Exploring color-octet scalar parameter space in minimal R-symmetric models

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Outline

Overview of R-Symmetric Models

Background

Supersymmetry (SUSY) remains a powerful framework for beyond Standard Model physics.

- The Minimal Supersymmetric Standard Model (MSSM)
  - $\mathbf{W}_{MSSM} = y_u \overline{U} H_u Q + y_d \overline{D} H_d Q + y_e \overline{E} H_d L + \mu H_u H_d$
  - $\mathcal{L}_{soft} \supset -\frac{1}{2}\left(M_1 \widetilde{B}\widetilde{B} + M_2 \widetilde{W}\widetilde{W} + M_3 \widetilde{g}\widetilde{g} + h.c.\right)$
  - Note that gaugino masses in the MSSM are Majorana!
- R-parity
  - $P_R = (-1)^{3(B-L)+2s}$
  - Bosons and fermions of the same SUSY multiplet have different R-parity.
  - If R-parity is conserved, the lightest supersymmetric particle (LSP) is stable (and may be a dark matter candidate).

Beyond the MSSM

- Current LHC constraints motivate a look to non-minimally supersymmetric models.
- We consider models in which Majorana gaugino mass terms are forbidden by a continuous R symmetry–one that differentiates between SM fields and their superpartners.
- Dirac masses necessitate the introduction of a new chiral superfield for each gaugino, and therefore a new scalar sector.
- Key features:
  - Natural hierarchy between gaugino and squark masses.
  - Suppression of squark pair production cross section.
  - No mixing between left- and right-chiral squarks.

A Minimal R-Symmetric Model

We add to the Lagrangian the following "supersoft" operator:

$$\mathcal{L} \supset \sum_{k=1}^{3} \int \mathrm{d}^2\theta \, \frac{\kappa_k}{\Lambda} \, \mathcal{W}'^{\alpha} \mathcal{W}^a_{k\alpha} \mathcal{A}^a_k + \text{h.c.},$$

where the $\mathcal{A}^a_k$ are the new chiral superfields for each gauge group.

- We will focus on the color-octet superfield $\mathcal{A}^a_3$, whose scalar part is named the *sgluon*.
- When the superfield $\mathcal{W}'^{\alpha}$ gains a VEV, the above operator generates Dirac gaugino masses as well as trilinear couplings of the sgluon to squarks.
- Assume $U(1)_R$ is only broken in the Higgs sector.

$U(1)_R$ Charge Assignments

	Superfield	R	Boson	R	Fermion	R
Gluon	$\mathcal{W}_3$	$+1$	g	0	λ_3	$+1$
Left-chiral quark	$\mathcal{Q}$	$+1$	$\tilde{q}_{\text{L}}$	$+1$	q_{L}	0
Right-chiral quark	$\overline{\mathcal{U}}^\dagger, \overline{\mathcal{D}}^\dagger$	0	$\tilde{u}_{\text{R}}, \tilde{d}_{\text{R}}$	0	$u_{\text{R}}, d_{\text{R}}$	$+1$
Higgs	$\mathcal{H}_{\text{u}}, \mathcal{H}_{\text{d}}$	$+1$	$H_{\text{u}}, H_{\text{d}}$	$+1$	$\tilde{H}_{\text{u}}, \tilde{H}_{\text{d}}$	0
$\text{SU}(3)_{\text{c}}$ adjoint	$\mathcal{A}_3$	0	φ_3	0	ψ_3	-1

R charges of selected fields in a minimal model, with R symmetry broken only by a B_μ term.

Sgluon Phenomenology

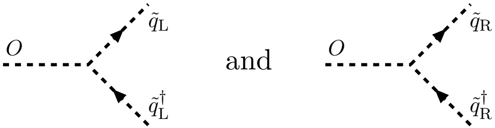
Couplings

The sgluon is a complex color-octet scalar; it is convenient to consider it as one real scalar O^a and one real pseudoscalar o^a. The interaction Lagrangian can be written as

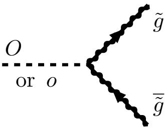
$$\begin{aligned}\mathcal{L}_O = &\frac{1}{2}(\nabla_\mu O)^\dagger_a(\nabla^\mu O)^a + \frac{1}{2}(\nabla_\mu o)^\dagger_a(\nabla^\mu o)^a \\ &- 2g_3 m_3 O^a[\tilde{q}_{\mathrm{L}}^\dagger t_3^a \tilde{q}_{\mathrm{L}} - \tilde{q}_{\mathrm{R}}^\dagger t_3^a \tilde{q}_{\mathrm{R}}] - \mathrm{i} g_3 f_{abc}\, O^a \bar{\tilde{g}}^b \tilde{g}^c + g_3 f_{abc}\, o^a \bar{\tilde{g}}^b \gamma_5 \tilde{g}^c \\ &- \sqrt{2} g_3\, \bar{q} t_3^a [\tilde{q}_{\mathrm{L}} \mathrm{P_R} \tilde{g}^a - \tilde{q}_{\mathrm{R}}^\dagger \mathrm{P_L} \tilde{g}^{ca}] - \sqrt{2} g_3 [\tilde{q}_{\mathrm{L}}^\dagger\, \bar{\tilde{g}}^a \mathrm{P_L} - \tilde{q}_{\mathrm{R}} \bar{\tilde{g}}^{\mathrm{c}\,a} \mathrm{P_R}] t_3^a q.\end{aligned}$$

Tree-Level Decays

(a)

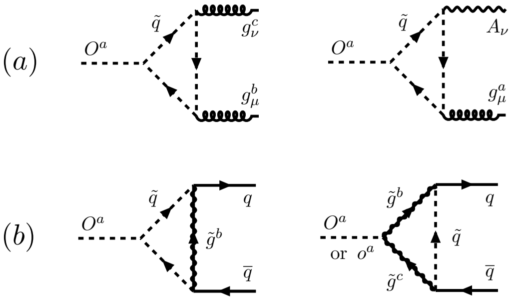


(b)



Diagrams for (a) scalar sgluon decays to squarks and (b) scalar or pseudoscalar decays to gluinos.

Loop-Level Decays



Diagrams for (a) scalar sgluon decays to bosons and (b) scalar or pseudoscalar decays to quark-antiquark pairs.

One Loop Decay Widths

$$\Gamma(O \to gg) = \frac{5}{192\pi^2}\,\alpha_3^3\,\frac{m_3^2}{m_O}\,|\mathcal{F}(O \to gg)|^2$$

$$\Gamma(O \to g\gamma) = \frac{8}{15}\frac{\alpha_1}{\alpha_3}\cos^2\theta_{\mathrm{w}}\,\Gamma(O \to gg)$$

$$\Gamma(O \to \bar{q}q) = \frac{9}{64\pi^2}\,\alpha_3^3\,m_O(m_3 m_q)^2\,\beta_q^3\,|\mathcal{F}(O \to \bar{q}q)|^2$$

- Form factors vanish to first order in QCD if stops are degenerate.
- Small stop mass splitting can result in long-lived sgluons.
- Decay widths to quarks are proportional to quark mass — only third flavor states are significant.

Three-Body Decay

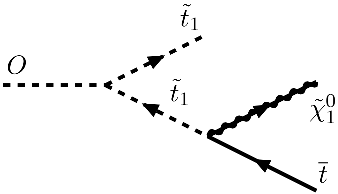


Diagram for scalar sgluon decay to a light stop, a top antiquark, and the lightest neutralino.

Numerical Analysis

Benchmarks

We selected a set of benchmarks for numerical analysis, under the following assumptions:

- The squark, sgluon, and gluino masses can be varied independently.
- The only source of R-breaking is in the Higgs sector, and the left- and right-chiral stops do not mix significantly.
- The LSP is a Higgsino-like neutralino.

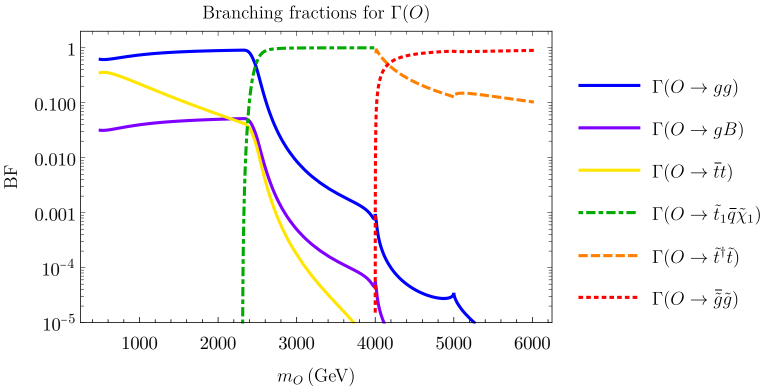
Branching fractions and production cross sections were then computed for each benchmark.

Benchmarks

	B1	B2	B3	B4	B5	B6
$m_{\tilde{t}_1}$ (GeV)	1000	1000	1500	1500	800	2000
$m_{\tilde{t}_2}$ (GeV)	1500	1500	2000	2000	900	2500
m_3 (GeV)	5000	3500	5000	3500	3000	2000
m_χ (GeV)	300	300	500	500	250	300

Benchmarks for quantitative investigation of sgluon decay and production.

Branching Fractions

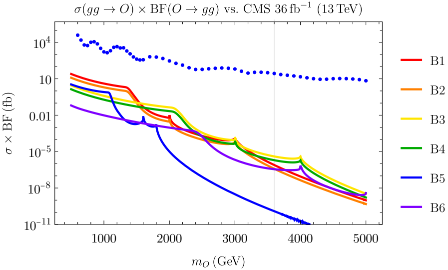


Branching fractions for the scalar sgluon in benchmark B6.

Constraints From LHC Data

Single Sgluon Production

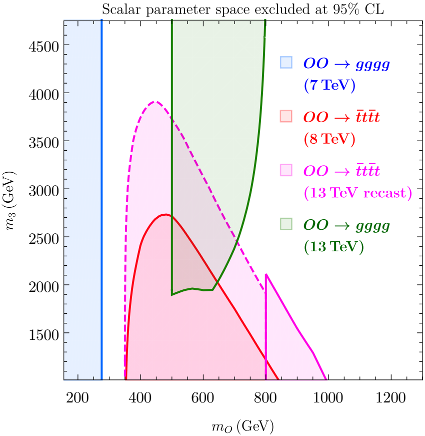
- Single scalar production can in principle be constrained by dijet resonance searches.
- However, our production cross section is much smaller than that assumed by recent CMS searches.



Pair Production

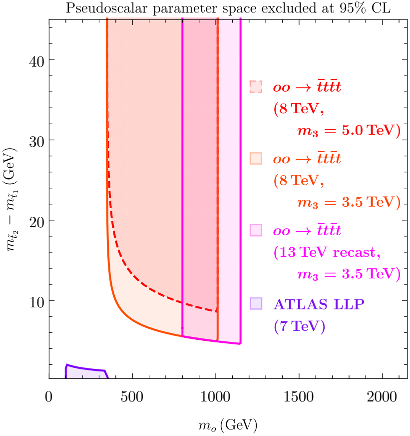
- For benchmarks B1-B5, an ATLAS four-flavorless-jet search provides the strongest constraints on the scalar.
- For B6, bounds from a CMS four-top search become significant.
- The pseudoscalar cannot decay to gluons, so it is primarily constrained by the same four-top search.

Excluded Scalar Parameter Space



Excluded parameter space in the (m_O, m_3) plane for the scalar, with all other parameters as in benchmark B6.

Excluded Pseudoscalar Parameter Space



Excluded parameter space in the $(m_o, m_{\tilde{t}_2} - m_{\tilde{t}_1})$ plane for the pseudoscalar, with $m_{\tilde{t}_1} = 2.0\,\text{TeV}$ and $m_3 = 3.5\,\text{TeV}$ or $5.0\,\text{TeV}$.

Conclusion and Outlook

- R-symmetric SUSY models remain of great interest.
- Sgluon parameter space is still wide open.
- Further work:
  - Examination of electroweak sector (Coming soon)
  - Effects of R-breaking operators (See talk by T. Murphy)