(In)dependence of various LFV observables in the non-minimal SUSY

Wojciech Kotlarski
Technische Universität Dresden

ICHEP 2018,
July 7, 2018, Seoul, Korea

in collaboration with D. Stöckinger and H. Stöckinger-Kim
**R-symmetry**

- additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem

- for \( N=1 \) it is a global \( U_R(1) \) symmetry under which the SUSY generators are charged

- implies that the spinorial coordinates are also charged \( Q_R(\theta) = 1, \ \theta \to e^{i\alpha} \theta \)

- superpotential example

\[
\mathcal{L} \equiv \int d^2 \theta \ W
\]

- Superpotential is polynomial in fields. For \( W \) to transform homogeneously superfields must have definite R-charges

\[
e^{i\alpha Q_R} \quad e^{i\alpha Q_R} \quad e^{i\alpha (Q_R - 1)}
\]

\[
\Phi = \phi(y) + \sqrt{2} \theta \psi(y) + \theta \theta F(y)
\]

- Similarly one can work out other parts of the Lagrangian
R-symmetry

- additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem

- for N=1 it is a global $U_R(1)$ symmetry under which the SUSY generators are charged

- implies that the spinorial coordinates are also charged $Q_R(\theta) = 1, \theta \rightarrow e^{i\alpha} \theta$

- superpotential example

(we want it to be) $\mathcal{L}$

$\mathcal{L} \ni \int d^2\theta \ W$

- Superpotential is polynomial in fields. For W to transform homogeneously superfields must have definite R-charges

$e^{i\alpha Q_R}$

$\Phi = \phi(y) + \sqrt{2}\theta \psi(y) + \theta \theta F(y)$

- Similarly one can work out other parts of the Lagrangian
R-symmetry

- additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem

- for N=1 it is a global $U_R(1)$ symmetry under which the SUSY generators are charged

- implies that the spinorial coordinates are also charged $Q_R(\theta) = 1, \theta \rightarrow e^{i\alpha} \theta$

- superpotential example

(we want it to be) $R$-invariant $\quad \mathcal{L} \quad \ni \quad \int d^2 \theta \quad W$

- Superpotential is polynomial in fields. For $W$ to transform homogeneously superfields must have definite $R$-charges

$$ e^{i\alpha Q_R} \quad e^{i\alpha Q_R} \quad e^{i\alpha (Q_R - 1)} $$

$$ \Phi = \phi(y) + \sqrt{2} \theta \psi(y) + \theta \theta F(y) $$

- Similarly one can work out other parts of the Lagrangian
R-symmetry

- additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem

- for N=1 it is a global $U_R(1)$ symmetry under which the SUSY generators are charged

- implies that the spinorial coordinates are also charged $Q_R(\theta) = 1, \theta \rightarrow e^{i\alpha} \theta$

- superpotential example

(we want it to be) R-invariant

Superpotential is polynomial in fields. For $W$ to transform homogeneously superfields must have definite R-charges

$$e^{i\alpha Q_R} \Phi = e^{i\alpha Q_R} \phi(y) + \sqrt{2} \theta \psi(y) + \theta \theta F(y)$$

- Similarly one can work out other parts of the Lagrangian
Low-energy R-symmetry realization

- Different possible models that one can construct
- "Natural" choice

\[ e^{i\alpha Q_R} \Phi = e^{i\alpha Q_R} \phi(y) + \sqrt{2} \theta \psi(y) + \theta \theta F(y) \]

leptons and quarks

- Good: no barion and lepton number violating terms
- Bad: No Majorana masses for higgsinos and gauginos

- Higgs

\[ Q_R = 1 \quad Q_R = 1 \quad Q_R = 0 \]
\[ Q_R = 0 \quad Q_R = 0 \quad Q_R = -1 \]

One way to fix it: Dirac masses

Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)

Kriis et al. arXiv:0712.3029

<table>
<thead>
<tr>
<th>Field</th>
<th>SU(3)\text{c}</th>
<th>SU(2)\text{L}</th>
<th>U(1)\text{Y}</th>
<th>U(1)\text{R}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet ( \hat{S} )</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Triplet ( \hat{T} )</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Octet ( \hat{O} )</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>R-Higgses ( \hat{R}_{u} )</td>
<td>1</td>
<td>2</td>
<td>-1/2</td>
<td>2</td>
</tr>
<tr>
<td>R-Higgses ( \hat{R}_{d} )</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
<td>2</td>
</tr>
</tbody>
</table>

Additional fields:

\[ W = \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u \]
\[ + \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u \]
\[ - Y_d \hat{q} \hat{H}_d - Y_e \hat{\ell} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u \]
MSSM vs. MRSSM

- **superpotential**
  \[
  \mu \hat{H}_u \hat{H}_d - Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u
  \]

- **soft-SUSY breaking terms**
  - $B_\mu$ - term
  - soft scalar masses
  - Majorana gaugino masses
  - $A$ - terms

- **superpotential**
  \[
  \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u - Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u \\
  \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u
  \]

- **soft-SUSY breaking terms**
  - $B_\mu$ - term
  - soft scalar masses
  - Dirac gaugino masses
  - no $A$-terms

One way to fix it: **Dirac masses**

**Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)**

<table>
<thead>
<tr>
<th>Additional fields</th>
<th>$SU(3)_C$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
<th>$U(1)_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet</td>
<td>$\hat{X}$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Triplet</td>
<td>$\hat{X}$</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Octet</td>
<td>$\hat{O}$</td>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>R-Higgses</td>
<td>$\hat{R}_u$</td>
<td>1</td>
<td>2</td>
<td>$-1/2$</td>
</tr>
<tr>
<td></td>
<td>$\hat{R}_d$</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Kribs, Popitz, Weiter (2008)
MSSM vs. MRSSM

- superpotencial
  \[ \mu \hat{H}_u \hat{H}_d \]
  \[-Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u \]

- soft-SUSY breaking terms
  - \( B_\mu \) - term
  - soft scalar masses
  - Majorana gaugino masses
  - \( \Lambda \) - terms

- superpotencial
  \[ \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u \]
  \[-Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u \]
  \[ \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u \]

- soft-SUSY breaking terms
  - \( B_\mu \) -term
  - soft scalar masses
  - Dirac gaugino masses
  - no \( \Lambda \) -terms

One way to fix it: Dirac masses
Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)

Kribs et al. arXiv:0712.2039

<table>
<thead>
<tr>
<th>Additional fields:</th>
<th>SU(3)</th>
<th>SU(2)</th>
<th>U(1)Y</th>
<th>U(1)R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet</td>
<td>( \hat{S} )</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Triplet</td>
<td>( \hat{T} )</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Octet</td>
<td>( \hat{O} )</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>R-Higgses</td>
<td>( \hat{R}_u )</td>
<td>1</td>
<td>2</td>
<td>(-1/2)</td>
</tr>
<tr>
<td></td>
<td>( \hat{R}_d )</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Kribs, Popitz, Weiter (2008)
Particle content summary: MSSM vs. MRSSM

<table>
<thead>
<tr>
<th></th>
<th>Higgs</th>
<th></th>
<th>R-Higgs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CP-even</td>
<td>CP-odd</td>
<td>charged</td>
<td>charginos</td>
</tr>
<tr>
<td>MSSM</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>MRSSM</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2+2</td>
</tr>
</tbody>
</table>

Different number of physical states

Completely new states

<table>
<thead>
<tr>
<th></th>
<th>neutralino</th>
<th>gluino</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>MRSSM</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>
As the LHC still sees nothing, we look into low energy experiments:

- prospects for $g-2$ measurement

$$a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = (28.1 \pm 6.3^{\text{exp}} \pm 3.6^{\text{th}}) \times 10^{-10}$$

- prospect for $\mu \rightarrow e\gamma$

    current: $4.2 \times 10^{-13}$ (MEG)  

    future: $\approx 4 \times 10^{-14}$

- prospect for $\mu \rightarrow e$ conversion

    current: $7 \times 10^{-13}$ (SINDRUM-II)  

    future: $\approx 10^{-16}$
Relation between \((g - 2)_\mu\) and LFV observables

\[ \mu \rightarrow e \]

\[ \mu \rightarrow e\gamma \]

\[ (g - 2)_\mu \]

\[ D, A_{1}^{21}, A_{2}^{21} \]

\[ A_{2}^{21} \]

\[ A_{2}^{22} \]

each observable requires a dedicated experiment
\((g - 2)_\mu\) in the MSSM

**Chargino**

\[ \propto m_\mu^2 \tan \beta \mu M_2 \]

\[ \tilde{H}_2^+ \quad \tilde{W}^+ \quad \tilde{H}_1^+ \quad \tilde{W}^+ \]

\[ \mu_R \quad \tilde{\nu}_\mu \quad \mu_L \]

**Neutralino**

\[ \propto m_\mu^2 \tan \beta \mu M_1 \]

\[ \tilde{B} \quad \tilde{B} \quad \tilde{H}_2^0 \quad \tilde{H}_1^0 \]

\[ \mu_R \quad \tilde{\mu}_R \quad \tilde{\mu}_L \quad \mu_L \]

and similarly for \(\mu \to e\gamma\) and \(\mu \to e\) - as long as \(\tan \beta\) is not very small all considered observables are dominated by the dipole contributions and therefore strongly correlated.

\[ \text{CR}(\mu \to e) \propto \alpha \cdot \text{BR}(\mu \to e\gamma) \]

\[ \text{CR}(\mu \to e) \leq 3 \cdot 10^{-15} \]
$(g - 2)_\mu$ in the MRSSM

**Chargino**

$\propto m^2_\mu \tan \beta \mu M_2$

**Neutralino**

$\propto m^2_\mu \tan \beta \mu M_1$

There is one class of enhanced diagram though
\((g - 2)_\mu\) in the MRSSM

- It is possible to obtain large contribution to g-2

- The price to pay are light EW-inos, in tension with experiment
For $|\lambda_d| \approx 1$ the dipoles dominate: $g-2$ scales linearly with $\lambda_d$, while $\mu\to e\gamma$ and $\mu\to e$ quadratically.

For $|\lambda_d| \approx 1$ the ratio of $\mu\to e\gamma$ over $\mu\to e$ is of the order 100, as in the MSSM where $\text{CR}(\mu \to e) \propto \alpha \cdot \text{BR}(\mu \to e\gamma)$.

Near $|\lambda_d| \approx 0$ the ratio is of order 10.
In the region dominated by the dipoles the \( \text{br}(\mu \to e\gamma) \sim \sin^2 2\theta \cdot a_\mu \)

- In the MRSSM this is a region of \( |\lambda_d| \gtrsim 1 \), in the MSSM \( \tan \beta \gtrsim 5 \)
Conclusions:

- Two distinct cases: $|\lambda_d| \approx 0$, $|\lambda_d| > 0$

- For large $|\lambda_d|$ observables get dominated by photon „penguins” and are strongly correlated

- Generating sufficient contribution to g-2 through large $\lambda_d$ overshots LFV observables (unless one fine-tunes the mixing angle)

- Similar things happen for $\Lambda_d$

- For $|\lambda_d| \approx 0$ the g-2 and $\mu \rightarrow e\gamma$ are still correlated but the $\mu \rightarrow e$ conversion rate can be dominated by so-called charge radius, Z-penguin and box contributions

- It is therefore possible to find a parameter points not excluded by current experimental results, within reach of the next $\mu \rightarrow e$ conversion (but not $\mu \rightarrow e\gamma$) experiment
Backup
The SM-like Higgs boson mass in the MRSSM has been calculated including full 1-loop and leading 2-loop corrections\textsuperscript{1,2}

Impact of EWPO was analyzed\textsuperscript{1}

MRSSM can predicts correct dark matter relic density while being in agreement with dark matter direct detection bounds\textsuperscript{3}

Its EW signatures were checked against available 7 and 8 TeV data\textsuperscript{3}

\textbf{1.} P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, JHEP \textbf{1412} (2014) 124


\textbf{3.} P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, JHEP \textbf{1603} (2016) 007
2 component dark matter

- consider scenarios where the lightest particle with $R=1$ is neutralino or sneutrino with mass $m_{\text{LSP1}}$

- if $m_{R_1^0} < 2m_{\text{LSP1}}$, lightest neutral $R$-Higgs is also stable

- two SUSY dark matter candidates with relic densities $\Omega_1$ and $\Omega_2$

- requirements
  - $\Omega_{\text{total}}h^2 \equiv (\Omega_1 + \Omega_2)h^2 \approx 0.11$
  - substantial fraction $\Omega_2/\Omega_{\text{total}}$

- (for now) best points are not collinear friendly:
  \[ m_{\tilde{\chi}_1^0} = 367 \text{ GeV} \]
  \[ m_{R_1^0} = 571 \text{ GeV} \]
Sgluon pair production at 13 TeV LHC

- Analysis of the sgluon pair production with subsequent decay into $tt$ pairs. Recasting ATLAS search in the same-sign lepton channel using 3.2/ fb of integrated luminosity.

- Signal simulated at NLO using MadGraph5_aMC@NLO + FeynRules + NLOCT and matched to parton shower in the MC@NLO scheme.

- Detector response parametrized using Delphes3.

- Analysis validated on background processes $t\bar{t}l^+l^-, t\bar{t}l^\pm\nu$.

- Mass of pair produced real sgluons decaying with $\text{BR}(O \rightarrow tt) = 1$ excluded up to 950 GeV.
Leading order analysis

LO cross-sections for sparticle production at the LHC at $\sqrt{s} = 13$ TeV

![Graph showing cross-sections for sparticles production in MSSM and MRSSM](image)
NLO improvements

Reduction of theoretical uncertainty

Shift of cross-sections

\( pp \rightarrow \tilde{u}_L \tilde{u}_R, m_{\tilde{q}} = 1500 \text{ GeV}, m_{\tilde{g}} = 2000 \text{ GeV} \)

\( \mu_R = \mu_F \) [GeV]

\( \sigma \) [fb]

\( K(\bar{q}q \rightarrow \bar{q}q) \)

\( m_{\tilde{g}} = 2000 \text{ GeV}, m_{\tilde{O}} = 5000 \text{ GeV} \)

\( \bar{q}q \) NLO

\( \bar{q}q \) LO

\( \bar{q}q \) NLO

\( \bar{q}q \) LO

Right figure summed over flavors

Reduction of theoretical uncertainty

Shift of cross-sections
Two possible definitions of $K$-factors:

- unsummed over L- and R-squarks
- summed
Differential distributions

\[ P_T, BM1, \tilde{q}_L, \tilde{q}_L^+ \]

- \( \sigma \text{ per bin [pb]} \)
- \( K(\text{NLO}) \)

Graph showing differential distributions with NLO and LO comparisons.
\( \mu \rightarrow e\gamma \) in the MRSSM

- first analysis performed by Fok and Kribs [Phys. Rev. D 82, 035010 (2010)]

- simplifying assumptions: \( M_2, \mu_u \rightarrow \infty \), only 2 neutralinos containing \( \tilde{B}, \tilde{H}_d \) contribute

\[
m_{\tilde{l}_2} = \frac{3}{2} m_{\tilde{l}}
\]

\[
m_{\tilde{l}} = \frac{3}{2} m_{\tilde{l}_2}
\]

\[
\mu_d = 100 \text{ GeV}
\]

maximal mixing

new MEG results

old MEG results