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95 GeV scalar and dark matter in the MRSSM

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The Minimal R-symmetric Supersymmetric Standard Model (MRSSM) is a well motivated supersymmetric extension of the Standard Model model with a distinct phenomenology. It was shown that it can accommodate the observed 125 GeV Higgs boson in agreement with electroweak precision data as well as explain a plethora of low-energy signatures like the muon $g-2$. In this note we report on the possibility of accounting within the MRSSM for the di-photon excess at a mass of around 95 GeV, recently observed by both ATLAS and CMS collaborations, and a potentially related excess seen at LEP in the $e^+e^- \to \bar{b}bZ$ channel at a similar mass. The proposed scenario necessarily leads to a light dark matter candidate, in agreement with direct and indirect detection experiments. We discuss prospects for the discovery of this scenario at the LHC.

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1. Introduction

After the discovery of a Standard Model (SM)-like Higgs boson at the LHC in 2012, an intriguing question that remains is whether there are any additional scalar particles, possibly with masses smaller than the discovered state. Searches for scalar particles below 125 GeV have been performed in the past at both LEP and Tevatron and now at the LHC. Results based on Run 1 and the first years of Run 2 data collected by the CMS in the di-photon channel showed an excess of 2.8σ (local) for an invariant mass of 95.3 GeV [?] and confirmed said excess at 2.9σ level for a mass of 95.4 GeV based on full Run 2 data set [?]. ATLAS search also found a 1.7σ (local) excess around 95 GeV [?]. This coincides with an excess around 95 GeV in the $b\bar{b}$ channel seen in LEP searches [?]. An analogous small excess has also been seen in the $\tau^+\tau^-$ channel in CMS [?]. All these findings point to a possible existence of some kind of a bosonic state with mass of around 95 GeV.

These findings have triggered speculations whether at least some of these excesses could arise from the production of a new, light, mostly singlet-like scalar from a Beyond the Standard Model (BSM) theory.

This anomaly can be explained for example by a scalar state s with a mass of 98 GeV whose combined production and branching ratio is roughly an order of magnitude smaller than that of a hypothetical SM-like Higgs $h_{98}^{\rm SM}$ of the same mass [?]

$$\mu_{Zb\bar{b}} = \frac{\sigma\left(e^+e^- \to Z^* s \to Zb\bar{b}\right)}{\sigma\left(e^+e^- \to Z^* h_{98}^{\rm SM} \to Zb\bar{b}\right)} = 0.117 \pm 0.057. \tag{1}$$

A naive combination of ATLAS and CMS results points to the 3.1σ (local) excess with mass 95.4 GeV and signal strength [?]

$$\mu_{\gamma\gamma}^{\rm ATLAS+CMS} = \frac{\sigma(gg \to s \to \gamma\gamma)}{\sigma(gg \to h_{95.4}^{\rm SM} \to \gamma\gamma)} = 0.24^{+0.09}_{-0.08}. \tag{2}$$

Finally, it is worthwhile mentioning that there is also a hint of an analogous excess in the $\tau\bar{\tau}$ channel with $\mu_{\tau\tau} = 1.2 \pm 0.5$ [?].

One of the popular BSM extensions, which was shown to be able to address a plethora of BSM signatures, is the Minimal R-symmetric Supersymmetric Standard Model (MRSSM) [?]. It can accommodate the 125 GeV Higgs boson in agreement with precision electroweak observables [? ?], muon $g-2$ and lepton-flavour violating observables [?] as well as avoid collider constraints [? ? ? ?]. It also provides an interesting testing ground for non-standard supersymmetric phenomenology. The possibility of an existence of a light scalar (though not in the context of 95 GeV anomalies) was explored within this model in [?], while the explanation of LEP and LHC anomalies was addressed in Ref. [?].

Here we summarize findings of Ref. [?], demonstrating that the aforementioned experimental deviations could be in fact accommodated within the MRSSM. The paper is structured as follows. In Sec. 2 we briefly describe the MRSSM, establish notation, and discuss the MRSSM setup with a light singlet. Phenomenological analysis is performed in Sec. 3. We then summarize our findings in Sec. 4.

2. The Minimal R-symmetric supersymmetric Standard Model

The MRSSM is distinct from the usual MSSM and NMSSM by imposing an exact, global $U(1)$ R-symmetry [**? ?**], under which SM-fields and superpartners have different charges. As a result additional scalar fields are not ad hoc (like in many non-minimal models) but are enforced by an $N = 2$ supersymmetric structure of the gauge/gaugino sector: for each gauge group factor there are gauge fields, Dirac instead of Majorana gauginos, and scalar fields in the adjoint representation. The MRSSM therefore contains sgluons — colour-octet scalars, a scalar $SU(2)_L$ triplet, and a scalar singlet. This scalar singlet behaves quite differently and is more strongly connected to the other sectors of the theory than the singlet of the NMSSM.

The essential field content and parameters of the MRSSM can be read off from the superpotential

$$\begin{aligned} W =&\mu_d \hat{R}_d \cdot \hat{H}_d + \mu_u \hat{R}_u \cdot \hat{H}_u + \Lambda_d \hat{R}_d \cdot \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \cdot \hat{T} \hat{H}_u \\ &+ \lambda_d \hat{S} \hat{R}_d \cdot \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \cdot \hat{H}_u - Y_d \hat{d} \hat{q} \cdot \hat{H}_d - Y_e \hat{e} \hat{l} \cdot \hat{H}_d + Y_u \hat{u} \hat{q} \cdot \hat{H}_u . \end{aligned} \tag{3}$$

The Higgs doublet superfields $\hat{H}_{d,u}$ and the quark and lepton superfields $\hat{q}$, $\hat{u}$, $\hat{d}$, $\hat{l}$, $\hat{e}$ are MSSM-like fields and the Yukawa couplings are the same as in the MSSM. The new fields are the doublets $\hat{R}_{d,u}$, which contain the Dirac mass partners of the higgsinos and the corresponding Dirac higgsino mass parameters are denoted as $\mu_{d,u}$. The singlet, the $SU(2)_L$-triplet and the color-octet chiral superfields, $\hat{S}$, $\hat{T}$ and $\hat{O}$, contain the Dirac mass partners of the usual gauginos. The superpotential contains Yukawa-like trilinear terms involving the new fields; $\lambda_{d,u}$ for the singlet and $\Lambda_{d,u}$ for the triplet terms, while for the octet terms are not allowed by R-symmetry. Likewise the trilinear sfermion couplings are forbidden by R-symmetry. Other important parameters are the Dirac mass parameters $M^D_{B,W,O}$ for the $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ gauginos, respectively, the soft scalar mass parameters $m^2_{S,T,O}$ for the singlet, triplet and octet states, the soft mass parameters $m^2_{H_d,H_u,R_d,R_u}$ for the Higgs and R-Higgs bosons, and the standard B_μ parameter and sfermion mass parameters. The explicit form of the soft SUSY breaking potential is given in Ref. [**?**].

Superfields $\hat{H}_{u,d}$, S and T present in Eq. (3) mix to form physical Higgs boson. The mass matrix of the CP-even neutral Higgs bosons in the weak basis $(\phi_d, \phi_u, \phi_S, \phi_T)$ is then given by [**?**]

$$\mathcal{M}_{H^0} = \begin{pmatrix} \mathcal{M}_{\text{MSSM}} & \mathcal{M}_{21}^T \\ \mathcal{M}_{21} & \mathcal{M}_{22} \end{pmatrix} \tag{4}$$

with the sub-matrices

$$\begin{aligned} \mathcal{M}_{\text{MSSM}} &= \begin{pmatrix} m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & -(m_Z^2 + m_A^2) s_\beta c_\beta \\ -(m_Z^2 + m_A^2) s_\beta c_\beta & m_Z^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix} , \\ \mathcal{M}_{22} &= \begin{pmatrix} 4(M_B^D)^2 + m_S^2 + \frac{\lambda_d^2 v_d^2 + \lambda_u^2 v_u^2}{2} & \frac{\lambda_d \Lambda_d v_d^2 - \lambda_u \Lambda_u v_u^2}{2\sqrt{2}} \\ \frac{\lambda_d \Lambda_d v_d^2 - \lambda_u \Lambda_u v_u^2}{2\sqrt{2}} & 4(M_W^D)^2 + m_T^2 + \frac{\Lambda_d^2 v_d^2 + \Lambda_u^2 v_u^2}{4} \end{pmatrix} , \\ \mathcal{M}_{21} &= \begin{pmatrix} v_d(\sqrt{2}\lambda_d \mu_d^{\text{eff},+} - g_1 M_B^D) & v_u(\sqrt{2}\lambda_u \mu_u^{\text{eff},-} + g_1 M_B^D) \\ v_d(\Lambda_d \mu_d^{\text{eff},+} + g_2 M_W^D) & -v_u(\Lambda_u \mu_u^{\text{eff},-} + g_2 M_W^D) \end{pmatrix} . \end{aligned}$$

where $m_A^2 = 2B_\mu/\sin 2\beta$ (with the usual definition of B_μ), $c_\beta \equiv \cos\beta$, $s_\beta \equiv \sin\beta$, $\tan\beta = v_u/v_d$ and

$$\mu_i^{\text{eff},\pm} = \mu_i + \frac{\lambda_i v_S}{\sqrt{2}} \pm \frac{\Lambda_i v_T}{2}, \quad i = u, d. \tag{5}$$

The phenomenologically viable scenario with light singlet can be realized by taking soft breaking parameter m_T large which is needed to suppress the tree-level triplet contribution to the W boson mass and ρ parameter. Additionally, one expects the SM-like Higgs boson to be ϕ_u-dominated. The scenario with a light scalar is then realised provided that

$$M_B^D, m_S \lesssim m_Z \tag{6}$$

and since $v_u \approx v = 246$ GeV for large $\tan\beta$, the coupling λ_u therefore must be also very small. The off-diagonal matrix element $v_u\left(\sqrt{2}\lambda_u\mu_u^{\text{eff},-} + g_1 M_B^D\right)$ must remain small in order not to disturb the properties of the SM-like Higgs state. This parameter is then further constrained by dark matter data as we will see in the next section.

3. Phenomenology of a 95 GeV scalar in the MRSSM

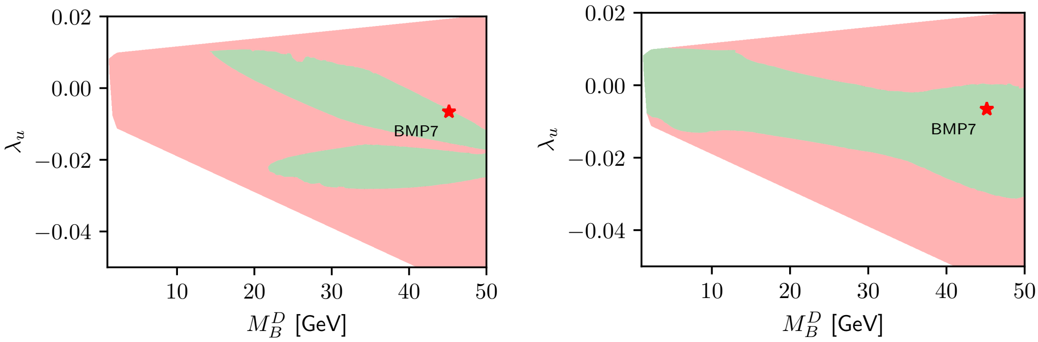
We looked for a set of parameter points fitting LEP and $\gamma\gamma$ anomalies from LHC while remaining in agreement with current 125 GeV Higgs measurements, other collider limits and dark matter constraints. The mass spectra and observables were computed using FlexibleSUSY spectrum-generator generator [**? ? ?**].

We scanned using SciPy [**?**] for MRSSM parameter points fitting $\mu_{Zb\bar{b}}$ in Eq. (1) and $\mu_{\gamma\gamma}^{\text{ATLAS+CMS}}$ in Eq. (2), where Higgs decay were evaluated using FlexibleDecay — a module of FlexibleSUSY. The properties of the Higgs sector were checked against experimental limits using HiggsTools [**?**], using the newly developed interface between FlexibleSUSY and HiggsTools and Lilith [**?**]. We have identified 2 benchmark points explaining both excesees and fullfiling all of the experimental constraints. The points differ mostly by how a correct relic density is being achieved. In Tab. 1 summarize the Higgs properties of both points. They fit both excesses, the SM-like Higgs boson properties are withing 95% C.L. in agreement with the data while the ratio of production cross-section of 95 GeV states to the 95% excluded cross-section is 0.4.

Correct relic density is achieved via s-channel Z annihilation through (R-)Higgsino admixture (controlled by μ_u and λ_u, see Fig. 2a) or t-channel stau exchange. Since Z-exchange contributes also to scattering from nuclei, direct detection of dark matter is avoided by destructive interference with squark exchange.

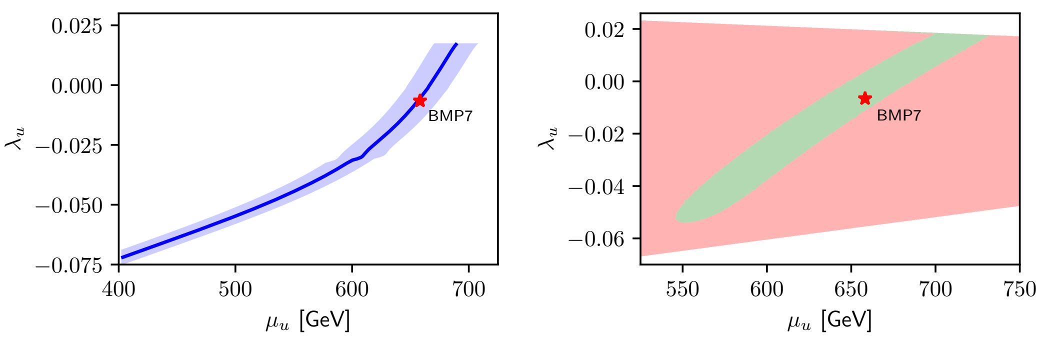
Since the original publication, we have re-evaluated benchmark points in Tab. 1 using the updated version of micrOMEGAs [**?**], v6.2.3, which contains newest results from the LUX-ZEPLIN [**?**] experiment. The points are still allowed at 95% C.L.

Benchmark points are checked w.r.t. collider limits using SModelS. An example allowed region around BMP7 is shown in Fig. 3. The lightest state in all spectra is one of the charginos or stau in case where dark matter annihilation occurs via stau exchange. Both of this scenarios are allowed by currently available experimental data.



(a) **(b)**

Figure 1: Region around BMP7 allowed by HiggsSignals (a) and HiggsBounds (b).



(a) **(b)**

Figure 2: Left: parameter space around BMP7 giving correct relic density $\Omega h^2 = 0.12 \pm 10\%$. Right: Region allowed by direct detection experiments.

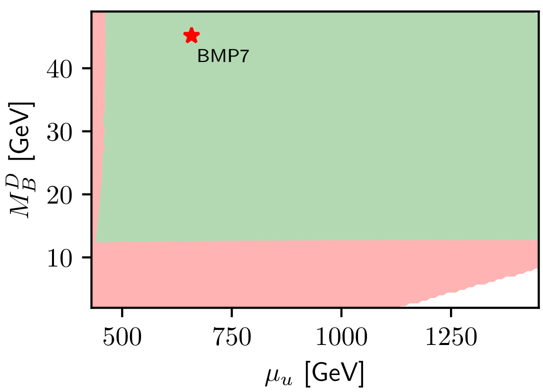


Figure 3: Regions allowed (green) and excluded (red) by direct searches of BSM particles at 95% C.L. as given by SModelS. White regions is where no spectrum could be generated.

	BMP7	BMP8
HiggsSignals p-value	0.120	0.0586
HiggsBounds h_1 obsRatio	0.40	0.40
Ωh^2	0.121	0.121
direct detection p-value	0.5	0.5
SModelS r_{95}	0.86	0.57

Table 1: Summary of experimental constraints passed by BMPs.

4. Conclusions

The Minimal R-symmetric Supersymmetric Standard Model (MRSSM) is an interesting, alternative realization of supersymmetric Standard Model. Its defining feature is its unbroken, global R-symmetry which leads to a distinct phenomenology. In this note we have reviewed how it can provide an elegant explanation to anomalies seen by LEP and LHC at the mass of around 95 GeV. The light, mostly singlet-like Higgs state in the MRSSM can fit the $\gamma\gamma$ excess seen by ATLAS and CMS and a LEP signal in Higgsstrahlung process in the $b\bar{b}$ channel while remaining in agreement with precision Higgs data. The setup necessitates the existence of a Dirac dark matter candidate, with mass below 95 GeV. LEP and LHC anomalies can be accommodated at the same time as direct and indirect constraints from dark matter, with a dark matter candidate of mass between around 40 and 45 GeV. The setup can feature a light chargino, with the rest of non-SM particles above a TeV scale while therefore any direct collider constraints.

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