THE EXTENDED HIGGS SYSTEM IN R–SYMMETRIC SUPERSYMMETRY THEORIES

S. Y. Choi,[1] D. Choudhury,[2] A. Freitas,[3] J. Kalinowski,[4] and P. M. Zerwas[5]

[1] *Department of Physics and RIPC, Chonbuk National University, Jeonju 561-756, Korea*

[2] *Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India*

[3] *Department of Physics & Astronomy, University of Pittsburgh, 3941 O'Hara St, PA 15260, USA*

[4] *Faculty of Physics, University of Warsaw, 00681 Warsaw, Poland*

[5] *Institut für Theoretische Teilchenphysik und Kosmologie,*
RWTH Aachen University, D-52074 Aachen, Germany, and
Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

(Dated: March 18, 2011)

The Higgs sector is extended in R-symmetric supersymmetry theories by two iso-doublets $R_{d,u}$ which complement the standard iso-doublets $H_{d,u}$. We have analyzed masses and interactions of these novel states and describe their [non-standard] decay modes and their production channels at the LHC and e^+e^- colliders.

1. INTRODUCTION

R-symmetry [1, 2] is taken in this letter as a continuous extension of the discrete R-parity concept. When this symmetry is imposed on the Minimal Supersymmetric Standard Model (MSSM) [3, 4], incorporating supersymmetry and electroweak symmetry breaking, some of the basic parameters are removed from the theory, *cf.* Ref. [5]. Majorana gaugino masses are forbidden, and so are the μ-term and higgsino masses. No A-terms are allowed and so the L- and R-squark and slepton mass mixing is absent. In addition the symmetry forbids baryon- and lepton-number changing terms in the superpotential, as well as dimension-five operators mediating proton decay [6, 7], while Majorana neutrino masses can be generated. However, by complementing the MSSM gauge supermultiplets $\hat{G} = \{G_\mu, \tilde{G}\}$ by additional chiral supermultiplets $\hat{\Sigma} = \{\tilde{G}', \sigma\}$ in the adjoint representations of the gauge symmetries, the two gaugino fields can be combined to a Dirac field, $\tilde{G} \oplus \tilde{G}' = \tilde{G}_D$, while preserving the R-symmetry for non-zero Dirac masses [8]. Complementing the MSSM Higgs sector $\hat{H}_{d,u}$ by two iso-doublet fields $\hat{R}_{d,u}$ allows one, analogously, to introduce R-symmetric μ-terms and the corresponding higgsino masses.

The transition from Majorana gauginos to Dirac gauginos has far reaching consequences on supersymmetric particle production at the LHC and e^+e^- colliders, Refs. [9–11], suppressing pair production channels and cascade decays which are realized in Majorana theories but forbidden in Dirac theories. S-wave LSP neutralino pair annihilation channels to light fermions are open in collisions of Cold Dark Matter particles [12–15], while other scenarios are studied in Ref. [16]. For TeV-scale gauginos, mechanisms for flavor-changing processes can be suppressed in Dirac theories, alleviating the flavor problem of supersymmetric theories in models other than gauge mediation [5]. [Additional aspects have recently been discussed in Refs. [17, 18].]

This letter is focussed on the extended $R_{d,u}$-Higgs sector of R-symmetric theories, of which the R-Higgs bosons are assigned the conserved R-charge $R = 2$. The mass matrices are derived and the properties of the mass eigenstates are

Field	Superfield		Boson		Fermion	
Matter	$\hat{L}, \hat{E}^c$	+1	$\tilde{L}, \tilde{E}^c$	+1	L, E^c	0
	$\hat{Q}, \hat{D}^c, \hat{U}^c$	+1	$\tilde{Q}, \tilde{D}^c, \tilde{U}^c$	+1	Q, D^c, U^c	0
H-Higgs	$\hat{H}_{d,u}$	0	$H_{d,u}$	0	$\tilde{H}_{d,u}$	−1
R-Higgs	$\hat{R}_{d,u}$	+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

Table I: *The R-charges of the superfields and the corresponding bosonic and fermionic components.*

determined. The dominant interaction terms of the states are identified. Driven by the high R-charge, the properties of the R-Higgs bosons are quite distinct from the ordinary H-Higgs bosons, rendering this system very interesting to explore. From the masses and vertices the decay modes and production channels can be predicted, building up the phenomenological picture of the R-symmetric Higgs sector which can experimentally be investigated at the LHC and e^+e^- colliders.

2. THEORETICAL BASIS

The spectrum of fields in the R-symmetric supersymmetry (SUSY) theory which we will analyze in this letter, consists of the standard MSSM matter, Higgs and gauge superfields augmented by chiral superfields $\hat{\Sigma}$ in the adjoint representations of the corresponding gauge groups and two Higgs iso-doublet superfields $\hat{R}_{d,u}$. The R-charges of the superfields and their component fields are listed in Tab. I [with R-charges $+1/-1$ assigned to the fermionic coordinates $\Theta/\bar{\Theta}$].

With these assignments the gauge, matter/gauge and Higgs/gauge actions of the MSSM are R-invariant, and so is the action associated with the trilinear Yukawa terms $y_d \hat{H}_d \cdot \hat{Q}\hat{D}^c$ *etc* in the superpotential, the R-symmetry being preserved when the electroweak symmetry is broken. In contrast, the action associated with the standard μ-term would be R-charged and non-invariant.

The presence of the new R-Higgs superfields $\hat{R}_{d,u}$ with $R = 2$ however allows bilinear μ-type mass terms of the form

$$\mathcal{W}_R = \mu_d \, \hat{H}_d \cdot \hat{R}_d + \mu_u \, \hat{H}_u \cdot \hat{R}_u \, , \tag{2.1}$$

in the superpotential, as well as trilinear terms for isospin and hypercharge interactions:

$$\mathcal{W}'_R = \lambda_d^{I,Y} \, \hat{H}_d \cdot \hat{\Sigma}_{I,Y} \hat{R}_d + \lambda_u^{I,Y} \, \hat{H}_u \cdot \hat{\Sigma}_{I,Y} \hat{R}_u \, . \tag{2.2}$$

Both components carry charges $R = +2$ so that the actions, $S^{(\prime)}_{\mathcal{W}} = \int d^2\Theta \, \mathcal{W}^{(\prime)}_R + \text{h.c.}$, are R-invariant. [The dots in the equations denote the antisymmetric contraction of the $\mathrm{SU}(2)_I$ doublet components.] The mixed μ terms of $\mathcal{W}_R$ can be generated by the Giudice-Masiero mechanism [19], $\int d^4\Theta \, \hat{X}^\dagger/M \; \hat{H}_i \cdot \hat{R}_i$, when the chiral spurion in the hidden sector $\hat{X}$, preserving the R-symmetry with charge $R = 2$, develops the vacuum expectation value $\langle \hat{X} \rangle = \Theta^2 \, F$. Similarly, the soft-supersymmetry breaking B_μ term can be generated by the R-symmetric interaction

$$\int d^4\Theta \, \frac{\langle \hat{X}^\dagger \hat{X} \rangle}{M^2} \, \hat{H}_u \cdot \hat{H}_d \quad \to \quad B_\mu H_u \cdot H_d \, . \tag{2.3}$$

No bilinear coupling of the R-Higgs fields, which would carry R-charges $R = 4$, is present in the R-symmetric theory. Thus, the bilinear Higgs coupling destroys the exchange symmetry between the H and R-Higgs fields.

The soft scalar mass terms of the R-Higgs fields can be generated in the same manner by the R-symmetric term

$$\int d^4\Theta \, \frac{\langle \hat{X}^\dagger \hat{X} \rangle}{M^2} \hat{R}_d^\dagger \hat{R}_d \quad \to \quad -m_{R_d}^2 (|R_d^+|^2 + |R_d^0|^2) \quad \text{etc}\,, \tag{2.4}$$

suggesting that $\mu_{d,u}$, B_μ and scalar masses should be similar in size, *i.e.* of the order of the supersymmetry breaking scale.

While Majorana gaugino masses are forbidden, Dirac gaugino masses are perfectly allowed in an R-symmetric theory. They can be induced by the interaction of gauge and adjoint chiral superfields with a hidden sector U(1) gauge superfield $\hat{W}'^\alpha$ with $R = 1$ which develops a vacuum D-term $\langle \hat{W}'^\alpha \rangle = D\,\Theta^\alpha$:

$$\int d^2\Theta \, \frac{\langle \hat{W}'^\alpha \rangle}{M} \, \hat{G}_\alpha \hat{\Sigma} + \text{h.c.} \quad \to \quad -M^D \, \tilde{G}\tilde{G}' + \cdots \,, \tag{2.5}$$

for isospin, hypercharge and color gauginos. Here, $\hat{G}_\alpha$ are the gauge superfield-strengths with $R = 1$.

It may be noted, for the sake of completeness, that bilinear couplings of the $\hat{W}'^\alpha$ and $\hat{X}$ fields with the adjoint chiral fields also generate contributions $\int d^2\Theta \, \langle \hat{W}'^\alpha \hat{W}'_\alpha \rangle / M^2 \, \mathrm{Tr}\, \hat{\Sigma}^2$ and $\int d^4\Theta \, \langle \hat{X}^\dagger \hat{X} \rangle / M^2 \, \mathrm{Tr}\, \hat{\Sigma}^2$ to the soft masses of the adjoint scalars in addition to the usual soft terms $\int d^4\Theta \, \langle \hat{X}^\dagger \hat{X} \rangle / M^2 \, \mathrm{Tr}\, \hat{\Sigma}^\dagger \hat{\Sigma}$ [the scale parameters M being generally different in the individual interactions]. In the following we will not study theoretical points such as SUSY breaking mechanisms, but explore only the phenomenology of the R-symmetric low-energy theory.

3. MASSES

The mixing among the states renders the Higgs/scalar sector of the R-symmetric theory very complex. However, since the σ sector involves an iso-vector, the associated mass parameters must be large so as to suppress the related vacuum expectation value, which is bounded stringently by the small deviation of the ρ parameter from unity, see Refs. [11, 13]. For the sake of simplicity we shall assume that all the mass parameters in the σ sector are large[1], *viz.* at least of TeV order; systematic expansions for the closely related N=1/N=2 Hybrid Model have been worked out in Ref. [11] and the formalism can easily be adjusted to the present analysis. In the same spirit we shall identify the λ couplings in Eq. (2.2) with the gauge couplings as prescribed by N=2 extensions, $\lambda_d^I = -\lambda_u^I = -g/\sqrt{2}$ and $\lambda_d^Y = \lambda_u^Y = -g'/\sqrt{2}$, just for definiteness. Genuine parameters in the H and R-Higgs sectors are consistently assumed of similar size.

3.1. Higgs Sector

The Higgs potential derives from the actions introduced in the preceding section. Leaving out the σ fields, as argued earlier, the neutral part of the potential is given by the sum of supersymmetric terms and soft SUSY-breaking terms

[1] Sgluons in the colored σ sector can nevertheless be produced copiously at the LHC, giving rise to resonance and multi-jet final states, see Refs. [20–23].

of the H and R-Higgs fields,

$$\begin{aligned}\mathcal{V}^0_{[H,R]} &= (m^2_{H_d}+\mu^2_d)|H^0_d|^2 + (m^2_{H_u}+\mu^2_u)|H^0_u|^2 - (B_\mu H^0_d H^0_u + \text{h.c.}) \\ &+ (m^2_{R_d}+\mu^2_d)|R^0_d|^2 + (m^2_{R_u}+\mu^2_u)|R^0_u|^2 \\ &+ \left|\lambda^I_d H^0_d R^0_d + \lambda^I_u H^0_u R^0_u\right|^2 + \left|\lambda^Y_d H^0_d R^0_d - \lambda^Y_u H^0_u R^0_u\right|^2 \\ &+ \frac{1}{8}(g^2+g'^2)\left(|H^0_d|^2 - |H^0_u|^2 - |R^0_d|^2 + |R^0_u|^2\right)^2 \, . \end{aligned} \tag{3.1}$$

Two important consequences follow immediately from the specific form of the Higgs potential, in particular the absence of the mixed $R^0_d R^0_u$ term as required by R-symmetry:

- For positive coefficients of the bilinear terms[2], the R-Higgs fields, $R_{d,u}$, do not develop non-zero vacuum expectation values, *i.e.* the potential is minimized for vanishing values of the fields;
- In the bilinear terms the R-Higgs fields with $R = 2$ do not mix with the other scalar fields with $R \neq 2$ so that, in particular, the R-Higgs and H-Higgs states are mutually independent of each other.

These conclusions remain valid even if the σ fields with $R = 0$ are not discarded.

After subtracting the vacuum expectation values $v_{d,u}/\sqrt{2}$ from the H-Higgs fields $H^0_{d,u}$, the coefficients of the bilinear terms in the neutral and the corresponding charged part of the potential are identified with the masses of the physical Higgs fields. The procedure follows the standard way for the H-Higgs fields and will not be repeated here. Given the structure of the Higgs potential, the 2×2 neutral R-Higgs mass matrix reads:

$$\mathcal{M}^2_{R^0} = \begin{bmatrix} m^2_{R_d} + \mu^2_d + \frac{1}{2}\left(\lambda^{I2}_d + \lambda^{Y2}_d\right) v^2_d - \frac{1}{8} g^2_Z (v^2_d - v^2_u) & \frac{1}{2}(\lambda^I_d\lambda^I_u - \lambda^Y_d\lambda^Y_u) v_d v_u \\ \frac{1}{2}(\lambda^I_d\lambda^I_u - \lambda^Y_d\lambda^Y_u) v_d v_u & m^2_{R_u} + \mu^2_u + \frac{1}{2}\left(\lambda^{I2}_u + \lambda^{Y2}_u\right) v^2_u + \frac{1}{8} g^2_Z (v^2_d - v^2_u)\end{bmatrix}, \tag{3.2}$$

with $g^2_Z = g^2 + g'^2$, in the neutral (R^0_d, R^0_u) basis while the closely-related 2×2 charged R-Higgs matrix,

$$\mathcal{M}^2_{R^\pm} = \begin{bmatrix} m^2_{R_d} + \mu^2_d + \lambda^{I2}_d v^2_d - \frac{1}{8} g'^2_Z (v^2_d - v^2_u) & 0 \\ 0 & m^2_{R_u} + \mu^2_u + \lambda^{I2}_u v^2_u + \frac{1}{8} g'^2_Z (v^2_d - v^2_u)\end{bmatrix}, \tag{3.3}$$

with $g'^2_Z = g^2 - g'^2$, must be diagonal in the charged $(R^\pm_d, R^\pm_u)$ basis because the same-sign charged $R_{d,u}$-Higgs bosons carry opposite R-charges. 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.

Denoting the diagonal/off-diagonal elements of the neutral R-Higgs scalar mass matrix (3.2) by $m'^2_{d,u}$ and δ_{du}, the corresponding mass-squared eigenvalues read:

$$M^2_{R^0_{1,2}} = \frac{1}{2}\left[m'^2_d + m'^2_u \mp \sqrt{(m'^2_d - m'^2_u)^2 + 4\delta^2_{du}}\right]. \tag{3.4}$$

For mass parameters alike in d, u, $(m^2_{R_{d,u}} + \mu^2_{d,u})^{1/2} \equiv m'_R$, the neutral and charged masses are degenerate *modulo* terms of order $g^2 v^2/m'_R$, in analogy to the heavy Higgs bosons of the MSSM. The R-spectrum is displayed for N=2 couplings $\lambda^{Y,I}$ and mass parameters m'_R in the range between the approximate LEP limit of about 100 GeV and 250 GeV, where the splitting is important, in the left frame of Fig. 1. The rotation angle between the neutral current and mass eigenstates,

$$\tan 2\alpha_R = 2\delta_{du}/(m'^2_d - m'^2_u)\, , \tag{3.5}$$

---

[2] Except for small mass parameters significantly below the electroweak scale, universal positivity of all the coefficients follows from requiring electric charge conservation not to be broken spontaneously.

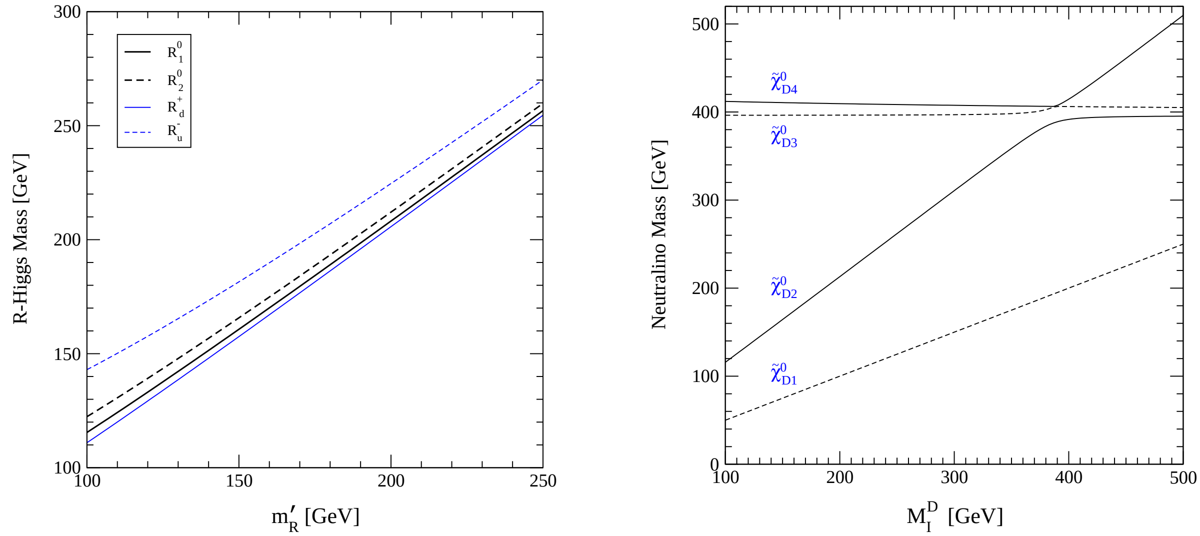

Figure 1: *Left: Masses of the two neutral* $R^0_{1,2}$ *and the two charged* $R^\pm_{d,u}$ *Higgs bosons for a common R-Higgs mass parameter* $m'_R = (m^2_{R_{d,u}} + \mu^2_{d,u})^{1/2}$ *[*$M_{R_d^+} \simeq M_{R_1^0}$ *as evident from the mass matrices]; Right: Masses of the four Dirac* $\tilde{\chi}^0_{Dj}$ *neutralinos for the SU(2)*$_I$ *Dirac gaugino mass* M_I^D *[adopting* $M_Y^D = M_I^D/2$*]; the N=2 values of the* $\lambda^{Y,I}$ *couplings are used and the other parameters are fixed to* $\tan\beta = 10$ *and* $\mu_d = \mu_u = 396$ *GeV corresponding to the SPS1a′ point [24].*

is generally small, of order $\lambda^2 v^2/\Delta m'^2$, except for degenerate d, u mass parameters.

The masses of the R-Higgs bosons are restricted only by the non-observation of their production at LEP and Tevatron, pairwise due to the non-vanishing R-charges. Note however that no dedicated searches for these unusual states, with very specific decay modes as shown later, have been reported. Moreover, due to the conserved R-charges, the standard electroweak precision observables, T and S, are affected by the novel fields only pairwise at 1-loop order and the contributions vanish in the limit of degenerate R-Higgs masses, in parallel to Refs. [25, 26]; the R-Higgs masses cannot be constrained in practice this way.

3.2. Charginos and Neutralinos

The SUSY partners of the non-colored gauge vector, gauge chiral, H-Higgs and R-Higgs bosons generate a rich ensemble of fermionic fields: four charged fields and their charge-conjugated fields, plus four neutral Dirac fields and their charge-conjugated fields (see also Ref. [16]).

Fields carrying identical R-charges are mixed by the mass matrices, which emerge from the supersymmetric gauge and Yukawa actions and the supersymmetry-breaking Dirac actions. They couple the original MSSM gaugino $\tilde{G}$ and higgsino $\tilde{H}$ with the new gaugino $\tilde{G}'$ and higgsino $\tilde{R}$ fields, generating Dirac mass eigenstates $\tilde{\chi}^+_{d1,d2}$, $\tilde{\chi}^-_{u1,u2}$, $\tilde{\chi}^0_{D1,\ldots D4}$ with $R = 1$ and their charge-conjugated states with $R = -1$. Specifically, the two 2×2 chargino mass matrices read

$$\mathcal{M}^\pm_d = \begin{bmatrix} M_I^D & \lambda_d^I v_d \\ g v_d/\sqrt{2} & -\mu_d \end{bmatrix} \; ; \quad \mathcal{M}^\pm_u = \begin{bmatrix} M_I^D & -\lambda_u^I v_u \\ g v_u/\sqrt{2} & \mu_u \end{bmatrix}, \tag{3.6}$$

in the $(\tilde{W}'^-, \tilde{H}_d^-)/(\tilde{W}^+, \tilde{R}_d^+)$ basis and the $(\tilde{W}'^+, \tilde{H}_u^+)/(\tilde{W}^-, \tilde{R}_u^-)$ basis, respectively, and the 4×4 neutralino mass matrix reads

$$\mathcal{M}^0 = \begin{bmatrix} M_Y^D & 0 & -\lambda_u^Y v_u/\sqrt{2} & \lambda_d^Y v_d/\sqrt{2} \\ 0 & M_I^D & -\lambda_u^I v_u/\sqrt{2} & -\lambda_d^I v_d/\sqrt{2} \\ g' v_u/2 & -g v_u/2 & -\mu_u & 0 \\ -g' v_d/2 & g v_d/2 & 0 & \mu_d \end{bmatrix}, \quad (3.7)$$

in the $(\tilde{B}', \tilde{W}'^0, \tilde{H}_u^0, \tilde{H}_d^0)/(\tilde{B}, \tilde{W}^0, \tilde{R}_u^0, \tilde{R}_d^0)$ basis. The two chargino mass matrices and the neutralino mass matrix, which is symmetric in the N=2 parametrization of the $\lambda^{I,Y}$ couplings, can be diagonalized by orthogonal transformations, in parallel to the techniques used in the MSSM. The physical masses are generally of the size of the diagonal parameters $M_I^D, M_Y^D, \mu_d, \mu_u$, split up by corrections of second order in the electroweak scale, $(gv)^2/M_{susy}$. The mixings are of first order in gv/M_{susy} where M_{susy} denotes the generic SUSY scale. The mass term of the Weyl bilinears transforms to the Dirac mass term by $M^D(\psi\psi' + \text{h.c.}) = M^D\,\overline{\psi_D}\,\psi_D$ with $\psi_D = \psi_L + \psi'_R$ and $\psi'_R = (\psi'_L)^c$. For Dirac mass terms varying between 100 GeV and 500 GeV and N=2 values of the $\lambda^{Y,I}$ couplings the neutralino masses are illustrated in the right frame of Fig. 1.

4. DECAY AND PRODUCTION OF R-HIGGS BOSONS

The conserved R-charge, $R = 2$, of the R-Higgs bosons restricts their trilinear couplings to a small set of exotic sfermion and chargino/neutralino combinations: the single and double couplings

$$\begin{aligned} &R\tilde{\ell}\tilde{\ell}\,,\; R\tilde{q}\tilde{q}\,;\; R\tilde{\chi}\tilde{\chi} \neq 0\,, \\ &RRH;\; RRV \neq 0\,, \end{aligned} \quad (4.1)$$

in symbolic notation. The R-Higgs bosons couple only to un-mixed L/R sfermion pairs and chargino/neutralino pairs transporting $R = 2$. The single R-Higgs couplings are generated by $\mathcal{W}_R$ and $\mathcal{W}'_R$ components of the superpotential, the double R-Higgs couplings by gauge $[V]$ and quartic $[H]$ interactions after electroweak symmetry breaking. Due to the conservation of R-charge, the couplings of R-Higgs bosons to pairs of SM-type particles, *i.e.* leptons/quarks, gauge bosons and Higgs bosons, vanish,

$$Rff;\; RVV;\; RHH = 0\,, \quad (4.2)$$

[even at loop order, in contrast to the σ fields with zero R-charges [11, 20–23]]. The mass spectrum is taken flavor-diagonal in the sfermion sector but otherwise most general in the phenomenological analysis.

4.1. Decay Modes

The R-Higgs bosons, if kinematically allowed, decay to the following modes, with the sfermions generated in pairs of L and R particles:

$$R_d^+ \;\to\; \tilde{u}_L \tilde{d}_R^* \;\text{ and }\; \tilde{\nu}_L \tilde{\ell}_R^* \;\; [\text{dimensionful couplings}:\; y_d\mu_d \text{ and } y_\ell\mu_d]\,, \quad (4.3)$$

$$R_d^+ \;\to\; \tilde{\chi}_{dj}^+ \tilde{\chi}_{Dk}^0 \;\; [\text{couplings}:\; g, g' \text{ for gauge, and } \lambda^{I,Y} \text{ for gauge}' \text{ components}]\,. \quad (4.4)$$

The neutral R_d and the charged/neutral R_u-Higgs bosons have similar decay channels, except for the neutral slepton channels. As a result of the vanishing neutrino Yukawa couplings, they do not decay to up-type sneutrinos. 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 $LSP = \tilde{\chi}_{D1}^0$. To guarantee unstable R Higgs bosons, as assumed in this letter, the R-Higgs masses must exceed twice the LSP mass.

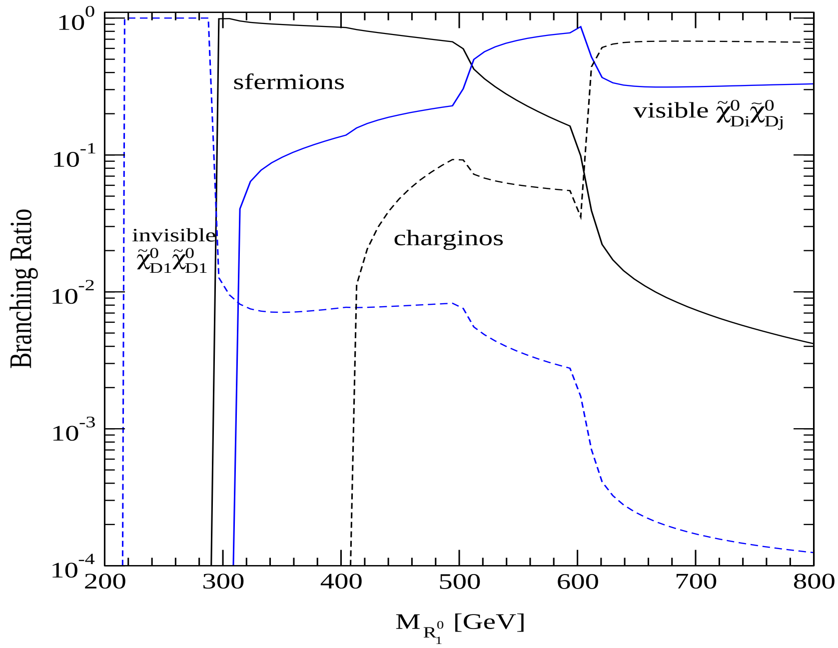

Figure 2: *The leading branching ratios for decays of the neutral R^0_1-Higgs boson to sfermions, neutralinos and charginos. The SPS1a′ point [24] for the sfermion, gaugino and higgsino parameters, but without sfermion mixings, is adopted for the numerical analysis.*

For effective sfermion couplings $\tilde\alpha$ and scalar/pseudoscalar $\tilde\chi$ couplings α/α', the partial on-shell decay widths can be cast into the form:

$$\Gamma[R \to \tilde f_L \tilde f'^*_R] \;=\; \frac{\lambda^{1/2}\,\tilde\alpha^2_{Rff'}}{16\pi M_R} \tag{4.5}$$

$$\Gamma[R \to \tilde\chi_{Dj}\tilde\chi_{Dk}] \;=\; \frac{\lambda^{1/2}}{8\pi M_R}\left\{\alpha^2_{Rjk}[M^2_R-(m_j+m_k)^2]+\alpha'^2_{Rjk}[M^2_R-(m_j-m_k)^2]\right\}, \tag{4.6}$$

with $\lambda = [1-(m_j-m_k)^2/M^2_R][1-(m_j+m_k)^2/M^2_R]$ denoting the standard phase-space coefficients. The α-coefficients are built up by the mixing matrix elements and the couplings of the current fields.

If none of the visible on-shell channels is open for kinematic reasons, the R^0-Higgs bosons decay visibly to one on-shell plus one off-shell or to two off-shell states, leading in cascades to final states $R^0 \to \tilde\chi^0_{D1}\tilde\chi^0_{D1} + X^0$, X^0 denoting a neutral set of SM particles. The branching ratios for these visible channels compete with the exclusive LSP decays, $R^0 \to \tilde\chi^0_{D1}\tilde\chi^0_{D1}$, and will be suppressed in most scenarios. Charged $R^\pm$-Higgs bosons decay in any case to charged SM particles, $R^\pm \to \tilde\chi^0_{D1}\tilde\chi^0_{D1} + X^\pm$, so that the charged visible decays are unsuppressed.

For small R-Higgs masses the decays $R \to \tilde\chi^0_{D1}\tilde\chi^0_{D1} + X$ may also be mediated, though generally at reduced level, by loops interfering with the tree-level off-shell amplitudes. The loops are built up by chargino/neutralino lines transforming to the lighter neutralinos by the exchange of W, Z gauge and Higgs bosons, and radiating the visible markers X. Since L/R squarks do not mix in R-symmetric theories, squark/quark triangles emitting pairs of neutralinos/charginos are restricted effectively to the third generation, with amplitudes of the order of the quark mass due to chirality flip in the quark line.

Branching ratios are illustrated for a set of 2-body on-shell neutral R^0_1-Higgs decays in Fig. 2.

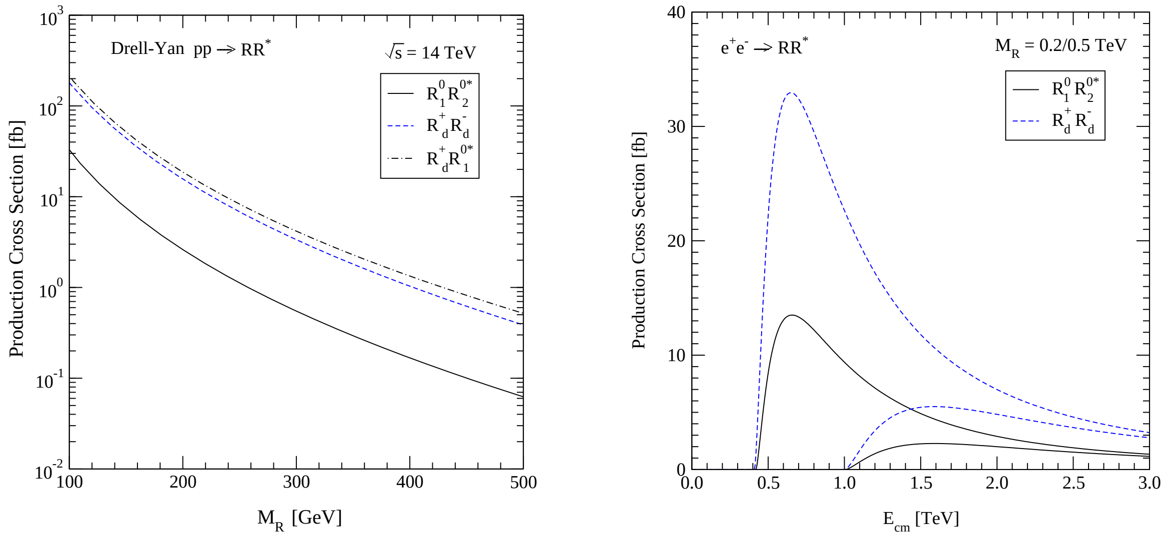

Figure 3: *Left: Drell-Yan production of the neutral/charged R-Higgs boson pairs, $R_1^0 R_2^{0^*}$, $R_d^+ R_d^-$ and $R_d^+ R_1^{0^*}$, at the LHC ($\sqrt{s} = 14\,\mathrm{TeV}$). The cross sections are plotted versus the averaged mass of the produced particles denoted generically by M_R; Right: Production 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.*

4.2. Production Channels

Since the R-Higgs bosons do not couple to pairs of SM fields, all standard-type channels are shut for the single production of these novel particles. Nevertheless, if they are not too heavy, the R-Higgs bosons can be produced in pairs at the pp collider LHC, via Drell-Yan mechanism, and at prospective e^+e^- colliders.

Pair production via Drell-Yan mechanism and e^+e^- annihilation is described by the cross sections:

$$\sigma[pp \to RR^*] \;=\; \sum_{q\bar{q}} \left\langle \frac{\pi\lambda^{3/2}}{9s} \left| \sum_V \alpha_{RRV}\, \frac{s}{s - m_V^2}\, \alpha_{qqV} \right|^2 \right\rangle_{q\bar{q}}, \tag{4.7}$$

$$\sigma[e^+e^- \to RR^*] \;=\; \frac{\pi\lambda^{3/2}}{3s} \left| \sum_V \alpha_{RRV}\, \frac{s}{s - m_V^2}\, \alpha_{eeV} \right|^2, \tag{4.8}$$

V denoting the intermediate gauge bosons and $\langle\ \rangle_{q\bar{q}}$ the convolution with the $q\bar{q}$ structure functions [27]. The typical size of the cross sections is illustrated for the neutral/charged R-Higgs pairs, $R_1^0 R_2^{0^*}$, $R_d^+ R_d^-$ and $R_d^+ R_1^{0^*}$, in Fig. 3. [The cross sections for diagonal neutral R-Higgs boson pairs, $R_1^0 R_1^{0^*}$ and $R_2^0 R_2^{0^*}$, 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.] While the Drell-Yan mechanism is useful for moderate R-Higgs mass values, *cf.* Ref. [28], the e^+e^- collider CLIC extends the mass range into the TeV region.

Additional production mechanisms are provided, with cross sections reduced to the level of 10 fb for Higgs masses of 100 GeV though, by fusion channels to Higgs pairs, *nota bene* $pp \to \gamma\gamma \to R^+R^-$ [29–31].

The production of R pairs can also be expected in heavy MSSM Higgs decays $H \to RR^*$, *cf.* $\Gamma[H \to RR^*] = \alpha^2_{RRH}\, \lambda^{1/2}/16\pi M_H$ with branching ratios up to the level of ten per-cent, depending in detail on the mixing parameters.

The double production of R-Higgs bosons in collider experiments determines the main characteristics of signatures which can be exploited to search for these novel states. Though comprehensive analyses are beyond the scope of this letter, a specific example may nevertheless illuminate the essential points. We will focus on R^0 cascades inspired by the SPS1a′ scenario, in which τ's are the dominating visible cascade components, *cf.* Ref. [32]: $R^0 \to \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D2}$ followed by $\tilde{\chi}^0_{D2} \to \tau\tilde{\tau}$ followed by $\tilde{\tau} \to \tau\tilde{\chi}^0_{D1}$, *i.e.*,

$$R^0 R^{0^*} \to \tau^+\tau^-\tau^+\tau^- + \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D1}\tilde{\chi}^{0c}_{D1}\tilde{\chi}^{0c}_{D1}\,. \tag{4.9}$$

Thus, the final states are characterized by two outstanding signatures: (i) the high lepton multiplicity of four τ's, and (ii) four invisible neutralino LSP's. The τ's 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. The τ and missing-energy/momentum distributions depend characteristically on the masses involved and can discriminate between signals and backgrounds. In the mass scenario $M_R \sim 2M_{\tilde{\chi}^0_{D2}} \sim 2M_{\tilde{\tau}} \sim 4M_{\tilde{\chi}^0_{D2}}$ the total missing energy amounts approximately to $E_{\perp,miss} \sim 2M_R$, while the missing transverse momentum adds up approximately to $p_{\perp,miss} \sim M_R$, both slightly supplemented by neutrino energies. Similar final states with multiple τ leptons and missing energy are generated, *mutatis mutandis*, by other charge configurations and decay channels of the R pairings. Thus, the multi-fold τ-multiplicity in association with high values of missing energy/transverse momentum offers promising signatures for detecting RR events.

5. SUMMARY

R-symmetry is the basis for an exciting extension of the Minimal Supersymmetric Standard Model, motivated by the suppression of unwanted processes at the grand unification scale, and in some scenarios also at the electroweak scale. In addition to introducing Dirac gauginos and scalar fields in adjoint gauge representations, the theory predicts two new R-Higgs iso-doublets in parallel to the two standard H-Higgs doublets. The R-Higgs bosons carry two units of conserved R-charge, leading to novel phenomena in production and decay of these Higgs bosons. With standard partons in the initial state the R-Higgs bosons can only be produced in pairs, and they decay, finally, to two LSP's, the lightest neutralinos in general.

- The leading production mechanism at the LHC is Drell-Yan production of R-Higgs pairs, mediated by the standard electroweak gauge bosons: $pp \to q\bar{q} \to RR^*$. This production mechanism is useful for low to moderate-size masses. For $R^\pm$-Higgs masses below 250 GeV the cross section exceeds 10 fb so that 3,000 pairs will be produced for an integrated luminosity $\int \mathcal{L}\, dt = 300$ fb^{-1}. In e^+e^- collisions particles with masses up to the beam energy can be produced at ILC/CLIC, heavy R-Higgs bosons with masses up to 1.5 TeV at CLIC.
- Due to the conserved R-charge of $R = 2$, the R-Higgs bosons can decay only into pairs of supersymmetric particles comprising states with $R = 2$. Decays exclusively to SM particles with no R-charge, in parallel to MSSM Higgs bosons, are forbidden. Depending on the mass spectra, the R-Higgs bosons decay to L/R sfermion pairs and pairs of neutralinos and charginos. At the end they cascade down to a pair of LSP's plus SM particles X: $R \to \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D1} + X$. The widths are of electroweak size and the lifetimes are short.

This well motivated expansion of the Higgs sector can give rise to exciting phenomena at the LHC and e^+e^- colliders which are very different from the MSSM. Searching for these novel R-Higgs particles and, if discovered, investigating their properties will therefore be quite interesting. Detailed discussions of this task are projected for a future study.

Acknowledgments

The work was partially supported by the Korea Research Foundation Grant funded by the Korean Government (MO-ERHRD, Basic Research Promotion Fund) (KRF-2008-521-C00069), by the Department of Science and Technology, India, under project number SR/S2/RFHEP-05/2006, as well as by the National Science Foundation under grant no. PHY-0854782, and by the Polish Ministry of Science and Higher Education Grant nos. N N202 103838 and N N202 230337. PMZ thanks the Institut für Theoretische Teilchenphysik und Kosmologie for the warm hospitality extended to him at RWTH Aachen University.

---

[1] A. Salam and J. A. Strathdee, Nucl. Phys. B **87** (1975) 85.
[2] P. Fayet, Nucl. Phys. B **90** (1975) 104.
[3] M. Gomez-Bock, M. Mondragon, M. Muhlleitner, M. Spira and P. M. Zerwas, arXiv:0712.2419 [hep-ph].
[4] A. Djouadi, Phys. Rept. **459**, 1 (2008) [arXiv:hep-ph/0503173].
[5] G. D. Kribs, E. Poppitz and N. Weiner, Phys. Rev. D **78** (2008) 055010 [arXiv:0712.2039 [hep-ph]].
[6] N. Sakai and T. Yanagida, Nucl. Phys. B **197** (1982) 533.
[7] S. Weinberg, Phys. Rev. D **26** (1982) 287.
[8] L. J. Hall and L. Randall, Nucl. Phys. B **352**, 289 (1991).
[9] M. M. Nojiri and M. Takeuchi, Phys. Rev. D **76** (2007) 015009 [arXiv:hep-ph/0701190].
[10] S. Y. Choi, M. Drees, A. Freitas and P. M. Zerwas, Phys. Rev. D **78** (2008) 095007 [arXiv:0808.2410 [hep-ph]].
[11] S. Y. Choi, D. Choudhury, A. Freitas, J. Kalinowski, J. M. Kim and P. M. Zerwas, JHEP **1008** (2010) 025 [arXiv:1005.0818 [hep-ph]].
[12] K. Hsieh, Phys. Rev. D **77** (2008) 015004 [arXiv:0708.3970 [hep-ph]].
[13] G. Belanger, K. Benakli, M. Goodsell, C. Moura and A. Pukhov, JCAP **0908** (2009) 027 [arXiv:0905.1043 [hep-ph]].
[14] E. J. Chun, J. C. Park and S. Scopel, JCAP **1002** (2010) 015 [arXiv:0911.5273 [hep-ph]].
[15] E. J. Chun, arXiv:1009.0983 [hep-ph].
[16] G. D. Kribs, A. Martin and T. S. Roy, JHEP **0901**, 023 (2009) [arXiv:0807.4936 [hep-ph]].
[17] K. Benakli and M. D. Goodsell, Nucl. Phys. B **840** (2010) 1 [arXiv:1003.4957 [hep-ph]].
[18] K. Benakli and M. D. Goodsell, Nucl. Phys. B **830** (2010) 315 [arXiv:0909.0017 [hep-ph]].
[19] G. F. Giudice and A. Masiero, Phys. Lett. B **206** (1988) 480.
[20] S. Y. Choi, M. Drees, J. Kalinowski, J. M. Kim, E. Popenda and P. M. Zerwas, Phys. Lett. B **672** (2009) 246 [arXiv:0812.3586 [hep-ph]].
[21] T. Plehn and T. M. P. Tait, J. Phys. G **36** (2009) 075001 [arXiv:0810.3919 [hep-ph]].
[22] A. Idilbi, C. Kim and T. Mehen, Phys. Rev. D **82** (2010) 075017 [arXiv:1007.0865 [hep-ph]].
[23] T. Han, I. Lewis and Z. Liu, arXiv:1010.4309 [hep-ph].
[24] J. A. Aguilar-Saavedra *et al.*, Eur. Phys. J. C **46** (2006) 43 [arXiv:hep-ph/0511344].
[25] M. Drees and K. Hagiwara, Phys. Rev. D **42** (1990) 1709.
[26] L. F. Li, Z. Phys. C **58**, 519 (1993).
[27] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky and W. K. Tung, JHEP **0207** (2002) 012 [arXiv:hep-ph/0201195].
[28] A. Alves and T. Plehn, Phys. Rev. D **71** (2005) 115014 [arXiv:hep-ph/0503135].
[29] J. Ohnemus, T. F. Walsh and P. M. Zerwas, Phys. Lett. B **328** (1994) 369 [arXiv:hep-ph/9402302].
[30] M. Drees, R. M. Godbole, M. Nowakowski and S. D. Rindani, Phys. Rev. D **50** (1994) 2335 [arXiv:hep-ph/9403368].
[31] J. de Favereau de Jeneret *et al.*, arXiv:0908.2020 [hep-ph].
[32] N. Ghodbane and H. U. Martyn, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)*, arXiv:hep-ph/0201233.