Phenomenology of extended gaugino sectors

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1. Theoretical framework: N=2 SUSY and R-symmetric SUSY
2. Production of squarks and gluinos at LHC
3. Decay chains
4. Adjoint scalars at LHC
5. ILC phenomenology
6. Summary

Theoretical framework: N=2 SUSY and R-symmetric SUSY

MSSM:

Superpartners of (self-conjugate) gauge fields are (self-conjugate) Majorana fermions

e.g. gluinos: $g^c = -\,g^T, \qquad \tilde{g}^c = -\,\tilde{g}^T$

Distinct difference between Dirac and Majorana fermion masses:

$$\mathcal{L}_D = -M(\psi_L^c\psi_R + \psi_R^c\psi_L) \qquad \mathcal{L}_M = -M(\psi_L^c\psi_L + \psi_R^c\psi_R)$$

Majorana masses mediate **fermion-number violating** processes like

$$q_Lq_L \to \tilde{q}_L\tilde{q}_L \quad \text{and} \quad q_Rq_R \to \tilde{q}_R\tilde{q}_R$$

or

$$\tilde{q}_L \to q\,\ell^\pm\,\tilde{\ell}^\mp$$

$\longrightarrow$ SUSY production and decay processes are sensitive to Majorana nature

N=2 gauge sector

N=1 SUSY gauge multiplet:

- One 2-helicity vector boson
- One 2-helicity Majorana fermion

N=2 SUSY gauge multiplet:

- One 2-helicity vector boson
- **Two** 2-helicity Majorana fermions $\longrightarrow$ Can form Dirac state
- One complex scalar

N=1 Superfields	Spin 1	Spin 1/2	Spin 0	
SU(3) gauge	g	$\tilde{g}$		} N=2 gauge
SU(3) chiral		$\tilde{g}'$	σ_C	} hypermultiplet
SU(2) gauge	$W^{\pm,0}$	$\tilde{W}^{\pm,0}$		}
SU(2) chiral		$\tilde{W}'^{\pm,0}$	σ_I	}
U(1) gauge	B	$\tilde{B}$		}
U(1) chiral		$\tilde{B}'$	σ_Y	}

N=1/N=2 hybrid model

Setup: Benakli, Moura '08

- $N{=}2$ gauge multiplets
- $N{=}2$ chiral/anti-chiral Higgs multiplet formed from $H_\mathrm{u} + H_\mathrm{d}$
- $N{=}1$ matter multiplets

$\longrightarrow$ Straw-man model to define a concrete model for this analysis

[but can be realized in an extra-dimensional model with $(N{=}2) \to (N{=}1)$ breaking on the 4-dim. branes
Chacko, Fox, Murayama '04]

New gauginos and adjoint scalars lead to distinctive phenomenology

R-symmetric supersymmetry

In model with **continuous** R-symmetry,
Majorana gaugino mass term $-M_G \tilde{G}\tilde{G}$ is forbidden ($\tilde{G} = \tilde{g}, \tilde{W}, \tilde{B}$)

$\longrightarrow$ Add extra chiral multiplet in adjoint representation: $\hat{\Sigma}_G = (\sigma_G, \tilde{G}')$

Superfield		Boson		Fermion	
Gauge vector $\hat{G}$	0	G_μ	0	$\tilde{G}$	$+1$
Adjoint chiral $\hat{\Sigma}_G$	0	σ_G	0	$\tilde{G}'$	-1

Can construct Dirac mass term $-M_G^D(\tilde{G}\tilde{G}' + \text{h.c.})$ Hall, Randall '91

$\hat{G}$ and $\hat{\Sigma}_G$ form a $N{=}2$ multiplet

MRSSM

Continuous R-symmetry also does not allow
$W_H = \mu\, H_\mathrm{u} \cdot H_\mathrm{d}$ (has R-charge 0 instead of 2)

$\longrightarrow$ Add new chiral R-Higgs superfields with $R = 2$:

Superfield		Boson		Fermion	
Gauge vector $\hat{G}$	0	G_μ	0	$\tilde{G}$	$+1$
Adjoint chiral $\hat{\Sigma}_G$	0	σ_G	0	$\tilde{G}'$	-1
Higgs $\hat{H}_{\mathrm{u,d}}$	0	$H_{\mathrm{u,d}}$	0	$\tilde{H}_{\mathrm{u,d}}$	-1
R-Higgs $\hat{R}_{\mathrm{u,d}}$	2	$R_{\mathrm{u,d}}$	2	$\tilde{R}_{\mathrm{u,d}}$	$+1$

Kribs, Poppitz, Weiner '07

$\longrightarrow$ Superpotential terms $W_R = \mu_\mathrm{u} H_\mathrm{u} \cdot R_\mathrm{u} + \mu_\mathrm{d} H_\mathrm{d} \cdot R_\mathrm{d}$

R-Higgses have interesting phenomenology,
but not discussed here Choi, Choudhury, Freitas, Kalinowski, Zerwas '11

Hyper-QCD sector

Choi, Drees, Freitas, Zerwas '08

Superpotential and SUSY-breaking mass terms [SU(3) as example]:

$$\mathcal{L}^{m}_{\rm QCD} = -\frac{1}{2}\left[M_3' \,\mathrm{Tr}(\overline{\tilde g'}\tilde g') + M_3 \,\mathrm{Tr}(\overline{\tilde g}\tilde g) + M_3^D \,\mathrm{Tr}(\overline{\tilde g'} gt + \overline{\tilde g}\tilde g')\right]$$

$\longrightarrow$ Matrix in $\{\tilde g', \tilde g\}$-space: $$\mathcal{M}_g = \begin{pmatrix} M_3' & M_3^D \\ M_3^D & M_3 \end{pmatrix}$$

- $M_3' \to \infty$: recover MSSM gluino sector
- $M_3 = M_3' = 0$, $M_3^D \neq 0$: two Majorana states $\tilde g', \tilde g$ paired to one Dirac state $\tilde g_D$
- intermediate: two Majorana mass eigenstates:

$$\begin{pmatrix} \tilde g_{1R} \\ \tilde g_{2R} \end{pmatrix} = \mathcal{U}^T \begin{pmatrix} \tilde g'_R \\ \tilde g_R \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \tilde g_{1L} \\ \tilde g_{2L} \end{pmatrix} = \mathcal{U}^\dagger \begin{pmatrix} \tilde g'_L \\ \tilde g_L \end{pmatrix}$$

Only standard gluino interacts with matter:

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

Hyper-electroweak sector

Neutralino mass matrix in $\{\tilde{B}'^0, \tilde{B}^0, \tilde{W}'^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0\}$-basis:

$$\mathcal{M}_n = \begin{pmatrix} M_1' & M_1^D & 0 & 0 & m_Z s_W s_\beta & m_Z s_W c_\beta \\ M_1^D & M_1 & 0 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & 0 & M_2' & M_2^D & -m_Z c_W s_\beta & -m_Z c_W c_\beta \\ 0 & 0 & M_2^D & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ m_Z s_W s_\beta & -m_Z s_W c_\beta & -m_Z c_W s_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W c_\beta & m_Z s_W s_\beta & -m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

Chargino mass matrix in $\{\tilde{W}'^\mp, \tilde{W}^\mp, \tilde{H}_{d,u}^\mp\}$-basis:

$$\mathcal{M}_c = \begin{pmatrix} M_2' & M_2^D & -\sqrt{2} m_W \sin\beta \\ M_2^D & M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \cos\beta & \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

Production of squarks and gluinos at LHC

Define path interpolating between Majorana and Dirac limits:

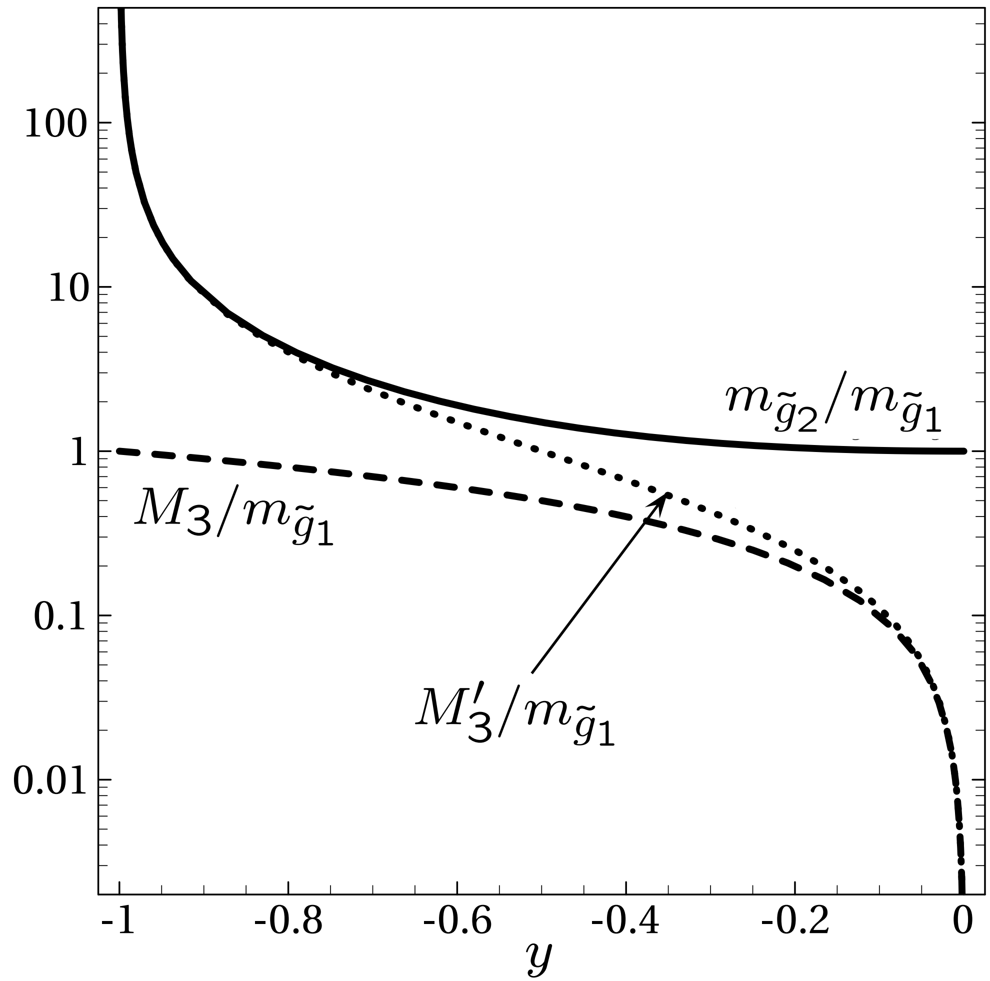
$$M_3' = m_{\tilde{g}_1} \frac{y}{1+y} \qquad -1 \leq y \leq 0$$
$$M_3^D = m_{\tilde{g}_1}$$
$$M_3 = m_{\tilde{g}_1} M_3' / (M_3' - m_{\tilde{g}_1})$$

$\longrightarrow$ One mass eigenvalue $m_{\tilde{g}_1}$ kept fixed,

$$m_{\tilde{g}_2} = m_{\tilde{g}_1} \left(y + \frac{1}{1+y} \right)$$

$y = -1$: Majorana limit

$y = 0$: Dirac limit



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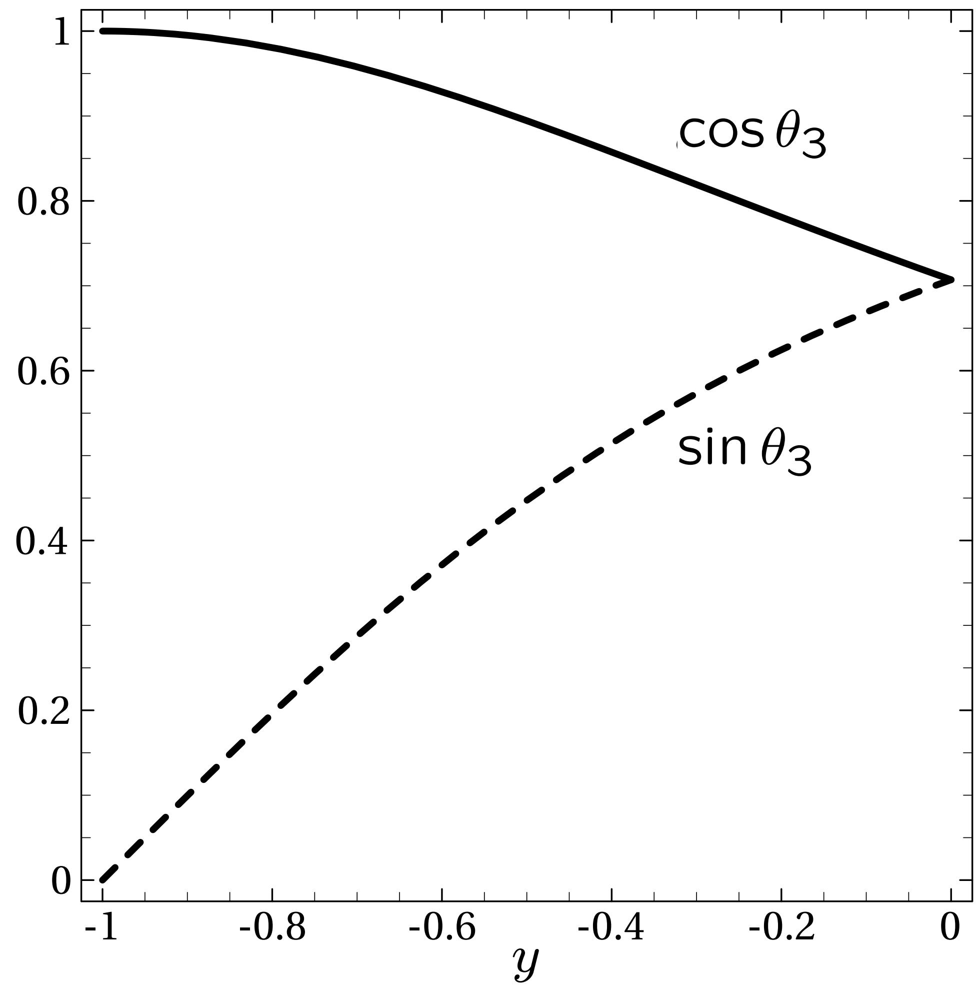


Partonic production processes

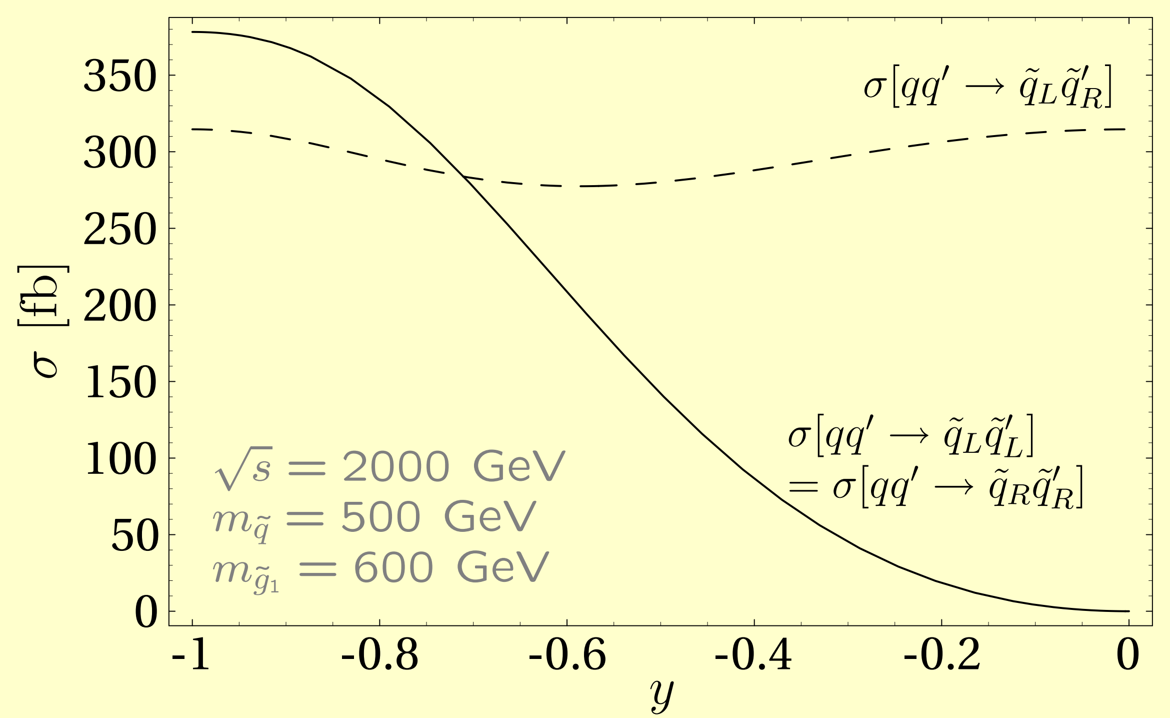
Choi, Drees, Freitas, Zerwas '08

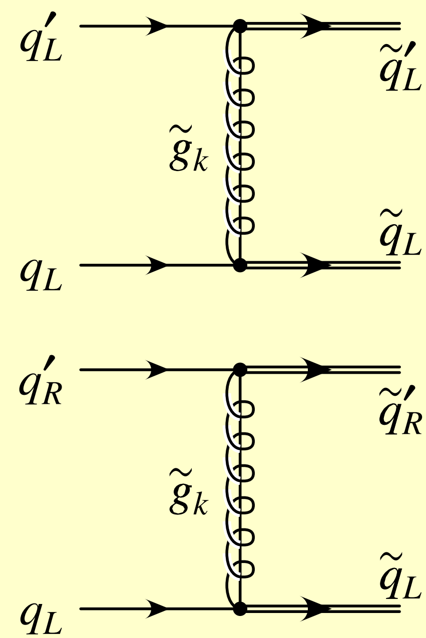
$qq' \to \tilde{q}\tilde{q}'$:

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

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

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





Partonic production processes

Choi, Drees, Freitas, Zerwas '08

$qq' \longrightarrow \tilde{q}\tilde{q}'$:

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

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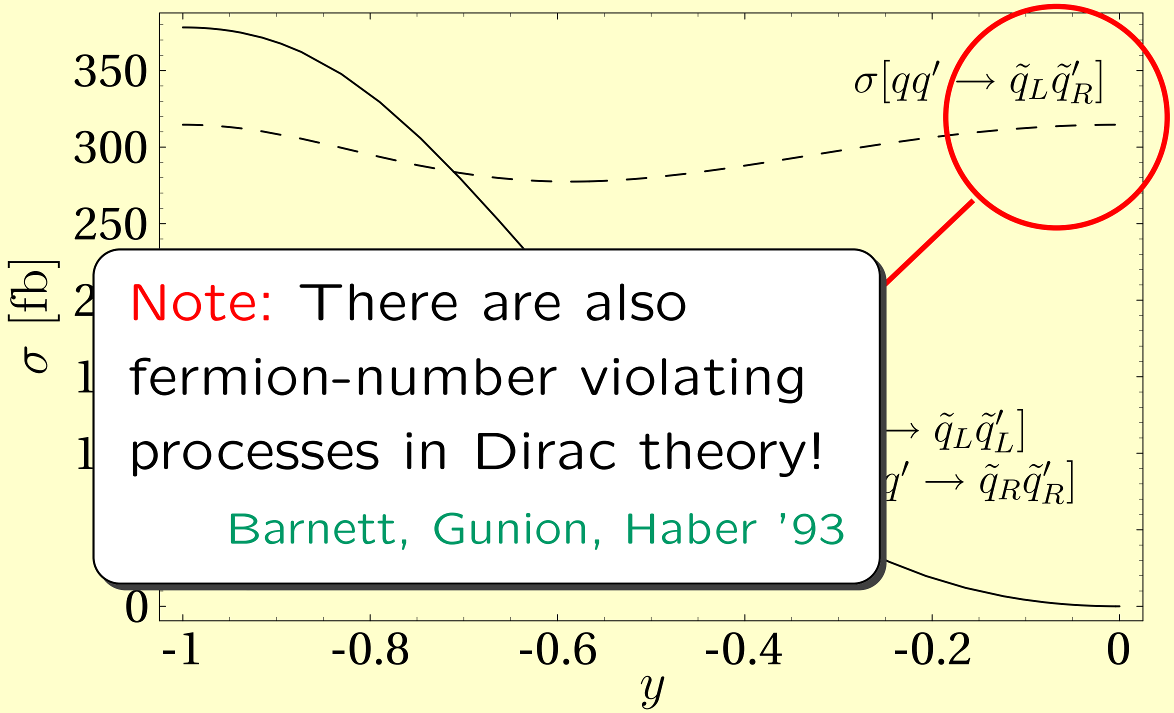
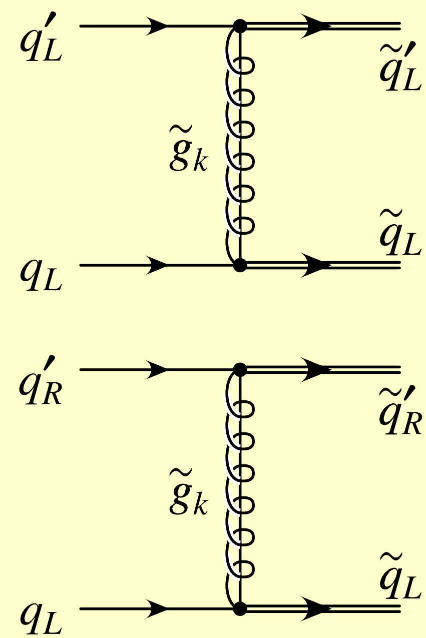


Note: There are also fermion-number violating processes in Dirac theory!

Barnett, Gunion, Haber '93



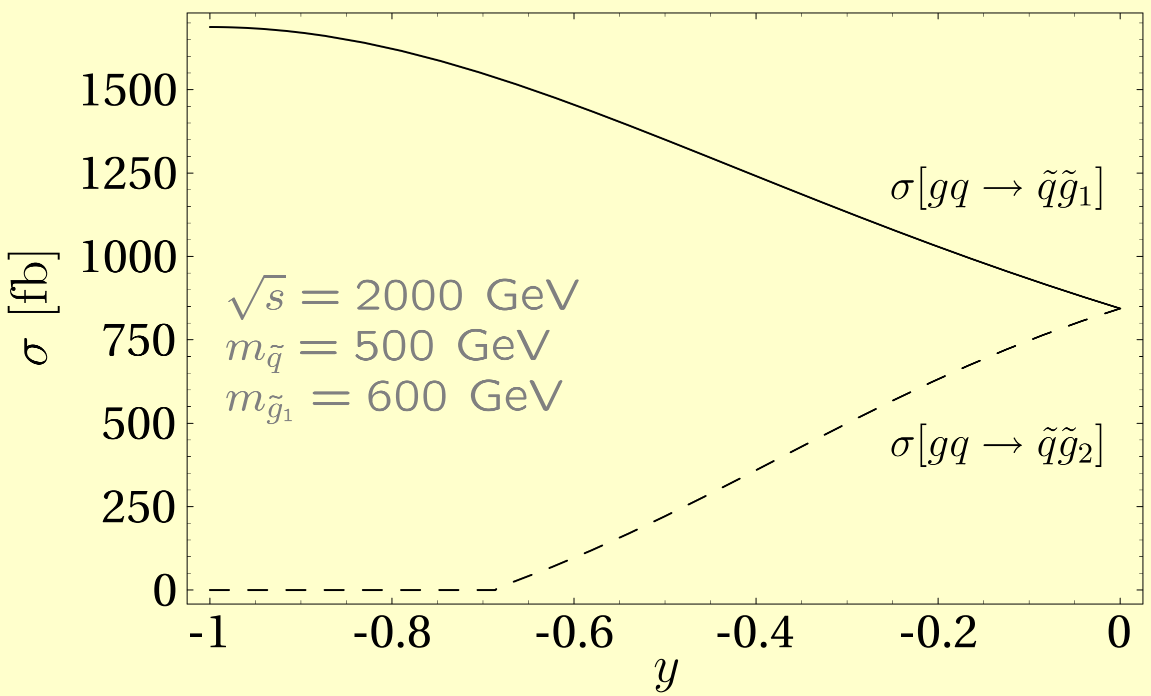
Partonic production processes

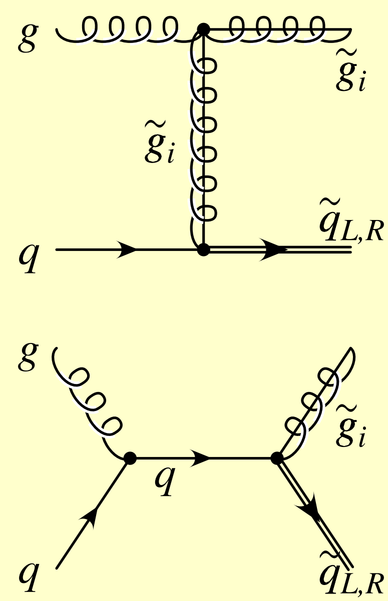
Choi, Drees, Freitas, Zerwas '08

$gq \to \tilde{g}\tilde{q}$:

$$\text{Majorana} = \text{Dirac}: \quad \sigma[gq \to \tilde{q}_{L,R}\tilde{g}] = \sigma[gq \to \tilde{q}_L\tilde{g}_D] = \sigma[gq \to \tilde{q}_R\tilde{g}^c_D]$$
$$= \frac{\pi\alpha_s^2}{18s^3}\Big[2(4s - 4m^2_{\tilde{g}_1} - 5m^2_{\tilde{q}})(m^2_{\tilde{g}_1} - m^2_{\tilde{q}})L'_1$$
$$+9(s(s+2m^2_{\tilde{g}_1}) + 2m^2_{\tilde{q}}(m^2_{\tilde{q}} - m^2_{\tilde{g}_1} - s))L_1$$
$$-\beta s(7s + 32(m^2_{\tilde{g}_1} - m^2_{\tilde{q}}))\Big]$$

$$\text{Dirac}: \quad \sigma[gq \to \tilde{q}_L\tilde{g}^c_D] = \sigma[gq \to \tilde{q}_R\tilde{g}_D] = 0,$$





Like-sign di-leptons at the LHC

In $\tilde{q}_L \to q\,\tilde{\chi}_1^\pm \to q\,\ell^\pm \nu_\ell \tilde{\chi}_1^0$ lepton charge is connected to squark charge

Majorana and Dirac gluinos lead to different $\tilde{q}/\tilde{g}$ production rates:

	Majorana	Dirac
$\tilde{q}_L \tilde{q}_L^{(\prime)}$	1	0
$\tilde{q}_L \tilde{q}_L^{(\prime)*}$	1	1
$\tilde{q}_L \tilde{g}_{(D)}$	1	1
$\tilde{g}_{(D)} \tilde{g}_{(D)}^{(c)}$	1	> 2

Majorana theory predicts larger $N(\ell^\pm\ell^\pm)/N(\ell^+\ell^-)$, from $\tilde{q}\tilde{q}$ production

Process	Majorana		Dirac		$N(\ell^+\ell^+)/N(\ell^-\ell^-)$	
	σ_{tot}	$\sigma_{\ell\ell}$ after cuts	σ_{tot}	$\sigma_{\ell\ell}$ 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	

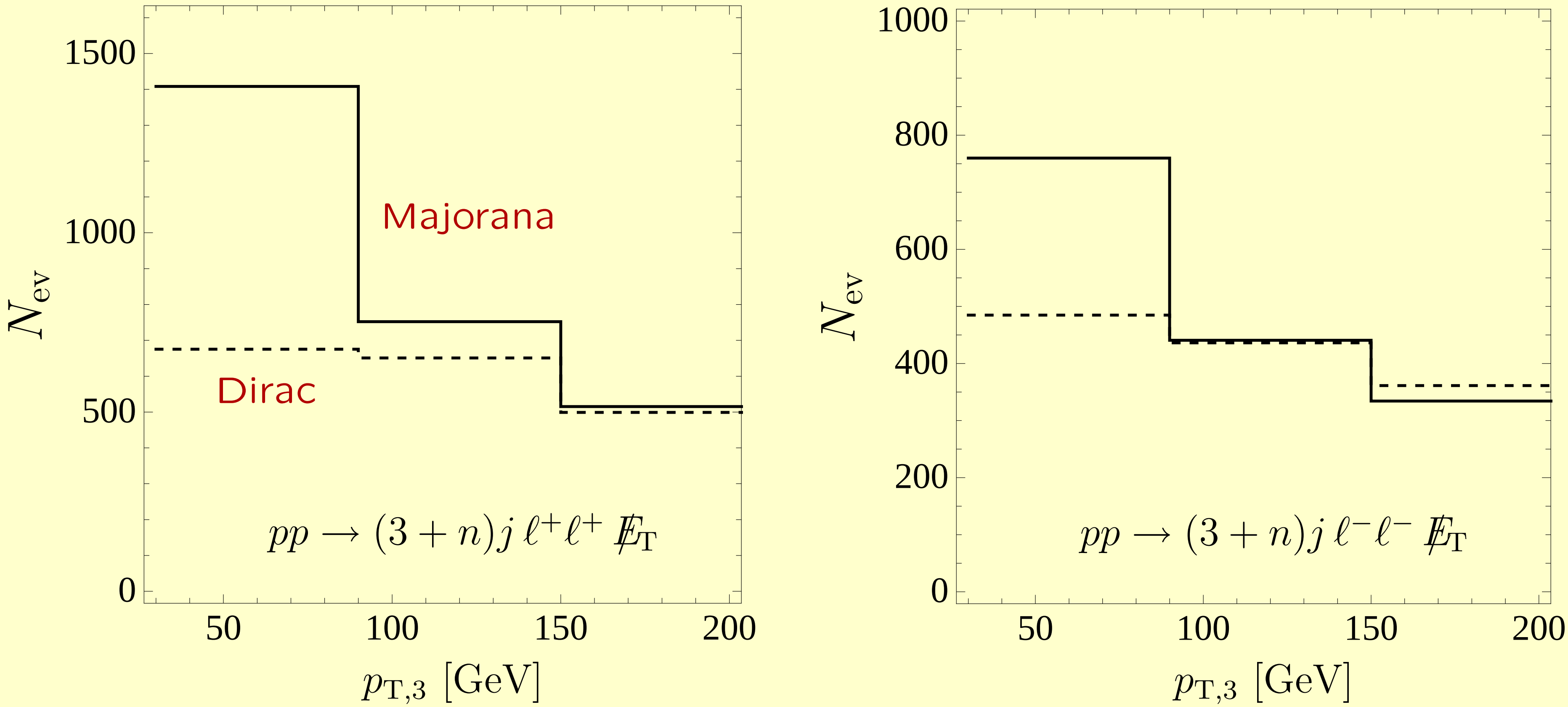
Like-sign di-leptons at the LHC

Choi, Drees, Freitas, Zerwas '08

Results from simulation with SM background:

Signal $2j + \ell^+\ell^- + \not{E}, \;\; \ell = e, \mu$ (SPS1a' scenario and $\sqrt{s} = 14$ TeV)

mostly $\tilde{q}\tilde{q}$ prod. mostly $\tilde{g}$ prod.



$\longrightarrow$ Discrimination at 10-11σ level (depending on systematic errors)

Decay chains

Chirality of neutralino interactions differ between Majorana and Dirac theory

$\longrightarrow$ Spin correlation effects in decay $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\, l^\pm\, \tilde{l}_R^\mp \to q\, l^\pm\, l^\mp\, \tilde{\chi}_1^0$

(for $m_{\tilde{\chi}_2^0} > m_{\tilde{l}_R} > m_{\tilde{\chi}_1^0}$)

Majorana: $\tilde{\chi}_2^0$ can decay into sleptons of $\pm$ charge:

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

Dirac: $\tilde{\chi}_{D2}^0$ decays only to $\tilde{l}_{\mathrm{R}}^-$,
while $\tilde{\chi}_{D2}^{0c}$ decays only to $\tilde{l}_{\mathrm{R}}^+$:

$$\tilde{q}_L \to q\, \tilde{\chi}_{D2}^{0c} \to q\, l_n^-\, \tilde{l}_R^+ \to q\, l_n^-\, l_f^+\, \tilde{\chi}_{D1}^{0c}$$

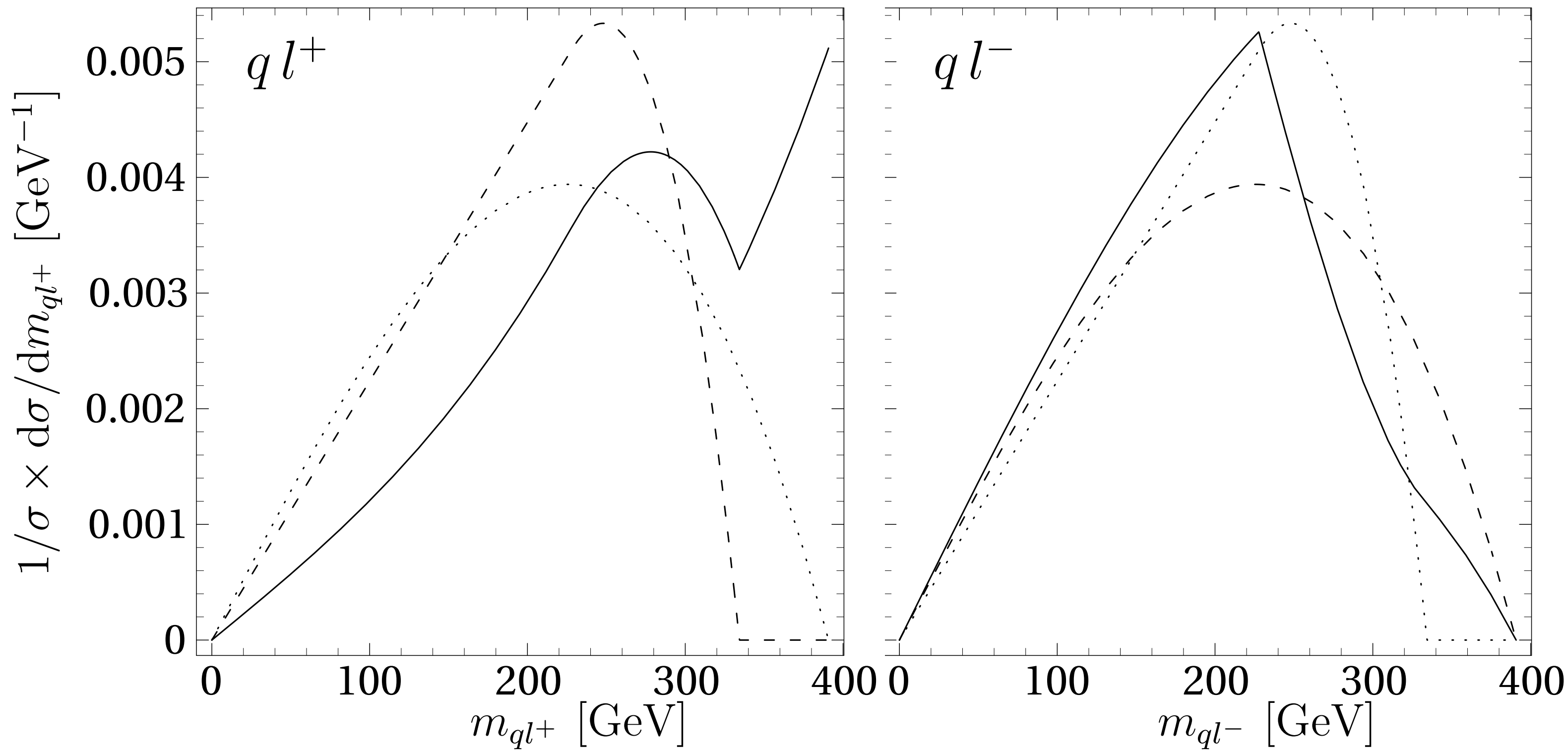
$$\tilde{q}_L^* \to \bar{q}\, \tilde{\chi}_{D2}^{0} \to \bar{q}\, l_n^+\, \tilde{l}_R^- \to \bar{q}\, l_n^+\, l_f^-\, \tilde{\chi}_{D1}^{0}$$

$\longrightarrow$ Effect on $ql^\pm$ invariant mass distributions

Neutralino cascade decays

———	$\tilde{q}_L \to q\tilde{\chi}^0_2 \to q l^{\mp}_n \tilde{l}^{\pm}_R \to q l^{\mp}_n l^{\pm}_f \tilde{\chi}^0_1$
— — —	$\tilde{q}_L \to q\tilde{\chi}^{0c}_{D2} \to q l^{-}_n \tilde{l}^{+}_R \to q l^{-}_n l^{+}_f \tilde{\chi}^{0c}_{D1}$
· · · · · ·	$\tilde{q}^*_L \to \bar{q}\tilde{\chi}^0_{D2} \to \bar{q} l^{+}_n \tilde{l}^{-}_R \to \bar{q} l^{+}_n l^{-}_f \tilde{\chi}^0_{D1}$

SPS1a' scenario



CP-invariance relates decay distributions of $\tilde{q}_L$ and $\tilde{q}^*_L$ for Dirac case

Chargino cascade decays

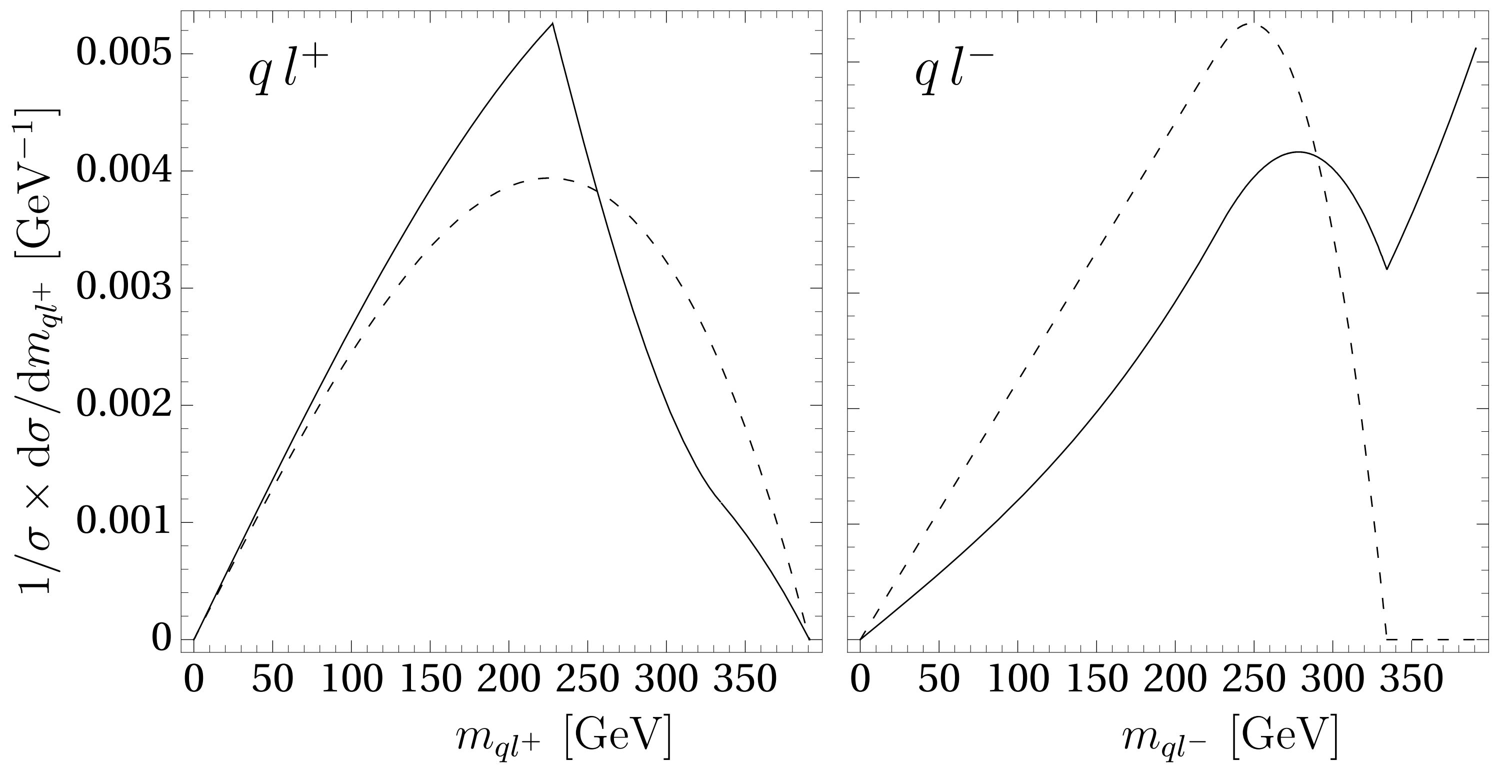
MSSM: ———— $\tilde{u}_L \to d\,\tilde{\chi}_1^+ \to d\,\nu_l\,\tilde{l}_L^+,\; d\,l^+\,\tilde{\nu}_l \to d\,l^+\,\nu_l\,\tilde{\chi}_1^0\,,$

$\tilde{d}_L \to u\,\tilde{\chi}_1^- \to u\,\bar{\nu}_l\,\tilde{l}_L^-,\; u\,l^-\,\tilde{\nu}_l^* \to u\,l^-\,\bar{\nu}_l\,\tilde{\chi}_1^0\,,$

Dirac: – – – $\tilde{u}_L \to d\,\tilde{\chi}_{D1}^+ \to d\,l^+\,\tilde{\nu}_l \to d\,l^+\,\nu_l\,\tilde{\chi}_{D1}^{0c}\,,$

$\tilde{d}_L \to u\,\tilde{\chi}_{D2}^- \to u\,\bar{\nu}_l\,\tilde{l}_L^- \to u\,l^-\,\bar{\nu}_l\,\tilde{\chi}_{D1}^{0c}\,,$

SPS1a' scenario



Choi, Choudhury, Freitas, Kalinowski, Kim, Zerwas '10

Adjoints scalars at LHC

N=2 gauge multiplets include (R-even) complex scalars σ_C^0, $\sigma_I^{0,\pm}$, σ_Y^0

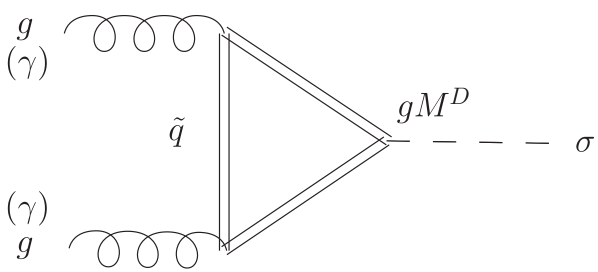
(EWSB: σs mix with Higgs bosons)

$\longrightarrow$ Do not couple to SM fermions (except through mixing)

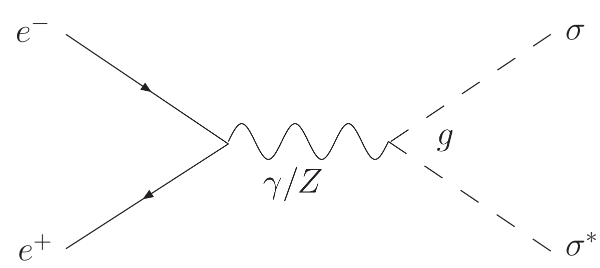
Main decay channels:

$M_\sigma < M_{\text{SUSY}}$	$M_\sigma > M_{\text{SUSY}}$
$\sigma_C \to gg$ (1loop)	$\sigma_Y \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}$
$\sigma_Y \to \gamma\gamma$ (1loop)	$\sigma_Y \to \tilde{f}\tilde{f}^*, \tilde{\chi}\tilde{\chi}$
$\sigma_I^\pm \to W^\pm\gamma$ (1loop)	$\sigma_I^\pm \to \tilde{f}\tilde{f}'^*, \tilde{\chi}^\pm\tilde{\chi}^0$

Single production $gg \to \sigma^0_{Y,I,C}$:

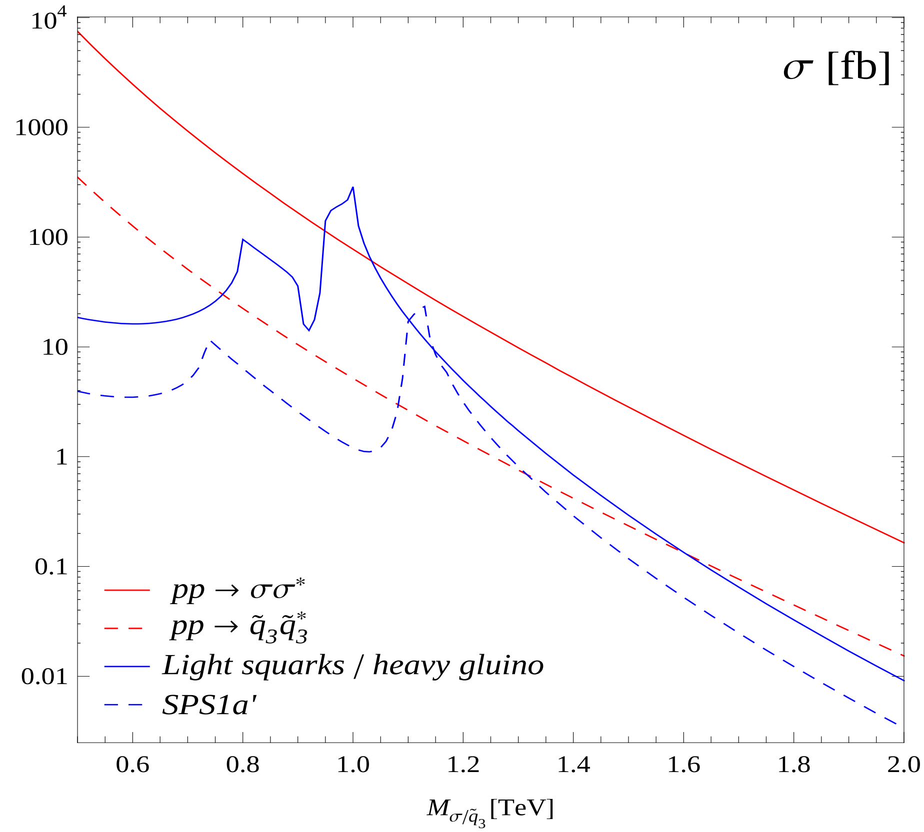


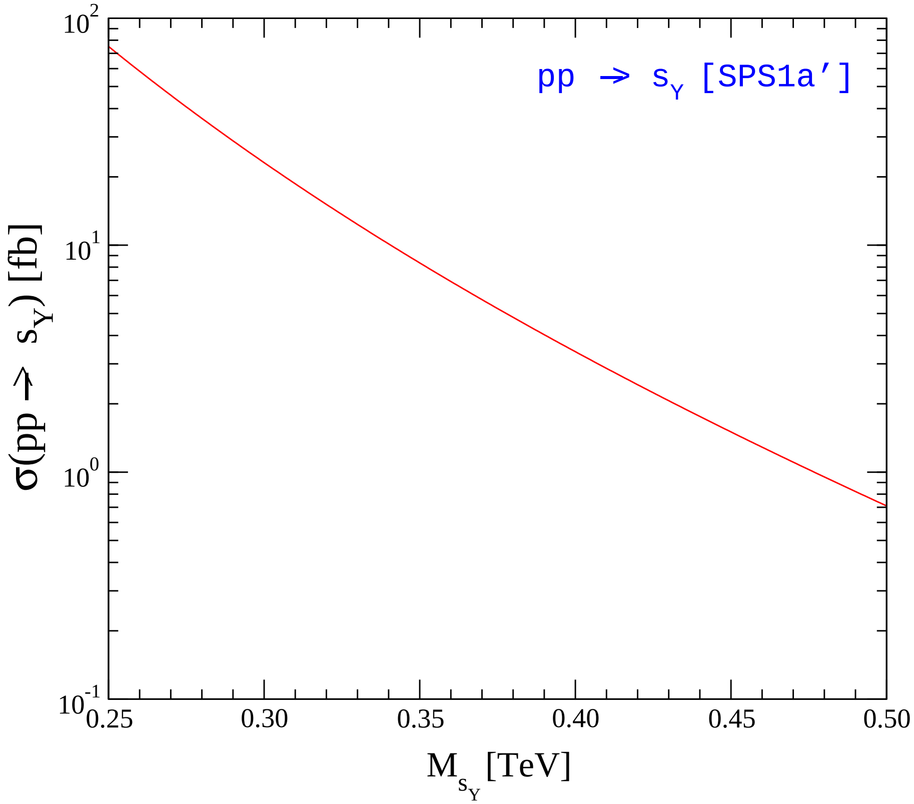
Pair prod. $gg \to \sigma_C\sigma_C$, $q\bar{q} \to \sigma_X\sigma_X^*$:



Production of adjoint scalars

Choi, Choudhury, Freitas, Kalinowski, Kim, Zerwas '10





$\sigma[\sigma_C\sigma_C] > 100$ fb for $M_\sigma \lesssim 1$ TeV

Large rate only for small M_{σ_Y}

$\longrightarrow$ $\sigma_Y \to \gamma\gamma$ dominates

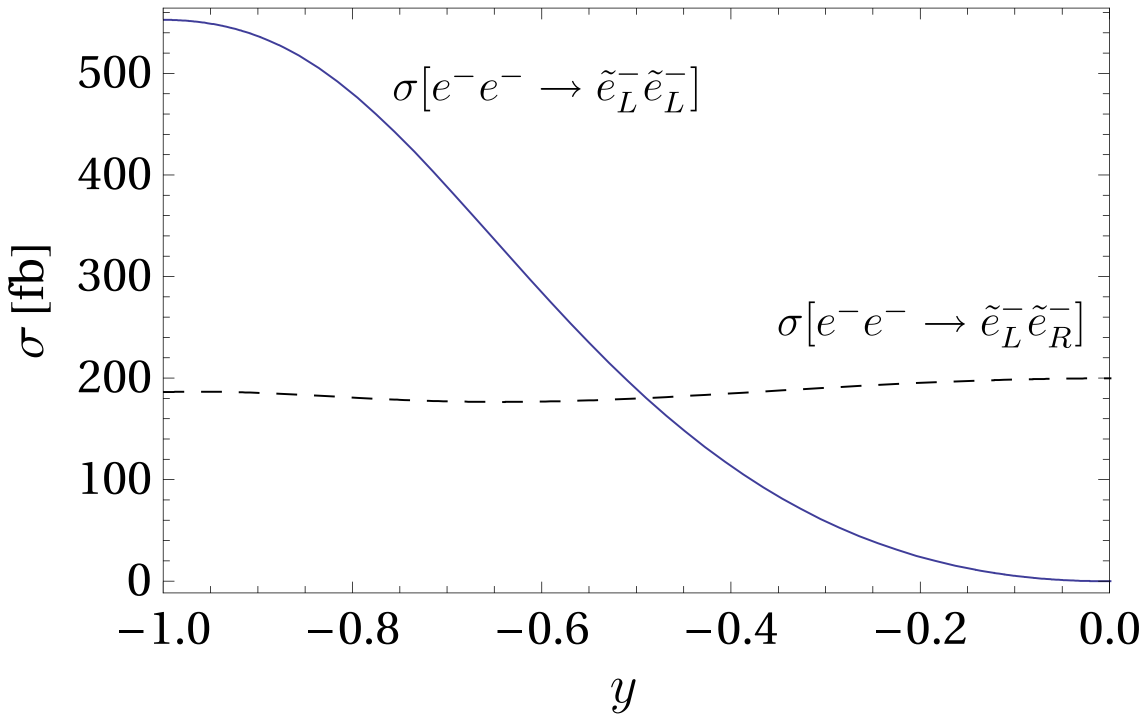
ILC phenomenology

Selectron production in e^-e^- collisions

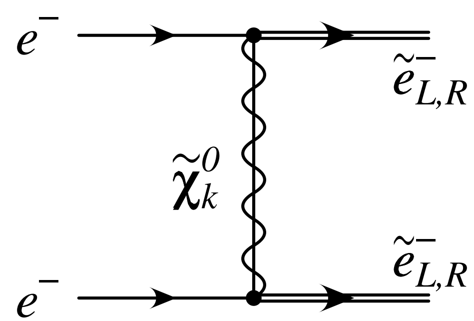
Majorana neutralinos can mediate **same-sign same-chirality** selectron production in e^-e^- collisions

Keung, Littenberg '83

Aguilar-Saavedra, Teixeira '03



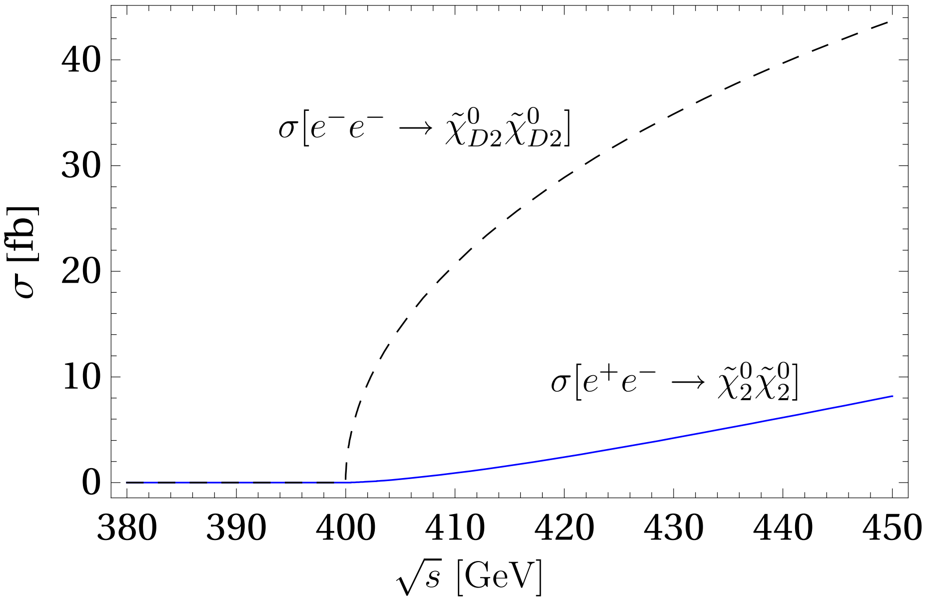
SPS1a' scenario

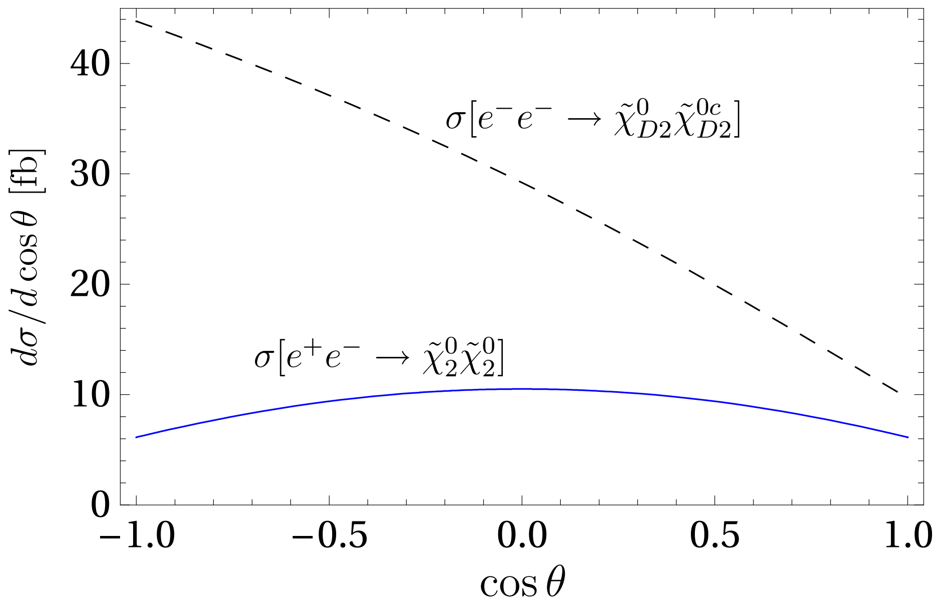


Choi et al. '10

Neutralino production in e^+e^- collisions

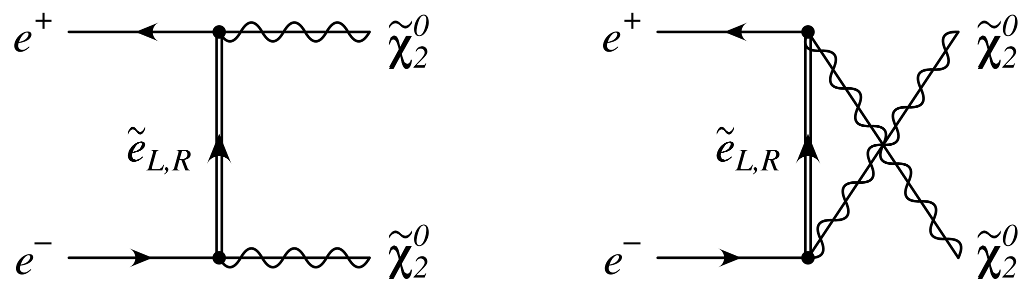
MSSM limit: p-wave, $t + u$ channels
Dirac limit: s-wave, t channel





$(m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^0_{D2}} = 200$ GeV, $m_{\tilde{e}_L} = 400$ GeV$)$

Choi et al. '10



Summary

- Majorana gauginos are predicted in MSSM,
  but Dirac gauginos are possible in extended SUSY models:
  - N=2 SUSY
  - R-symmetric SUSY

- Majorana/Dirac nature in strong sector can be tested through
  - Production rates for squarks and gluinos
  - Branching ratios for $\tilde{g} \to \tilde{t}, \bar{t}, \tilde{t}^{*} t$ Barnett, Gunion, Haber '93

- Majorana/Dirac nature in ew. sector can be tested through
  - Distributions of cascade decays at LHC
  - Production processes at ILC

- Adjoint scalars predicted in N=2 SUSY

  likely within reach of LHC, but ew. neutral states have low rates and difficult signatures

Backup slides

Like-sign di-leptons at the LHC

Simulation performed with Pythia 6.4;

jet clustering algorithm

Freitas, Skands '06

Freitas, Skands, Spira, Zerwas '07

Cuts:

- $N_j \geq 2$ with $p_{\mathrm{T,j}} > 200$ GeV
- $\not{E}_{\mathrm{T}} > 300$ GeV
- $N_\ell = 2$ with $p_{\mathrm{T},\ell} > 7$ GeV $(\ell = e, \mu)$
- bottom-flavor veto

SPS1a'' scenario:

$m_{\tilde{g}} = 700$ GeV

$m_{\tilde{q}_{\mathrm{L}}} = 565$ GeV

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

$m_{\tilde{\chi}_1^0} = 98$ GeV

SPS1a′ scenario

Aguilar-Saavedra et al. '06

$\tilde{q}_L$	565 GeV
$\tilde{q}_R$	547 GeV
$\tilde{e}_L$	190 GeV
$\tilde{e}_R$	125 GeV

M_1	103 GeV
M_2	193 GeV
μ	396 GeV
$\tan\beta$	10

$\tilde{\chi}_1^0$	98 GeV
$\tilde{\chi}_2^0$	184 GeV
$\tilde{\chi}_4^0$	414 GeV
$\tilde{\chi}_1^\pm$	184 GeV

$\tilde{g}$	607 GeV