
| $\tilde{E}^c_i$ | $(1, 1, 2)$ | 1        |
| $H_u$       | $(1, 2, 1)$ | 0        |
| $\tilde{H}_d$ | $(1, 2, -1)$ | 0        |
| $R_u$       | $(1, 2, -1)$ | 2        |
| $\tilde{R}_d$ | $(1, 2, 1)$ | 2        |
| $S$         | $(1, 1, 0)$ | 0        |
| $\tilde{T}$ | $(1, 3, 0)$ | 0        |
| $\tilde{\phi}$ | $(8, 1, 0)$ | 0        |

This potential can now be minimised to find the scalar eigenstates of the model. It is important to note that after electroweak symmetry breaking, the $R_u^0$ and $R_d^0$ scalars mix with each other, but not with the $H^0$ state.
Moreover, the $R$-charge assignments of these $R$-scalars restrict their trilinear couplings only to (a) sfermions and chargino/neutralino combinations, e.g. $R\tilde{\ell}\tilde{\ell}$, $R\tilde{q}\tilde{q}$, $R\tilde{\chi}_1\tilde{\chi}_1$, and (b) paired-$R$ scalars to SM bosons, i.e. $RRH$ and $RRV$, where $V = W^\pm, Z^0$. $R$-scalar couplings to pairs of any SM particle vanish. $R$-scalar couplings to sfermions, which play a major role in our work, are

$$
\mathcal{L}_{R\tilde{f}\tilde{f}} = -\mu_u Y_u R_u^0 \bar{\tilde{u}}_R \tilde{u}_L^* - \mu_d Y_d R_d^0 \bar{\tilde{d}}_R \tilde{d}_L^* - \mu_{\tilde{u}} Y_{\tilde{u}} R_{\tilde{u}}^0 \bar{\tilde{u}}_R \tilde{u}_L^*.
$$

where $Y_u$, $Y_d$ and $Y_{\tilde{u}}$ are Yukawa couplings of the SM and a sum over generations is implicit. For third generation quarks we have $Y_t \gg Y_b$ and therefore we will mostly confine ourselves to the $R^0_u$ scalar. It is important to note that the $R^0_u$ scalar couples only to $\tilde{q}_L\tilde{q}_R^*$ pairs, and not to $\tilde{q}_L\tilde{q}_L^*$ or $\tilde{q}_R\tilde{q}_R^*$ pairs. As a result, in the $R$-conserving scenario, the $R^0_u$ scalar cannot couple to photon pairs through top-squark loops as there is no mixing between the $t_L$ and $t_R$ states. It is clear, therefore, that a diphoton signal from decay of a resonant $R^0_u$ requires us to break $R$-symmetry.

### III. $R$-SYMMETRY BREAKING

In addition to the phenomenological need mentioned in the previous section, there exist strong motivations for the breaking of $R$-symmetry from cosmological considerations \[31\]. Assuming, therefore, that the $R$-symmetry breaks spontaneously in the hidden sector (like supersymmetry) the $R$-breaking information must be communicated to the visible sector by some mechanism such as gravity mediation, anomaly mediation, etc. For our purposes, we do not require to consider a particular breaking mechanism, but it suffices to parametrise the $R$-breaking information in terms of a set of trilinear scalar couplings (which also break SUSY). In fact, for an $R^0_u$-scalar decaying to two photons via top-squark loops, the only relevant $R$-breaking term in the Lagrangian is given as

$$
\mathcal{L}_{\mu R} = A_t H_u \tilde{Q}_3 \tilde{U}_3^*,
$$

where $A_t$ is the trilinear scalar coupling. After electroweak symmetry-breaking, this term generates a mixing between the left- and the right-chiral top-squarks. The mass-squared matrix for the top-squarks takes the form

$$
M_t^2 = \begin{pmatrix}
(M_t^2)_{11} & (M_t^2)_{12} \\
(M_t^2)_{21} & (M_t^2)_{22}
\end{pmatrix}
$$

where

$$
(M_t^2)_{11} = \frac{1}{8} (g_t^2 + \frac{g_\tau^2}{3}) (v_u^2 - v_u^2) + m_{t_L}^2 + \frac{1}{2} Y_t^2 v_u^2,
$$

$$
(M_t^2)_{12} = (M_t^2)_{21} = A_t v_u,
$$

$$
(M_t^2)_{22} = \frac{g_\tau^2}{6} (v_u^2 - v_u^2) + m_{t_R}^2 + \frac{1}{2} Y_t^2 v_u^2.
$$

in terms of the vev's $v_u$ and $v_d$ of the two Higgs doublets $H_u$ and $H_d$ respectively. The mixing angle $\theta_t$ is now given by

$$
\tan 2\theta_t = \frac{2 v_u A_t}{\frac{1}{4} (v_u^2 - v_u^2) (g_t^2 - g_\tau^2) + (m_{t_L}^2 - m_{t_R}^2)}.
$$

It is amusing to note that one can generate maximal mixing even without taking the $R$-breaking parameter $A_t$ to be unnaturally large, for the same effect can be obtained by setting $v_u \approx v_d$ and $m_{t_L}^2 \approx m_{t_R}^2$.

This mixing between $\tilde{t}_L$ and $\tilde{t}_R$ is crucial for our analysis, since it permits the $R^0_u$-scalar to decay to diphotons and to be produced through gluon fusion by top-squark loops — which would not be possible otherwise, as explained in the previous section.

### IV. FITTING THE DI PHOTON SIGNAL

The decay of the $R^0_u$-scalar to a $\gamma\gamma$ pair is mediated at the one-loop level dominantly by the diagrams shown in Figure II (including a crossed diagram). Similar diagrams exist for its decay to a $gg$ pair. Evaluation of these diagrams leads to the partial widths

$$
\Gamma(R \rightarrow \gamma\gamma) \approx \frac{\alpha^2 N_c^2 Q_L^4 M_t^3 v_u^2 |F(\tau)|^2}{1024 \pi^3 M_t^2},
$$

$$
\Gamma(R \rightarrow gg) \approx \frac{\alpha_s^2 M_t^3 v_u^2 |M_R^{\mu_R}|^2 |F(\tau)|^2}{512 \pi^3 M_t^2},
$$

where $\alpha$ and $\alpha_s$ are the electromagnetic and strong coupling constants, $N_c$ is the colour factor, $Q_L = 2 / 3$ is the fractional charge of the top-squark and $M_R$ is the mass of the $R^0_u$-scalar. In the above formulae, $\mu_R$ is an effective coupling defined as

$$
\mu_R = \frac{\mu_u Y_t}{4} \sin^2 2\theta_t,
$$

and $F(\tau)$ is the loop integral function

$$
F(\tau) = \left( \tau \sin^{-1} \frac{1}{\sqrt{\tau}} \right)^2 - \tau
$$

where $\tau = 4 M_t^2 / M_R^2$. Here, $M_t$ is the mass of the lighter eigenstate of the top squark. This particular form of $F(\tau)$
arises only in the case $2M_t > M_R$, which is assumed by us to ensure that the $R^0_u$ does not decay at the tree level to a pair of top-squarks.

We are now in a position to compare the predictions of this model with the experimental results quoted in the Introduction. It is necessary to point out, at this stage itself, that we assume that all tree-level decays of the $R^0_u$ scalar are kinematically disallowed. The spectrum of superparticles can be chosen to satisfy this without conflicting with any known theoretical or experimental requirements.

It is most convenient to treat the two widths $\Gamma_{\gamma\gamma} = \Gamma(R^0_u \to \gamma\gamma)$ and $\Gamma_{gg} = \Gamma(R^0_u \to gg)$ as correlated variables, and study the plane formed by plotting them against each other. The production cross-section for the $R^0_u$ scalar will be given in terms of $\Gamma_{gg}$ by

$$\sigma_R = \frac{\pi^2 G_{gg} K_{gg}}{8 s M_R} \Gamma_{gg}$$

where $C_{gg}$ is the gluon density function given by

$$C_{gg} = \int_0^1 \frac{dx}{x} f_{g/p}(x) f_{\bar{g}/p} \left( \frac{\delta}{x} \right)$$

with $\delta = M_{R_u}^2 / s$, where $\sqrt{s} = 13$ TeV, the machine energy. The functions $f_{g/p}(x)$ are, of course, the gluon parton-density functions. $K_{gg}$ is a QCD correction factor which we take to be approximately 1.5 [32]. In fact, using the CTEQ-6 [32] set of structure functions, we evaluate $C_{gg} \approx 2914$, from which it follows that the production cross-section is

$$\sigma_R \approx 12.4 \text{ nb} \times \frac{\Gamma_{gg}}{M_R}$$

We now have the cross-section for

- dijets, given by

$$\sigma_{\gamma\gamma} = \sigma_R \frac{\Gamma_{\gamma\gamma}}{\Gamma_R}$$

where $\Gamma_R = \Gamma_{gg} + \Gamma_{\gamma\gamma}$ is the total width of of the $R^0_u$ resonance, assuming that no other decay modes are available to the $R^0_u$ scalar — which will be the case if $2M_t > M_R$, as assumed.

- dijets, given by

$$\sigma_{gg} = \sigma_R \frac{\Gamma_{gg}}{\Gamma_R}$$

As the $R^0_u$ scalar has no coupling with quarks and it is lighter than all the squark pairs, we can safely assume that the decay of a $R^0_u$ to dijets is completely dominated by the $gg$ mode.

Our analysis is then based on the following constraints.

1. The total width $\Gamma_R$ of the $R^0_u$ scalar should satisfy

$$\Gamma_R < 50 \text{ GeV}$$

Since the best-fit width is about 45 GeV, the value 50 GeV chosen above seems to provide a reasonable leeway for errors.

2. The dijet cross-section observed at the LHC in the 13 TeV run is consistent with the SM prediction of about $12.5 \pm 1.2$ pb [34]. Thus, we must demand that the dijet excess arising from decay of the $R^0_u$ satisfies

$$\sigma_{gg} < 2.5 \text{ pb}$$

assuming agreement with the SM at the 95% confidence level.

3. The diphoton excess must be consistent with the observed values as presented by the ATLAS and CMS Collaborations (see Introduction). If we consider the 95% confidence level, the ATLAS results require

$$4 \text{ fb} < \sigma_{\gamma\gamma} < 16 \text{ fb}$$

and the CMS results may be taken to require

$$1 \text{ fb} < \sigma_{\gamma\gamma} < 12 \text{ fb}$$

Combining all these constraints, we display our results in Figure 2 which shows the $\Gamma_{\gamma\gamma} - \Gamma_{gg}$ plane for a wide range of values from $10^{-5}$ to $10^2$. The dark-green shaded strip along the top and right of this panel represents the range ruled out by the total width constraint in Eqn. (16). The larger region on the right side of the panel, shaded grey, represents the dijet constraint in Eqn. (17), i.e. all points in the region would lead to an observable dijet signal at the 13 TeV run, which is not the case. The L-shaped regions depict the regions allowed by the ATLAS (blue) and CMS (pink) observations, with the overlap region appearing purple. Obviously, the two ends of each strip indicate either a large $\Gamma_{gg}$ with a small $\gamma\gamma$...
branching ratio, or a small $\Gamma_{\gamma\gamma}$ (i.e., a small production cross-section) but a $\gamma\gamma$ branching ratio almost unity.

The oblique black line close to the lower end of Figure 2 represents the predictions of the MRSSM model, as we vary $\mu_{R}$ up to a value of 2.5 TeV (which is well within the perturbative limit) and the (lighter) top-squark mass from $M_t/2$ to about 1 TeV. It is immediately clear that the predictions are nicely consistent with both the ATLAS and CMS observations, as the line passes clearly through both the allowed strips. We may claim, therefore, to have a neat explanation of the observed diphoton excess (and the absence of other signals) in the MRSSM, without having had to extend the field content specifically for this purpose.

We note, however, that this MRSSM solution leads to the prediction of a somewhat low width of 100 MeV or less for the $R^0_u$ resonance. This, while definitely larger than the Higgs boson width in the SM (4 MeV), is still small compared to the widths of the $W$ and $Z$ bosons. We can attribute the long life of the $R^0_u$ to the fact that it can only decay through one-loop diagrams. After all, it is an ‘inert’ scalar! A small decay width is not a problem for the model at this stage of experimentation, since the kind of low statistics available at the moment leads to very poor estimations of the decay width. It is also important to note that larger widths of 200 MeV or more are incompatible with the non-observation of a dijet excess — this is a generic feature of models having a scalar decaying exclusively to $\gamma\gamma$ and $gg$ modes.

V. CRITICAL SUMMARY

In this article, therefore, we have shown that among the various possible explanations of the diphoton excess observed at the LHC, there exists the possibility of a SUSY solution which invokes an extra symmetry – the $R$-symmetry – but does not require us to postulate new fields specifically to explain the effect. Apart from introducing a pair of new scalars and some superfields to convert the gauginos from Majorana to Dirac fermions, this model retains the MSSM field content. However, we also obtain a good explanation of the failure of LHC to discover SUSY signals till date. We also require the $R$-symmetry to be broken by a solitary scalar trilinear operator, for otherwise the ‘inert’ scalars could not be produced at all in hadron-hadron collisions.

An obvious question to be asked before concluding this analysis is whether there are any confirmatory tests which could be used to verify if the ideas presented here are indeed correct. This can be answered quite easily in the affirmative. We argue as follows. The straight line shown in Figure 2 enters the allowed region only if the (lighter) top-squark has a mass in the range of a few hundred GeV, which would bring it very much within the kinematic range accessible for discovery at the LHC Run-2. Moreover, the neutral scalars $R^0_u$ and $R^0_u$ will be accompanied by their charged counterparts $R^\pm$ and $R^\pm$, and one could expect the mass ranges not to be very different. Charged scalars, of course, are easy to detect, and if they lie within the kinematic range of LHC (as we have good reason to suspect), it cannot be long before they will be discovered. Thus, we have a couple of very clear ways in which the model in question can be falsified. The truth will only be known when more data are acquired and analysed, but, for the moment, we may rest satisfied that the MRSSM has enough pleasing features to be taken very seriously as an explanation of the recent LHC enigma.

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