(Non-minimal) SUSY
Phenomenology of the minimal R-symmetric SUSY model

Dominik Stöckinger

TU Dresden

KIAS Workshop, October 2016

based on work with: [Philip Diessner, Jan Kalinowski, Wojciech Kotlarski, and Sebastian Liebschner '14, '15, '16]
Outline

1. Motivation: SUSY and non-minimal SUSY
2. R-symmetric SUSY as a concrete example
3. Higgs, W, dark matter vs. LHC data in MRSSM
4. Summary
Fundamental new symmetry, unique extension of Poincaré
Relation to gravity, string theory
Fundamental new symmetry, unique extension of Poincaré
Relation to gravity, string theory
Fine tuning problem/stabilization of EW scale
Unification of gauge couplings
Dynamic generation of mexican hat potential
Dark matter
Fundamental new symmetry, unique extension of Poincaré
Relation to gravity, string theory
Fine tuning problem/stabilization of EW scale
Unification of gauge couplings
Dynamic generation of mexican hat potential
Dark matter
Minimality was never an argument! These motivations hold equally well in minimal and non-minimal SUSY!
Fundamental new symmetry, unique extension of Poincaré
Relation to gravity, string theory
Fine tuning problem/stabilization of EW scale
Unification of gauge couplings
Dynamic generation of mexican hat potential
Dark matter

some non-minimal models even better motivated than MSSM
(improve $\mu$-problem, flavor problem, allow lighter/heavier sparticles)
Tools for non-minimal SUSY (advertisement/warning)

<table>
<thead>
<tr>
<th>Model</th>
<th>Spectrum generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>Softsusy, Spheno, Isasusy, SuseFlav, Suspect</td>
</tr>
<tr>
<td>NMSSM</td>
<td>NMSpec, Softsusy</td>
</tr>
<tr>
<td>any SUSY model</td>
<td>Sarah [F. Staub], <strong>FlexibleSUSY</strong> [Athron, JH Park, DS, Voigt]</td>
</tr>
</tbody>
</table>

**FlexibleSUSY properties:**

- simple def. of model (→ Sarah)/boundary condition
- c++ code modular, readable, can be reused, customized, extended!
  
  “hacking vs. programming” (Jae-hyeon Park)

Later calculations based on both codes + selected by-hand one-loop/two-loop calculations ∼ cross-checks very important!
Outline

1 Motivation: SUSY and non-minimal SUSY

2 R-symmetric SUSY as a concrete example

3 Higgs, W, dark matter vs. LHC data in MRSSM

4 Summary
Continuous, conserved R-charge. R-charges fixed by SUSY-algebra

(in superfields: $\theta \rightarrow e^{i\alpha} \theta$)
R-symmetric model MRSSM [Kribs, Poppitz, Weiner]

- some MSSM-processes forbidden
- surviving ones have stronger $m_{\text{gluino}}$-suppression
**R-symmetric model MRSSM** [Kribs, Poppitz, Weiner]

- **q** \( (R=0) \) → \( \tilde{q}_L \) \( (R=+1) \) → \( \tilde{q}_R \) \( (R=-1) \) → \( q \) \( (R=0) \)

- Gluino (and other gauginos/Higgsinos) = Dirac-fermion
  - Gluon: 2 d.o.f.
  - Gluino: 4 d.o.f.
  - New scalar sgluon: 2 d.o.f

(SU(3) × SU(2) × U(1) requires new chiral superfields (adjoint) \( \hat{O}, \hat{T}, \hat{S} \))
R-symmetric model MRSSM [Kribs, Poppitz, Weiner]

\[ q \ (R=0) \]
\[ \tilde{q}_L \ (R=+1) \]
\[ \tilde{q}_R \ (R=-1) \]

Same for all gauginos \(\Rightarrow\) new scalars
- colour octet scalars (s gluons)
- SU(2) triplet scalar (Higgs Triplet!)
- Higgs singlet
Technical summary of MRSSM

New symmetry, $\theta \rightarrow e^{i\alpha \theta}$

- $\tilde{q}_L: R=+1$, $\tilde{q}_R: R=-1$, no LR-mixing!

Dirac gauginos, new superfields $\hat{O}$, $\hat{T}$, $\hat{S}$

- Dirac gluinos

- new scalars: sgluons, Higgs triplet, Higgs singlet

Dirac Higgsinos, new superfields $\hat{R}_u$, $\hat{R}_d$

- New superpotential terms

$$W_{\text{MRSSM}} = \ldots + \mu_u \hat{H}_u \hat{R}_u + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u + \lambda_u \hat{H}_u \hat{S} \hat{R}_u + y_u \hat{Q} \hat{H}_u \hat{U}$$

$\Rightarrow$ Mass eigenstates: 4 Dirac neutralinos, 4 Dirac charginos
Interesting properties of MRSSM, sample scenarios

- R-charges forbid some processes
- Dirac gauginos, and Dirac Higgsinos
- new: sgluon, Higgs triplet/singlet
- solves SUSY flavor problem
Outline

1. Motivation: SUSY and non-minimal SUSY
2. R-symmetric SUSY as a concrete example
3. Higgs, W, dark matter vs. LHC data in MRSSM
4. Summary
Higgs, W, dark matter vs. LHC data in MRSSM

- $M^E_{h} = 125.09 \pm 0.24$ GeV, $M^E_{W} = 80.385 \pm 15$ GeV
- $\Omega h^2 = 0.1199 \pm 0.0027$, no dark matter direct detection
- LHC searches have not found new particles
Question 1: MRSSM compatible with Higgs, W mass measurements?

[Diessner, Kalinowski, Kotlarski, DS '14, '15]

Bad/difficulty for $M_h$: more scalars $S$, $T^0$ mix, reduced tree-level mass
Question 1: MRSSM compatible with Higgs, W mass measurements? [Diessner, Kalinowski, Kotlarski, DS ’14, ’15]

Bad/difficulty for $M_h$: more scalars $S$, $T^0$ mix, reduced tree-level mass

$$M_{\text{limit}_{\phi;2,3}} = \begin{pmatrix} m_Z^2 & \nu_u(\sqrt{2}\lambda_u\mu_u^{\text{eff}} + g_1m_B^B) \\ \nu_u(\sqrt{2}\lambda_u\mu_u^{\text{eff}} + g_1m_B^B) & 4(m_D^B)^2 + m_S^2 + \frac{\lambda_u^2\nu_u^2}{2} \end{pmatrix}$$

(for $\nu_S, T \ll \nu$, $m_D^2 \ll m_{\text{soft}}$)

- off-diag. elements=Higgsino/gaugino masses shouldn’t be too large, loop corrections very important
Question 1: MRSSM compatible with Higgs, W mass measurements?

Good for $M_h$: large loop contributions to $M_h$ from “Yukawa couplings”
Question 1: MRSSM compatible with Higgs, W mass measurements?

Good for $M_h$: large loop contributions to $M_h$ from “Yukawa couplings”

- Top Yukawa: $y_u \hat{Q} \hat{H}_u \hat{U}$:

  $$ (\Delta m_h)^2 \propto y_u^4 \log \frac{m_{\tilde{t}}^2}{m_{\tilde{t}}^2} $$

- New Yukawa: $\Lambda_u \hat{H}_u \hat{T} \hat{R}_u$:

  $$ (\Delta m_h)^2 \propto \frac{4\lambda^4 + 4\lambda^2\Lambda^2 + 5\Lambda^4}{4} \log \frac{m_{\text{scalar}}^2}{m_D^2} $$

  (additional positive two-loop contributions from sgluons!)
Question 1: MRSSM compatible with Higgs, W mass measurements?

Good for $M_h$: large loop contributions to $M_h$ from “Yukawa couplings”

- Top Yukawa: $y_u \hat{Q} \hat{H}_u \hat{U}$:
  
  $$ (\Delta m_h)^2 \propto y_u^4 \log \frac{m_t^2}{m_t^2} $$

- New Yukawa: $\Lambda_u \hat{H}_u \hat{T} \hat{R}_u$:
  
  $$ (\Delta m_h)^2 \propto \frac{4\lambda^4 + 4\lambda^2\Lambda^2 + 5\Lambda^4}{4} \log \frac{m_{\text{scalar}}^2}{m_D^2} $$

  (additional positive two-loop contributions from sgluons!)

- motivates large “Yukawa coupling” $\Lambda_u$ and mass splitting
  
  $m_D \ll m_{\text{scalar}}$
Question 1: MRSSM compatible with Higgs, W mass measurements?

Additionally: positive two-loop corrections from sgluons

However, danger for $M_W$:

- Yukawas shouldn’t be too large!
- Higgs Triplet VEV must be small!
Question 1: MRSSM compatible with Higgs, W mass measurements?

Additionally: positive two-loop corrections from sgluons

However, danger for $M_W$:

- Yukawas shouldn’t be too large!
- Higgs Triplet VEV must be small!

Answer 1: There is viable parameter space!  
[Diessner, Kalinowski, Kotlarski, DS '14, '15]
Interesting properties of MRSSM, sample scenarios

- R-charges forbid some processes
- Dirac gauginos, and Dirac Higgsinos
- new: sgluon, Higgs triplet/singlet
- solves SUSY flavor problem
- $M_h$: motivates rather light charginos
- ... and large “Yukawa coupling” $\Lambda_u$
Question 2: light singlet possible/helpful?

- Should be an advantage:
- No tree-level reduction for SM-like Higgs
- relevant $H_u-S$ mass matrix shows the requirements:

$$
\mathcal{M}_{\text{phi};2,3}^{\text{limit}} = \begin{pmatrix}
    m_Z^2 & \nu_u(\sqrt{2}\lambda_u\mu_u^{\text{eff}-} + g_1 m_D^B) \\
    \nu_u(\sqrt{2}\lambda_u\mu_u^{\text{eff}-} + g_1 m_D^B) & 4(m_D^B)^2 + m_S^2 + \frac{\lambda_u^2\nu_u^2}{2}
\end{pmatrix}.
$$

- small $m_D^B$, $m_S$, $\lambda_u\nu_u \rightarrow$ is this viable?
Question 2: light singlet possible/helpful?

- Should be an advantage:
- No tree-level reduction for SM-like Higgs
- relevant $H_u - S$ mass matrix shows the requirements:

$$
M_{\text{phi};2,3}^{\text{limit}} = \begin{pmatrix}
  m_Z^2 & \nu_u \left( \sqrt{2} \lambda_u \mu_u^{\text{eff}} + g_1 m_D^B \right) \\
  \nu_u \left( \sqrt{2} \lambda_u \mu_u^{\text{eff}} + g_1 m_D^B \right) & 4 \left( m_D^B \right)^2 + m_S^2 + \frac{\lambda_u^2 \nu_u^2}{2}
\end{pmatrix}.
$$

- small $m_D^B$, $m_S$, $\lambda_u \nu_u \rightarrow$ is this viable?

Answer 2:
Yes! Light bino Dirac mass possible!

[Diessner, Kalinowski, Kotlarski, DS '15]

Now study dark matter and LHC data!
Interesting properties of MRSSM, sample scenarios

- R-charges forbid some processes
- Dirac gauginos, and Dirac Higgsinos
- New: sgluon, Higgs triplet/singlet
- Solves SUSY flavor problem
- $M_h$: motivates rather light charginos
- ... and large “Yukawa coupling” $\Lambda_u$
- Light singlet possible $\rightarrow$ small $m_D^B$, $m_S$
3 Higgs, W, dark matter vs. LHC data in MRSSM

- $M^\text{Exp}_h = 125.09 \pm 0.24$ GeV, $M^\text{Exp}_W = 80.385 \pm 15$ GeV
- $\Omega h^2 = 0.1199 \pm 0.0027$, no dark matter direct detection
- LHC searches have not found new particles
Question 3: dark matter explained in MRSSM with(out) light singlet?

Relic density \( (f = \tau) \):
- LSP = Dirac Bino
- \( m_{\text{LSP}} < 60 \ldots 300 \text{GeV} \)
- annihilates into \( \tau \)
- light stau mass fixed, \( m_{\tilde{\tau}} - m_{\text{LSP}} < 100 \text{GeV} \)

Direct detection limits \( (f = q) \):
- Interference between terms \( \propto \frac{1}{\mu_u^2}, \frac{1}{m_q^2} \)
- \( \mu_u \approx 400 \ldots 700 \text{GeV} \) preferred to evade limits
Question 3: dark matter explained in MRSSM with(out) light singlet?

Relic density \((f = \tau)\):
- LSP = Dirac Bino
- \(m_{\text{LSP}} < 60 \ldots 300\text{GeV}\)
- annihilates into \(\tau\)
- light stau mass fixed, \(m_{\tilde{\tau}} - m_{\text{LSP}} < 100\text{GeV}\)

Direct detection limits \((f = q)\):
- Interference between terms \(\propto \frac{1}{\mu_u^2}, \frac{1}{m_{\tilde{q}}^2}\)
- \(\mu_u \approx 400 \ldots 700\text{GeV}\) preferred to evade limits
Interesting properties of MRSSM, sample scenarios

- R-charges forbid some processes
- Dirac gauginos, and Dirac Higgsinos
- new: sgluon, Higgs triplet/singlet
- solves SUSY flavor problem
- $M_h$: motivates rather light charginos
- $\ldots$ and large “Yukawa coupling” $\Lambda_u$
- light singlet possible $\rightarrow$ small $m_D^B$, $m_S$
- dark matter: LSP=Dirac Bino, light stau; $\sim$ 500GeV Higgsino $\mu_u$ preferred
Higgs, W, dark matter vs. LHC data in MRSSM
- $M_h^{\text{Exp}} = 125.09 \pm 0.24$ GeV, $M_W^{\text{Exp}} = 80.385 \pm 15$ GeV
- $\Omega h^2 = 0.1199 \pm 0.0027$, no dark matter direct detection
- LHC searches have not found new particles
Question 4: Allowed by EW LHC searches?

Recast LHC limits for MSSM to MRSSM:
Assume very light singlet and LSP $\sim 50$ GeV; light stau $\sim 100$ GeV;
discuss limits on one degenerate neutralino/chargino $\chi^{0,\pm}$

MSSM:
- $\chi^{0,\pm} =$ wino-like
- decays to Higgs/Z/W/stau
- searches not effective

MRSSM (more dangerous!):
- $\chi^{0,\pm} =$ down-higgsino-like
- decay to stau if possible
- searches effective, but scenario alive, e.g. for $m_{\chi^{0,\pm}} > 350$ GeV!
Question 4: Allowed by EW LHC searches?

Answer 3/4: Dark matter can be explained in this scenario!

Recast LHC limits for MSSM to MRSSM:
Assume very light singlet and LSP $\sim 50$ GeV; light stau $\sim 100$ GeV;

discuss limits on one degenerate neutralino/chargino $\chi^{0,\pm}$

MSSM:
- $\chi^{0,\pm} =$ wino-like
- decays to Higgs/Z/W/stau
- searches not effective

MRSSM (more dangerous!):
- $\chi^{0,\pm} =$ down-higgsino-like
- decay to stau if possible
- searches effective, but scenario alive, e.g. for $m_{\chi^{0,\pm}} > 350$ GeV!
Question 5: How about LHC searches for colored sparticles? [DKKS+Liebschner]

Hope: total cross section reduced, lighter masses possible!

- simple study without MRSSM NLO corrections: [Kribs, Martin '12]
  “squarks in MRSSM can be a few 100 GeV lighter than in the MSSM”

- preliminary result for NLO corrections [Diessner, Kalinowski, Kotlarski, Liebschner, DS]:
  K-factor in MRSSM is higher than in MSSM! Depends e.g. on sgluon mass
Question 5: How about LHC searches for colored sparticles? [DKKS+Liebschner] Lighter squarks possible!

Hope: total cross section reduced, lighter masses possible!

- simple study without MRSSM NLO corrections: [Kribs, Martin ’12] “squarks in MRSSM can be a few 100 GeV lighter than in the MSSM”
- preliminary result for NLO corrections [Diessner, Kalinowski, Kotlarski, Liebschner, DS]: K-factor in MRSSM is higher than in MSSM! Depends e.g. on sgluon mass
- outlook: compare to LHC data!
Interesting properties of MRSSM, sample scenarios

- R-charges forbid some processes
- Dirac gauginos, and Dirac Higgsinos
- new: sgluon, Higgs triplet/singlet
- solves SUSY flavor problem
- $M_h$: motivates rather light charginos
- ... and large “Yukawa coupling” $\Lambda_u$
- light singlet possible $\rightarrow$ small $m_D^B$, $m_S$
- dark matter: LSP=Dirac Bino, light stau; $\sim 500\text{GeV}$ Higgsino $\mu_u$ preferred
- LHC EW searches: ok
- LHC squark searches: to do precisely
Interesting properties of MRSSM, sample scenarios

- R-charges forbid some processes
- Dirac gauginos, and Dirac Higgsinos
- new: sgluon, Higgs triplet/singlet
- solves SUSY flavor problem
- $M_h$: motivates rather light charginos
- ...and large “Yukawa coupling” $\Lambda_u$
- light singlet possible $\rightarrow$ small $m^B_D$, $m_S$
- dark matter: LSP=Dirac Bino, light stau; $\sim 500$GeV Higgsino $\mu_u$ preferred
- LHC EW searches: ok
- LHC squark searches: to do precisely
Outline

1. Motivation: SUSY and non-minimal SUSY
2. R-symmetric SUSY as a concrete example
3. Higgs, W, dark matter vs. LHC data in MRSSM
4. Summary
Summary and Outlook

- **Non-minimal SUSY well motivated**
  - general + model-specific motivations
  - model-specific LHC signals/limits

- **Example R-symmetry: distinct, motivated model**
  - $M_W$, $m_h$, dark matter can be explained
  - very light spectrum possible ($\tilde{B}$, $S$, $\tilde{\tau}$, $\chi^{0,\pm}$)
  - (Heavy singlet scenario: LSP $\sim 250$GeV)
  - Dirac fermions, new scalars
  - beautiful, more symmetry

- **Other “non-minimal” SUSY models also of interest**
  - e.g. E$_6$SSM unifies quarks–leptons–Higgs
    - predicts observable leptoquark(ino)s
  - e.g. MSSM for $\tan \beta \rightarrow \infty$
    - $(g - 2)_\mu$ explained for $M_{\text{LSP}} \sim 1000$GeV!