R-symmetric Higgs Bosons

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Motivation

Continuous R Symmetry

Minimal R-symmetric Supersymmetric SM

R-symmetric Scalar Sector

Expectations at High Energy Colliders

Summary

SYC, Choudhury, Freitas, Kalinowski, Zerwas, PLB697 (2011) 215

Motivation

TeV-scale supersymmetry (SUSY) is still the most elegant BSM proposition

Natural Higgs sector
DM candidate(s)
Matter-antimatter asymmetry

In the MSSM each SM particle is paired with a sparticle differing in spin by ½

fermions ⇔ sfermions
gauge bosons ⇔ gauginos
Higgses ⇔ higgsinos

N=1 SUSY ⟹

Gluinos and neutralinos are Majorana fermions

However, this minimal version is already under very severe constraints

dim-4 B/L violating operators ⇒ symmetries like R parity
flavor /CP problems due to parameter misalignments
little fine tuning driven experimentally

Continuous R Symmetry

[Fayet, 1975, ··]

The constraints can be removed /softened by a continuous R symmetry eliminating

soft trilinear scalar couplings
μ term
Majorana gaugino masses
dim-4 B/L violating terms
dim-5 proton decay terms

which is an anomaly-free global U(1) symmetry under $\theta \rightarrow e^{i\alpha}\,\theta$

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

Component fields have different R charges with the condition R(SM) = 0 as

Vector gauge

$$\hat{G} = \theta\sigma_\mu\bar{\theta}G^\mu + \bar{\theta}\bar{\theta}\theta\tilde{G} + \cdots$$

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

Chiral

matter

$$\hat{f} = \tilde{f} + \sqrt{2}\theta f + \cdots$$

$$\boxed{R(\hat{f}) = +1} \quad \Rightarrow \quad R(\tilde{f}) = +1, \quad R(f) = 0$$

Higgs

$$\hat{H} = H + \sqrt{2}\theta\tilde{H} + \cdots$$

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

Forbidden

Superpotential (R = 2)	μ term	$\mu \hat{H}_d \hat{H}_u$	R = 0
	L/B violation	$\hat{L}\hat{Q}\hat{D}^c$	R = 3
	Proton decay	$\hat{Q}\hat{Q}\hat{Q}\hat{L}$	R = 4
Soft terms (R=0)	trilinear scalar couplings	$A_d H_d \tilde{Q} \tilde{d}^*$	R = 2
	Majorana gaugino masses	$M^M \, \tilde{G}\tilde{G}$	R = 2

Allowed

Superpotential (R = 2)	Yukawa	$y_d \hat{H}_d \hat{Q} \hat{D}^c, \quad y_u \hat{H}_u \hat{Q} \hat{U}^c, \quad y_e \hat{H}_d \hat{L} \hat{E}^c$	R = 2
	neutrino	$\frac{\lambda_\nu}{M} \hat{H}_u \hat{H}_u \hat{L}\hat{L}$	R = 2
Soft terms (R=0)	scalar masses	$M^2_{\tilde{f}} \, \lvert\tilde{f}\rvert^2$	R = 0
	Higgs bilinear	$B_\mu H_d H_u$	R = 0

Minimal R-symmetric Supersymmetric Standard Model (MRSSM)

[Kribs, Martin, Roy, 2009]

Massive gauginos and adjoint scalars

⊙ Introduce a chiral superfield in the adjoint representation of each group

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

to build a R-symmetric Dirac gaugino mass $M^D \tilde{G}\tilde{G}'$ and to contain SU(3) color-octet/SU(2) iso-triplet /U(1) hyper-singlet adjoint scalars

Collider signatures ⇒ [SYC ea, Nojiri ea, Plehn ea, Han ea, ··]
DM/EW Baryogenesis ⇒ [Hsieh, Chun ea, Belanger ea, Kumar ea, ··]
Flavor ⇒ [Kribs ea, Benakli ea, Fox ea, ··]

Dirac higgsinos ⇔ H/R-Higgs bosons

⊙ Introduce two chiral iso-doublets $\hat{R}_u,\ \hat{R}_d$ with R = 2
in order to avoid too light higgsino-type charginos

by building R-symmetric μ-type terms $\mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u$
and in addition trilinear terns $\lambda_d^i \hat{H}_d \hat{\Sigma}^i \hat{R}_d + \lambda_u^i \hat{H}_u \hat{\Sigma}^i \hat{R}_u$

[A simpler formulation: Davies, March-Russell, McCullough (DMM), 2011]

$$H = H_u, \quad \eta = R_u$$

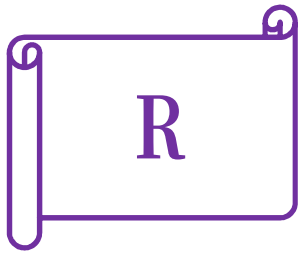
MRSSM

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

Physical fields

MSSM matter, gauge and H-Higgs fields

Dirac gluinos and neutralinos
Additional pair of charginos
Gauge adjoint scalars
R-Higgs bosons



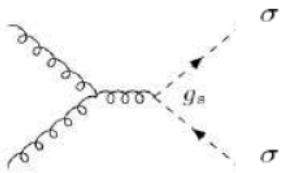
R-symmetric Scalar Sector

Color-octet adjoint scalars = sgluons

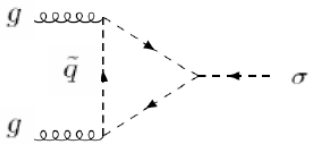
[SYC, Drees, Kalinowski, JM Kim, Popenda, Zerwas, PLB672]

Production (huge)

pair



single



Decays

tree

$$\sigma \to \tilde{g}\tilde{g} \to qq\tilde{q}\tilde{q} \to qqqq + \tilde{\chi}\tilde{\chi}\,,$$
$$\sigma \to \tilde{q}\tilde{q} \to qq + \tilde{\chi}\tilde{\chi}\,,$$

$\Downarrow$

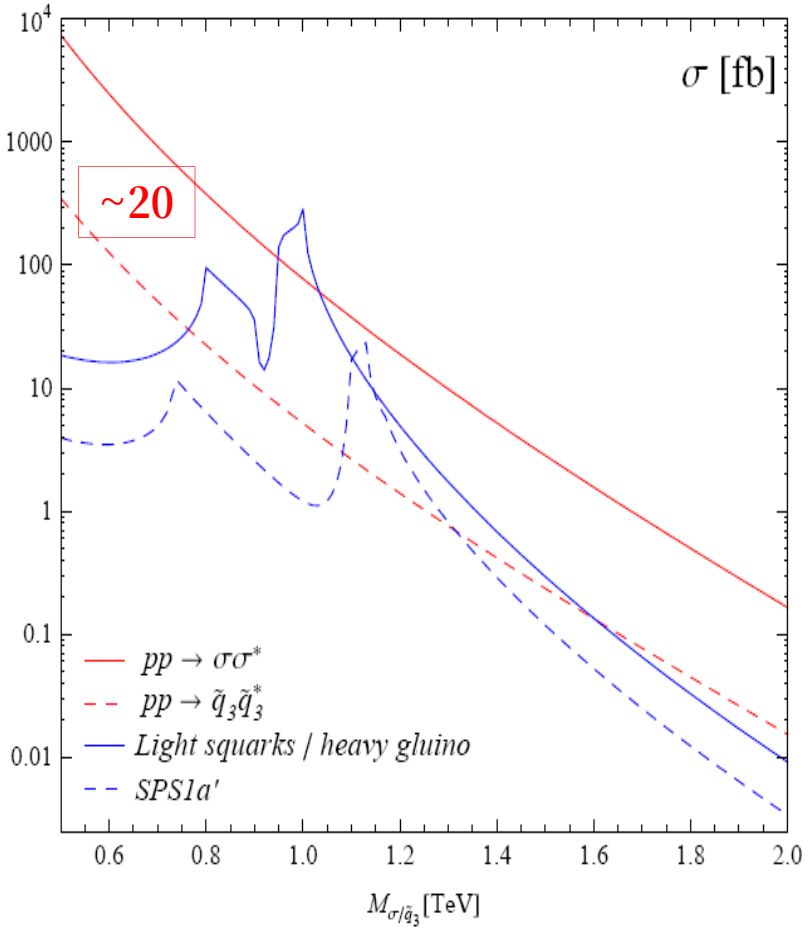
$$pp \;\to\; 8\,\text{jets} + 4\,\text{LSP's}$$

loop

$$\sigma \to t\bar{t} \to b\bar{b}W^+W^-$$
$$\sigma \to gg\,.$$

$\Downarrow$

$$pp \;\to\; tt\bar{t}\bar{t}$$



Striking signatures (large L/R splitting)

H-Higgs and R-Higgs Bosons

$$m_Z^2 = \frac{1}{4}(g'^2 + g^2)v^2\,, \qquad m_W^2 = \frac{1}{4}g^2v^2 + g^2v_I^2$$

$$\Delta\rho = \rho - 1 = 4v_I^2/v^2 \;\Rightarrow\; v_I \leq 3\,\text{GeV}$$

$\Rightarrow$ Heavy EW (iso-triplet) scalars

Higgs potential (assuming heavy EW adjoint scalars)

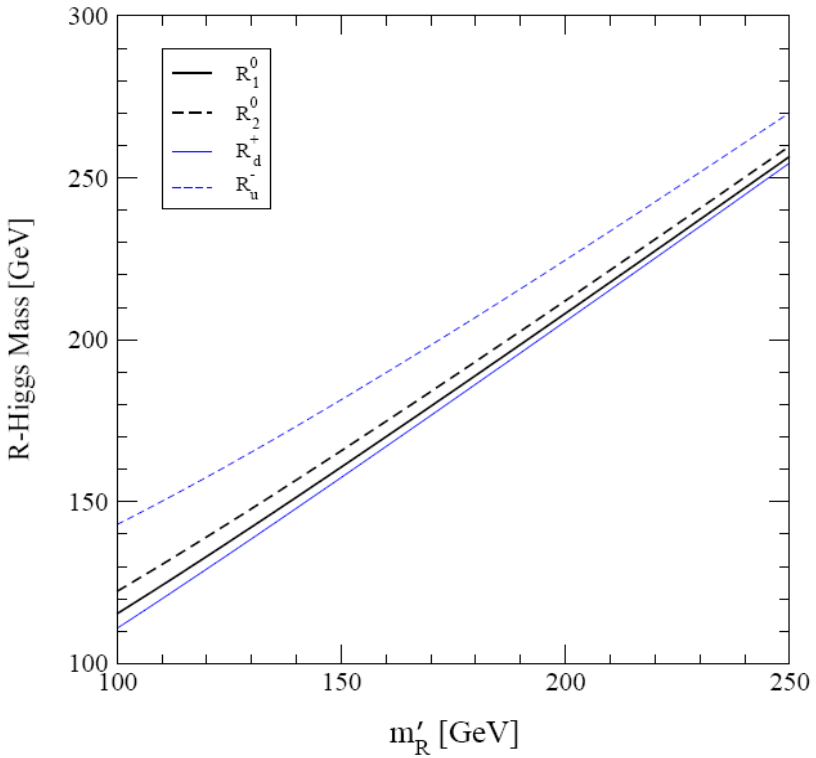
$$\begin{aligned}
\mathcal{V}^0_{[H,R]} \;=\; & (m_{H_d}^2 + \mu_d^2)|H_d^0|^2 + (m_{H_u}^2 + \mu_u^2)|H_u^0|^2 - (B_\mu H_d^0 H_u^0 + \text{h.c.}) \\
& + (m_{R_d}^2 + \mu_d^2)|R_d^0|^2 + (m_{R_u}^2 + \mu_u^2)|R_u^0|^2 \\
& + \left|\lambda_d^I H_d^0 R_d^0 + \lambda_u^I H_u^0 R_u^0\right|^2 + \left|\lambda_d^Y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

R-Higgs bosons do NOT develop vev's and H/R-Higgs bosons do NOT mix, even if EW adjoint scalars are present (R symmetry)

R-Higgs Mass Matrices

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

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



$$\lambda^I_d = -\lambda^I_u = -g/\sqrt{2}$$
$$\lambda^Y_d = \lambda^Y_u = -g'/\sqrt{2}$$

N=2

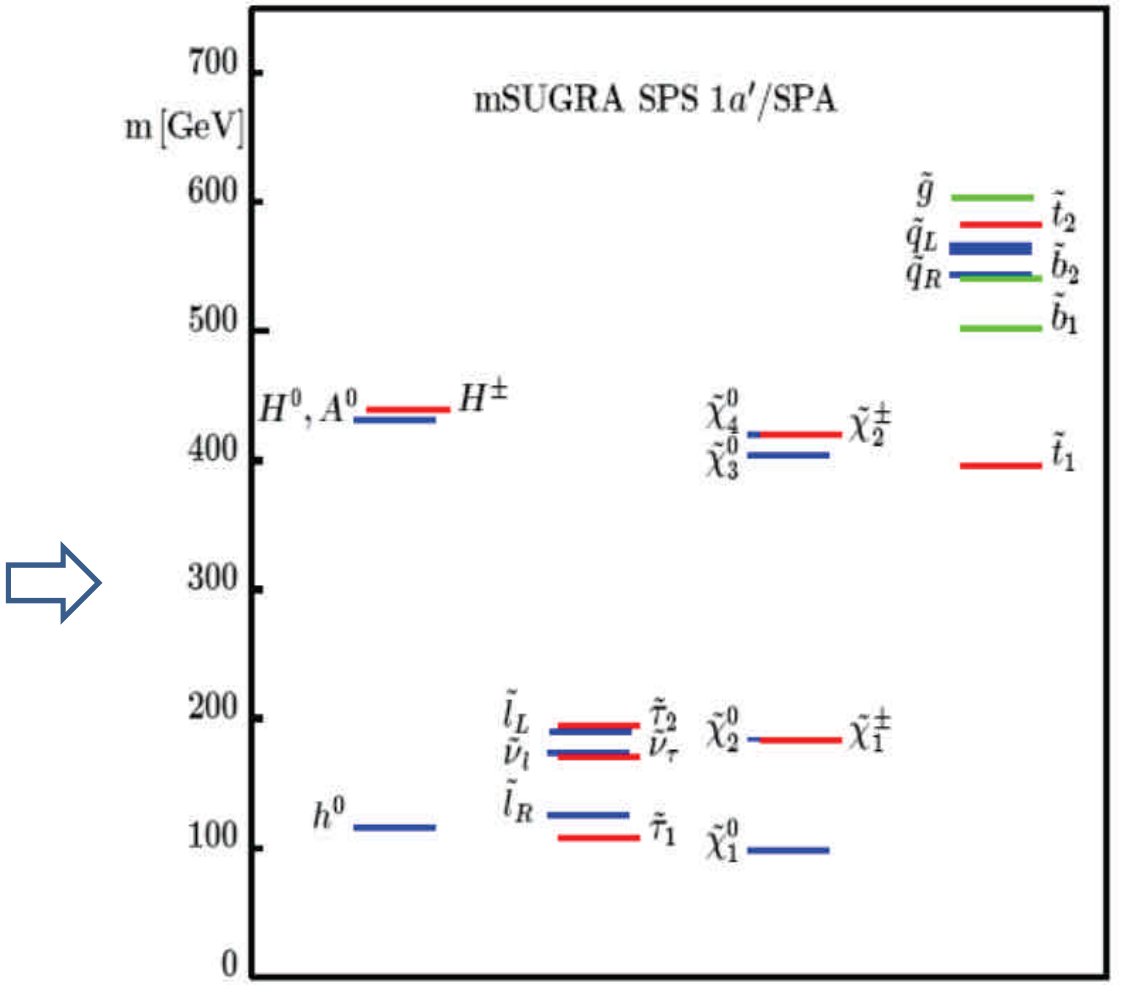
$$m'_R = (m^2_{R_{d,u}} + \mu^2_{d,u})^{1/2}$$

[other parameters as in SPS1a']

⇨ Asymptotically degenerate pairs

SPS1a ’

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



R-Higgs Couplings

Conserved R charge restricts couplings of R-Higgs bosons to other particles

forbidden ~~$Rff,\ RVV,\ RHH$~~

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

(in symbolic notation)

⇩ ⇗ Scalar DM?

Decays ONLY to pairs of sparticles (otherwise stable)

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

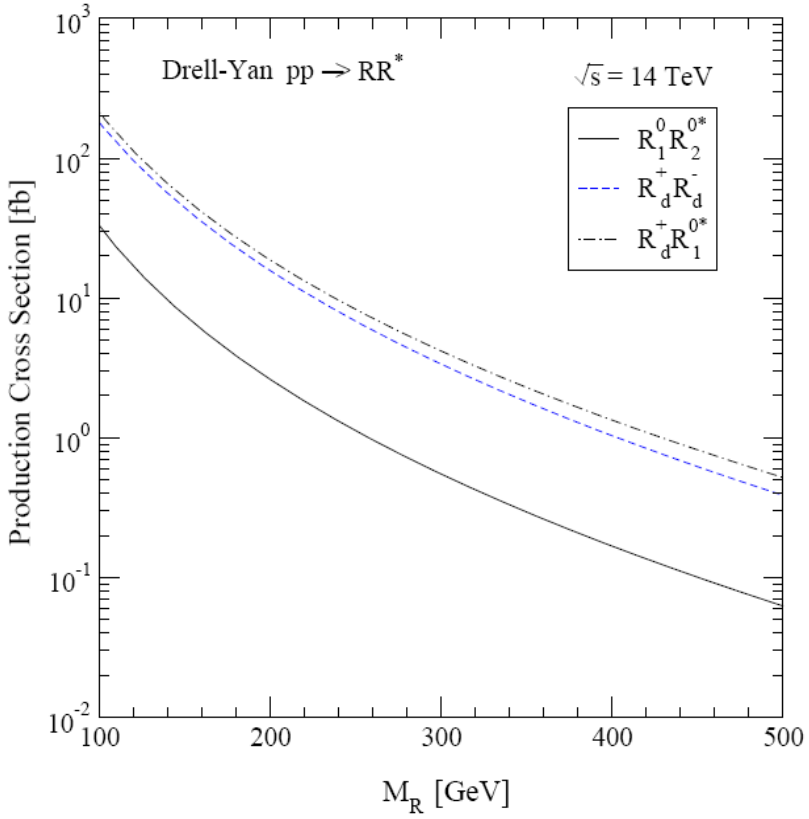
$$\Gamma[R \to \tilde{\chi}_{Dj}\tilde{\chi}_{Dk}] = \frac{\lambda^{1/2}}{8\pi M_R}\{\alpha^2_{Rjk}[M_R^2-(m_j+m_k)^2]+\alpha'^2_{Rjk}[M_R^2-(m_j-m_k)^2]\}$$

Production ONLY in pairs via Drell-Yan mechanism

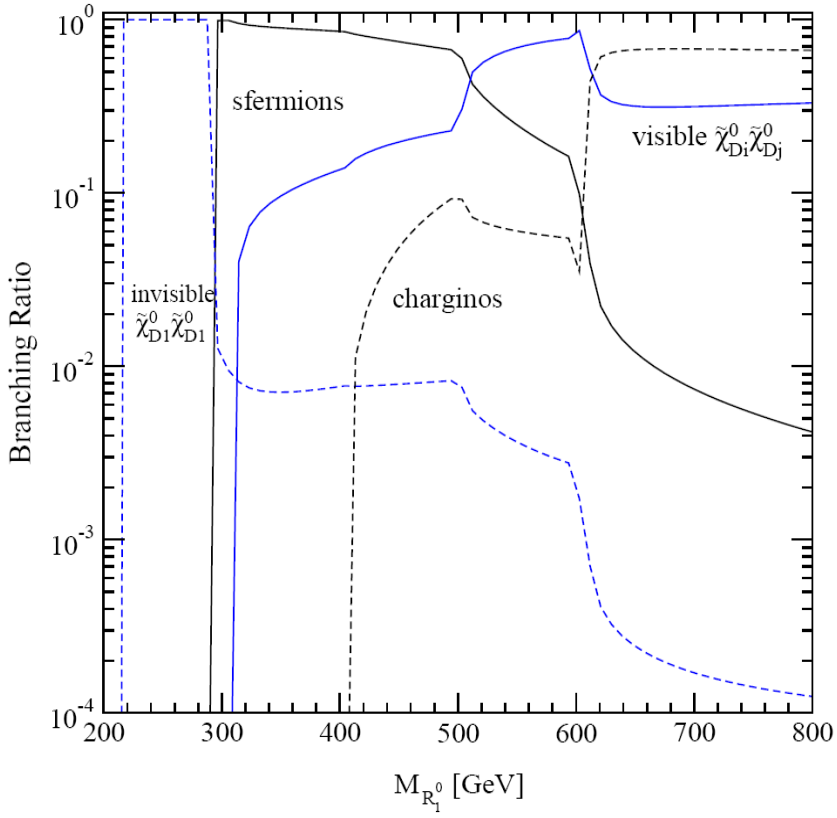
$$\sigma[pp \to RR^*] = \sum_{q\bar{q}} \left\langle \frac{\pi\lambda^{3/2}}{9s}\left|\sum_V \alpha_{RRV}\,\frac{s}{s-m_V^2}\,\alpha_{qqV}\right|^2 \right\rangle_{q\bar{q}}$$

Expectations at High Energy Colliders

Production at LHC



Branching ratios



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

Characteristic signatures (SPS1a')

$$R^0 \to \tilde{\chi}^0_{D1}\tilde{\chi}^0_{D2} \quad \oplus \quad \tilde{\chi}^0_{D2} \to \tau\bar{\tilde{\tau}} \quad \oplus \quad \tilde{\tau} \to \tau\tilde{\chi}^0_{D1}$$

$$\Downarrow$$

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

High lepton multiplicity of four τ leptons and four invisible LSP's
Other patterns $\Rightarrow$ Similar final states with multiple τ's and missing E

$$\Downarrow$$

High τ-multiplicity in association with large missing E /p_T
offers promising signatures for detecting RR events

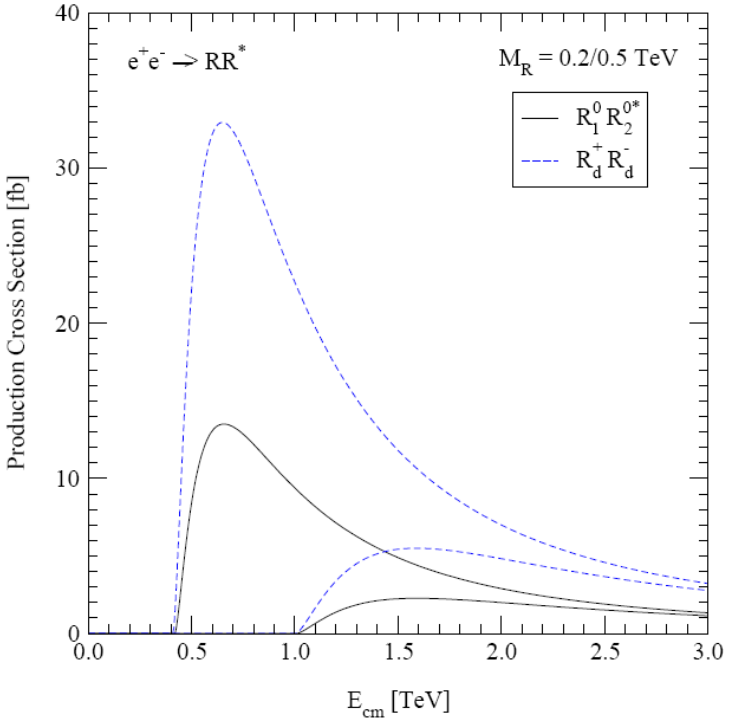
Other production channels

Cascade decays $\tilde{q} \to q\tilde{\chi}_n \to q\tilde{\chi}_1 R$ light R

$\gamma\gamma$ fusion $pp \to \gamma\gamma \to R^+R^-$

CLIC for heavy R-Higgs bosons

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



Summary

Well-motivated R-symmetric SUSY theories developed

Ameliorated flavor and CP problems
Dirac gauginos and higgsinos
Expanded scalar part with R-Higgs bosons and adjoint scalars

Restricted production /decay modes of adjoint scalars and R-Higgs bosons

Striking signatures at colliders
More detailed/realistic analyses required

Distinct / interesting phenomenological/cosmological implications

Back-up Slides

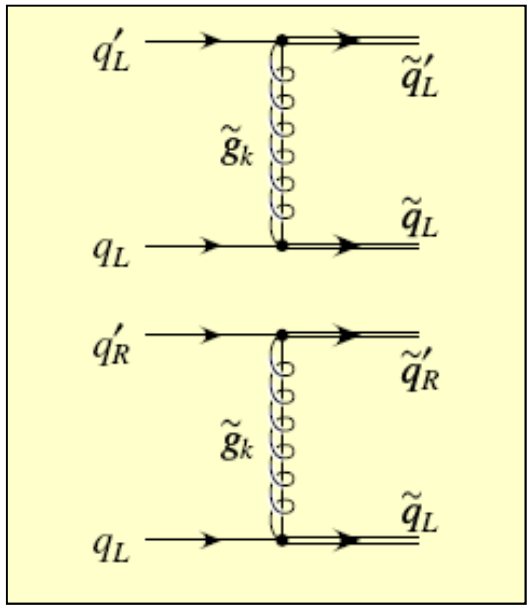
Dirac gluinos ⇔ MSSM gluinos

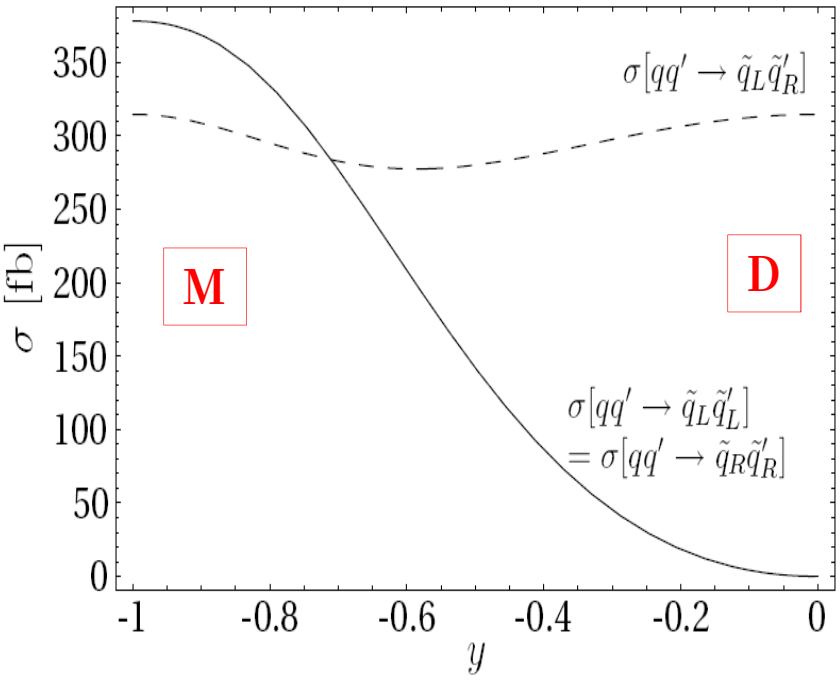
[SYC, Drees, Freitas , Zerwas PRD79]

$$\text{Majorana}: \quad \sigma[qq' \to \tilde{q}_L \tilde{q}'_L] \;=\; \sigma[qq' \to \tilde{q}_R \tilde{q}'_R] = \frac{2\pi\alpha_s^2}{9} \frac{\beta m_{\tilde{g}_1}^2}{s m_{\tilde{g}_1}^2 + (m_{\tilde{g}_1}^2 - m_{\tilde{q}}^2)^2}$$

$$\text{Dirac}: \quad \sigma[qq' \to \tilde{q}_L \tilde{q}'_L] \;=\; \sigma[qq' \to \tilde{q}_R \tilde{q}'_R] = 0$$

$$\text{Majorana} = \text{Dirac}: \quad \sigma[qq' \to \tilde{q}_L \tilde{q}'_R] \;=\; \frac{2\pi\alpha_s^2}{9s^2}\left[(s + 2(m_{\tilde{g}_1}^2 - m_{\tilde{q}}^2))L_1 - 2\beta s\right],$$





Squark and gluino production and decays

SPS1a' scenario:

$m_{\tilde{g}} = 700$ GeV $\quad m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} = 184$ GeV

$m_{\tilde{q}_L} = 565$ GeV $\quad m_{\tilde{\chi}_1^0} = 98$ GeV

Process	Majorana		Dirac		$N(\ell^+\ell^+)/N(\ell^-\ell^-)$	
	σ_{tot}	σ_{ll} after cuts	σ_{tot}	σ_{ll} after cuts	Majorana	Dirac
$\tilde{q}_L\tilde{q}_L^{(\prime)}$	2.1 pb	6.1 fb	0	0	2.5	–
$\tilde{q}_L\tilde{q}_L^{(\prime)*}$	1.4 pb	3.1 fb	1.4 pb	3.1 fb	1.4	1.4
$\tilde{q}_L\tilde{g}_{(D)}$	7.0 pb	7.6 fb	7.0 pb	7.6 fb	1.5	1.5
$\tilde{g}_{(D)}\tilde{g}_{(D)}^{(c)}$	3.2 pb	1.4 fb	7.0 pb	3.2 fb	1.0	1.0
SM	800 pb	<0.6 fb	800 pb	<0.6 fb	1.0	

$\tilde{q}_L \to q\,\tilde{\chi}_2^0 \to q\,l^+l^-\tilde{\chi}_1^0$ or $\tilde{q}_L \to q\,\tilde{\chi}_1^\pm \to q\,l^\pm\nu_l\tilde{\chi}_1^0$

$\tilde{q}_R \to q\,\tilde{\chi}_1^0$

Majorana and Dirac gluinos lead to different rates of $\ell^+\ell^+$, $\ell^-\ell^-$, $\ell^+\ell^-$

Squark cascade decays

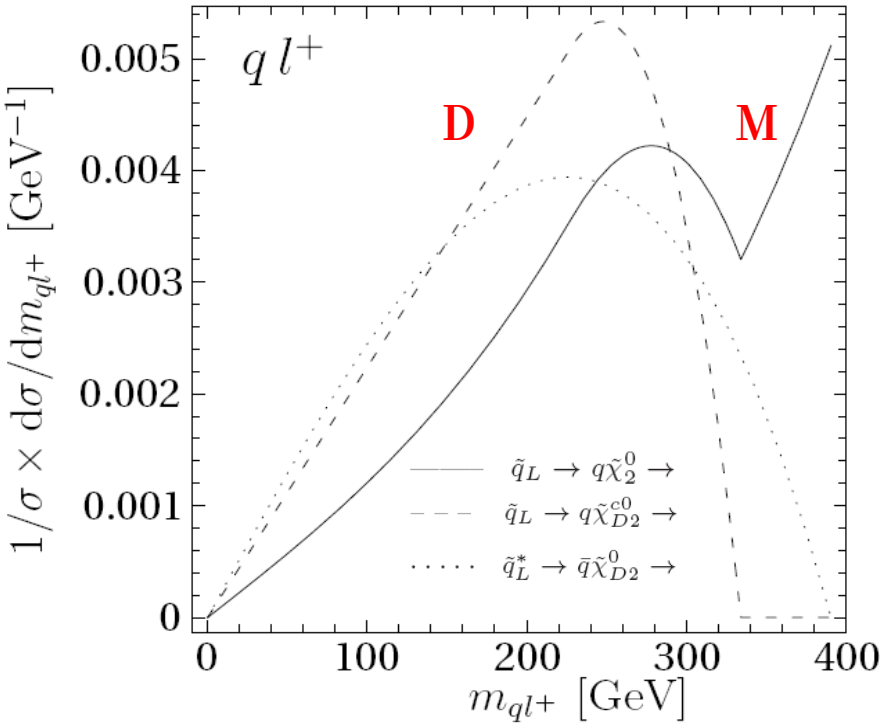
Dirac ⇒ **Conserved Global charge**

$$D[\tilde{q}_L^{1,2}] = D[\tilde{\ell}_L^{1,2}] = D[\tilde{\nu}^{1,2}] = D[\tilde{\chi}_D^{0c}] = D[\tilde{\chi}_{D1}^{+}] = D[\tilde{\chi}_{D2}^{-}] = -1$$
$$D[\tilde{q}_R^{1,2}] = D[\tilde{\ell}_R^{1,2}] \qquad = D[\tilde{\chi}_D^{0}] = D[\tilde{\chi}_{D1}^{-}] = D[\tilde{\chi}_{D2}^{+}] = +1$$

Neutralino path

MSSM: $\tilde{q}_L \to q\,\tilde{\chi}_2^0 \to q\,l^{\pm}\,\tilde{l}_R^{\mp} \to q\,l^{\pm}\,l^{\mp}\,\tilde{\chi}_1^0\,,$

Dirac: $\tilde{q}_L \to q\,\tilde{\chi}_{D2}^{c0} \to q\,l^{-}\,\tilde{l}_R^{+} \to q\,l^{-}\,l^{+}\,\tilde{\chi}_1^0$

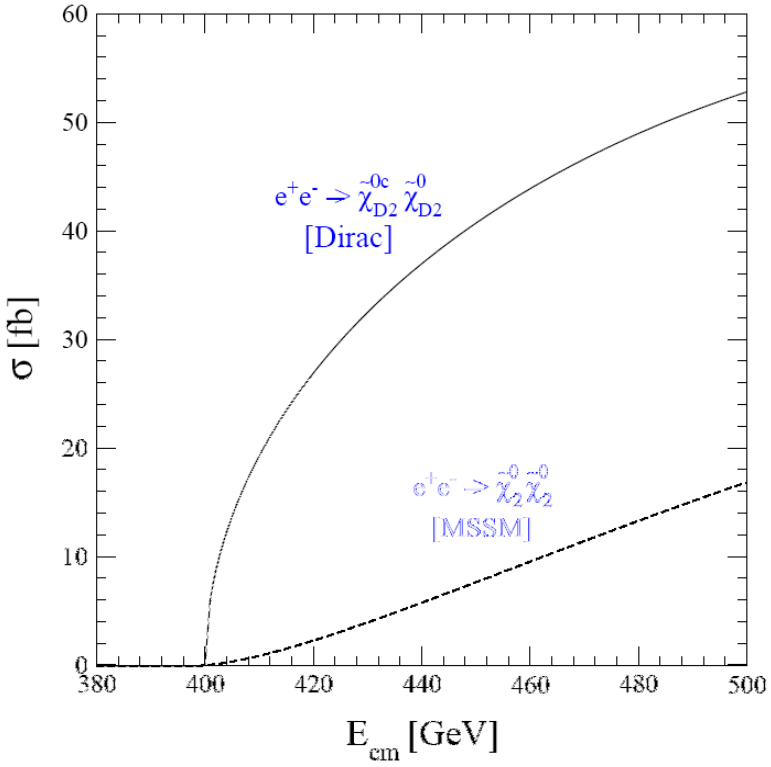


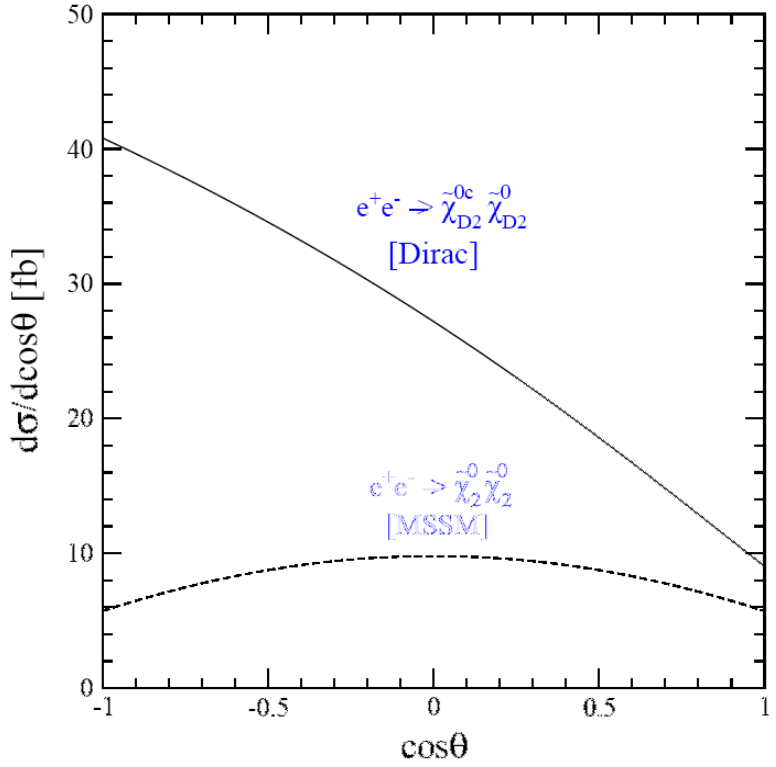
hard **hard**

$$(ql^+)_M = (ql^+)_n \oplus (ql^+)_f$$
$$(ql^+)_D = (ql^+)_f$$

Similar striking difference through the chargino path

Neutralino diagonal-pair production

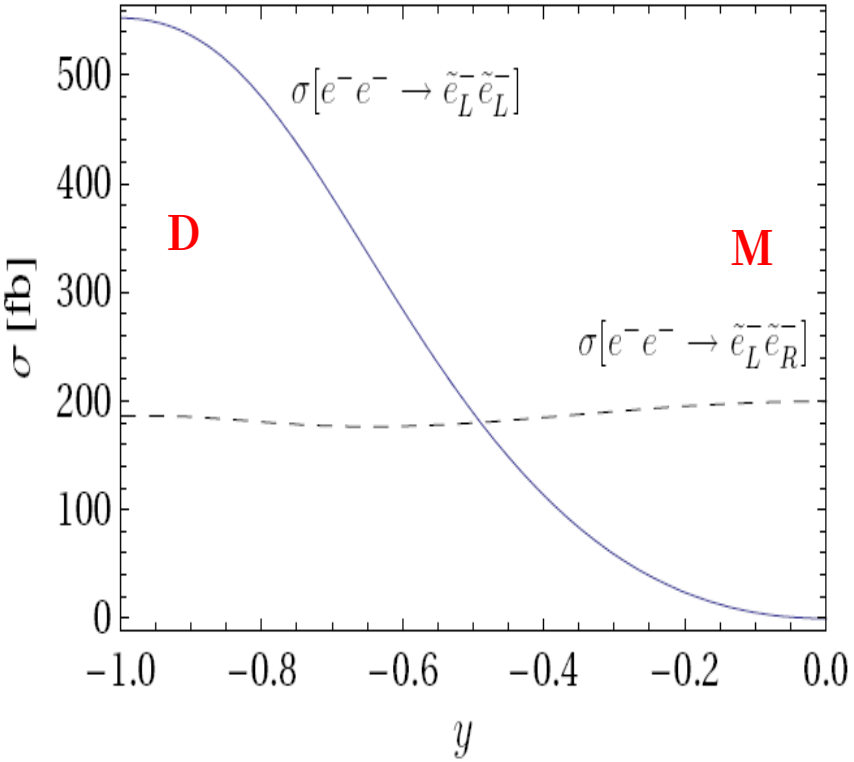




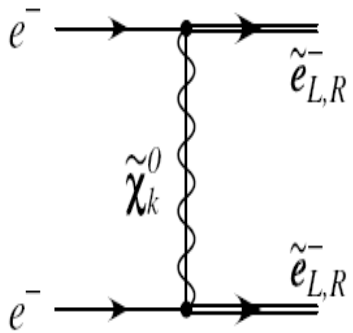
Dirac: S-wave threshold excitations
⇒ enhanced DM annihilation

Dirac: not FB symmetric.

Selector pair production in e^-e^- collisions



SPS1a' scenario

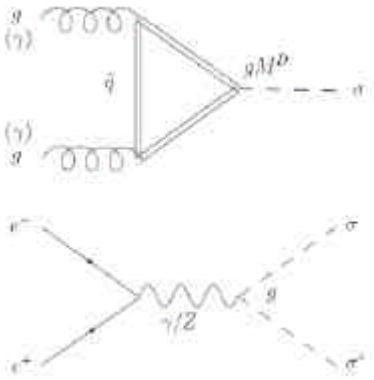


Dirac ⇨ The conserved D charge kills the same (opposite) sign and chirality selectron production in e^-e^- (e^-e^+) collisions

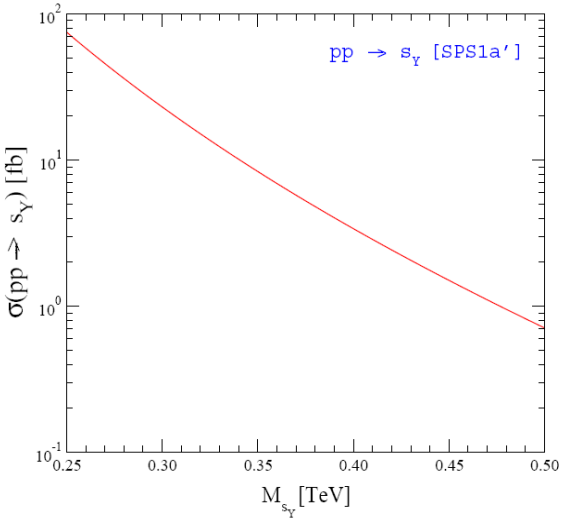
EW adjoint scalar production and decays

[SYC, Choudhury, Freitas, Kalinowski, JM Kim, Zerwas, 1005.0808 & JHEP]

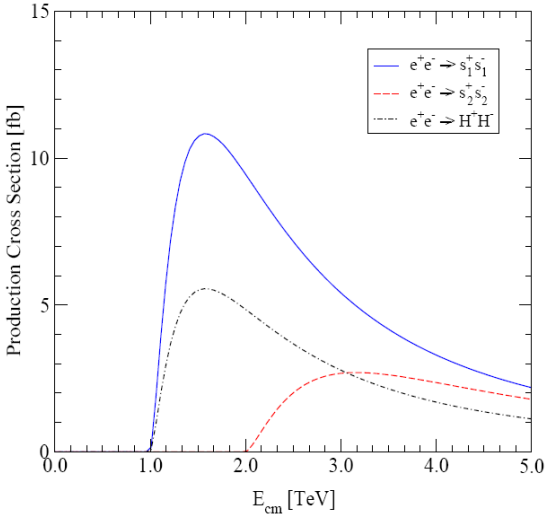
Production



indirect



direct



Decays