Phenomenological constraints on an R-symmetric supersymmetric model

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Going beyond the MSSM

Motivation

- LHC Run 1 mostly analyzed, Run 2 started
- Invites to look into non-minimal models for diverse spectrum of predictions
- Including interesting and unconventional features

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- Here: **R-Symmetry**
  - Includes solution to flavor problem of the MSSM
  - Dirac gauginos (esp. gluino) might explain SUSY non-discovery
  - Gauge-mediated scenario possible as UV completion
- Have to allow for 125 GeV Higgs and other experimental constraints

Outline

1. R-Symmetry
   - Definition and Motivation
   - MRSSM
2. Predictions
   - Lightest CP-even Higgs Mass
   - Electroweak Precision Observables
   - Non-MSSM scenario

R-Symmetry

- additional symmetry allowed by SUSY algebra described in "Haag-Łopuszański-Sohnius-Theorem"
- For $N = 1$ SUSY it is a global $U(1)_\mathrm{R}$ symmetry
  $\rightarrow$ charged Spinor coordinates:
  $Q_\mathrm{R}(\theta) = 1$, $Q_\mathrm{R}(\bar{\theta}) = -1$; $\quad (\theta \rightarrow e^{i\alpha}\theta, \bar{\theta} \rightarrow e^{-i\alpha}\bar{\theta})$
- Lagrangian has to be invariant:
  - terms in superpotential have $Q_\mathrm{R} = 2$; $\mathcal{L}_\mathcal{W} = \int \mathrm{d}^2\theta \mathcal{W}$
  - softbreaking terms have $Q_\mathrm{R} = 0$
- SM fields have $Q_\mathrm{R} = 0$

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R charges of component fields

	Q_R	scalar	vector	fermionic
vector superfield	0	-	0	1
chiral superfield	Q	Q	-	$Q-1$

$\rightarrow$ Higgs superfield: $Q_\mathrm{R} = 0$; lepton and quark superfields: $Q_\mathrm{R} = 1$

Consequences for model building

Symmetry forbids terms in Lagrangian

- Superpotential ($Q_R = 2$): $\mu \hat{H}_u \hat{H}_d$, $\lambda \hat{E}\hat{L}\hat{L}$, $\kappa \hat{U}\hat{D}\hat{D}$
- Soft breaking ($Q_R = 0$): $M_i \tilde{\lambda}_i \tilde{\lambda}_i$, $A y_e h_d \tilde{l} \tilde{e}_R$, $A y_u h_u \tilde{q} \tilde{u}_R$, $A y_d h_d \tilde{q} \tilde{d}_R$

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One way to fix it: Dirac masses

Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)

Kribs et.al. (Phys.Rev. D78 (2008) 055010)

Additional fields:

		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathrm{R}}$
Singlet	$\hat{S}$	1	1	0	0
Triplet	$\hat{T}$	1	3	0	0
Octet	$\hat{O}$	8	1	0	0
R-Higgses	$\hat{R}_u$	1	2	$-1/2$	2
	$\hat{R}_d$	1	2	$1/2$	2

New interactions

Superpotential

$$
\begin{aligned}
\mathcal{W} = & y_e \hat{H}_d \hat{L} \hat{E} + y_d \hat{H}_d \hat{Q} \hat{d} - y_u \hat{H}_u \hat{Q} \hat{U} + \\
& \mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u + \\
& \lambda_d \hat{H}_d \hat{R}_d \hat{S} + \lambda_u \hat{H}_u \hat{R}_u \hat{S} + \Lambda_d \hat{H}_d \hat{T} \hat{R}_d + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u
\end{aligned}
$$

New interactions

Superpotential

$$\begin{aligned}\mathcal{W} = & y_e \hat{H}_d \hat{L} \hat{E} + y_d \hat{H}_d \hat{Q} \hat{d} - y_u \hat{H}_u \hat{Q} \hat{U} + \\ & \mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u + \\ & \lambda_d \hat{H}_d \hat{R}_d \hat{S} + \lambda_u \hat{H}_u \hat{R}_u \hat{S} + \Lambda_d \hat{H}_d \hat{T} \hat{R}_d + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u\end{aligned}$$

Soft SUSY Breaking

$$\begin{aligned}-\mathcal{L}_{\text{soft}} = & M_i^D \tilde{\lambda}_i^a \psi_j^a - \sqrt{2} M_i^D D_j^a \phi_i^a + m_k^2 \phi_k \phi_k^* + B\mu h_u h_d \\ & + h.c. \\ \{i, j\} \in & \{\{G, O\}, \{W, T\}, \{B, S\}\}; \\ k \in & \{q, u, d, l, e, H_d, H_u, R_d, R_u, S, T, O\}\end{aligned}$$

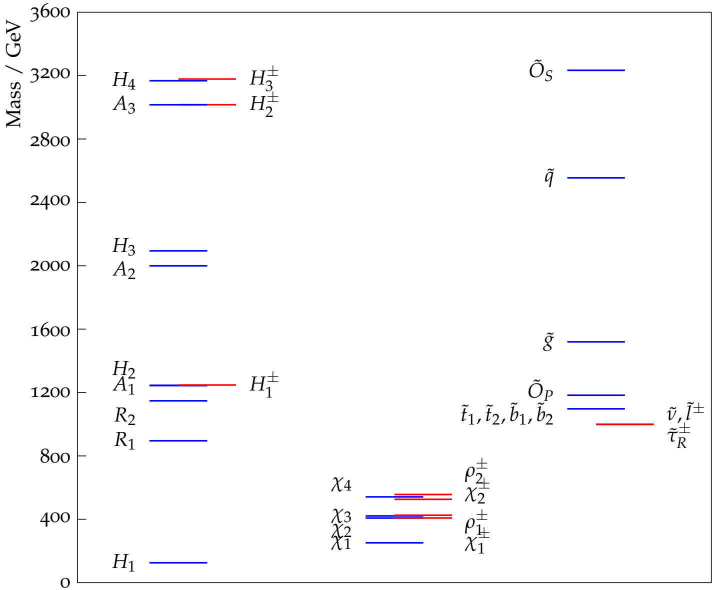
Other soft breaking terms related to S, T, O possible but for simplicity excluded here

Details of Calculation

PD et.al. (JHEP 1412 (2014) 124), (arXiv:1504.05386)

- Implementation of the model in `SARAH`
- All tree level relations generated, Interface to `FeynArts`
- Mass spectrum at one-loop level with generators linked to `SARAH`: `SPheno` and `FlexibleSUSY`
- `SPheno` with Higgs mass up to approx. two-loop order
- `HiggsBounds` and `HiggsSignals` to constrain Higgs sector
- Additionally `Herwig++` combined with `CheckMATE` for LHC and `micrOMEGAs` for Dark matter searches (work in progress)
- Automatizing for such a model complicated, many cross checks required and done

Example mass spectrum



Lightest Higgs mass - Tree level

EWSB

- Separating h_u, h_d, s, t in vevs, scalar and pseudo-scalar part
- Forming mass eigenstates with (4×4) mass matrices

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For $v_S, v_T \ll v$ and $(M^D)^2 \ll m^2_{\text{soft}}$
$(\lambda_u = \lambda_d = \lambda,\ \Lambda_u = \Lambda_d = \Lambda,\ \mu_u = \mu_d = \mu)$:

$$m^2_{h,\text{tree}} = m_Z^2 \cos^2 2\beta - v^2 \cos^2 2\beta \left(\frac{\left(g_1 M_B^D + \sqrt{2}\lambda\mu\right)^2}{8(M_B^D)^2 + 2m_S^2} + \frac{\left(g_2 M_W^D + \Lambda\mu\right)^2}{8(M_W^D)^2 + 2m_T^2} \right)$$

No enhancement from singlet like in the NMSSM, additional states lower lightest mass on tree level $\rightarrow$ one loop even more important

Lightest Higgs mass - One Loop

Analytical approximation from the effective potential:

- Usual MSSM stop contribution with no mixing

$$\Delta m^2_{h,y_t} = \frac{6 v_u^2}{16\pi^2}\left[y_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)\right]$$

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- Additional terms from new parameters
(Scenario as before, add. $m_S^2 = m_T^2 = m_{R_u}^2 = m_{soft}^2$, $M_B^D = M_W^D = M_D$)

$$\Delta m_h^2 = \frac{2v^2}{16\pi^2}\left(\frac{\Lambda^2\lambda^2}{2} + \frac{4\lambda^4 + 4\lambda^2\Lambda^2 + 5\Lambda^4}{4}\log\frac{m_{soft}^2}{M_D^2}\right)$$

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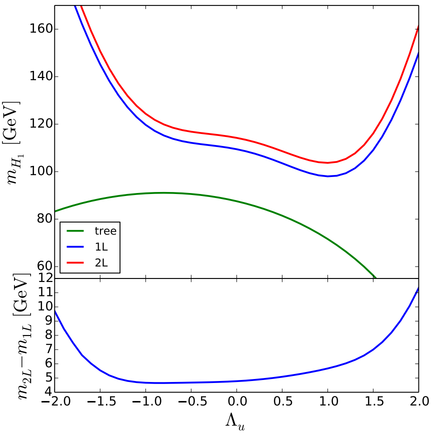
λ or/and Λ can give sizeable contribution, reducing the need for large stop mass

Lightest Higgs mass - Numerical



- Large upward correction from Λ
- Comparable to top/stop contribution, when $\Lambda \approx y_u$
- Also showing 2-loop shift, $\approx$ 5 Gev in viable region, mainly $\mathcal{O}(\alpha_s \alpha_t)$

W mass

Muon decay constant G_μ precisly measured $\rightarrow$ make prediction for m_W

tree level: $m_W^2 = g_2^2 \left(\frac{v^2}{4} + v_T^2\right) \quad \rightarrow \quad \hat{\rho} = \frac{c^2}{\hat{c}^2} \neq 1$ ($\rightarrow v_T < 4$ GeV)

one loop: $\hat{\rho}$ gets contributions from y_u, expect similar for $\Lambda \rightarrow$ add. contributions to m_W

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Write down consistent one-loop formula, which also resums leading two-loop SM effects:

$$m_W^2 = \frac{1}{2} m_Z^2 \hat{\rho} \left[1 + \sqrt{1 - \frac{4\pi \hat{\alpha}^{\overline{\text{DR}},\ \text{MRSSM}}}{\sqrt{2} G_\mu m_Z^2 \hat{\rho} (1 - \Delta \hat{r}_W)}} \right]$$

$\Delta \hat{r}_W$ contains vertex and box contributions, also partly corrections from W self-energy

W mass – qualitatively

Only oblique corrections

$$m_W = m_W^{\text{ref}} + \frac{\hat{\alpha} m_Z \hat{c}_W}{2(\hat{c}_W^2 - \hat{s}_W^2)} \left(-\frac{S}{2} + \hat{c}_W^2 T + \frac{\hat{c}_W^2 - \hat{s}_W^2}{4\hat{s}_W^2} U \right)$$

For the simplified case as before:

$$T = \frac{1}{16\pi \hat{s}_W^2 \hat{m}_W^2} \frac{v^4(4\lambda^4 + 5\Lambda^4)}{10 M_D^2} + \mathcal{O}\left(\frac{v^4}{M_D^4}\right)$$

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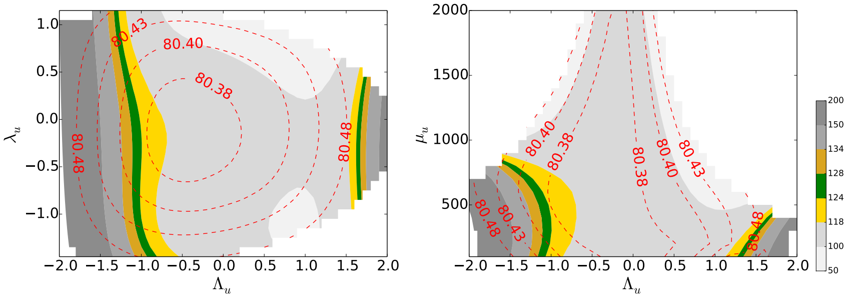
The top contribution:

$$T = \frac{3 v_u^2 y_t^2}{32\pi \hat{s}_W^2 \hat{m}_W^2}$$

Higgs mass (colour) vs. W mass (red lines)



Higgs mass calculated at full one-loop and approx. two-loop order;
W mass at full one-loop order with SARAH/SPheno

Non-trivial to find overlap for both mass predictions, but possible!

Singlet as lightest state

$$m_{h,\text{tree}}^2 \approx m_Z^2 \cos^2 2\beta - v^2 \cos^2 2\beta \left(\frac{\left(g_1 M_B^D + \sqrt{2}\lambda\mu\right)^2}{8(M_B^D)^2 + 2m_S^2} \right)$$

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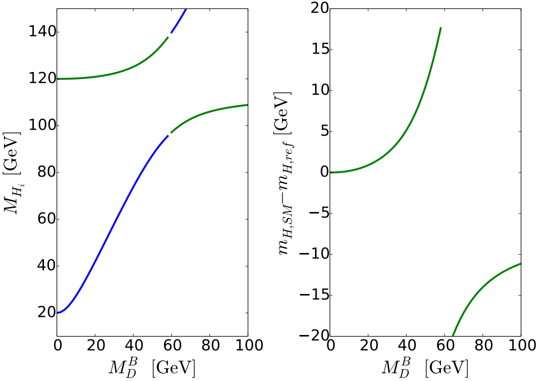
Level crossing of Higgs states

Upper limit on $M_B^D < 60$ GeV



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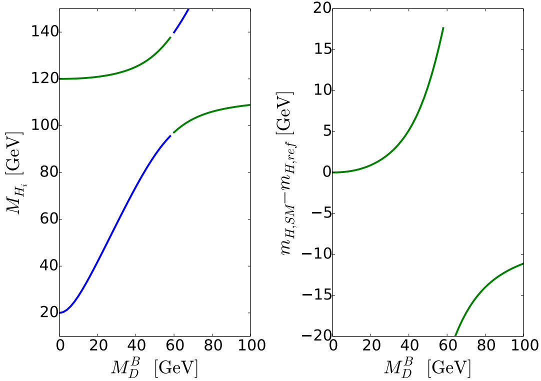
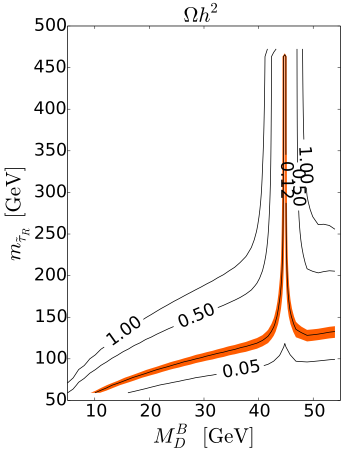
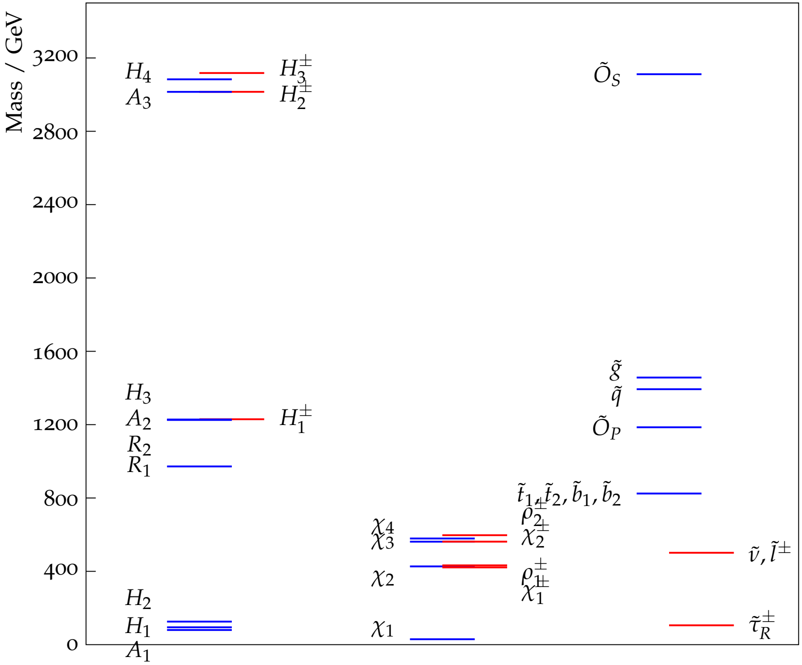


Relic density by `micrOMEGAs`




Mass / GeV
0
400
800
1200
1600
2000
2400
2800
3200
H_4
A_3
$H_3^\pm$
$H_2^\pm$
$\tilde{O}_S$
$\tilde{g}$
$\tilde{q}$
$\tilde{O}_P$
H_3
A_2
$H_1^\pm$
R_2
R_1
$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
$\rho_2^\pm$
χ_4
χ_3
$\chi_2^\pm$
$\tilde{\nu}, \tilde{l}^\pm$
χ_2
$\rho_1^\pm$
$\chi_1^\pm$
H_2
H_1
χ_1
$\tilde{\tau}_R^\pm$
A_1

Conclusions

- Introduction to R-symmetry for model building:
  $\rightarrow$ global $U(1)$ symmetry allowed by
  "Haag-Łopuszański-Sohnius-Theorem"
- Overview of MRSSM: minimal model with R-Symmetry and soft breaking
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Thanks for the attention!

References

MRSSM G. D. Kribs, E. Poppitz and N. Weiner, "Flavor in supersymmetry with an extended R-symmetry," Phys. Rev. D **78** (2008) 055010 [arXiv:0712.2039 [hep-ph]].

P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, JHEP **1412** (2014) 124 [arXiv:1410.4791 [hep-ph]].

P. Diessner, J. Kalinowski, W. Kotlarski and D. Stöckinger, arXiv:1504.05386 [hep-ph].

Backup

SUSY and R-Symmetry

usual: $\{Q, Q\} = \{\bar{Q}, \bar{Q}\} = 0$
in "Haag-Łopuszański-Sohnius-Theorem": $\{Q^L_\alpha, Q^M_\beta\} = \epsilon_{\alpha\beta} \sum_l (a^l)^{LM} R^l$
$[R, Q] = -Q, \quad [R, \bar{Q}] = \bar{Q},$
$\rightarrow$ in $\mathcal{N} = 1$ is $U(1)_R$

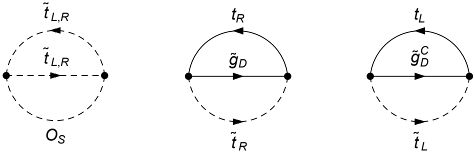
Dirac masses for soft breaking

$$\mathcal{L}_{\text{dirac}} = \int \mathrm{d}\theta^2 \hat{S} \hat{W}'^{\alpha} \hat{W}_{B\alpha} = -M^D \tilde{\lambda}_B \psi_S^a + \sqrt{2} M^D D_B^a \phi_S^a$$

using Spurion: $\hat{W}'^{\alpha} = \sqrt{2} M^D \theta^{\alpha}$

Lightest Higgs mass - Two Loop

Contributions to effective potential:



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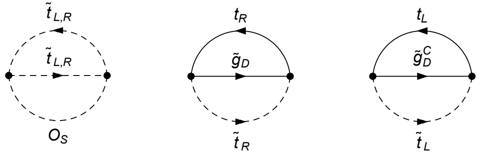
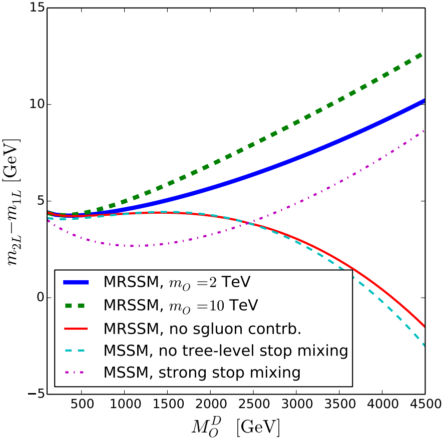


$$V_{eff}^{(2)} = \frac{8g_3^2}{(16\pi^2)^2}(M_O^D)^2 \sum_{i=L,R} f_{SSS}(m_{\tilde{t}_i}^2, m_{\tilde{t}_i}^2, m_{O_S}^2)$$
$$+ \frac{8g_3^2}{(16\pi^2)^2} \sum_{i=L,R} f_{FFS}(m_t^2, m_{\tilde{t}_i}^2, m_{\tilde{g}_D}^2)$$

Lightest Higgs mass - Numerical



First glance at LHC bounds

Only electro-weak searches (ATLAS 2 and more leptons)