LHC phenomenology of supersymmetric models with a $U(1)_R$ baryon number

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2. $U(1)_R$ baryon number

3. Phenomenology

4. Conclusion
The Minimal Supersymmetric Standard Model (MSSM)

Quarks:
- u
- c
- t
- d
- s
- b

Squarks:
- \(\tilde{u}\)
- \(\tilde{c}\)
- \(\tilde{t}\)
- \(\tilde{d}\)
- \(\tilde{s}\)
- \(\tilde{b}\)

Leptons:
- \(\nu_e\)
- \(\nu_\mu\)
- \(\nu_\tau\)
- \(\tilde{\nu}_e\)
- \(\tilde{\nu}_\mu\)
- \(\tilde{\nu}_\tau\)

Sleptons:
- \(\tilde{e}\)
- \(\tilde{\mu}\)
- \(\tilde{\tau}\)

Gauge bosons:
- \(Y\)
- \(Z\)
- \(\tilde{B}\)
- \(W^\pm\)
- \(\tilde{W}\)
- \(g\)
- \(\tilde{g}\)

Higgs bosons:
- \(A\)
- \(\tilde{H}^0_d\)
- \(H^\pm\)
- \(\tilde{H}^-_d\)
- \(H\)
- \(\tilde{H}^+_u\)
- \(h\)
- \(\tilde{H}^0_u\)
The Minimal Supersymmetric Standard Model (MSSM)
### MSSM: field content

<table>
<thead>
<tr>
<th>Superfield</th>
<th>$SU(3)_c$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>3</td>
<td>2</td>
<td>1/6</td>
</tr>
<tr>
<td>$U^c$</td>
<td>3</td>
<td>1</td>
<td>$-2/3$</td>
</tr>
<tr>
<td>$D^c$</td>
<td>3</td>
<td>1</td>
<td>1/3</td>
</tr>
<tr>
<td>$L$</td>
<td>1</td>
<td>2</td>
<td>$-1/2$</td>
</tr>
<tr>
<td>$E^c$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$H_u$</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
</tr>
<tr>
<td>$H_d$</td>
<td>1</td>
<td>2</td>
<td>$-1/2$</td>
</tr>
<tr>
<td>$B$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$W^i$</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>$G^a$</td>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
MSSM: superpotential

The most general superpotential:

\[ W = y_u Q H_u U^c - y_d Q H_d D^c - y_e L H_d E^c + \mu H_u H_d \leftarrow \text{good} \]
\[ + \frac{1}{2} \lambda L L E^c + \lambda' L Q D^c + \frac{1}{2} \lambda'' U^c D^c D^c + \epsilon H_u L \leftarrow \text{bad} \]

lepton number violating  baryon number violating

Can we forbid the undesirable terms?
Discrete $Z_2$ symmetry forbids undesirable terms. Consequences:

- supersymmetric particles are produced in pairs
- decaying supersymmetric particles must produce at least one supersymmetric particle
- the lightest supersymmetric particle (LSP) is stable
# ATLAS susy searches

## ATLAS SUSY Searches* - 95% CL Lower Limits

**Status:** March 2017

<table>
<thead>
<tr>
<th>Model</th>
<th>c_t, μ, T, Y</th>
<th>Jets</th>
<th>E_{T}^{min}</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0.3, μ, 1.2</td>
<td>2-10 jets</td>
<td>36.1</td>
<td>1507.0520</td>
</tr>
<tr>
<td>GGM (compressed)</td>
<td>0</td>
<td>2-6 jets</td>
<td>36.1</td>
<td>1604.0077</td>
</tr>
<tr>
<td>GGM (wino NLSP)</td>
<td>0</td>
<td>2-6 jets</td>
<td>36.1</td>
<td>1507.0520</td>
</tr>
<tr>
<td>GGM (higgsino-bino NLSP)</td>
<td>0</td>
<td>2-6 jets</td>
<td>36.1</td>
<td>1507.0520</td>
</tr>
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<td>GGM (higgsino-bino NLSP)</td>
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</tr>
</tbody>
</table>

## Other

- | Scalar charm, c_t → c

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*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*
ATLAS susy searches involving MET
Thinking beyond the MSSM: $R$-symmetries

Instead of a discrete $Z_2$ symmetry, consider a global $U(1)_R$ symmetry.

$$\theta \rightarrow e^{i\alpha} \theta, \quad \theta^\dagger \rightarrow e^{-i\alpha} \theta^\dagger$$

Chiral superfield $\Phi$ with $R$-charge $r_\Phi$ transforms as $\Phi \rightarrow e^{ir_\Phi \alpha} \Phi$. Then

$$\phi \rightarrow e^{ir_\Phi \alpha} \phi, \quad \chi \rightarrow e^{i(r_\Phi - 1)\alpha} \chi, \quad F \rightarrow e^{i(r_\Phi - 2)\alpha} F$$

Vector superfields are real $V^\dagger = V$ and so have zero $R$-charge, $V \rightarrow V$.

gauginos have $R$-charge 1, $\lambda \rightarrow e^{i\alpha} \lambda$

Minimal $R$-symmetric Supersymmetric Standard Model (MRSSM)
Kribs, Poppitz, Weiner ‘07

Different $R$-charge assignments are possible.
Frugiuele, Grégoire, Kumar, Pontón ‘12
Consequences of $R$-symmetries

Two consequences of $R$-symmetries:

- gauginos are now required to be Dirac fermions
- in the MSSM gauginos are Majorana fermions
- however, Majorana mass terms are forbidden
- $\mu$-term in the superpotential is forbidden by the $R$-symmetry

We must introduce additional fields.
### $U(1)_R$ baryon number 1

<table>
<thead>
<tr>
<th>Superfield</th>
<th>$R$-charge</th>
<th>Superfield</th>
<th>$R$-charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>4/3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U^c$</td>
<td>2/3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D^c$</td>
<td>2/3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E^c$</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_u$</td>
<td>0</td>
<td>$R_d$</td>
<td>2</td>
</tr>
<tr>
<td>$H_d$</td>
<td>0</td>
<td>$R_u$</td>
<td>2</td>
</tr>
<tr>
<td>$B$</td>
<td>0</td>
<td>$S$</td>
<td>0</td>
</tr>
<tr>
<td>$W^i$</td>
<td>0</td>
<td>$T^i$</td>
<td>0</td>
</tr>
<tr>
<td>$G^a$</td>
<td>0</td>
<td>$O^a$</td>
<td>0</td>
</tr>
</tbody>
</table>
This $R$-charge assignment is referred to as $U(1)_R$ baryon number because $R$-charges of SM particles corresponds to their baryon number.

New superpotential:

$$W = y_u Q H_u U^c - y_d Q H_d D^c - y_e L H_d E^c + \mu_u H_u R_d + \mu_d R_u H_d$$

$$+ \lambda_u^t H_u T R_d + \lambda_d^t R_u T H_d + \lambda_u^s S H_u R_d + \lambda_d^s S R_u H_d + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c$$

 phenomenologically interesting, but take only $\lambda''_{312}, \lambda''_{313}, \lambda''_{323}$ non-zero to avoid flavour issues
Stop phenomenology: stop LSP 1

Stops both resonantly produced, $pp \to \tilde{t}^*$, and pair produced $pp \to \tilde{t}\tilde{t}^*$.  

13 TeV →

Stops can decay back to quarks, $\tilde{t}^* \to d_i d_j$. 

![Graph showing the cross section for different scenarios](image URL)
Signals:

- dijets: \( pp \rightarrow \tilde{t}^* \rightarrow d_i d_j \)
- paired dijets: \( pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow d_i d_j \bar{d}_i \bar{d}_j \)

similar to Monteux ‘16
Consider a Higgsino-up LSP. The stop can now decay three different ways:

\[ \tilde{t}^* \rightarrow d_i d_j, \quad \tilde{t}^* \rightarrow \bar{t} \chi^0, \quad \tilde{t}^* \rightarrow \bar{b} \chi^- .\]

600 GeV stop and 200 GeV neutralino
Stop phenomenology: neutralino LSP 2

Stops decaying through charginos:

\[
\tilde{t}^* \rightarrow \bar{b} \chi^- b \tilde{t}^*
\]

Stops decaying through Dirac neutralinos:

\[
\tilde{t}^* \rightarrow \bar{t} \chi^{0,D} t \tilde{t}^*
\]

Stops decaying through Majorana neutralinos:

\[
\tilde{t}^* \rightarrow \bar{t} \chi^{0,M}_{1,2} t \tilde{t}^* \quad \text{and} \quad \bar{t} \chi^{0,M}_{1,2} \tilde{t}
\]
Stop phenomenology: neutralino LSP 3

Unavoidable $U(1)_R$ breaking generates Majorana gauginos masses.

How large does the breaking need to be so that same sign and opposite sign tops are produced equally from stop decays?
Stop phenomenology: neutralino LSP 4

Two production mechanisms:
- $pp \rightarrow \tilde{t}^*$
- $pp \rightarrow \tilde{t}^*\tilde{t}$

Three decay possibilities:
- $\tilde{t}^* \rightarrow d_i d_j$
- $\tilde{t}^* \rightarrow \bar{t}\chi^0$
- $\tilde{t}^* \rightarrow \bar{b}\chi^-$

Nine possible decay topologies. Can use LHC searches to constrain the parameter space.

Also possible to use displaced vertices from neutralino decays to constrain the parameter space.
Stop phenomenology: neutralino LSP 5

200 GeV Dirac neutralinos:
Stop phenomenology: neutralino LSP 6

200 GeV Majorana neutralinos:

similar to Monteux ‘16
To summarize:

- lack of signals continues to push MSSM superpartner masses upwards
- this suggests thinking beyond the MSSM
- $U(1)_R$ baryon number is an example of an extended supersymmetry model
- the parameter space of this model is also constrained by recent LHC SUSY searches