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Higgs bosons of R-symmetric supersymmetric theories

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Outline

- Motivation
- Supersymmetry
- R-symmetry
- Structure of the Minimal R-symmetric Supersymmetric
  Standard Model
- Expectations at the LHC
  production and decay modes

- Summary

Motivation

Very successful 2010-11 LHC runs with plenty of data

The biggest question: the nature of the electroweak symmetry breaking

In the SM: Higgs mechanism ➡ Higgs particle – the only missing piece of the SM

Although very successful, the SM is not the ultimate theory

- the Higgs sector unnatural
- matter-antimatter asymmetry
- dark matter/energy

➡ Hints for new physics at a TeV scale

Supersymmetry – the most elegant and respected proposition for the beyond SM physics

In the simplest realisation each SM particle is paired with a sparticle that differs in spin by ½:

- fermions – sfermions
- gauge bosons – gauginos
- Higgses – higgsinos

→ gluinos and neutralinos are Majorana fermions – must be checked exp.

Minimal SUSY under pressure:

- dim-4 B- and L-violating operators → extra symmetry (e.g. R-parity)
- possible flavor and CP problem due to misalignement between soft parameters and CKM → strong constraints on the parameter space
- little fine tuning

Continuous R-symmetry can ameliorate the above problems by removing

- soft tri-linear scalar couplings
- mu-term
- Majorana gaugino masses
- dim-4 B- and L-violating terms as well as dim-5 mediating proton decay

Supersymmetry

Supersymmetry: superspace $\{x^\mu, \theta, \bar\theta\}$

superfields

matter and Higgs – chiral $\hat\Phi(x^\mu, \theta) = \{\varphi, \psi^\alpha\}$

gauge fields – vector $\hat G(x^\mu, \theta, \bar\theta) = \{\tilde G^\alpha, G^\mu\}$

Lagrangian

- kinetic terms $\int d^2\theta\, d^2\bar\theta\, \hat\Phi^\dagger\, e^{-2g\hat G}\hat\Phi + (\int d^2\theta\, \hat G^\alpha \hat G_\alpha + h.c.)$

where $\hat G^\alpha \sim \bar D^2\, D^\alpha \hat G$ field-strength superfield

- potential $\int d^2\theta\, W$ where superpotential

$$W \sim \mu \hat H_d \hat H_u + y_d \hat H_d \hat Q \hat D^c + \ldots$$

- soft-SUSY breaking: tri-linear scalar couplings and soft masses

R-symmetry

R-symmetry – a continuous U(1) global symmetry under $\theta \to e^{i\alpha}\theta$

[Fayet, Salam & Strathdee, ...]

Grassmann coordinates have non-trivial R-charge

$$R(\theta) = +1, \quad R(d\theta) = -1, \quad R(\bar\theta) = -1, \quad R(d\bar\theta) = +1$$

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

gauge $R(\hat{G}) = 0 \qquad \Rightarrow R(G^\mu) = 0, \quad R(\tilde{G}^\alpha) = +1$

kinetic terms are automatically R-symmetric

chiral

matter $R(\hat{q}) = +1 \qquad \Rightarrow R(\tilde{q}) = +1, \quad R(q) = 0$

Higgs $R(\hat{H}) = 0 \qquad \Rightarrow R(H) = 0, \quad R(\tilde{H}) = +1$

R-symmetry

terms allowed:

Yukawa $y_d \hat{H}_d \hat{Q} \hat{D}^c$

scalar masses $M_{\tilde{q}}^2 |\tilde{q}|^2$

terms forbidden

mu-term $\mu \hat{H}_d \hat{H}_u$

L- and B-violation $\hat{L} \hat{Q} \hat{D}^c$

tri-linear scalar couplings $A\, \tilde{H}_d \tilde{Q} \tilde{D}^c$

Majorana gaugino masses $M_{\tilde{G}} \tilde{G}^{\alpha} \tilde{G}_{\alpha}$

Minimal R-symmetric SSM

The field content of MRSSM: fields of the MSSM with addition of

- chiral superfields in the adjoint rep. of the corresponding gauge group

$$\hat{\Sigma} = \{\sigma, \tilde{G}'^{\alpha}\}$$

$$R(\hat{\Sigma}) = 0 \qquad \Rightarrow R(\sigma) = 0, \quad R(\tilde{G}'^{\alpha}) = -1$$

to build a Dirac gaugino mass $\quad M^D \tilde{G}^{\alpha} \tilde{G}'_{\alpha}$

Dirac gauginos ➔ important consequences for colliders [Nojiri ea, Choi ea, ...]
dark matter [Belanger ea, Hsieh, Chun ea, ...]
flavour [Kribbs ea, Benakli ea, Fox ea, ...]
scalar adjoints (e.q. sgluons) [Plehn ea, Han ea, ...]

- two chiral iso-dublets $\hat{R}_u, \hat{R}_d$ with R-charge 2

to build a mu-type term $\quad \mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u$

and in addition $\quad \lambda_d^i \hat{H}_d \hat{\Sigma}^i \hat{R}_d + \lambda_u^i \hat{H}_u \hat{\Sigma}^i \hat{R}_u, \qquad i = I, Y$

➔ R-Higgs bosons

[for alternative formulation see Davies, March-Russell, McCullough]

MRSSM

R-charges of the superfields and their component fields

Field	Superfield		Boson		Fermion	
Matter	$\hat{Q}, \hat{D}^c, \hat{U}^c$	$+1$	$\tilde{Q}, \tilde{D}^c, \tilde{U}^c$	$+1$	Q, D^c, U^c	0
Higgs	$\hat{H}_{d,u}$	0	$H_{d,u}$	0	$\tilde{H}_{d,u}$	-1
	$\hat{R}_{d,u}$	$+2$	$R_{d,u}$	$+2$	$\tilde{R}_{d,u}$	$+1$
Gauge Vector	$\hat{G}$	0	G_μ	0	$\tilde{G}$	$+1$
Gauge Chiral	$\hat{\Sigma}$	0	σ	0	$\tilde{G}'$	-1

Physical fields: matter, gauge and Higgs fields as in the MSSM
Dirac gluinos and neutralinos
additional pair of charginos
gauge-adjoint scalars (e.g. sgluons)
R-Higgs bosons

Higgs sector

Higgs potential (assuming EW scalar adjoints heavy)

$$
\begin{aligned}
\mathcal{V}_{HR}^{0} = \quad & (m_{H_d}^2 + \mu_d^2)|H_d^0|^2 + (m_{H_u}^2 + \mu_u^2)|H_u^0|^2 - (B_\mu H_d^0 H_u^0 + \text{h.c.}) \\
& + (m_{R_d}^2 + \mu_d^2)|R_d^0|^2 + (m_{R_u}^2 + \mu_u^2)|R_u^0|^2 \\
& + \left|\lambda_d^I H_d^0 R_d^0 + \lambda_u^I H_u^0 R_u^0\right|^2 + \left|\lambda_d^Y H_d^0 R_d^0 - \lambda_u^Y H_u^0 R_u^0\right|^2 \\
& + \frac{1}{8}(g^2 + g'^2)\left(|H_d^0|^2 - |H_u^0|^2 - |R_d^0|^2 + |R_u^0|^2\right)^2 .
\end{aligned}
$$

Important consequences (even if EW scalars present):

- R-Higgses do not develop vev’s
- H-Higgses and R-Higgses do not mix

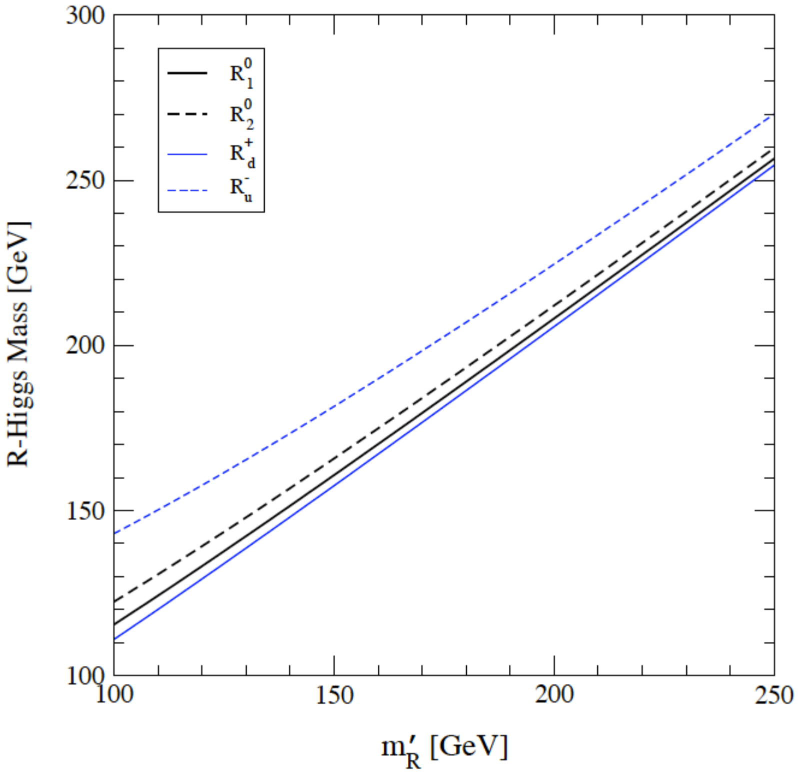
R-Higgses masses

(R_d^0, R_u^0) basis

$$\mathcal{M}^2_{R^0} = \begin{bmatrix} m^2_{R_d} + \mu_d^2 + \frac{1}{2}\left(\lambda_d^{I2} + \lambda_d^{Y2}\right) v_d^2 - \frac{1}{8} g_Z^2 (v_d^2 - v_u^2) & \frac{1}{2}(\lambda_d^I \lambda_u^I - \lambda_d^Y \lambda_u^Y) v_d v_u \\ \frac{1}{2}(\lambda_d^I \lambda_u^I - \lambda_d^Y \lambda_u^Y) v_d v_u & m^2_{R_u} + \mu_u^2 + \frac{1}{2}\left(\lambda_u^{I2} + \lambda_u^{Y2}\right) v_u^2 + \frac{1}{8} g_Z^2 (v_d^2 - v_u^2) \end{bmatrix}$$

$(R_d^\pm, R_u^\pm)$ basis

$$\mathcal{M}^2_{R^\pm} = \begin{bmatrix} m^2_{R_d} + \mu_d^2 + \lambda_d^{I2} v_d^2 - \frac{1}{8} g_Z'^2 (v_d^2 - v_u^2) & 0 \\ 0 & m^2_{R_u} + \mu_u^2 + \lambda_u^{I2} v_u^2 + \frac{1}{8} g_Z'^2 (v_d^2 - v_u^2) \end{bmatrix}$$



$$m'_R = (m^2_{R_{d,u}} + \mu^2_{d,u})^{1/2}$$

other parameters as in SPS1a′

R-Higgses - couplings

Conserved R-charge restricts couplings of R-Higgs bosons

allowed: $R\tilde{\ell}\tilde{\ell}\,,\ R\tilde{q}\tilde{q}\,,\ R\tilde{\chi}\tilde{\chi}\,,\ \ RRH,\ RRV$

vanishing: $Rff\,,\ RVV\,,\ RHH$ (NB. adjoints scalars have R=0)

Decay modes: only to pairs of sparticles

$$\Gamma[R \to \tilde{f}_L \tilde{f}'^*_R] = \frac{\lambda^{1/2}\,\tilde{\alpha}^2_{Rff'}}{16\pi M_R}$$

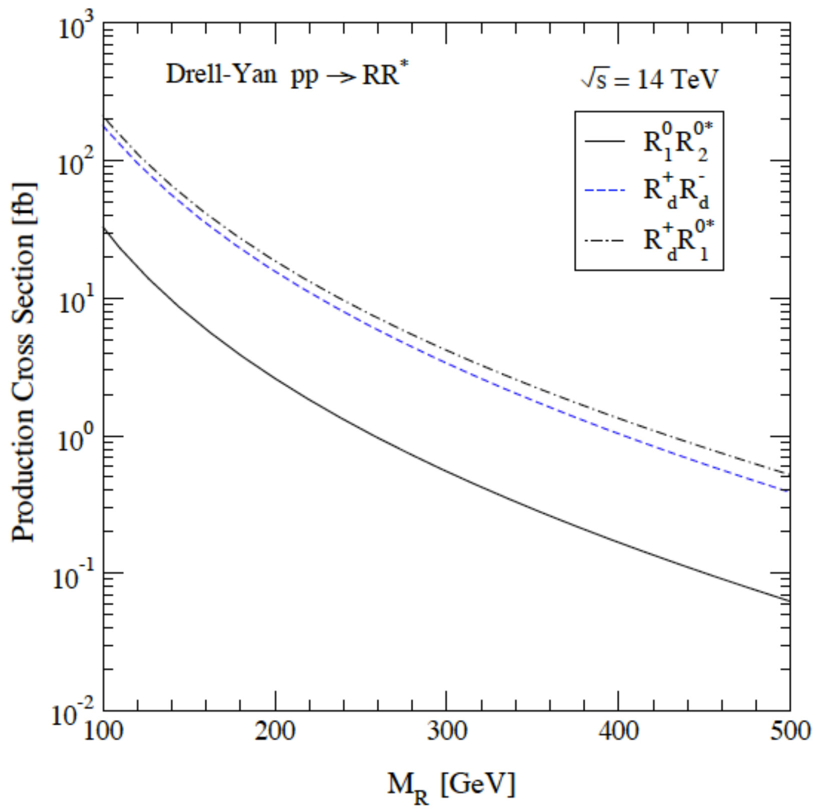
$$\Gamma[R \to \tilde{\chi}_{Dj}\tilde{\chi}_{Dk}] = \frac{\lambda^{1/2}}{8\pi M_R}\{\alpha^2_{Rjk}[M_R^2 - (m_j+m_k)^2] + \alpha'^2_{Rjk}[M_R^2 - (m_j-m_k)^2]\}$$

Production channels: only in pairs via Drell-Yan

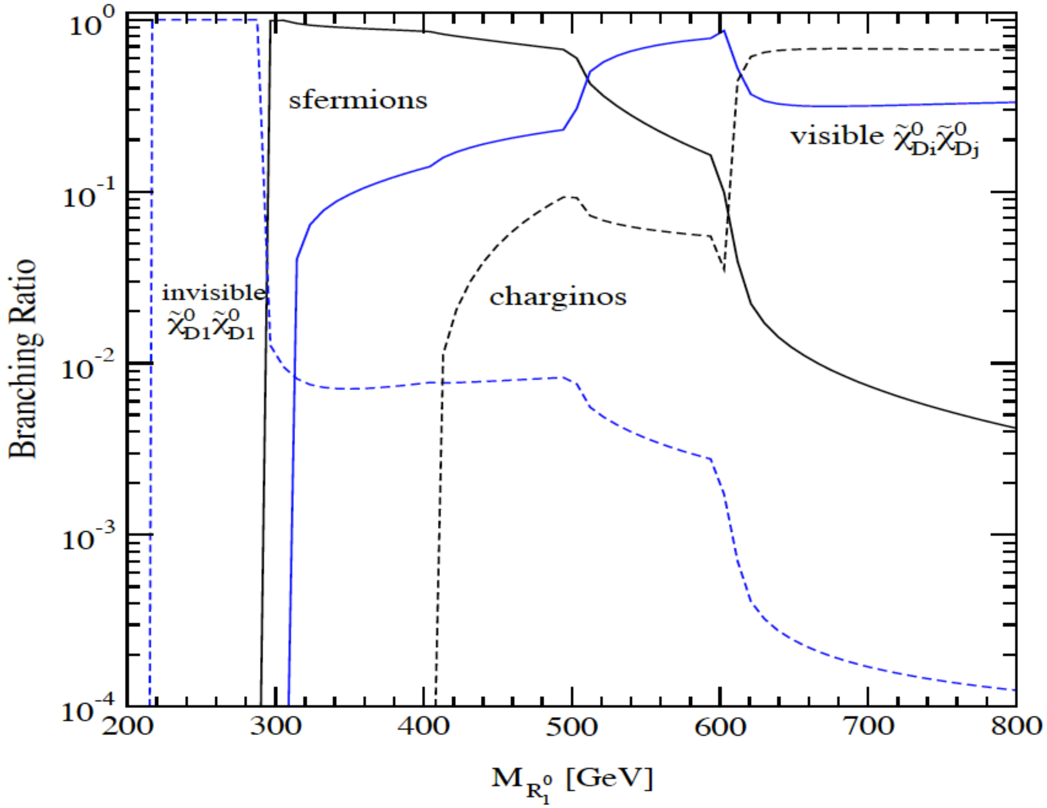
$$\sigma[pp \to RR^*] = \sum_{q\bar{q}} \left\langle \frac{\pi\lambda^{3/2}}{9s}\left|\sum_V \alpha_{RRV}\,\frac{s}{s-m_V^2}\,\alpha_{qqV}\right|^2 \right\rangle_{q\bar{q}}$$

Expectations at the LHC

Production:



Branching ratios:



other parameters as in the SPS1a' scenario (with Dirac gauginos)

Expectations at the LHC

Other production channels:

cascade decays: $\tilde{q} \to q\tilde{\chi}_n \to q\tilde{\chi}_1 R$

gamma fusion $pp \to \gamma\gamma \to RR^*$

Expectations at the LHC

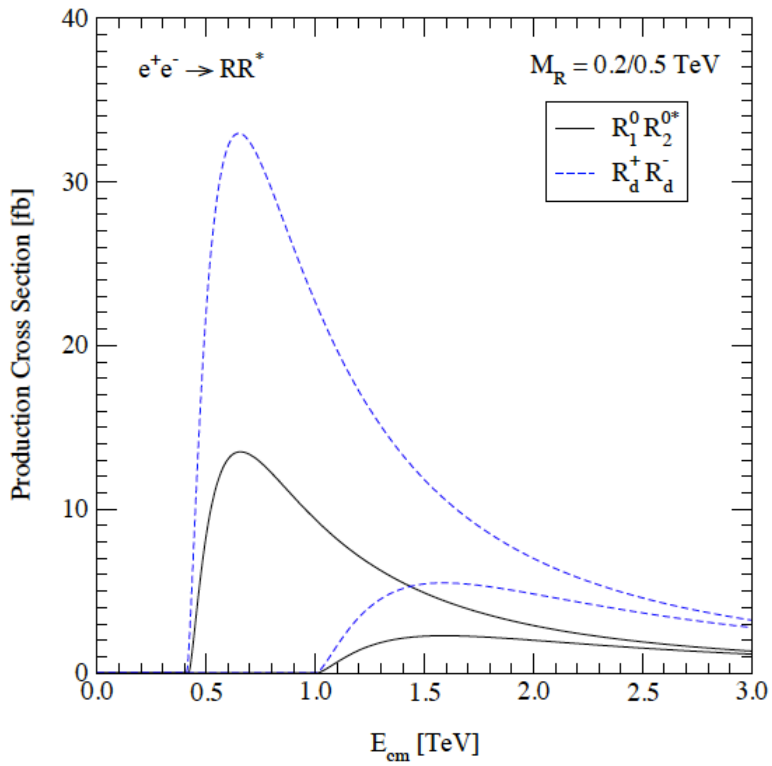
Other production channels:

cascade decays: $\tilde{q} \to q\tilde{\chi}_n \to q\tilde{\chi}_1 R$

gamma fusion $pp \to \gamma\gamma \to RR^*$

for heavier R-Higgs: wait for CLIC

$$\sigma[e^+e^- \to RR^*] = \frac{\pi\lambda^{3/2}}{3s}\left|\sum_V \alpha_{RRV}\,\frac{s}{s-m_V^2}\,\alpha_{eeV}\right|^2$$



Summary

- Well motivated R-symmetric SUSY model discussed
- Ameliorates MSSM flavour and CP problems
- Gauginos become Dirac particles
- R-scalars expand significantly the scalar sector
- Conserved R-charge restricts production channels and decay modes
- Other sectors (colored, -inos) not discussed here

distinct phenomenology at colliders

consequences for DM relic abundance

Backups

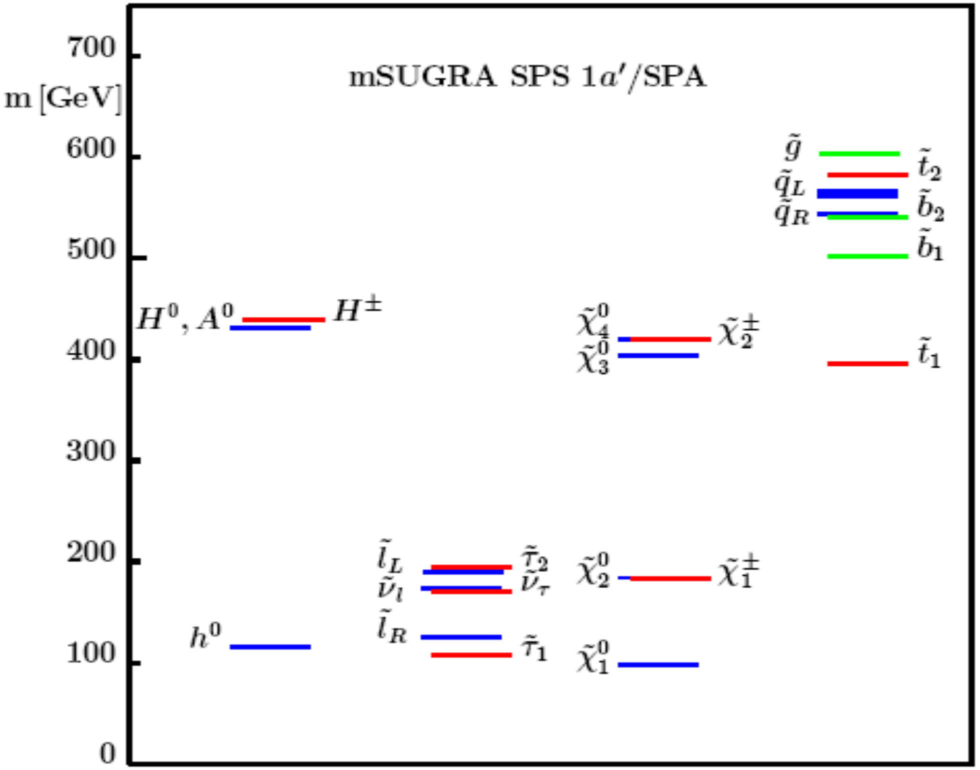
soft masses

B_{mu}-term	$\int d^2\theta d^2\bar{\theta}\ \frac{X^\dagger X}{M^2}\ \hat{H}_u\hat{H}_d$	$\rightarrow B_\mu H_u H_d$
scalar masses for R-Higgses	$\int d^2\theta d^2\bar{\theta}\ \frac{X^\dagger X}{M^2}\ \hat{R}_u^\dagger \hat{R}_d$	$\rightarrow M^2_{R_d}(\lvert R_d^+\rvert^2 + \lvert R_d^0\rvert^2)$
scalar masses for sigma fields	$\int d^2\theta d^2\ \frac{\hat{W}^\alpha \hat{W}_\alpha}{M^2}\ \mathrm{Tr}\hat{\Sigma}^2$	$\rightarrow \mathrm{M}^2_\sigma(\sigma^2 + \sigma^{*2})$
Dirac gaugino masses	$\int d^2\theta d^2\ \frac{\hat{W}^\alpha}{M}\ \hat{G}_\alpha\hat{\Sigma}$	$\rightarrow M^D \tilde{G}\tilde{G}'$

when hidden sector spurion fields develop vevs

$$\langle X \rangle = \theta^2\, F$$
$$\langle \hat{W}^\alpha \rangle = \theta^\alpha\, D$$

SPS1a' scenario



m_0	70 GeV
$m_{1/2}$	250 GeV
A_0	-300 GeV
$\tan\beta$	10
sign μ	$+$