Exploring the phenomenology of weak adjoint scalars in minimal R-symmetric models

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Introduction

- We study SUSY models with continuous R symmetry.
- These models feature Dirac masses for gauginos as well as additional scalar particles in the adjoint representations of the SM gauge group.
- We focus on the phenomenology of the gauge singlet and $SU(2)_L$ triplet scalars.
- We compute decay widths and production cross sections to one loop order, and analyze them numerically in a series of benchmarks.

Dirac Gauginos

Dirac masses for gauginos can be generated via a supersoft interaction

$$W_{\text{supersoft}} \supset \frac{\mathcal{W}'_\alpha \mathcal{W}_i^\alpha A_i}{\Lambda_i}$$

- $\mathcal{W}'$ is a hidden sector $U(1)'$ field that gets a D term vev.
- $\mathcal{W}_i$ are the SM gauge superfields.
- A_i are additional chiral superfields in the adjoint representations.

Inserting the vev results in mass terms marrying the gauginos to novel adjoint fermions.

Particle Content

Supermultiplet	$SU(3) \times SU(2)_L \times U(1)_Y$	$U(1)_R$
$(S,\ \psi_S)$	$(\mathbf{1}, \mathbf{1}, \mathbf{0})$	0
$(T,\ \psi_T)$	$(\mathbf{1}, \mathbf{3}, \mathbf{0})$	0
$(O,\ \psi_O)$	$(\mathbf{8}, \mathbf{1}, \mathbf{0})$	0
$(H_u,\ \tilde{H}_u)$	$(\mathbf{1}, \mathbf{2}, \mathbf{\frac{1}{2}})$	+1
$(H_d,\ \tilde{H}_d)$	$(\mathbf{1}, \mathbf{2}, -\mathbf{\frac{1}{2}})$	+1
$(\tilde{q},\ q)$	$(\mathbf{3}, \mathbf{2}, \mathbf{\frac{1}{6}})$	$+\frac{1}{2}$
$(\tilde{\overline{u}},\ \overline{u})$	$(\overline{\mathbf{3}}, \mathbf{1}, -\mathbf{\frac{2}{3}})$	$+\frac{1}{2}$
$(\tilde{\overline{d}},\ \overline{d})$	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{\frac{1}{3}})$	$+\frac{1}{2}$
$(\tilde{l},\ l)$	$(\mathbf{1}, \mathbf{2}, -\mathbf{\frac{1}{2}})$	$+\frac{1}{2}$
$(\tilde{\overline{e}},\ \overline{e})$	$(\mathbf{1}, \mathbf{1}, \mathbf{1})$	$+\frac{1}{2}$

The particle content of this model, along with gauge quantum numbers and the R-charge of the scalar part of the multiplet.

Electroweak Scalar Sector

- The strongly interacting sector is studied in earlier work (L.M.C., T. Murphy, M.J.S., arXiv:2006.15217, arXiv:2107.13565).
- We turn our attention to the gauge singlet S and the $SU(2)_L$ triplet T.
- The superpotential is

$$W = (\mu + \lambda_S S)\, H_u \cdot H_d + 2\lambda_T H_d \cdot T H_u + W_{\text{Yukawa}} + W_{\text{supersoft}},$$

- and soft Lagrangian

$$-\mathcal{L}_{\text{soft}} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + 2m_T^2 \,\text{Tr}(T^\dagger T) + \\ + \left(\frac{1}{2} B_S S^2 + B_T \,\text{Tr}(TT) + h.c.\right) + LS + + B_\mu H_u \cdot H_d$$

Scalar Interactions

- Supersoft term generates trilinear interaction between adjoints and MSSM scalars:

$$-\mathcal{L} \supset m_{1D}^2 \left(S + S^*\right)^2 + m_{2D}^2 \left(T^a + T^{*a}\right)^2 + \\ + \sqrt{2} g m_{2D} \left(T^a + T^{*a}\right) \sum_j \varphi_j^* \cdot \tau^a \varphi_j + \\ + \sqrt{2} g' m_{1D} \left(S + S^*\right) \sum_j \varphi_j^* Y_j \varphi_j,$$

Scalar Interactions

- It is convenient to use the basis

$$S = \frac{v_S + S_R + \mathrm{i}S_I}{\sqrt{2}}, \;\; T^0 = \frac{v_T + T_R^0 + \mathrm{i}T_I^0}{\sqrt{2}},$$
$$T_R^+ = \frac{T_R^1 - \mathrm{i}T_R^2}{\sqrt{2}}, \;\; T_R^- = (T_R^+)^*,$$
$$T_I^+ = \frac{\mathrm{i}T_I^1 + T_I^2}{\sqrt{2}}, \;\; T_I^- = (T_I^+)^*.$$

- Only the even states get tree level trilinear interactions:

$$-\mathcal{L} \supset 2g' m_{1D} S_R \sum_j Y_j |\varphi_j|^2 + 2g m_{2D} T_R^0 \sum_j I_j |\varphi_j|^2 +$$
$$+ \left(g m_{2D} T_R^+ \sum_j {\varphi_j}^\dagger \sigma^+ \varphi_j + h.c.\right)$$

- Odd states couple only to neutralinos and charginos at tree level.

Scalar Mass Spectrum

- Insertion of scalar vevs gives contributions to squark and slepton masses:

$$\Delta m_j^2 = 2g m_{2D} v_T I_j + 2g' m_{1D} v_S Y_j.$$

- Though v_T is constrained ($\lesssim$ 3 GeV) by electroweak precision measurements, the Dirac mass term can be multi-TeV.
- This can then be a source of $\mathcal{O}$(10-50 GeV) mass splitting between scalars in weak doublets.

Scalar Mass Spectrum

- In general the weak adjoint scalars will mix with the MSSM Higgs doublet fields.
- We take the fields T_R^0 and $T_R^{\pm}$ to be heavy enough to decouple. The remainder of the CP even Higgs sector resembles that of the NMSSM.
- We may assume the mixing of T_I^0 and S_I with the pseudoscalar A^0 is negligible.
- The charged state $T_I^{\pm}$ can be heavier than T_I^0 by $\mathcal{O}(\text{GeV})$, due to vev insertions in the quartic interaction.

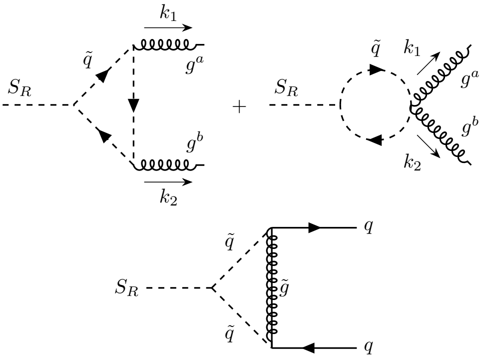
Benchmarks

λ_S	λ_T	$M_{D1} = M_{D2} = M_{D3}$	m_χ
$\frac{g'}{\sqrt{2}}$	$\frac{g}{\sqrt{2}}$	3 TeV	120 GeV

	$m_{\tilde{\nu}}$ (GeV)	$m_{\tilde{\tau}}$ (GeV)	$m_{\tilde{t}_1}$ (GeV)	$m_{\tilde{t}_2}$ (GeV)
B1	100	150	800	900
B2	160	200	800	900
B3	500	550	1000	1500
B4	500	550	800	900

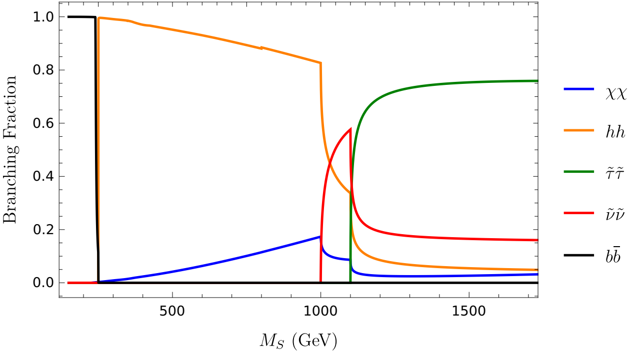
The benchmark scenarios considered in our numerical analysis.

Real Scalar Singlet



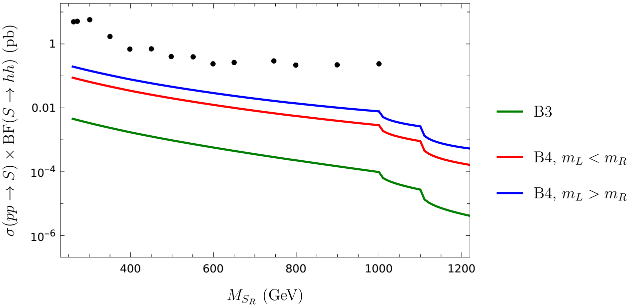
S_R couples to quarks and gluons at one loop. Dominant decays will be at tree level to MSSM scalars.

Singlet Branching Fractions



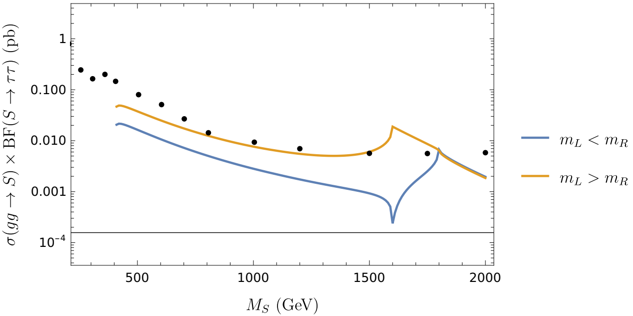
Branching fractions for decay of the CP-even singlet in benchmark B3.

Di-Higgs Production



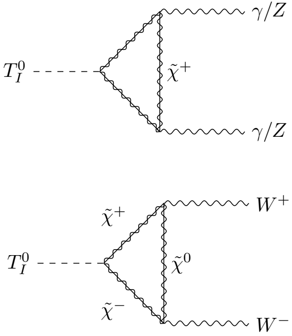
Singlet production and decay to two SM Higgs bosons. In black is the cross section exclusion limit from a CMS search for di-Higgs resonances.

Di-tau Production

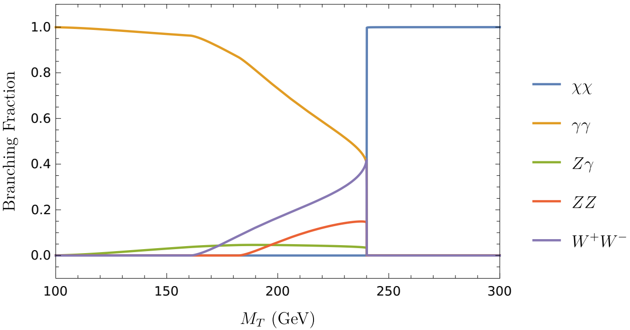


Singlet production and decay to two tau leptons plus missing energy in benchmark B2. In black is the cross section exclusion limit from an ATLAS search for di-tau resonances.

Pseudoscalar Triplet

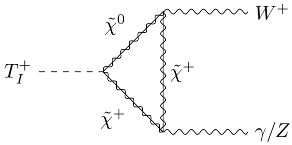


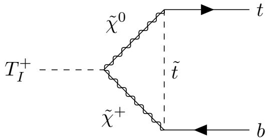
Neutral Triplet Branching Fractions

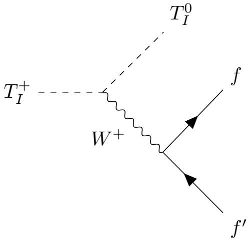


Branching fractions for decay of the CP-odd triplet.

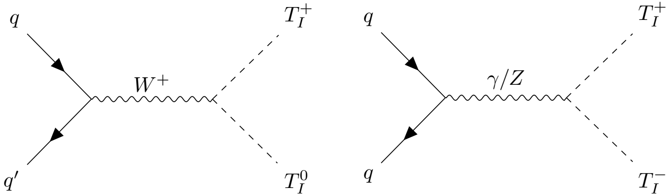
Charged Triplet



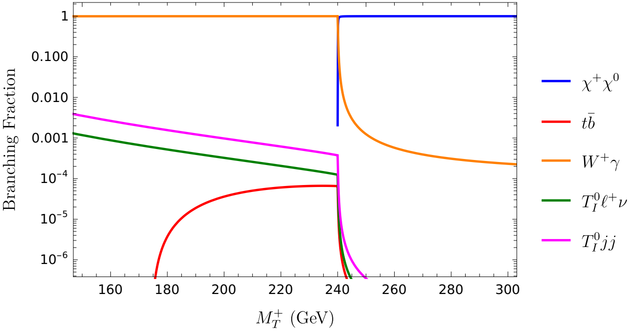




Charged Triplet Production

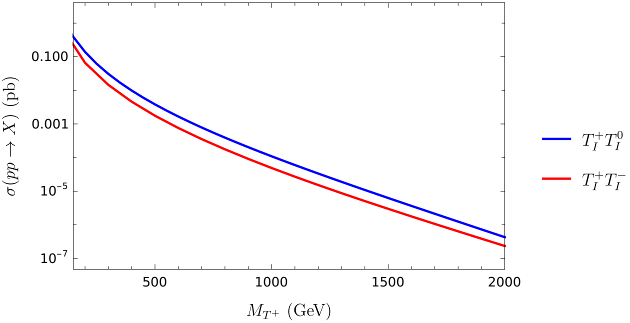


Charged Triplet Branching Fractions



Branching fractions for decay of the charged triplet.

Charged Triplet Production



Pair production cross section of triplet scalars.

Conclusion

- R-symmetric models are particularly well motivated, and the full scalar sector has rich phenomenology.
- Adjoint scalars have interesting decay channels.
  - di-Higgs, multi-tau, multi-photon, $W\gamma$
- Parameter space remains relatively wide open.