New directions in weak scale supersymmetry

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The talk is about a few aspects of phenomenology of weak scale supersymmetry but not directly about MSSM.
but before beginning
let’s recap
Particle zoo in the MSSM

SM particles

\[ A^a_\mu \quad q_i \quad h \]

new particles

\[ \lambda^a \quad \tilde{q}_i \quad \{ h_u , \tilde{H}_u \} \equiv H_u \]
\[ \{ h_d , \tilde{H}_d \} \equiv H_d \]

new mass terms

\[ m^2_{ij} \tilde{q}_i^* \tilde{q}_j \]
\[ M_a \lambda^a \lambda^a \]
\[ \mu H_u H_d \]
\[ B_\mu h_u h_d \]
Standard Model

MSSM
minimum weak scale
supersymmetric extension
of SM

gauge coupling
unification

candidate for
dark matter

hierarchy
problem

flavor
problem
Supersymmetric Flavor problem

\[ m_{ij}^2 \tilde{q}_i^* \tilde{q}_j \]

arbitrary \( m_{ij}^2 \) is totally ruled out
For example, $K_0 - \bar{K}_0$ mixing has contribution from superpartner loops.

\[ \delta_{12} \equiv \frac{\tilde{m}_{12}^2}{\tilde{m}_q^2} < 0.06 \rightarrow 10^{-3} \]

\[
\begin{align*}
\tilde{m}_q &= 500 \text{ GeV} \\
M\tilde{g} &= 500 \text{ GeV}
\end{align*}
\]
20 Years of model building

susy breaking is communicated through flavor universal messengers

at weak scale soft terms have restricted flavor structure

MSSM is characterized by rather lack of flavor
A new direction

don’t kill flavor

make the flavor
violating observables rather insensitive to mixing elements
A new direction

give up minimality of the MSSM

Recipe:

supersymmetrize standard model

and

impose an additional $U(1)_R$ symmetry

Kribs, Poppitz, Weiner (0712.2039)
The Minimal R-symmetric Supersymmetric Model

Kribs, Poppitz, Weiner

\[ \frac{X}{\Lambda} W_a W_a \rightarrow \frac{W'}{\Lambda} W_a \Phi_a \]

\[ \mu H_u H_d \rightarrow \mu_u H_u R_u \]

\[ \mu_d H_d R_d \]
The Minimal R-symmetric Supersymmetric Model

Kribs, Poppitz, Weiner

\[ M \lambda_a \lambda_a \rightarrow \frac{W'}{\Lambda} W_a \Phi_a \]

\[ \mu H_u H_d \rightarrow \mu_u H_u R_u \mu_d H_d R_d \]
The Minimal R-symmetric Supersymmetric Model

Kribs, Poppitz, Weiner
Flavor physics is different in the MRSSM because:

- Dirac gluinos can naturally be far heavier than squarks/sleptons
- No L-R sfermion mixing
- New higgsino mass term
Supersoft

\[ \int d^4 \theta \frac{1}{\Lambda^6} |W'W'|^2 Q^\dagger Q \]

no counterterm is needed and hence D-term induces finite contribution to the scalars

\( \tilde{Q}^\dagger \tilde{Q} \)

\( \frac{M^4}{\Lambda^2} \)

extra suppression

gaugino mass

(Fox, Nelson, Weiner ‘02)
heavy Dirac gaugino and no dimensional 5 operators

Flavor violating operators in

leading contribution is due to ‘n’ insertions of Majorana masses
leading operator is dimensional 5

MSSM

MRSSM

leading contribution is due to ‘2n’ insertions of Dirac masses
leading operator is dimensional 6

see Kribs, Poppitz, Weiner (0712.2039)
some sort of outline

• Introducing Minimal R-symmetric Supersymmetric Standard Model.

• Unconventional features of the MRSSM:
  1. its delicious
  2. it has a surprising ino-mass hierarchy

• Implications at the collider
Particle zoo in the MRSSM

<table>
<thead>
<tr>
<th>Fields</th>
<th>$SU(3)_C$</th>
<th>$SU(2)_W$</th>
<th>$U(1)_Y$</th>
<th>$U(1)_R$</th>
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<td>2</td>
<td>$\frac{1}{6}$</td>
<td>1</td>
</tr>
<tr>
<td>$U$</td>
<td>3</td>
<td>1</td>
<td>$-\frac{2}{3}$</td>
<td>1</td>
</tr>
<tr>
<td>$D$</td>
<td>$\bar{3}$</td>
<td>1</td>
<td>$\frac{1}{3}$</td>
<td>1</td>
</tr>
<tr>
<td>$L$</td>
<td>1</td>
<td>2</td>
<td>$-\frac{1}{2}$</td>
<td>1</td>
</tr>
<tr>
<td>$E$</td>
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<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\Phi_{\tilde{B}}$</td>
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<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Phi_{\tilde{W}}$</td>
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<td>3</td>
<td>0</td>
<td>0</td>
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<tr>
<td>$\Phi_{\tilde{g}}$</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<tr>
<td>$H_u$</td>
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<td>2</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
</tr>
<tr>
<td>$H_d$</td>
<td>1</td>
<td>2</td>
<td>$-\frac{1}{2}$</td>
<td>0</td>
</tr>
<tr>
<td>$R_u$</td>
<td>1</td>
<td>2</td>
<td>$-\frac{1}{2}$</td>
<td>2</td>
</tr>
<tr>
<td>$R_d$</td>
<td>1</td>
<td>2</td>
<td>$\frac{1}{2}$</td>
<td>2</td>
</tr>
</tbody>
</table>
neutralinos and charginos

\(\tilde{\psi}^\pm, \tilde{\psi}_3^0, \tilde{B}, \tilde{H}_u^+, \tilde{H}_d^-, \tilde{H}_u^0, \tilde{H}_d^0\)

\(\psi^\pm, \psi_3, \psi_0, \tilde{R}_u^0, \tilde{R}_d^+, \tilde{R}_u^0, \tilde{R}_d^0\)
The neutralino mass matrix

\[
\begin{bmatrix}
\tilde{B} & \tilde{W}_3^0 & \tilde{R}_u^0 & \tilde{R}_d^0 \\
\end{bmatrix}
\begin{bmatrix}
M_1 & 0 & -g' v_u / \sqrt{2} & g' v_d / \sqrt{2} \\
0 & M_2 & g v_u / \sqrt{2} & -g v_d / \sqrt{2} \\
0 & 0 & \mu_u & 0 \\
0 & 0 & 0 & \mu_d \\
\end{bmatrix}
\begin{bmatrix}
\psi_0 \\
\psi_3 \\
\tilde{H}_u^0 \\
\tilde{H}_d^0 \\
\end{bmatrix}
\]

\( R = +1 \)

\( R = -1 \)
The chargino mass system

\[
\begin{bmatrix}
\psi^+ & \tilde{H}_u^+
\end{bmatrix}
\begin{bmatrix}
M_2 & 0 \\
-gv_u & \mu_u
\end{bmatrix}
\begin{bmatrix}
\tilde{W}^- \\
\tilde{R}_u^-
\end{bmatrix}
\]

\[R = +1 \quad Q = +1\]

\[
\begin{bmatrix}
\tilde{W}^+ & \tilde{R}_d^+
\end{bmatrix}
\begin{bmatrix}
M_2 & -gv_d \\
0 & \mu_d
\end{bmatrix}
\begin{bmatrix}
\psi^- \\
\tilde{H}_d^-
\end{bmatrix}
\]

\[R = -1 \quad Q = -1\]

\[R = -1 \quad Q = +1\]

\[R = +1 \quad Q = -1\]
\[
\begin{array}{ccccc}
M_1 & 0 & -\frac{g'v_u}{\sqrt{2}} & \frac{g'v_d}{\sqrt{2}} & \\
0 & M_2 & \frac{gv_u}{\sqrt{2}} & -\frac{gv_d}{\sqrt{2}} & \\
0 & 0 & \mu & 0 & \\
0 & 0 & 0 & \mu & \\
\end{array}
\]

\[
\begin{array}{cc}
M_2 & 0 \\
gv_u & \mu \\
\end{array}
\]
\[
\begin{array}{cccc}
M_1 & 0 & -\frac{g'v_u}{\sqrt{2}} & 0 \\
0 & M_2 & \frac{gv_u}{\sqrt{2}} & -\frac{gv_d}{\sqrt{2}} \\
0 & 0 & \mu & 0 \\
0 & 0 & 0 & \mu \\
\end{array}
\]

\[
M_2 \quad 0
\]

\[
gv_u \quad \mu
\]
\[
\begin{array}{cccc}
M_1 & 0 & -\frac{g' \nu_u}{\sqrt{2}} & 0 \\
0 & M_2 & \frac{g \nu_u}{\sqrt{2}} & 0 \\
0 & 0 & \mu & 0 \\
0 & 0 & 0 & \mu \\
\end{array}
\]
\[
\begin{array}{cccc}
M_1 & 0 & -\frac{g'v_u}{\sqrt{2}} & 0 \\
0 & M_2 & \frac{gv_u}{\sqrt{2}} & 0 \\
0 & 0 & \mu & 0 \\
0 & 0 & 0 & \mu
\end{array}
\]

\[
\begin{pmatrix}
M_2 & 0 \\
gv_u & \mu
\end{pmatrix}
\]
At tree level
a chargino can be lighter
than the lightest neutralino

see Kribs, Martín, Roy (0807.4936)
At tree level
a neutralino is always lighter than all charginos in the MSSM unless

\[ \text{sign}(M_1) \neq \text{sign}(M_2) \]

At loop level also holds in

- bino limit
  \[ M_1 \ll M_2 \text{ and } \mu \]  
  (obviously)

- wino limit
  \[ M_2 \ll M_1 \text{ and } \mu \]  
  (e.g. hep-ph/9904350)

- Higgsino limit
  \[ \mu \ll M_1 \text{ and } M_2 \]  
  (e.g. hep-ph/9512337)
\[ \Delta m_\chi = m_{\tilde{\chi}_\pm} - m_{\tilde{\chi}_0} \text{ (GeV)} \]

for example:

\[ \tan \beta = 10, \; \mu = 200 \text{ GeV} \]
collider implications:

a chargino can be the NLSP when
gravitino is the LSP
**Traditional NLSPs**
when gravitino is the LSP

<table>
<thead>
<tr>
<th>spin</th>
<th>charge</th>
<th>0</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>sneutrino</td>
<td>neutralino</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>slepton</td>
<td>×</td>
<td></td>
</tr>
</tbody>
</table>
### Traditional NLSPs

<table>
<thead>
<tr>
<th>Spin</th>
<th>Charge</th>
<th>sneutrino</th>
<th>neutralino</th>
</tr>
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<tr>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>slepton</td>
<td>×</td>
</tr>
</tbody>
</table>

*Chargino*
LHC Signatures: Chargino NLSP, Gravitino LSP

two on-shell $W$
in every
supersymmetry event

NLSP is charged

if long-lived leaves track
in the detector
LHC Signatures: Chargino NLSP, Gravitino LSP

\[ pp \rightarrow W^+W^- + \text{MET} + X \]

NLSP is charged if long-lived leaves track in the detector
LHC Signatures: Chargino NLSP, Gravitino LSP

\[
pp \rightarrow \tilde{q}_u \tilde{q}_u \\
\quad\quad \rightarrow q_d \bar{\chi}^+_2 \\
\quad\quad \rightarrow \bar{q}_u \bar{\chi}^+_1 \rightarrow q_u \ell^+ \tilde{\chi}^-_1 \rightarrow 5q \tilde{\chi}^+_1 \rightarrow 5q W^+ \tilde{G}
\]

\[
pp \rightarrow \tilde{q} \tilde{d} \\
\quad\quad \rightarrow \bar{q}_u \tilde{\chi}^+_1 \rightarrow \bar{q} \tilde{\chi}^+_1 \rightarrow \bar{q} W^+ \tilde{G}
\]

NLSP is charged

if long-lived leaves track in the detector
two on-shell $W$
in every
supersymmetry event

$NLSP$ is charged
if long-lived leaves track
in the detector
LHC Signatures: Chargino NLSP, Gravitino LSP

two on-shell $W$
in every
supersymmetry event

$m_{\tilde{\chi}_\pm} \sim m_W$

$m_{\tilde{e}} \gg m_e$

chargino NLSP and slepton NLSP
have different kinematics
LHC Signatures: Chargino NLSP, Gravitino LSP

two on-shell $W$
in every supersymmetry event
LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

lifetime crucially depends on gravitino mass

\[ \tau_{\text{NLSP}} \approx 0.07 \left( \frac{1 \text{ ev}}{m_{3/2}} \right)^2 \text{ ns} \]

for 100 GeV NLSP
supersymmetry breaking interactions
renormalize all susy soft masses

• scalar soft masses are modified with respect to the gauginos as well as with respect to each other

• gravitino masses are modified with respect to the rest of the spectrum

Cohen, Roy, Schmaltz (hep-ph/0612100)
Roy, Schmaltz (0708.3593)
Murayama, Nomura, Poland (0709.0775)
Lesson:

take gravitino mass as a free parameter
LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

\[ \gamma \tilde{\chi}_\pm \ll 1 \text{ ns} \]
\[ (m_{3/2} \lesssim 1 \text{ eV}) \]

Immediate decay. Conventional variables for discovery

\[ H_T = \sum_{\text{leptons}} p_T + \sum_{\text{jets}} p_T, \quad M_{\text{eff}} = H_T + \text{MET} \]
LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

\[ \gamma \tilde{\chi}_\pm \sim \mathcal{O}(5 \text{ ns}) \]
\[ (m_{3/2} \sim 10 \text{ eV}) \]

displaced vertex but no trigger resolution issues.
timing can reduce many background

kink + displaced jets/leptons \rightarrow chargino NLSP
LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

\[ \gamma \tilde{\chi}_\pm ^{\pm} \sim \mathcal{O}(25 \text{ ns}) \]
\[ (m_{3/2} \sim 10 - 100 \text{ eV}) \]

displaced vertex, but length of decay causes triggering issues.
Rely on other decay-chain particles for triggering
LHC Signatures: Chargino NLSP, Gravitino LSP

Detection method depends on the lifetime:

\[ \gamma \tilde{\chi}_\pm \gg O(100 \text{ ns}) \]
\[ (m_{3/2} \gg 100 \text{ eV}) \]

decay occurs outside detector, subject to massive (stable) charged particle limits
Hunt for flavor at the LHC

MRSSM could be full of flavors but can LHC see them?
3 signals of 3 cases

• **Case I:** neutralino is the $\tilde{\mathcal{P}}_T$
• **Case II:** gravitino is the $\tilde{\mathcal{P}}_T$
  neutralino is the NLSP
• **Case III:** gravitino is the $\tilde{\mathcal{P}}_T$
  chargino is the NLSP

*(Kribs, Martin, Roy 0901.4105)*
Case I: neutralino is the $E_T$

MRSSM single top excess:

$$pp \rightarrow \tilde{u}^* \tilde{u} \rightarrow t + j + E_T$$

$$b + W(l)$$
• **Case I:** neutralino is the $\tilde{E}_T$

Both the vertices need to be sizable

$\tilde{\chi}_1^0$ should mostly be a bino

Squark masses must **not** be degenerate

need to be summed over all up-squarks
**Case I:** neutralino is the $\not{E}_T$

- Exactly 1 lepton, $p_T > 30$ GeV, $|\eta| < 2.5$.
- Exactly 2 jets and one $b$-tagged
- $\not{E}_T > 100$ GeV
- $\not{E}_T > 0.25 \times M_{eff}$
- Transverse mass of the $W$, $m_{T,W} > 120$ GeV

\[ m_{\tilde{\nu}_L_1} = m_{\tilde{\nu}_R_1} = 1 \text{ TeV}, \quad m_{\tilde{\nu}_L_3} = 1 \text{ TeV}, \quad m_{\tilde{\nu}_R_3} = 300 \text{ GeV}, \]
\[ M_1 = 50 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 3 \text{ TeV}, \]
\[ \mu_u = \mu_d = 1 \text{ TeV}, \quad \text{and} \quad \tan \beta = 10 \]
\[ \theta_R = \pi/3, \quad \theta_L = 0. \]

*(full study in Kribs, Martín, Roy 0901.4105)*
• **Case I:** neutralino is the $E_T$

\[
\text{significance } S = \frac{S}{\sqrt{S+B}}
\]

\[
\theta_R = \frac{\pi}{6}
\]

\[
\theta_R = \frac{\pi}{4}
\]

\[
\theta_R = \frac{\pi}{3}
\]
Case II: gravitino is the $E_T$
neutralino is the NLSP

$\tilde{\chi}^0_1$ $\tilde{G}$

2 extra hard photons
almost background free signal
Case II: gravitino is the neutralino is the NLSP

\[ \tilde{u}_{R,i} \tilde{u}_{R,i}^* \rightarrow tj\chi_1 \bar{\chi}_1 \rightarrow bj\gamma\gamma + E_T \]
\[ m_{\tilde{u}_R} = 300 \text{ GeV}, \ m_{\tilde{\chi}_1} = 50 \text{ GeV} \]

<table>
<thead>
<tr>
<th>Process</th>
<th># events in 10 fb^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{u}<em>{R,i} \tilde{u}</em>{R,i}^* \rightarrow tj\chi_1 \bar{\chi}_1 \rightarrow bj\gamma\gamma + E_T$</td>
<td>481</td>
</tr>
<tr>
<td>$tt \rightarrow bbj\ell\nu$</td>
<td>1.3</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \ell\ell'\nu\nu'$</td>
<td>1.4</td>
</tr>
<tr>
<td>$t + q \rightarrow bj\ell\nu$</td>
<td>0</td>
</tr>
<tr>
<td>$t + b \rightarrow bbl\nu$</td>
<td>0</td>
</tr>
<tr>
<td>$t(\text{inc.}) + W(\ell\nu)$</td>
<td>0</td>
</tr>
<tr>
<td>$t(\text{inc.}) + W(\ell\nu) + j$</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>$W + \bar{b}b \rightarrow bbl\nu$</td>
<td>0</td>
</tr>
<tr>
<td>$Z + \bar{b}b \rightarrow bb\nu\bar{\nu}$</td>
<td>0</td>
</tr>
<tr>
<td>$WZ + \text{jets} : \rightarrow 3\ell + \nu + \text{jets}$</td>
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</tr>
<tr>
<td>$W(\ell\nu) + \text{jets}$</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>$Z(\ell^+\ell^-) + \text{jets}$</td>
<td>0</td>
</tr>
<tr>
<td>$Z(\bar{\nu}\nu) + \text{jets}$</td>
<td>0</td>
</tr>
<tr>
<td>Total Background</td>
<td>$\leq 5$</td>
</tr>
</tbody>
</table>
Case III: gravitino is the $E_T$

chargino is the NLSP

chargino is the NLSP in the Higgsino scenario when squarks decay exclusively to top

very few signal events

If NLSP is long-lived - almost background free signal - even a handful of events can be picked up
Conclusion

- **MRSSM** is the new direction of weak scale supersymmetry
  - it addresses the hierarchy and the flavor problem together
  - it is qualitatively different from MSSM
    - No L-R sfermion mixing
    - gauginos are ~10 times heavier than scalars

- **prospect of unconventional signature at the LHC**
  - signatures of gravitino LSP and a longlived chargino NLSP
  - plenty of flavor to be discovered in the single top channel if we are lucky - even flavor in the squark sector