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R-SYMMETRIC SUPERSYMMETRIC HIGGS BOSONS AT THE LHC*

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The Higgs sector of the minimal R-symmetric supersymmetry theory is analyzed. Decay modes and production channels of the novel Higgs bosons at the LHC and e^+e^- colliders are studied.

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1. Introduction

Imposing continuous R-symmetry [1] on the Minimal Supersymmetric Standard Model (MSSM) removes some of the phenomenologically embarrassing parameters of the theory. Assigning the R charges to the MSSM superfields as in Table I, the μ term and baryon- and lepton-number changing terms in the superpotential as well as soft-supersymmetry breaking Majorana gaugino masses and trilinear A-terms are forbidden. Thus the L- and R-squark and slepton mass mixing is absent, as well as dimension-five operators mediating proton decay, while Majorana neutrino masses can be generated. In order to give the gaugino masses the superfield content of the model has to be extended. In the so called Minimal R-symmetric Supersymmetric Standard Model (MRSSM) [2,3] new chiral superfields $\hat{\Sigma}_K = \{\sigma_K, \tilde{G}'_K\}$ in the adjoint representation of the gauge group (with $K = C, I, Y$ for SU(3), SU(2), U(1) respectively) are introduced in addition to the standard vector superfields $\hat{G}_K = \{\tilde{G}_K, G^\mu_K\}$. With suitably chosen mass matrices, the gauginos from vector $\tilde{G}$ and chiral $\tilde{G}'$ supermultiplets can be combined to form Dirac fermions $\tilde{G}_D = \tilde{G} \oplus \tilde{G}'$ [4]. Two iso-dublet chiral superfields $\hat{R}_u, \hat{R}_d$ (R-Higgs) complement the standard Higgses $\hat{H}_u, \hat{H}_d$ to generate R-symmetric μ-terms and the corresponding higgsino masses.

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TABLE I

The R-charges of the MSSM and of the new gauge chiral $\hat{\Sigma}_K$ and R-Higgs superfields (R-charges of the fermionic coordinates $\Theta/\bar{\Theta}$ are $+1/-1$).

Superfield	R-charge
Matter $\hat{L}$, $\hat{E}^c$, $\hat{Q}$, $\hat{D}^c$, $\hat{U}^c$	$+1$
Gauge vector $\hat{G}_K$	0
Higgs $\hat{H}_d$, $\hat{H}_d$	0
Gauge chiral $\hat{\Sigma}_K$	0
R-Higgs $\hat{R}_{d,u}$	$+2$

The transition from Majorana gauginos to Dirac gauginos as well as presence of new $R_{u,d}$ and adjoint scalar fields σ has far reaching consequences on supersymmetric particle production at the LHC and e^+e^- colliders [5,6], cold dark matter expectations [7], and flavor- and CP-changing processes [2, 8]. Here we present how the phenomenological picture of the R-symmetric Higgs sector can experimentally be investigated at the LHC and e^+e^- colliders [3].

2. The model

The spectrum of fields in the MRSSM consists of the standard MSSM matter, Higgs and gauge superfields augmented by chiral superfields $\hat{\Sigma}_K$ in the adjoint representations of the corresponding gauge groups and two Higgs iso-doublet superfields $\hat{R}_{d,u}$.

The assignment of R charges, as in Table I, admits the trilinear Yukawa terms $y_d \hat{H}_d \hat{Q} \hat{D}^c$ *etc.* in the superpotential, while forbids the standard μ-term as well as L- and B-violating couplings. The presence of the new R-Higgs superfields $\hat{R}_{d,u}$ with $R = 2$, however, allows bilinear μ-type mass terms as well as trilinear terms for isospin and hypercharge interactions in the superpotential

$$\mathcal{W}_R = \mu_d \, \hat{H}_d \hat{R}_d + \mu_u \, \hat{H}_u \hat{R}_u \,, \tag{1}$$

$$\mathcal{W}'_R = \lambda_d^{I,Y} \, \hat{H}_d \hat{\Sigma}_{I,Y} \hat{R}_d + \lambda_u^{I,Y} \, \hat{H}_u \hat{\Sigma}_{I,Y} \hat{R}_u \,. \tag{2}$$

Both terms can be thought of as generated by the Giudice–Masiero mechanism [9], $\int d^4\Theta \, \hat{X}^\dagger / M \;\; \mathcal{W}^{(\prime)}$, when the chiral spurion $\hat{X}$, preserving the R-symmetry with charge $R = 2$, develops the vacuum expectation value $\langle \hat{X} \rangle = \Theta^2 \, F$ in the hidden sector. Note however, no bilinear coupling of the R-Higgs fields is allowed, removing the exchange symmetry between the H and R-Higgs fields.

In a similar way the soft-supersymmetry breaking parameters can also be generated by the R-symmetric interaction:

- B_μ term: $\int d^4\Theta \left\langle \hat{X}^\dagger \hat{X} \right\rangle / M^2 \, \hat{H}_u \hat{H}_d \,,$

- soft scalar masses of the R-Higgs fields: $\int d^4\Theta \left\langle \hat{X}^\dagger \hat{X} \right\rangle / M^2 \, \hat{R}_d^\dagger \hat{R}_d \,,$

- Dirac gaugino masses: $\int d^2\Theta \left\langle \hat{W}'^\alpha \right\rangle / M \, \mathrm{Tr}\, \hat{G}_\alpha \hat{\Sigma}$ for isospin, hypercharge and color ($\hat{G}_\alpha$ are the corresponding gauge superfield-strengths with $R = 1$),

- soft masses of the adjoint scalars: $\int d^2\Theta \left\langle \hat{W}'^\alpha \hat{W}'_\alpha \right\rangle / M^2 \, \mathrm{Tr}\, \hat{\Sigma}^2$, $\int d^4\Theta \left\langle \hat{X}^\dagger \hat{X} \right\rangle / M^2 \, \mathrm{Tr}\, \hat{\Sigma}^2$ and $\int d^4\Theta \left\langle \hat{X}^\dagger \hat{X} \right\rangle / M^2 \, \mathrm{Tr}\, \hat{\Sigma}^\dagger \hat{\Sigma}$.

Here $\hat{W}'^\alpha$ denotes a hidden sector U(1) gauge superfield with $R = 1$ which develops a vacuum D-term $\langle \hat{W}'^\alpha \rangle = D\,\Theta^\alpha$, and the scale parameters M can be different in the above interactions.

The Higgs potential derives from the superpotential and the soft terms. In general, it is very complex due to the mixing among the H, R and $\sigma_{I,Y}$ states. Since the SU(2) sector involves an iso-vector σ_I, its mass parameters must be large enough to suppress the related vacuum expectation value, as demanded by the small deviation of the ρ parameter from unity. In what follows we assume that the mass parameters in the σ sector are large, of TeV order[1]. Leaving out the σ fields, the neutral part of the potential is given by

$$\begin{aligned}
\mathcal{V}^0_{[H,R]} \;=\; & \left(m^2_{H_d} + \mu_d^2\right) \left|H_d^0\right|^2 + \left(m^2_{H_u} + \mu_u^2\right) \left|H_u^0\right|^2 - \left(B_\mu H_d^0 H_u^0 + \text{h.c.}\right) \\
& + \left(m^2_{R_d} + \mu_d^2\right) \left|R_d^0\right|^2 + \left(m^2_{R_u} + \mu_u^2\right) \left|R_u^0\right|^2 \\
& + \left|\lambda_d^I H_d^0 R_d^0 + \lambda_u^I H_u^0 R_u^0\right|^2 + \left|\lambda_d^Y H_d^0 R_d^0 - \lambda_u^Y H_u^0 R_u^0\right|^2 \\
& + \tfrac{1}{8}\left(g^2 + g'^2\right) \left(\left|H_d^0\right|^2 - \left|H_u^0\right|^2 - \left|R_d^0\right|^2 + \left|R_u^0\right|^2\right)^2 . \qquad (3)
\end{aligned}$$

The absence of the mixed $R_d^0 R_u^0$ term, as required by R-symmetry, implies that *(i)* the R-Higgs fields, $R_{d,u}$, do not develop non-zero vacuum expectation values, *(ii)* the R-Higgs fields do not mix with the other scalar fields, *i.e.* the R-Higgs and H-Higgs states are mutually independent of each other. Thus, the R-symmetric theory incorporates four neutral and four charged R-Higgs states in addition to the standard three neutral and two charged MSSM H-Higgs states.

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[1] Sgluons σ_{C} in the colored sector can, nevertheless, be produced copiously at the LHC, giving rise to resonance and multi-jet final states, see contribution by Kotlarski, these proceedings [10] and Ref. [11].

Expanding around the vacuum expectation values $v_{d,u}/\sqrt{2}$ of the H-Higgs fields $H^0_{d,u}$, one easily finds the mass-squared eigenvalues of the neutral R-Higgs fields

$$M^2_{R^0_{1,2}} = \frac{1}{2}\left[m'^2_d + m'^2_u \mp \sqrt{\left(m'^2_d - m'^2_u\right)^2 + 4\delta^2_{du}}\right] , \tag{4}$$

where $(g^2_Z = g^2 + g'^2)$

$$\begin{aligned} m'^2_d &= m^2_{R_d} + \mu^2_d + \tfrac{1}{2}\left(\lambda^{I2}_d + \lambda^{Y2}_d\right) v^2_d - \tfrac{1}{8} g^2_Z \left(v^2_d - v^2_u\right) , & (5)\\ m'^2_u &= m^2_{R_u} + \mu^2_u + \tfrac{1}{2}\left(\lambda^{I2}_u + \lambda^{Y2}_u\right) v^2_u + \tfrac{1}{8} g^2_Z \left(v^2_d - v^2_u\right) , & (6)\\ \delta_{du} &= \tfrac{1}{2}\left(\lambda^I_d \lambda^I_u - \lambda^Y_d \lambda^Y_u\right) v_d v_u . & (7) \end{aligned}$$

Since the same-sign charged $R_{d,u}$ carry opposite R-charges, $R^\pm_d$, $R^\pm_u$ bosons do not mix and their masses are simply given by $(g'^2_Z = g^2 - g'^2)$

$$\begin{aligned} M^2_{R^\pm_d} &= m^2_{R_d} + \mu^2_d + \lambda^{I2}_d v^2_d - \tfrac{1}{8} g'^2_Z \left(v^2_d - v^2_u\right) , & (8)\\ M^2_{R^\pm_u} &= m^2_{R_u} + \mu^2_u + \lambda^{I2}_u v^2_u + \tfrac{1}{8} g'^2_Z \left(v^2_d - v^2_u\right) . & (9) \end{aligned}$$

The conserved R-charge restricts the R-Higgs boson trilinear couplings to pairs of sfermions, $R\tilde{\ell}\tilde{\ell}$, $R\tilde{q}\tilde{q}$ and chargino/neutralino combinations, $R\tilde{\chi}\tilde{\chi}$; the couplings to pairs of SM particles and Higgs bosons, Rff, RVV, RHH vanish (even at loop order). The R symmetry admits also RRH and RRV couplings. Thus in pp and e^+e^- collisions the R-Higgs bosons can be produced in pairs. Although dedicated searches for these unusual states, with very specific decay modes as shown below, have not been performed, we take the approximate LEP limit of about 100 GeV as a lower limit on their masses. The conserved R-charge implies that the electroweak precision observables, T and S, are affected by the R fields only pairwise at 1-loop order and their contribution vanishes for degenerate R-Higgs masses, in parallel to [12]; the R-Higgs masses cannot be constrained in practice this way. In what follows we assume that the R-Higgs bosons are unstable, *i.e.* their masses must exceed twice the LSP mass.

In the left frame of Fig. 1 the R-spectrum is displayed for couplings $\lambda^I_d = -\lambda^I_u = -g/\sqrt{2}$ and $\lambda^Y_d = \lambda^Y_u = -g'/\sqrt{2}$ as predicted in $n = 2$ SUSY, and mass parameters m'_R in the range between 100 GeV and 250 GeV, where the mixing between the neutral states is important.

The R-Higgs bosons, if kinematically allowed, decay to sfermions (generated in pairs of L and R particles) and pairs of charginos/Dirac neutralinos. More specifically, the decay

$$R^+_d \to \tilde{u}_L \tilde{d}^*_R \quad \text{and} \quad \tilde{\nu}_L \tilde{\ell}^*_R \tag{10}$$

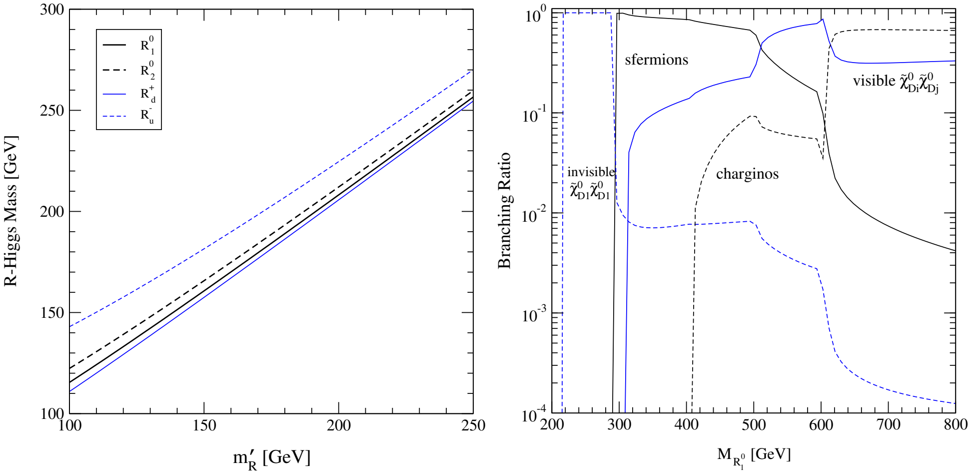

Fig. 1. Left: Masses of the two neutral $R^0_{1,2}$ and the two charged $R^\pm_{d,u}$ Higgs bosons for a common R-Higgs mass parameter $m'_R = (m^2_{R_{d,u}} + \mu^2_{d,u})^{1/2}$; Right: Branching ratios for decays of the neutral R^0_1-Higgs boson to sfermions, Dirac neutralinos and charginos for the SPS1a$'$ parameter point (sfermion mixing removed).

is controlled by dimensionful couplings given by $y_d\mu_d$ and $y_\ell\mu_d$, while

$$R^+_d \to \tilde\chi^+_{dj}\,\tilde\chi^0_{Dk} \tag{11}$$

with couplings g, g' for the *gaugino*, and $\lambda^{I,Y}$ for the *gaugino*$'$ components. The neutral R_d and the charged/neutral R_u-Higgs bosons have similar decay channels. The Yukawa couplings y between L/R sfermions strongly enhance decays to third-generation channels. The charginos and neutralinos decay, eventually through cascades, to the lightest stable neutralino LSP $= \tilde\chi^0_{D1}$.

Denoting the effective R-Higgs boson couplings to sfermions by $\tilde\alpha$ and scalar/pseudoscalar couplings to chargino/neutralino by α/α', the partial on-shell decay widths can be cast into the form

$$\Gamma\left[R \to \tilde f_{\rm L}\tilde f'^*_{\rm R}\right] = \frac{\lambda^{1/2}\,\tilde\alpha^2_{Rff'}}{16\pi M_R}\,, \tag{12}$$

$$\Gamma\left[R \to \tilde\chi_{Dj}\tilde\chi_{Dk}\right] = \frac{\lambda^{1/2}}{8\pi M_R}\left\{\alpha^2_{Rjk}\left[M^2_R - (m_j+m_k)^2\right]\right. \tag{13}$$

$$\left. +\alpha'^2_{Rjk}\left[M^2_R - (m_j-m_k)^2\right]\right\}\,, \tag{14}$$

with the standard phase-space coefficients $\lambda = [1-(m_j-m_k)^2/M^2_R][1-(m_j+m_k)^2/M^2_R]$. The α-coefficients are built up by the mixing matrix elements and the couplings of the current fields. Charged $R^\pm$-Higgs bosons will always have charged SM particles among decay products, $R^{\pm} \to \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D1} + X^{\pm}$, so that they have visible decays. For the neutrals R^0, they will cascade to $R^0 \to \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D1} + X^0$, X^0 denoting a neutral set of SM particles, or decay invisibly via the exclusive decay $R^0 \to \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D1}$. The right panel of Fig. 1 shows branching ratios for a set of 2-body on-shell neutral R^0_1-Higgs decays in the SPS1a' scenario [13] in which the gauginos are taken as Dirac and the sfermion mixing is removed.

3. Phenomenology of *R*-Higgs bosons at colliders

The conserved R-charge implies that the R-Higgs bosons can be produced only in pairs at the pp collider LHC, via Drell–Yan mechanism, and in e^+e^- annihilation at prospective linear colliders. The production cross sections are given as

$$\sigma\left[pp \to RR^*\right] = \sum_{q\bar{q}} \left\langle \frac{\pi\lambda^{3/2}}{9s} \left| \sum_V \alpha_{RRV}\, \frac{s}{s-m_V^2}\, \alpha_{qqV} \right|^2 \right\rangle_{q\bar{q}}, \quad (15)$$

$$\sigma\left[e^+e^- \to RR^*\right] = \frac{\pi\lambda^{3/2}}{3s} \left| \sum_V \alpha_{RRV}\, \frac{s}{s-m_V^2}\, \alpha_{eeV} \right|^2, \quad (16)$$

where V denotes intermediate gauge bosons and $\langle\ \rangle_{q\bar{q}}$ implies the convolution with the $q\bar{q}$ structure functions. Fig. 2 shows the expected size of the cross-sections for the production of neutral/charged R-Higgs pairs, $R^0_1 R^{0^*}_2$, $R^+_d R^-_d$ and $R^+_d R^{0^*}_1$; cross-sections for the diagonal neutral R-Higgs boson pairs, $R^0_1 R^{0^*}_1$ and $R^0_2 R^{0^*}_2$, vanish for the common R-Higgs mass parameter $m'_R = (m^2_{R_{d,u}} + \mu^2_{d,u})^{1/2}$ and $N = 2$ values of the $\lambda^{I,Y}$ couplings. Additional sources of R Higgs bosons, though in general at reduced levels, are provided by the fusion channel $pp \to \gamma\gamma \to R^+R^-$, or from heavy MSSM Higgs decays $H \to RR^*$, *cf.* $\Gamma(H \to RR^*) = \alpha^2_{RRH}\, \lambda^{1/2}/16\pi M_H$.

Although the details of the experimental signature depend on the specific scenario, the pair-production of R-Higgs bosons determines the main characteristics. To illustrate the essential points we consider again the SPS1a$'$ scenario, in which τ's are the dominating visible cascade components, *cf.* Ref. [14]: $R^0 \to \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D2}$ followed by $\tilde{\chi}^0_{D2} \to \tau\tilde{\tau}$ followed by $\tilde{\tau} \to \tau\tilde{\chi}^0_{D1}$, *i.e.*,

$$R^0 R^{0^*} \to \tau^+\tau^-\tau^+\tau^- + \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D1}\tilde{\chi}^{0c}_{D1}\tilde{\chi}^{0c}_{D1}\,. \quad (17)$$

Two outstanding signatures characterize the final states: *(i)* four τs, and *(ii)* four invisible neutralino LSPs. The τs give rise to e, μ leptons and pencil-like hadronic jets. The four LSP's generate a large amount of missing energy in e^+e^- collisions and missing transverse momentum in proton collisions. If $M_R \sim 2M_{\tilde{\chi}^0_{D2}} \sim 2M_{\tilde{\tau}} \sim 4M_{\tilde{\chi}^0_{D1}}$ the total missing energy amounts

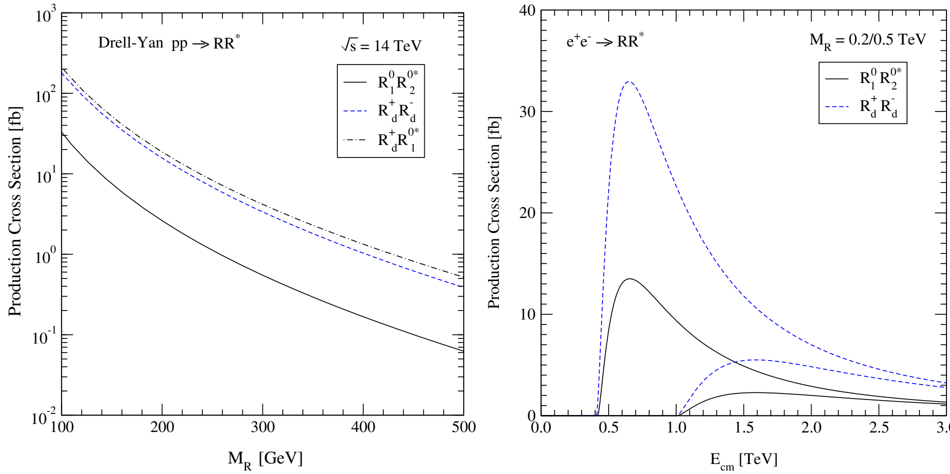

Fig. 2. Left: Drell–Yan production of the neutral/charged R-Higgs boson pairs, $R_1^0 R_2^{0^*}$, $R_d^+ R_d^-$ and $R_d^+ R_1^{0^*}$, at the LHC ($\sqrt{s} = 14$ TeV). The cross-sections are plotted *versus* the averaged mass of the produced particles denoted generically by M_R; Right: Production of the neutral and charged R-Higgs boson pairs $R_1^0 R_2^{0^*}$ and $R_d^+ R_d^-$ at TeV e^+e^- colliders [ILC/CLIC]. Two values, 0.2 TeV and 0.5 TeV, are taken for the masses.

approximately to $E_{\perp,\mathrm{miss}} \sim 2M_R$, while the missing transverse momentum adds up approximately to $p_{\perp,\mathrm{miss}} \sim M_R$, both slightly supplemented by neutrino energies. Other charge configurations and decay channels of the R pairings have similar characteristics. Thus, the multi-fold τ-multiplicity in association with high values of missing energy/transverse momentum offers promising signatures for detecting RR events.

4. Summary

R-symmetry provides an interesting extension of the Minimal Supersymmetric Standard Model. On the one hand, it suppresses unwanted processes at the grand unification scale, and in some scenarios also at the electroweak scale, on the other, it gives rise to distinct phenomenology. The conserved R-charge implies both the production of R-Higgs bosons in pairs in pp and e^+e^- collisions, and their decays only into pairs of supersymmetric particles comprising states with $R = 2$. As a result the signatures of the R-Higgs boson production, with high multiplicity of leptons and large missing transverse momentum, are very different from the MSSM. Searching for these novel R-Higgs particles and, if discovered, investigating their properties will therefore be quite interesting.

Note added: Recently, an interesting R-symmetric realization has been proposed [15], in which no extra Higgs doublets are introduced. Although the particle content of the model is reduced, the main features of the R-Higgs boson phenomenology are similar.

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