Dirac versus Majorana Gauginos and Higgsinos

MRSSM (Dirac) ⇔ MSSM (Majorana)

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Motivation

Continuous R Symmetry

Minimal R-symmetric Model (MRSSM)

Expectations at the LHC and an e^+e^- LC

Summary

SYC, Drees, Freitas, Zerwas, PRD76 (2008)
SYC, Drees, Kalinowski, JM Kim, Popenda, Zerwas, PLB672 (2009)
SYC, Choudhury, Freitas, Kalinowski, JM Kim, Zerwas, JHEP08 (2010)
SYC, Choudhury, Freitas, Kalinowski, Zerwas, PLB697 (2011)

Motivation

TeV-scale supersymmetry (SUSY) is YET one of the most elegant BSM propositions

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, especially by LHC

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

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

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

Chiral

matter

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

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

Higgs

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

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

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	$M_{\tilde{f}}^2\, \lvert\tilde{f}\rvert^2$	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]

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

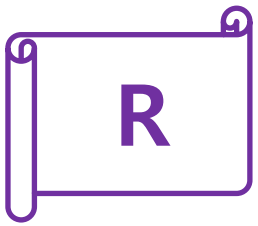
MRSSM

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



Generalization: Gluinos

[SYC, Drees, Freitas, Zerwas, 2008]

Gluino mass matrix

$$\mathcal{L}^{m}_{\rm QCD} = -\frac{1}{2}\left[M_3' \,{\rm Tr}(\overline{\tilde{g}'}\tilde{g}') + M_3\,{\rm Tr}(\overline{\tilde{g}}\tilde{g}) + M_3^D\,{\rm Tr}(\overline{\tilde{g}'}\tilde{g} + \overline{\tilde{g}}\tilde{g}')\right] \Rightarrow \mathcal{M}_g = \begin{pmatrix} M_3' & M_3^D \\ M_3^D & M_3 \end{pmatrix}$$

In general the mass matrix gives rises to two Majorana mass eigenstates.

Two limits

- for $M_3' \to \pm\infty$ the MSSM Majorana gluino is recovered
- for $M_3' = M_3 = 0$ a Dirac gluino $\tilde{g}_D = \tilde{g}_L + \tilde{g}'_R$ with mass $|M_3^D|$

Couplings

The MSSM and new gluinos are coupled minimally to the gluon field

$$\mathcal{L}^{g\tilde{g}\tilde{g}}_{\rm QCD} = g_s {\rm Tr}\left(\overline{\tilde{g}}\gamma^\mu[g_\mu, \tilde{g}] + \overline{\tilde{g}'}\gamma^\mu[g_\mu, \tilde{g}']\right)$$

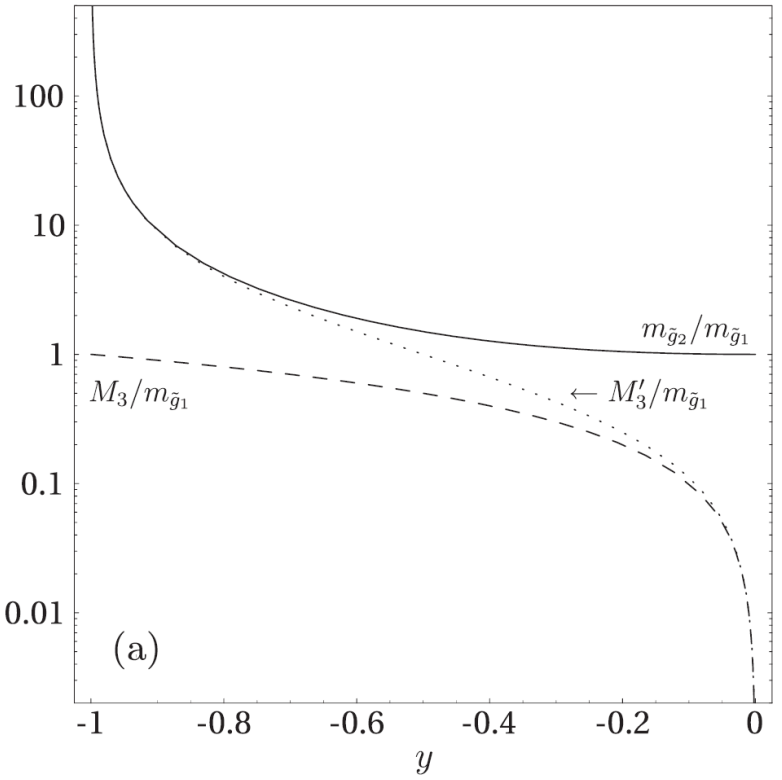
Quarks and squarks interact only with the MSSM gluinos

$$\mathcal{L}^{q\tilde{q}\tilde{g}}_{\rm QCD} = -g_s\left[\overline{q_L}\tilde{g}\,\tilde{q}_L - \overline{q_R}\tilde{g}\,\tilde{q}_R + {\rm h.c.}\right]$$

MSSM ⇒ MRSSM (Dirac) Path

$$M_3' = m_{\tilde{g}_1} \frac{y}{1+y} \qquad -1 \le y \le 0$$
$$M_3^D = m_{\tilde{g}_1}$$
$$M_3 = m_{\tilde{g}_1} M_3'/(M_3' - m_{\tilde{g}_1})$$

y=-1 : MSSM ⇔ y=0 : Dirac



MSSM D

A similar description for each neutral EW gaugino sector

MRSSM Charginos and Neutralinos

The MRSSM contains new gauginos sand R-higgsinos
The fields carrying the same R-charge mix due to EWSB

2+2 Charginos

$$\mathcal{M}_d^{\pm} = \begin{bmatrix} M_I^D & \lambda_d^I v_d \\ g v_d/\sqrt{2} & -\mu_d \end{bmatrix}; \quad \mathcal{M}_u^{\pm} = \begin{bmatrix} M_I^D & -\lambda_u^I v_u \\ g v_u/\sqrt{2} & \mu_u \end{bmatrix}$$

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

4 Dirac Neutralinos

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

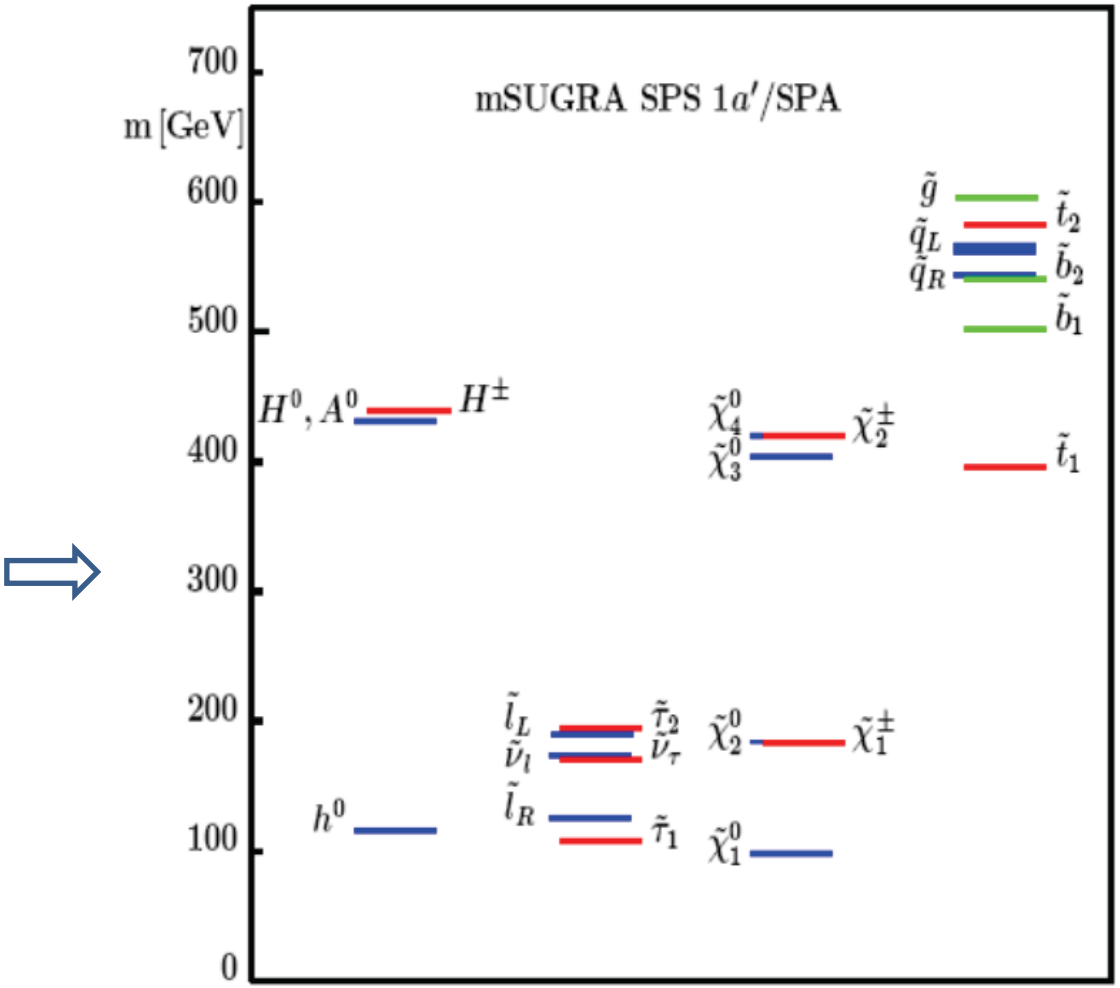
in the $(\tilde{B}', \tilde{W}'^0, \tilde{H}_u^0, \tilde{H}_d^0)/(\tilde{B}, \tilde{W}^0, \tilde{R}_u^0, \tilde{R}_d^0)$ basis

Expectations at the LHC

SPS1a′

[hep-ph/0202233]

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



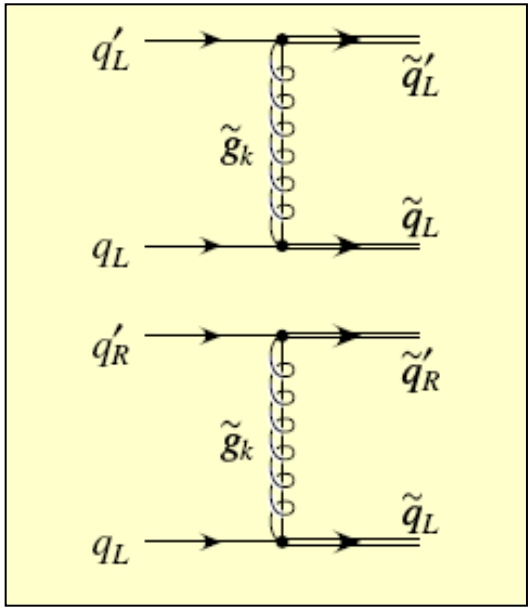
MSSM ⇔ Dirac gluinos

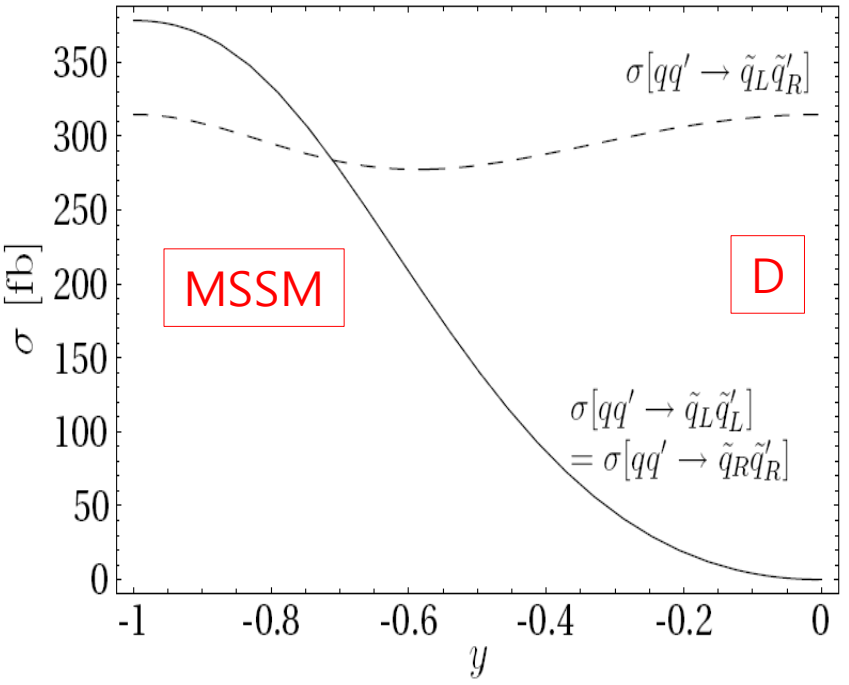
[SYC, Drees, Freitas , Zerwas, 2008]

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

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

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





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

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

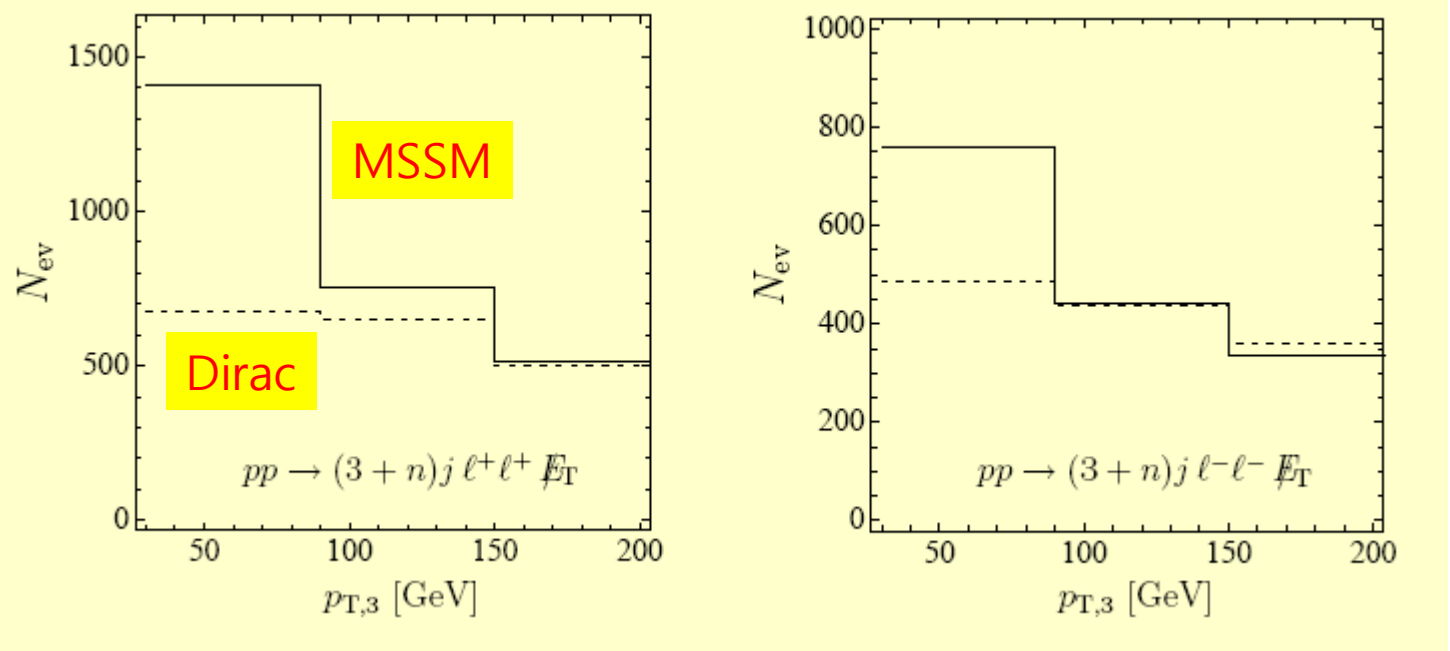
Majorana and Dirac gluinos lead to different rates of $\ell^+\ell^+$, $\ell^-\ell^-$, $\ell^+\ell^-$

Like-sign dileptons at the LHC

Discrimination between $\tilde{g}$ and $\tilde{q}$ production from $p_{T,3}$

$pp \to \tilde{q}\tilde{q}$ peaked at small $p_{T,3}$

$pp \to \tilde{g}\tilde{g}$ peaked at larger $p_{T,3}$



Discrimination at 10.5σ with systematics for 300 fb^{-1}

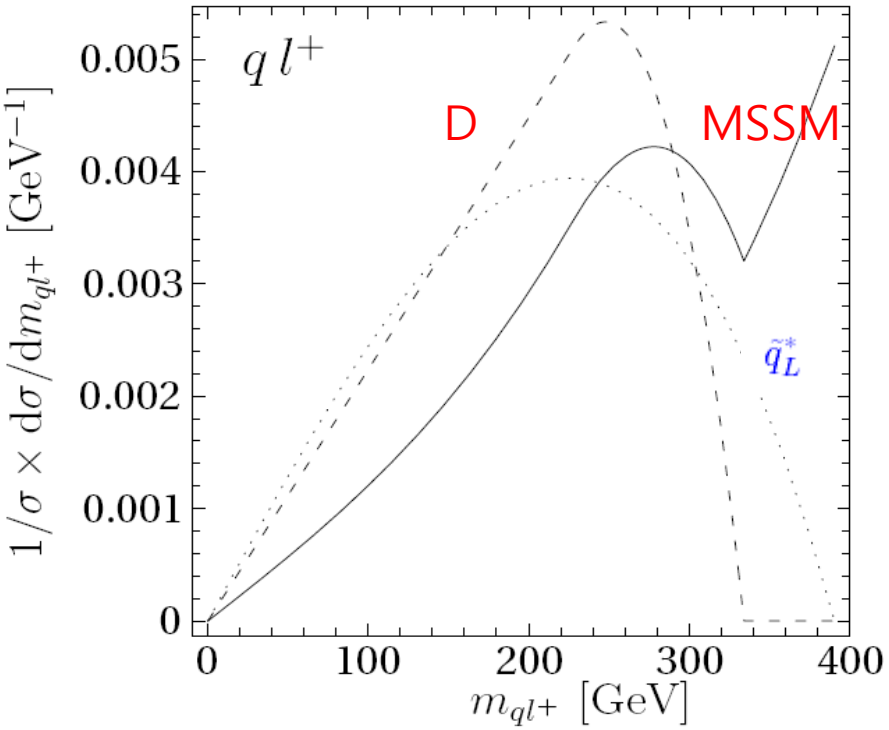
Squark cascade decays

Dirac ⇒ Conserved R-charge

$$R[\tilde{q}_L] = R[\tilde{\ell}_L] = R[\tilde{\chi}^0_D] = +1$$
$$R[\tilde{q}_R] = R[\tilde{\ell}_R] = R[\tilde{\chi}^{0c}_D] = -1$$

Neutralino path

$$\text{MSSM}: \quad \tilde{q}_L \to q\tilde{\chi}^0_2 \to q\ell^{\pm}\tilde{\ell}^{\mp}_R \to q\ell^{\pm}\ell^{\mp}\tilde{\chi}^0_1$$
$$\text{Dirac}: \quad \tilde{q}_L \to q\tilde{\chi}^0_{D2} \to q\ell^{-}\tilde{\ell}^{+}_R \to q\ell^{-}\ell^{+}\tilde{\chi}^0_{D1}$$



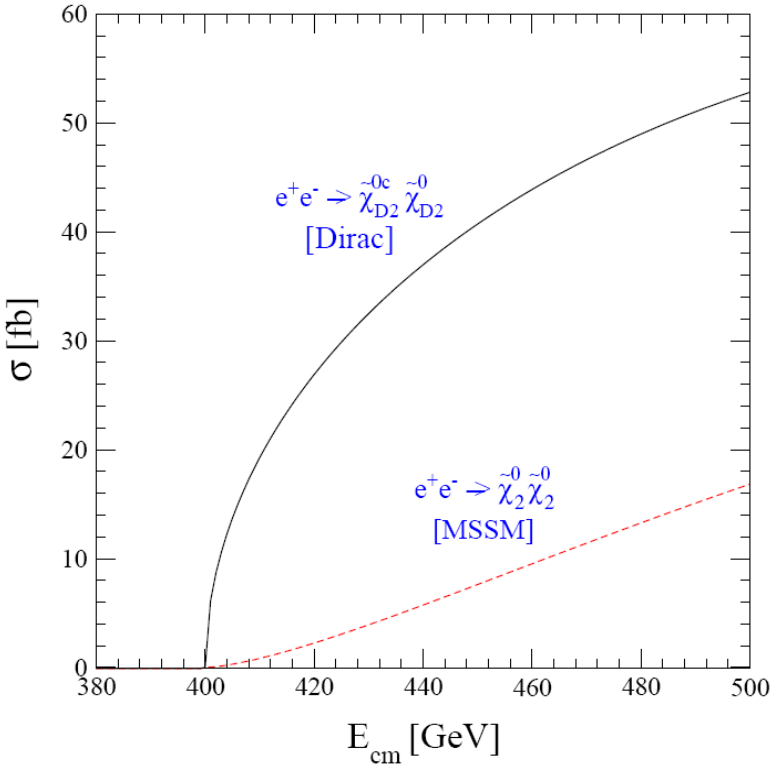
hard hard

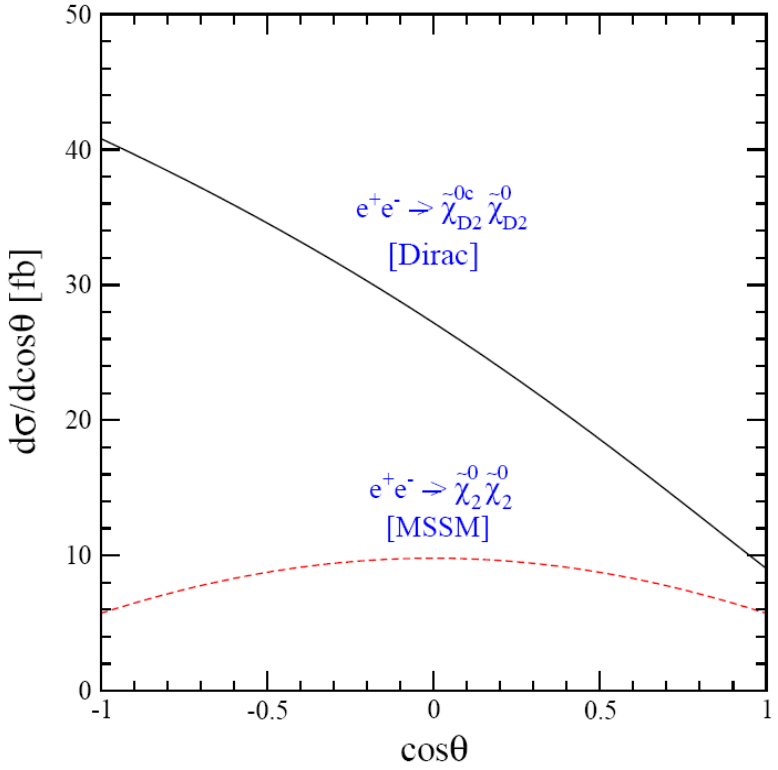
$$(ql^+)_M = (ql^+)_n \oplus (ql^+)_f$$
$$(ql^+)_D = (ql^+)_f$$

Similar striking D/MSSM difference expected through the chargino path

Expectations at an e^+e^- LC

Neutralino diagonal-pair production

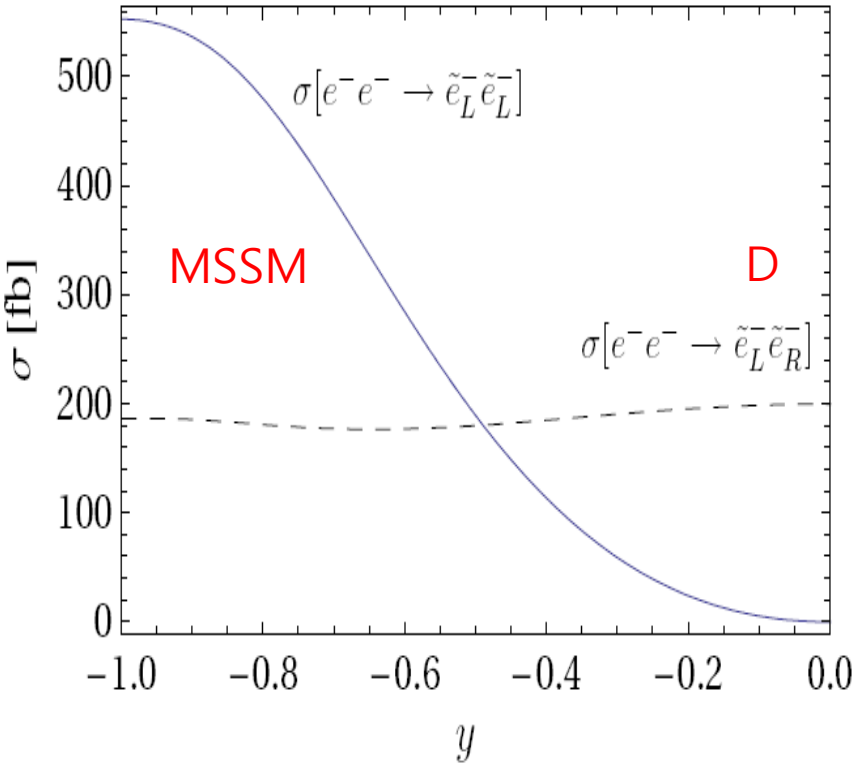




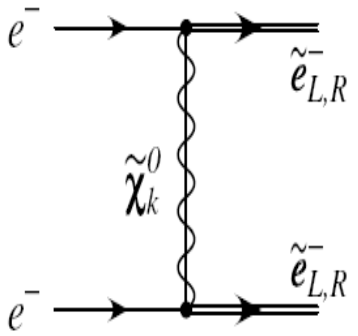
Dirac: S-wave threshold excitations
⇒ enhanced DM annihilation

Dirac: not FB symmetric.

Selectron pair production in e-e- collisions



SPS1a' scenario



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

Summary

A 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

Characteristic production /decay modes of gluinos and neutralinos

Striking signatures at colliders
More detailed/realistic analyses required

Distinct / interesting phenomenological/cosmological implications

Flavor + Dirac + DM/B + Scalar + …

Back-up Slides

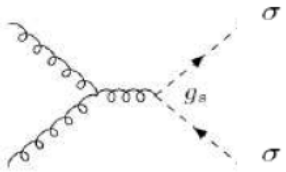
R-symmetric Scalar Sector

Color-octet adjoint scalars = sgluons

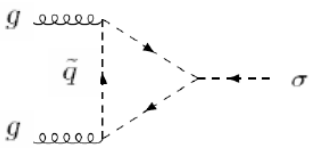
[SYC, Drees, Kalinowski, JM Kim, Popenda, Zerwas, 2009]

Production (huge)

pair



single



Decays

tree

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

$\Downarrow$

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

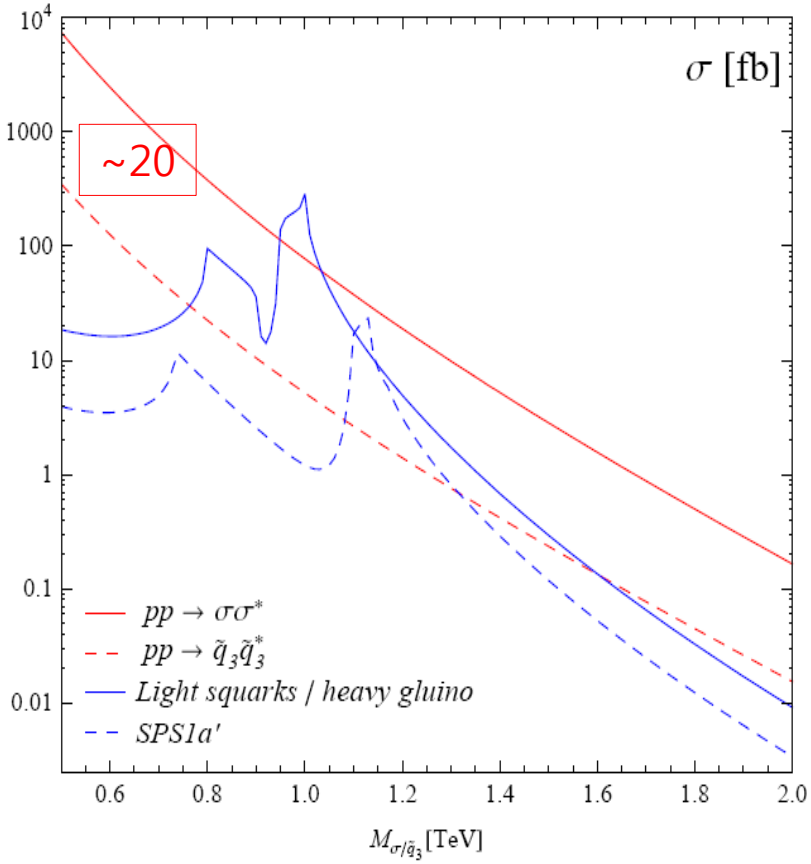
loop

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

$\Downarrow$

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

Striking signatures (large L/R splitting)

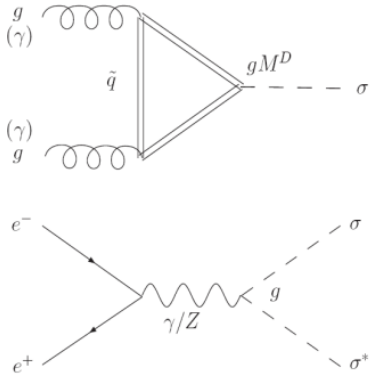


[No S/P mass splitting assumed]

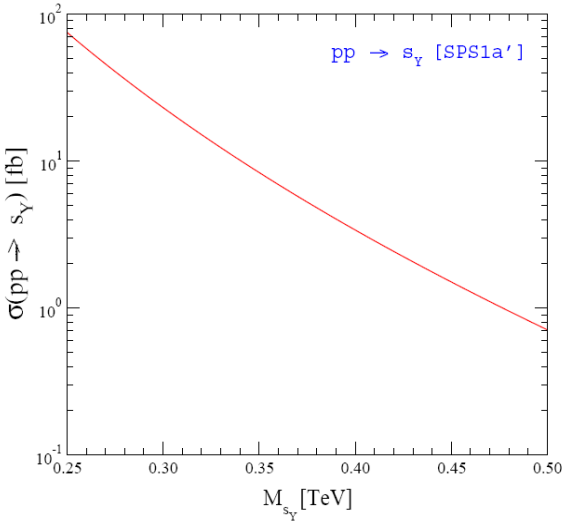
EW adjoint scalar production and decays

[SYC, Choudhury, Freitas, Kalinowski, JM Kim, Zerwas, 2010]

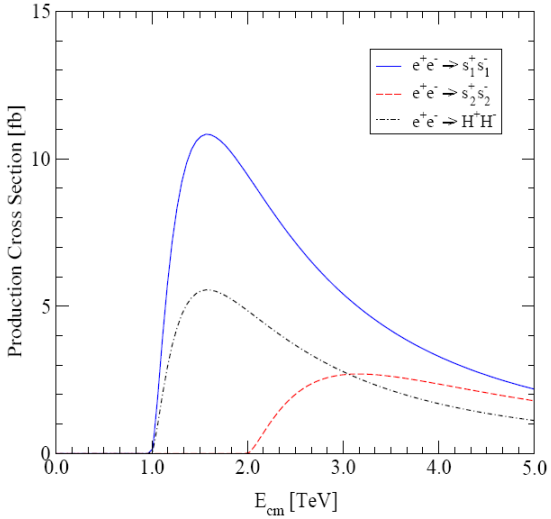
Production



indirect



direct



Decays