

Corfu Greece 20



Corfu Summer Institute 17th Hellenic School and Workshops on Elementary Particle Physics and Gravity

A light singlet at the LHC and DM

of the R-symmetric supersymmetric model

Jan Kalinowski University of Warsaw

in collaboration with P.Diessner, W. Kotlarski and D.Stoeckinger

Supported in part by Harmonia Project form



Summary

- Well motivated R-symmetric SUSY model
- SUSY flavor problem relaxed, Dirac gauginos and higgsinos
- Extended Higgs sector with unconventional phenomenology
- Viable benchmarks with
 - ~ 125 GeV Higgs boson mass
 - agreement with EWPO and flavor physics
 - stable vacuum
- Scenario with a light singlet is very predictive
 - consistent with LHC constraints
 - viable candidate for dark matter
 - some states light and could be seen at the LHC

Outline

Introduction

SUSY with R-symmetry MRSSM

Higgs sector

Higgs boson masses electroweak observables

- Confronting the experiment

 light singlet phenomenology
 LHC constraints
 dark matter connection
- Summary

Based on papers JHEP 1412 (2014) 124, Adv. HEP (2015) 760729, JHEP 1603 (2016) 007, Acta Phys.Polon.B (2016) 203, PoS LL2016, 012.

Minimal supersymmetry



- ✓ Solves hierarchy problem
- $\checkmark\,$ LSP can be DM candidate

Expect some SUSY states directly to show up at LHC

Experimental searches

PACEI PRACMSSM •p60 •p61	e, µ, T, Y 0-3 e,µ/1-2 r 0 mono-jet 0 3 e,µ 0 1-2 r + 0-1 2 Y 7 2 e,µ(Z) 0 0 0-1 e,µ 0-1 e,µ	2-10 jets(3 h 2-6 jets 1-3 jets 2-6 jets 2-6 jets 2-6 jets 2-6 jets 4 jets 7-11 jets 2-6 jets 2- jets 1-b 2 jets mono-jet 3-b 3-b	T Vies Vies Vies Vies Vies Vies Vies Vies	20.3 36.1 3.2 36.1 36.1 36.1 36.1 36.1 36.1 36.1 32 3.2 20.3 13.3 20.3 20.3	Mass limit Vi # 7 4.2 1.05 TeV 4 1.05 TeV 4 1.05 TeV 2 0.01 TeV 2 2.01 Te 2 2.02 Te 2 1.825 TeV 2 1.05 TeV 2 1.05 TeV 2 1.05 TeV 3 1.05 TeV 4 1.05 TeV 5 1.37 TeV 8 900 GeV	العن العن العن العن العن العن العن العن	Heterence 1507.05525 ATLAS-CONF-0017-022 ATLAS-CONF-2017-022 ATLAS-CONF-2017-022 ATLAS-CONF-2017-020 ATLAS-CONF-2017-033 1607.05679 1507.05695 ATLAS-CONF-2016-066 1503.03260
RACMSSM $q_{1}^{\phi_{1}$	0-3 e, µ/1-2 r 0 mono-jet 0 0 3 e, µ 2 r, µ 2 r, µ 2 e, µ (Z) 0 0 0-1 e, µ 0	2-10 jets/3 b 2-6 jets 1-3 jets 2-6 jets 2-6 jets 2-6 jets 4 jets 7-11 jets 0-2 jets 1-b 2 jets 1-b 2 jets mono-jet 3 b 3 b	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 36.1 36.1 36.1 36.1 36.1 3.2 3.2 20.3 13.3 20.3 20.3	4.2 1.85 TeV 4 1.57 TeV 2 608 GeV 2.01 TeV 2 2.01 TeV 2.01 TeV 2 1.825 TeV 2.01 TeV 2 2.01 TeV 2.01 TeV 2 1.825 TeV 2.01 TeV 2 1.82 TeV 2.01 TeV 2 1.05 TeV 2.01 TeV 2 1.05 TeV 2.01 TeV 2 1.05 TeV 1.05 TeV 2 1.05 TeV 1.0 TeV 2 900 GeV 1.0 TeV	m(i)=m(j) m(i)=200 GeV, m(1" gen. i)=m(2" gen. i) m(j)=m(i)=200 GeV m(i)=200 GeV m(i)=200 GeV m(i)=200 GeV m(i)=200 GeV cr(MLSP)=0.1 mm m(i)=580 GeV, cr(MLSP)=0.1 mm, µ=0 m(i)=580 GeV, cr(MLSP)=0.1 mm, µ=0	1507.05625 ATLAS-CONF-2017.022 1504.07773 ATLAS-CONF-2017.022 ATLAS-CONF-2017.020 ATLAS-CONF-2017.030 ATLAS-CONF-2017.033 1607.05675 1507.056493 ATLAS-CONF-2016-066 1503.03260
οδέξη καξή οδιξη οι →δεξή →δεξή →δεξή	0 0.1 e.µ 0.1 e.µ	3 4	Yes		Prin scale 865 GeV	m(G)>1.8 × 10 ⁻⁴ eV, m(g)=m(g)=1.5 TeV	1502.01518
$\dot{h}_1 \rightarrow d\hat{t}_1^0$ $\dot{h}_1 \rightarrow d\hat{t}_1^0$ $\rightarrow d\hat{t}_1^n$	0	3.6	Yes	36.1 36.1 20.1	2 1.92 TeV 2 1.97 TeV 2 1.37 TeV	m(i ²)<600 GeV m(i ²)<200 GeV m(i ²)<300 GeV	ATLAS-CONF-2017-021 ATLAS-CONF-2017-021 1407.0600
$\rightarrow Wh \tilde{k}_{1}^{0} \text{ or } i \tilde{k}_{1}^{0}$ $\rightarrow c \tilde{k}_{1}^{0}$ tural GMSB) $\rightarrow \tilde{t}_{1} + Z$ $\rightarrow \tilde{t}_{1} + h$	2 e, µ (SS) 0-2 e, µ 0-2 e, µ 0 2 e, µ (Z) 3 e, µ (Z) 1-2 e, µ	2 b 1 b 1-2 b 0-2 jets/1-2 l mono-jet 1 b 1 b 1 b 4 b	Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 4.7/13.3 20.3/36.1 3.2 20.3 36.1 36.1	Jr. 950 GeV 41 275-700 GeV 7 90-198 GeV 7 90-198 GeV 8 90-323 GeV 7 90-790 GeV 7 90-323 GeV 7 90-323 GeV 7 90-323 GeV 8 90-323 GeV 10 250-790 GeV 13 290-790 GeV	m(i ²)-420 GeV m(i ²)-200 GeV, m(i ²)- m(i ²)+100 GeV m(i ²)-10 GeV m(i ²)-10 GeV m(i ²)-150 GeV m(i ²)-150 GeV m(i ²)-0 GeV m(i ²)-0 GeV	ATLAS-CONF-2017-038 ATLAS-CONF-2017-030 1208.2102, ATLAS-CONF-2017-03 1506.08016, ATLAS-CONF-2017-03 1604.07773 1400.5222 ATLAS-CONF-2017-019 ATLAS-CONF-2017-019
$\begin{array}{l} \mathbf{x}_{i} \in \mathcal{I} \rightarrow \mathcal{I} \mathcal{K}_{i}^{0} \\ \mathcal{K}_{i}^{i} \rightarrow \mathcal{I} \wedge \mathcal{I} (\mathcal{K}) \\ \mathcal{K}_{i}^{i} \rightarrow \mathcal{I} \wedge \mathcal{I} (\mathcal{K}), \mathcal{K}_{i}^{2} \rightarrow \mathcal{I} \pi (\mathcal{K}) \\ \mathcal{K}_{i}^{i} \mathcal{K}_{i} (\mathcal{K}), \mathcal{K} \\ \mathcal{K}_{i}^{i} \mathcal{K}_{i}^{i} \mathcal{K}_{i}^{i} \\ \mathcal{K}_{i}^{i} \mathcal{K}_{i}^{i} \\ \mathcal{K}_{i}^{i} \rightarrow \mathcal{M} \\ \mathcal{K}_{i}^{i} \mathcal{K}_{i}^{i}, h \rightarrow b h / W W / \pi \tau / \gamma \gamma \\ \mathcal{K}_{i}^{i} \rightarrow \mathcal{K}_{i}^{i} \\ \text{wino NLSP} weak prod. \\ \mathcal{K}_{i}^{i} \rightarrow \\ \text{bino NLSP} \end{pmatrix}$	2 e, µ 2 e, µ 2 τ 3 e, µ 2 3 e, µ e, µ, γ 4 e, µ γG 1 e, µ + γ γG 2 γ	0 0 0-2 jets 0-2 b 0 -	Yes Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 36.1 36.1 20.3 20.3 20.3 20.3 20.3	Z 90-440 GeV X ⁺ ₁ 710 GeV X ⁺ ₁ 760 GeV X ⁺ ₁ , x ⁺ ₁ 580 GeV X ⁺ ₁ , x ⁺ ₂ 580 GeV X ⁺ ₁ , x ⁺ ₂ 270 GeV X ⁺ ₁ , x ⁺ ₂ 580 GeV X ⁺ ₁ , x ⁺ ₂ 580 GeV X ⁺ ₁ , x ⁺ ₂ 580 GeV X ⁺ ₁ , x ⁺ ₂ 580 GeV X ⁺ ₁ , x ⁺ ₂ 580 GeV	$\begin{split} m(\tilde{r}_{1}^{2}) = 0 & m(\tilde{r}_{1}^{2}) = 0, m(\tilde{r}_{1}^{2}) = 0, m(\tilde{r}_{1}^{2}) = 0, m(\tilde{r}_{1}^{2}) = 0, m(\tilde{r}_{1}^{2}) = m(\tilde{r}_{1}^{2}) = 0, m(\tilde{r}_{1}^{2}) = m(\tilde{r}_{1}^{2})) = m(\tilde{r}_{1}^{2}) = m(\tilde{r}_{1}^{2})) = m(\tilde{r}_{1}^{2}) = m(\tilde{r}_{1}^{2})) = m(\tilde{r}_{1}^{2}) = m(\tilde{r}_{1}^{2})) = m(\tilde{r}_{1}^{2}) = m(\tilde{r}_{1}^{2})) = m(\tilde{r}_{1}^{2})) = m(\tilde{r}_{1}^{2})) = m(\tilde{r}_{1}^{2}$	ATLAS-CONF-2017-039 ATLAS-CONF-2017-039 ATLAS-CONF-2017-039 ATLAS-CONF-2017-039 ATLAS-CONF-2017-039 1501.071160 1507.05493 1507.05493
$\hat{k}_{1}^{+}\hat{k}_{1}^{-}$ prod., long-lived \hat{k}_{1}^{+} $\hat{k}_{1}^{+}\hat{k}_{1}^{-}$ prod., long-lived \hat{k}_{1}^{+} slooped \hat{x} H-hadron \hat{x} R-hadron able \hat{x} R-hadron \hat{x} R-hadron \hat{y}	Disapp. trk dE/dx trk 0 trk dE/dx trk 1-2 µ 2 y displ. ce/rgr/y displ. vtx + je	1 jet 1-5 jets 	Yes Yes Yes Yes	36.1 18.4 27.9 3.2 3.2 19.1 20.3 20.3 20.3	3° 430 GeV 4° 495 GeV 2 850 GeV 2 850 GeV 2 1.58 TeV 2 1.57 TeV 3° 537 GeV 3° 440 GeV 3° 1.0 TeV 3° 1.0 TeV	$\begin{array}{l} m(\tilde{r}_{1}^{2}) + m(\tilde{r}_{1}^{2}) + 160 \; MeV, \; r(\tilde{r}_{1}^{2}) + 0.2 \; ns \\ m(\tilde{r}_{1}^{2}) + m(\tilde{r}_{1}^{2}) + 160 \; MeV, \; r(\tilde{r}_{1}^{2}) + 15 \; ns \\ m(\tilde{r}_{1}^{2}) + 100 \; GeV, \; 10 \; \mu s < r(\tilde{r}_{1}^{2}) + 100 \; s \\ 10 \cdot tagr(\tilde{r}_{1}^{2}) + 30 \; GeV, \; r > 10 \; ns \\ 10 \cdot tagr(\tilde{r}_{1}^{2}) + 3 \; ns, \; SP88 \; model \\ 1 < r(\tilde{r}_{1}^{2}) - 740 \; mm, \; m(\tilde{g}) = 1.3 \; TeV \\ 7 < rr(\tilde{r}_{1}^{2}) < 740 \; mm, \; m(\tilde{g}) = 1.3 \; TeV \\ 7 < rr(\tilde{r}_{1}^{2}) < 740 \; mm, \; m(\tilde{g}) = 1.1 \; TeV \end{array}$	ATLAS-CONF-2017-017 1506.05332 1310.6564 1606.05129 1604.04520 1411.6795 1409.5542 1504.05162 1504.05162
$\begin{array}{l} p \rightarrow \theta_{T} + X_{c} \theta_{T} \rightarrow e \mu/e \tau / \mu \tau \\ r \ RPV \ CMSSM \\ \tilde{K}_{1}^{c} \rightarrow W \tilde{K}_{0}^{c} X_{0}^{c} \rightarrow e e r, e \mu r, \mu \mu r \\ \tilde{K}_{1}^{c} \rightarrow W \tilde{K}_{0}^{c} + \tilde{K}_{1}^{c} \rightarrow e r r, e r r_{e} \\ \gamma e q \phi \tilde{K}_{1}^{c} + \tilde{K}_{1}^{c} \rightarrow q \phi q \\ q \phi \tilde{K}_{1}^{c} + \tilde{K}_{1}^{c} \rightarrow q \phi q \\ \tilde{M}_{1}^{c} + \tilde{K}_{1}^{c} \rightarrow d \phi q \\ \tilde{M}_{1}^{c} + \tilde{L}_{1}^{c} \rightarrow b s \\ \rightarrow b s \\ \rightarrow b \end{array}$	eµ.er.µr 2 e.µ (SS) 4 e.µ 3 e.µ + r 0 4 1 e.µ 1 e.µ 0 2 e.µ	0-3 b 1-5 large-R je 1-5 large-R je 8-10 jets/0-4 8-10 jets/0-4 2 jets + 2 b 2 b	Yes Yes Yes cs b b b	3.2 20.3 13.3 20.3 14.8 14.8 36.1 36.1 15.4 36.1	Image: Network of the second	$\begin{split} & \mathcal{K}_{(1)} = 0.11, \ \mathcal{K}_{(12),(13),(13)} = 0.07 \\ & m(j) = m(j), \ e_{T(j)} = 4.00 \\ m(i^{T}_{1}) > 400GeV, \ \mathcal{K}_{(23)} \neq 0 \ (k = 1, 2) \\ & m(i^{T}_{1}) > 400GeV, \ \mathcal{K}_{(23)} \neq 0 \\ & 0H(j) = BH(j) = BH(j) = BH(j) \\ & m(i^{T}_{1}) = 1 \\ & FU(\ \mathcal{K}_{(12)} \neq 0 \\ & BH(j) = 1 \\ & FU(\ \mathcal{K}_{(23)} \neq 0 \\ & BH(j) = -kbr(\mu) > 20\% \end{split}$	1607.08079 1404.2500 ATLAS-CONF-2016-075 1405.5066 ATLAS-CONF-2016-057 ATLAS-CONF-2016-057 ATLAS-CONF-2017-013 ATLAS-CONF-2017-013 ATLAS-CONF-2017-013 ATLAS-CONF-2019-022, ATLAS-CONF-2017-036
charm, $\bar{c} \rightarrow c \hat{k}_{1}^{0}$	0	2 c	Yes	20.3	2 510 GeV	m(iî)<200 GeV	1501.01325
	$\begin{array}{l} \begin{array}{l} \sum_{k=1}^{2} - \operatorname{str}(r(v), k_{1}^{2} - \operatorname{str}(r(v))\\ \sum_{k=1}^{2} - \operatorname{str}(r(v), k_{1}^{2}, \operatorname{str}(r(v))\\ d_{k} v_{k}^{2}(k_{1}^{2}, k - \operatorname{sb}(W)) rr/\gamma y\\ \sum_{k=1}^{2} - d_{k}^{2} \\ \operatorname{wich}(k_{1}^{2}, k_{1}^{2}, h - \operatorname{sb}(W)) rr/\gamma y\\ \sum_{k=1}^{2} - d_{k}^{2} \\ \operatorname{wich}(k_{1}^{2}, h - \operatorname{sb}(r))\\ \operatorname{wich}($	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{cccccccccccccccccccccccccccccccccccc$

Going beyond the MSSM

LHC Run 2 on-going: so far no sign of SUSY

Possibilities:

- > No supersymmetry
- Non-minimal SUSY
 - More Higgs NMSSM, THMSSM, ...
 - More gauge USSM, E6SSM, BLSMMS, ...
 - Less symmetry RPV, split SUSY
 - More symmetry R-symmetry, …

Going beyond the MSSM

LHC Run 2 on-going: so far no sign of SUSY

Possibilities:

- > No supersymmetry
- Non-minimal SUSY
 - More Higgs NMSSM, THMSSM, ...
 - More gauge USSM, E6SSM, BLSMMS, ...
 - Less symmetry RPV, split SUSY
 - More symmetry R-symmetry, …

• • • •

Our choice \rightarrow R-symmetry

R-symmetry

Additional symmetry allowed by Haag-Łopuszański-Sohnius Theorem

R-symmetry almost as old as SUSY itself

[Fayet '76; Salam & Strathdee '76, ...]

For N=1 SUSY it is a continuous U(1) global symmetry under

 $heta
ightarrow e^{ilpha} heta$ [Chamseddine&Dreiner `95,..]

i.e. Grassmann coordinates have non-trivial R-charge

 $R(\theta) = +1, \quad R(d\theta) = -1, \quad R(\overline{\theta}) = -1, \quad R(d\overline{\theta}) = +1$

superfields $\hat{X}_i(x^\mu, \theta, \bar{\theta}) \to e^{i\xi_i \alpha} \hat{X}_i(x^\mu, e^{i\alpha}\theta, e^{-i\alpha}\bar{\theta})$

→ component fields have different R-charge

Symmetry or Parity ?

Transformation of superfield

 $\exp(i\tau R)F(x^{\mu},\theta,\overline{\theta})\exp(-i\tau R) = \exp(i\tau Q_R)F(x^{\mu},\exp(-i\tau)\theta,\exp(i\tau)\overline{\theta})$ $\tau \in \{0,2\pi\}$

For R-parity τ fixed, as Z_2 : $\tau = n\pi$

$$n \text{ odd} \Rightarrow \exp(-i\tau) = \exp(i\tau) = -1$$

 $n \text{ even} \Rightarrow \exp(-i\tau) = \exp(i\tau) = 1$

End up with matter parity $((-1)^{3B+L+2S})$

R-symmetry

 $\theta \to e^{i\alpha}\theta$ Lagrangian has to be invariant under $\hat{G}^{\alpha} \sim \bar{D}^2 D^{\alpha} \hat{G}$ > Kinetic terms $\int d^2\theta \, d^2\bar{\theta} \, \hat{\Phi}^{\dagger} \, e^{-2g\hat{G}}\hat{\Phi} + (\int d^2\theta \, \hat{G}^{\alpha}\hat{G}_{\alpha} + h.c.)$ vector superfield $R(\hat{G}) = 0 \implies R(G^{\mu}) = 0, \quad R(\tilde{G}^{\alpha}) = 1$ are automatically R-symmetric > Superpotential $\int d^2\theta W$ \longrightarrow must have R=2 Soft breaking terms must have R=0

- > soft gaugino masses $R(M_{\tilde{G}}\tilde{G}^{\alpha}\tilde{G}_{\alpha})=2 \longrightarrow$ forbidden
- freedom to assign the R-charges to chiral superfields
 - MRSSM: SM particles have R=0, superpartners $R\neq 0$

[Kribs Poppitz Weiner 2007]

$$\begin{array}{ll} \mbox{matter} & R(\hat{Q}) = 1 & \Rightarrow & R(\tilde{q}) = 1, \quad R(q) = 0 \\ \mbox{Higgs} & R(\hat{H}) = 0 & \Rightarrow & R(H) = 0, \quad R(\tilde{H}) = -1 \end{array}$$

other choices:	Frugiuele, Gregoire
	Frugiuele, Gregoire, Kumar, Ponton
	Davies, March-Russell, McCullough
	Riva, Biggio, Pomarol







Good: R-symmetry ameliorates SUSY flavor problems by removing

- dim-4 B- and L-violating terms, and dim-5 in proton decay
- ✤ soft tri-linear scalar couplings
- some MSSM contributions to flavor-violating observables forbidden

Good: R-symmetry ameliorates SUSY flavor problems by removing

- dim-4 B- and L-violating terms, and dim-5 in proton decay
- soft tri-linear scalar couplings
- some MSSM contributions to flavor-violating observables forbidden
- But: mu-term and Majorana masses are forbidden, need new means to give masses to gauginos/higgsinos
 - Solution for gauginos: Dirac masses M_i^D λ_i^a ψ_j^a where λ_i^a from vector , and ψ_j^a from additional chiral superfield
 Need chiral superfields in adjoint representations: Ô, Î, Ŝ
 Solution for higgsinos: μ_d Ĥ_d R̂_d + μ_u Ĥ_u R̂_u
 Need two chiral superfields with R=2: R̂_{d,u}

R-charges of the superfields and their component fields

Field	Superfi	eld	Boson	L	Fermion		
Gauge Vector	\hat{g},\hat{W},\hat{B}	0	g, W, B	0	$ ilde{g}, ilde{W} ilde{B}$	+1	
Matter	\hat{l}, \hat{e}	+1	\tilde{l}, \tilde{e}_R^*	+1	l, e_R^*	0	
	$\hat{q}, \hat{d}, \hat{u}$	+1	$\tilde{q}, \tilde{d}_R^*, \tilde{u}_R^*$	+1	q, d_R^*, u_R^*	0	
$H ext{-Higgs}$	$\hat{H}_{oldsymbol{d},oldsymbol{u}}$	0	$H_{d,u}$	0	$ ilde{H}_{d,u}$	-1	
R-Higgs	$\hat{R}_{\boldsymbol{d},\boldsymbol{u}}$	+2	$R_{d,u}$	+2	$ ilde{R}_{d,u}$	+1	
Adjoint Chiral	$\hat{\mathcal{O}},\hat{T},\hat{S}$	0	O,T,S	0	$ ilde{O}, ilde{T}, ilde{S}$	-1	

R-charges of the superfields and their component fields

Field	Superfi	eld	Bosor	ı	Fermion		
Gauge Vector	\hat{g},\hat{W},\hat{B}	0	g, W, B	0	$ ilde{g}, ilde{W} ilde{B}$	+1	
Matter	\hat{l}, \hat{e}	+1	\tilde{l}, \tilde{e}_R^*	+1	l, e_R^*	0	
	$\hat{q}, \hat{d}, \hat{u}$	+1	$\tilde{q}, \tilde{d}_R^*, \tilde{u}_R^*$	+1	q, d_R^*, u_R^*	0	
$H ext{-} ext{Higgs}$	$\hat{H}_{\boldsymbol{d},\boldsymbol{u}}$	0	$H_{d,u}$	0	$ ilde{H}_{d,u}$	-1	
R-Higgs	$\hat{R}_{\boldsymbol{d},\boldsymbol{u}}$	+2	$R_{d,u}$	+2	$ ilde{R}_{d,u}$	+1	
Adjoint Chiral	$\hat{\mathcal{O}},\hat{T},\hat{S}$	0	O,T,S	0	$ ilde{O}, ilde{T}, ilde{S}$	-1	

Physical fields:

matter, gauge and Higgs as in MSSM

R-charges of the superfields and their component fields

Field	Superfi	eld	Bosor	1	Fermion		
Gauge Vector	\hat{g},\hat{W},\hat{B}	0	g, W, B	0	$ ilde{g}, ilde{W} ilde{B}$	+1	
Matter	\hat{l},\hat{e}	+1	$\tilde{l}, \tilde{e}_{R}^{*}$	+1	l, e_R^*	0	
	$\hat{q}, \hat{d}, \hat{u}$	+1	$\tilde{q}, \tilde{d}_R^*, \tilde{u}_R^*$	+1	q, d_B^*, u_B^*	0	
<i>H</i> -Higgs	$\hat{H}_{d,u}$	0	$H_{d.u}$	0	$ ilde{H}_{d,u}$	-1	
R-Higgs	$\hat{R}_{\boldsymbol{d},\boldsymbol{u}}$	+2	$R_{d,u}$	+2	$\tilde{R}_{d,u}$	+1	
Adjoint Chiral	$\hat{\mathcal{O}},\hat{T},\hat{S}$	0	O, T, S	0	$ ilde{O}, ilde{T}, ilde{S}$	-1	

Physical fields:

matter, gauge and Higgs as in MSSM

gluinos and neutralinos are Dirac additional pair of charginos

R-charges of the superfields and their component fields

Field	Superfi	eld	Bosor	1	Fermion		
Gauge Vector	\hat{g},\hat{W},\hat{B}	0	g, W, B	0	$ ilde{g}, ilde{W} ilde{B}$	+1	
Matter	\hat{l}, \hat{e}	+1	\tilde{l}, \tilde{e}_R^*	+1	l, e_R^*	0	
	$\hat{q}, \hat{d}, \hat{u}$	+1	$\tilde{q}, \tilde{d}_R^*, \tilde{u}_R^*$	+1	q, d_B^*, u_B^*	0	
$H ext{-Higgs}$	$\hat{H}_{\boldsymbol{d},\boldsymbol{u}}$	0	$H_{d.u}$	0	$ ilde{H}_{d,u}$	-1	
R-Higgs	$\hat{R}_{d,u}$	+2	$R_{d,u}$	+2	$\tilde{R}_{d,u}$	+1	
Adjoint Chiral	$\hat{\mathcal{O}},\hat{T},\hat{S}$	0	O, T, S	0	$ ilde{O}, ilde{T}, ilde{S}$		

Physical fields:

matter, gauge and Higgs as in MSSM

gluinos and neutralinos are Dirac additional pair of charginos

gauge-adjoint scalars (e.g. sgluons) and R-Higgs bosons



MRSSM Lagrangian

Superpotential

$$W = \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u$$

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

soft SUSY breaking terms

$$\begin{split} V_{SB}^{EW} &= B_{\mu} \big(H_d^- H_u^+ - H_d^0 H_u^0 \big) + \text{h.c.} \\ &+ m_{H_d}^2 \big(|H_d^0|^2 + |H_d^-|^2 \big) + m_{H_u}^2 \big(|H_u^0|^2 + |H_u^+|^2 \big) \\ &+ m_{R_d}^2 \big(|R_d^0|^2 + |R_d^+|^2 \big) + m_{R_u}^2 |R_u^0|^2 + m_{R_u}^2 |R_d^-|^2 \\ &+ m_S^2 |S|^2 + m_T^2 |T^0|^2 + m_T^2 |T^-|^2 + m_T^2 |T^+|^2 + m_O^2 |O|^2 \\ &+ \tilde{d}_{L,i}^* m_{q,ij}^2 \tilde{d}_{L,j} + \tilde{d}_{R,i}^* m_{d,ij}^2 \tilde{d}_{R,j} + \tilde{u}_{L,i}^* m_{q,ij}^2 \tilde{u}_{L,j} + \tilde{u}_{R,i}^* m_{u,ij}^2 \tilde{u}_{R,j} \\ &+ \tilde{e}_{L,i}^* m_{l,ij}^2 \tilde{e}_{L,j} + \tilde{e}_{R,i}^* m_{e,ij}^2 \tilde{e}_{R,j} + \tilde{\nu}_{L,i}^* m_{l,ij}^2 \tilde{\nu}_{L,j} \,. \end{split}$$

Mass spectrum calculations

- > Take Standard Model input at Z mass scale
- > Convert everything consistently to \overline{DR}
- > Run to M_{SUSY}
- > Take MRSSM input parameters and calculate one-loop corrected masses
- > Add further corrections to Higgs mass
- > Tools: SARAH, SPheno,FlexibleSUSY,
- > Automatizing for such a model complicated, many cross checks required

Philip Diessner, JK, Wojciech Kotlarski, Dominik Steckinger

JHEP 1412 (2014) 124, Adv. HEP (2015) 760729, JHEP 1603 (2016) 007,

MRSSM confronting experiment

Can the MRSSM accomodate the Higgs mass, EWPO and LHC constraints?

First option: 125 GeV Higgs – the lightest state

- > In SM Higgs boson mass is a free parameter
- In SUSY it is prediction of SUSY parameters as quartic coupling connected to gauge couplings
- > Experimental value: 125.1 ± 0.3 GeV

In MRSSM the lightest Higgs at tree level:

$$m_h^2 < m_Z^2 \cos^2 2\beta - v^2 \left(\frac{\left(g_1 M_B^D + \sqrt{2}\lambda\mu\right)^2}{4(M_B^D)^2 + m_S^2} + \frac{\left(g_2 M_W^D + \Lambda\mu\right)^2}{4(M_W^D)^2 + m_T^2} \right) \cos^2 2\beta$$



always lower than in the MSSM due to mixing with S and T

Higgs sector at one-loop level and beyond

Lightest Higgs and PO observables

Getting 125 GeV Higgs and PO not obvious because:

 \succ mixing with other states lowers the tree level mass

needs even larger radiative corrections than in MSSM

no LR stop mixing – an important MSSM mechanism to rise

the Higgs mass is not present

the vev of the EW triplet contributes to the rho parameter at tree-level

$$m_Z^2 = rac{g_1^2 + g_2^2}{4} v^2 \;, \qquad m_W^2 = rac{g_2^2}{4} v^2 + g_2^2 v_T^2 \;, \qquad \hat{
ho}_{
m tree} = 1 + rac{4 v_T^2}{v^2}$$

The W mass (and other PO) affected by loops

LHC and flavor constraints

Lightest Higgs

New Yukawa-like couplings

 $\lambda_d \hat{H}_d \hat{R}_d \hat{S} + \lambda_u \hat{H}_u \hat{R}_u \hat{S} + \Lambda_d \hat{H}_d \hat{T} \hat{R}_d + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u$

$$\begin{split} \Delta m_{H_{1},\text{eff.pot},\lambda}^{2} &= \frac{2v^{2}}{16\pi^{2}} \Bigg[\frac{\lambda^{4}}{2} \left(\log \frac{m_{R_{u}}^{2}}{(M_{B}^{D})^{2}} + \log \frac{m_{S}^{2}}{(M_{B}^{D})^{2}} \right) \\ &+ \frac{5\Lambda^{4}}{8} \left(\log \frac{m_{R_{u}}^{2}}{(M_{W}^{D})^{2}} + \log \frac{m_{T}^{2}}{(M_{W}^{D})^{2}} \right) \Bigg] \end{split}$$

Lightest Higgs



 \blacktriangleright 125 GeV Higgs for $~~\Lambda,\lambda\sim-1$

without stop mixing

- light stops possible
- > dominant two-loop ~ 5 GeV

W mass – full one-loop level

Beyond tree-level

$$\frac{G_{\mu}}{\sqrt{2}} = \frac{\pi \hat{\alpha}}{2\hat{s}_W^2 m_W^2} \frac{1}{1 - \Delta \hat{r}_W}$$

we get the master formula of Degrassi, Franchiotti, Sirlin (1990)

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

need to calculate $\hat{\alpha}, \hat{\rho}, \text{ and } \Delta \hat{r}_{W}$ at one-loop level

W mass – full one-loop level



 $\tan\beta = 40$

1.5

2.0

0.5

1.0

W mass – full one-loop level



Benchmarks:

$$\tan \beta = 3, 10, 40$$

	BMP1	BMP2	BMP3
m_{H_1}	$125.3{ m GeV}$	$125.1{ m GeV}$	$125.1{ m GeV}$
m_W	$80.399{ m GeV}$	$80.385{\rm GeV}$	$80.393{\rm GeV}$
HiggsBounds's obsratio	0.61	0.61	0.63
HiggsSignals's p-value	0.42	0.40	0.40
S	0.0097	0.0092	0.0032
T	0.090	0.091	0.085
U	0.00067	0.00065	0.0010
Vevacious	\checkmark	\checkmark	\checkmark
selected b physics observables	\checkmark	\checkmark	\checkmark

MRSSM confronting experiment

Can the MRSSM accomodate the Higgs mass, EWPO and LHC constraints?

First option: 125 GeV Higgs – the lightest state

Diessner, JK, Kotlarski, Stockinger, JHEP 1412 (2014) 124 Diessner, JK, Kotlarski, Stockinger, Adv. HEP (2015) 760729

MRSSM confronting experiment

Can the MRSSM accomodate the Higgs mass, EWPO and LHC constraints?

First option: 125 GeV Higgs – the lightest state

Diessner, JK, Kotlarski, Stockinger, JHEP 1412 (2014) 124 Diessner, JK, Kotlarski, Stockinger, Adv. HEP (2015) 760729

Second option: 125 GeV Higgs – the next-to-lightest state

Diessner, JK, Kotlarski, Stockinger, JHEP 1603 (2016) 007

For the second-lightest, mixing with other fields pushes the tree-level mass upwards

Light singlet scenario

MRSSM with a light singlet

> In large $\tan \beta$, M_A limit, the (ϕ_u, ϕ_S) mass submatrix

$$\mathcal{M}_{u,S}^{\phi} = egin{pmatrix} m_Z^2 + \Delta m_{
m rad}^2 & v_u \left(\sqrt{2}\lambda_u \mu_u^{
m eff,-} + g_1 M_B^D
ight) \ v_u \left(\sqrt{2}\lambda_u \mu_u^{
m eff,-} + g_1 M_B^D
ight) & 4(M_B^D)^2 + m_S^2 + rac{\lambda_u^2 v_u^2}{2} \end{pmatrix} \ \mu_i^{
m eff,\pm} = \mu_i + rac{\lambda_i v_S}{\sqrt{2}} \pm rac{\Lambda_i v_T}{2}, \qquad \qquad i = u, d.$$

> to realise light singlet scenario

$$m_S, M_B^D < m_Z < \mu_u, \qquad |\lambda_u| \ll 1$$

then the SM-like Higgs at tree level

$$m_{h,\text{tree}}^2 \approx m_Z^2 \cos^2 2\beta + v^2 \cos^2 2\beta \left(\frac{(g_1 M_B^D + \sqrt{2\lambda\mu})^2}{|m_S^2 + 4(M_B^D)^2 - m_Z^2 \cos^2 2\beta|} \right)$$

MRSSM with a light singlet – one loop



level crossing of two lightest Higgs bosons

 $m_{H_S} \approx \sqrt{m_S^2 + 4(M_B^D)^2}$

MRSSM with a light singlet – one loop



> $m_{H_S} \approx \sqrt{m_S^2 + 4(M_B^D)^2}$ (red) > Upper limit on singlet mass ~ 110 GeV > $M_B^D \lesssim 55$ GeV

→ light fermion - LSP

	BMP4	BMP5	BMP6
m_{H_1}	100	94	95
m_{H_2}	125.8	125.5	125.8
HiggsSignals p-value	0.75	0.76	0.72
Allowed by HiggsBounds	\checkmark	\checkmark	\checkmark
m_W	80.384	80.392	80.404

Light singlet – mass spectrum



.

MRSSM dark matter - direct detection



MRSSM dark matter - relic density



Light singlet: very predictive scenario



- ✓ 125 GeV Higgs fixess Λ_u
- 🖌 If light singlet found at the LHC: constrains M^D_B and μ_u
- ✓ Fermionic superpartner is LSP
- $\checkmark\,$ DM constrains put redictions for squark masses
- $\checkmark\,$ Predictions for other electroweakinos

Summary

- Well motivated R-symmetric SUSY model
- SUSY flavor problem relaxed, Dirac gauginos and higgsinos
- Extended Higgs sector with unconventional phenomenology
- Viable benchmarks with
 - ~ 125 GeV Higgs boson mass
 - agreement with EWPO and flavor physics
 - stable vacuum
- Scenario with a light singlet is very predictive
 - consistent with LHC constraints
 - viable candidate for dark matter
 - some states light and could be seen at the LHC

Summary

- Well motivated R-symmetric SUSY model
- SUSY flavor problem relaxed
- Extended Higgs sector with unconventional phenomenology
- Viable benchmarks with
 - ~ 125 GeV Higgs boson mass
 - agreement with EWPO and flavor physics
 - stable vacuum
- Scenario with a light singlet is very predictive
 - consistent with LHC constraints
 - viable candidate for dark matter
 - some states light and could be seen at the LHC

Many things to do: rich phenomenology to explore

Backup

benchmarks:

		BMP1	BMP2	BMP3				
	$\tan\beta$	3	10	40				
	B_{μ}	500^{2}	300^{2}	200^{2}				
	λ_d, λ_u	1.0, -0.8	1.1, -1.1	0.15, -0.15				
	Λ_d, Λ_u	-1.0, -1.2	-1.0, -1.0	-1.0, -1.15				
	M_B^D	600	1000	250				
	$m_{R_u}^2$	2000^{2}	1000^{2}	1000^{2}				
one loop	μ_d, μ_u		400,400					
	M_W^D		500					
	M_O^D		1500					
	m_T^2, m_S^2, m_O^2	30	00^{2}					
	$m_{O;1,2}^2, m_{O;3}^2$	$2500^2, 1000^2$						
	$m_{D;1,2}^2, m_{D;3}^2$	$2500^2, 1000^2$						
	$m_{U;1,2}^2, m_{U;3}^2$	$2500^2, 1000^2$						
	m_{L}^{2}, m_{E}^{2}		1000^{2}					
	$m_{R_d}^2$		700^{2}					
	v_S	5.9	1.3	-0.14				
	v_T	-0.33	-0.19	-0.34				
	$m_{H_d}^2$	671^{2}	761^{2}	1158^{2}				
	$m_{H_u}^2$	-532^{2}	-544^{2}	-543^{2}				
m_{H_1}		$125.3\mathrm{GeV}$	$125.1{ m GeV}$	$125.1{ m GeV}$				
m_W		$80.399\mathrm{GeV}$	$80.385{ m GeV}$	$80.393{ m GeV}$				
HiggsBounds'	s obsratio	0.61	0.61	0.63				
HiggsSignals's p-value		0.42	0.40	0.40				

benchmarks:

		BMP1	BMP2	BMP3				
	$\tan\beta$	3	10	40	incl	uding two-lo	oop corr.	
	B_{μ}	500^{2}	300^{2}	200^{2}				
	λ_d, λ_u	1.0, -0.8 $1.1, -1.1$ $0.15, -0.$		0.15, -0.15	Λ_u reduces to			
	Λ_d, Λ_u	-1.0, -1.2	-1.0, -1.0	-1.0, -1.15	-1.11	-0.85	-1.03	
	M_B^D	600	1000	250				
	$m_{R_u}^2$	2000^{2}	1000^{2}	1000^{2}				
one loon	μ_d, μ_u		400, 400					
	M_W^D		500					
	M_O^D		1500					
	m_T^2, m_S^2, m_O^2	300	$00^2, 2000^2, 100$	00^{2}				
	$m_{Q;1,2}^2, m_{Q;3}^2$		$2500^2, 1000^2$					
	$m_{D;1,2}^2, m_{D;3}^2$		$2500^2, 1000^2$					
	$m_{U;1,2}^2, m_{U;3}^2$		$2500^2, 1000^2$					
	m_L^2, m_E^2		1000^{2}					
	$m_{R_d}^2$		700^{2}					
	v_S	5.9	1.3	-0.14	5.2	1.01	_0.22	
	v_T	-0.33	-0.19	-0.34	-0.25	-0.02	-0.21	
	$m_{H_d}^2$	671^{2}	761^{2}	1158^{2}	674^2	764^2	1160^2	
	$m_{H_u}^2$	-532^{2}	-544^{2}	-543^{2}	-502^{2}	-512^{2}	-516^{2}	
m_{H_1}		$125.3\mathrm{GeV}$	$125.1{ m GeV}$	$125.1{ m GeV}$	125.3 GeV	125.5 GeV	125.4 GeV	
m_W		$80.399\mathrm{GeV}$	$80.385{ m GeV}$	$80.393{ m GeV}$	80.397 GeV	80.381 GeV	80.386 GeV	
HiggsBounds'	${ m s}$ obsratio	0.61	0.61	0.63	0.61	0.65	0.87	
HiggsSignals	s's p-value	0.42	0.40	0.40	0.72	0.66	0.72	

benchmarks



	BMP4	BMP5	BMP6
aneta	40	20	6
B_{μ}	200^{2}	200^{2}	500^{2}
λ_d,λ_u	0.01, -0.01	0.0, -0.01	0.0, 0.0
Λ_d,Λ_u	-1, -1.2	-1,-1.15	-1,-1.2
M^D_B	50	44	30
m_S^2	30^{2}	40^{2}	80^{2}
$m_{R_u}^2,m_{R_d}^2$		$1000^2,700^2$	
μ_d,μ_u	130, 650	400,550	550, 550
M_W^D	600	500	400
M_O^D		1500	
m_T^2,m_O^2		$3000^2, 1000^2$	
$m^2_{Q;1,2},m^2_{Q;3}$	$1500^2,700^2$	$1300^2,700^2$	$1400^2,700^2$
$m^2_{D;1,2},m^2_{D;3}$	$1500^2, 1000^2$	$1300^2, 1000^2$	$1400^2, 1000^2$
$m^2_{U;1,2},m^2_{U;3}$	$1500^2,700^2$	$1300^2,700^2$	$1400^2,700^2$
$m^2_{L;1,2},m^2_{E;1,2}$	$800^2, 800^2$	$1000^2,1000^2$	$500^2, 350^2$
$m^2_{L;3,3},m^2_{E;3,3}$	$800^2,136^2$	$1000^2,1000^2$	$500^2, \ 95^2$
m_{H_d}	1217^{2}	211^{2}	1042^{2}
m_{H_u}	$-(767^2)$	$-(207^2)$	$-(201)^2$
v_S	-64.9	-42.5	-56.1
v_T	-1.08	-1.2	-1.1

benchmarks for light singlet scenario

	χ^0_1	χ^0_2	χ^0_3	χ_4^0	χ_1^\pm	χ^\pm_2	$ ho_1^\pm$	$ ho_2^\pm$	$ ilde{ au}_R$	$ ilde{\mu}_R$	\widetilde{e}_R	$\widetilde{\ell}_L$	m_{H_1}
BMP4	49.8	132	617	691	131	625	614	713	128	802	802	808	100
BMP5	43.9	401	519	589	409	524	519	610	1000	1001	1001	1005	94
BMP6	29.7	427	562	579	422	562	433	587	106	353	353	508	95

Table 5. Masses of the non-SM particles in the BMPs relevant for the LHC studies discussed here.All values given in GeV.