Probing the nature of neutralinos at the ILC

Majorana (MSSM) ⇔ Dirac (MRSSM)

S.Y. Choi (Chonbuk, Korea)

Motivation

Minimal R-symmetric Model (MRSSM)
for Dirac neutralinos

Distinguishing MSSM vs. Dirac at ILC

Summary

SYC, Drees, Freitas, Zerwas, PRD76 (2008)
SYC, Choudhury, Freitas, Kalinowski, JM Kim, Zerwas, JHEP08 (2010)
SYC, Kalinowski, et al., in preparation

Motivation

◆ Terascale supersymmetry (SUSY) is still one of the best BSM propositions

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

◆ In the minimal SUSY extension (MSSM), each SM particle is paired with a sparticle differing in spin by ½ but with identical gauge quantum #'s

fermions ⇔ sfermions
gauge bosons ⇔ gauginos
Higgses ⇔ higgsinos

MSSM
(N=1 SUSY)

Neutral gauginos/higgsinos are Majorana fermions

$\Delta S = 1/2$
Majorana ⇔ Dirac

Neutralinos at ILC
(Gluinos at LHC)

Majorana ⇔ Dirac Fermion

$$\text{Majorana} \quad \Leftrightarrow \quad m^M \overline{\Psi}_M \Psi_M = m^M \left(\overline{\Psi_R}\Psi_L + \overline{\Psi_L}\Psi_R\right)$$

$$\Psi_M = \Psi_L + \Psi_R = (\Psi_M)^c \;\; \text{with} \;\; \Psi_R = (\Psi_L)^c$$

- The Majorana fermion must have a positive and negative charge of same magnitude simultaneously, if any, (i.e. no definite charge)

$$\text{Dirac} \quad \Leftrightarrow \quad m^D \overline{\Psi}_D \Psi_D = m^D \left(\overline{\Psi'_R}\Psi_L + \overline{\Psi'_L}\Psi_R\right)$$

$$\Psi_D = \Psi_L + \Psi'_R \neq (\Psi'_D)^c \;\; \text{with} \;\; \Psi \neq \Psi' \;\; \text{and} \;\; \Psi'_R = (\Psi'_L)^c$$

- The Dirac fermion can have a definite global charge in a theory invariant with the charge assignments as

$$Q(\Psi_L) = Q(\Psi'_R) = -Q(\Psi_R) = -Q(\Psi'_L)$$

Minimal R-symmetric Supersymmetric Standard Model (MRSSM)

[Fayet, 1975; Kribs, Poppitz, Weiner 2007, ...]

- A continuous R symmetry provides us with a natural framework for Dirac gauginos/higgsinos as explained in some detail as follows

- The R symmetry is an anomaly-free global continuous U(1) symmetry under $\theta \rightarrow e^{i\alpha}\theta$ with the R-charge assignments

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

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 Terms

Superpotential (R = 2)

- μ term: $\mu \hat{H}_d \hat{H}_u$ — R = 0
- L/B violation: $\hat{L}\hat{H}_u,\ \hat{L}\hat{Q}\hat{D}^c$ — R = 1, 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

No LR sfermion mixing

Too light gauginos/higgsinos!

Two extensions for R-symmetric gaugino/higgsino masses required

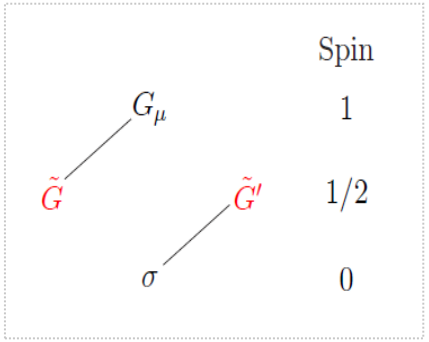
Dirac gauginos (+ adjoint scalars)

◆ 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 also to contain adjoint scalars).



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

$\mu_d \hat{H}_d \cdot \hat{R}_d + \mu_u \hat{H}_u \cdot \hat{R}_u$ and also trilinear terns $\lambda_d^i \hat{H}_d \cdot \hat{\Sigma}^i \hat{R}_d + \lambda_u^i \hat{H}_u \cdot \hat{\Sigma}^i \hat{R}_u$

N=2 SUSY $\longrightarrow$

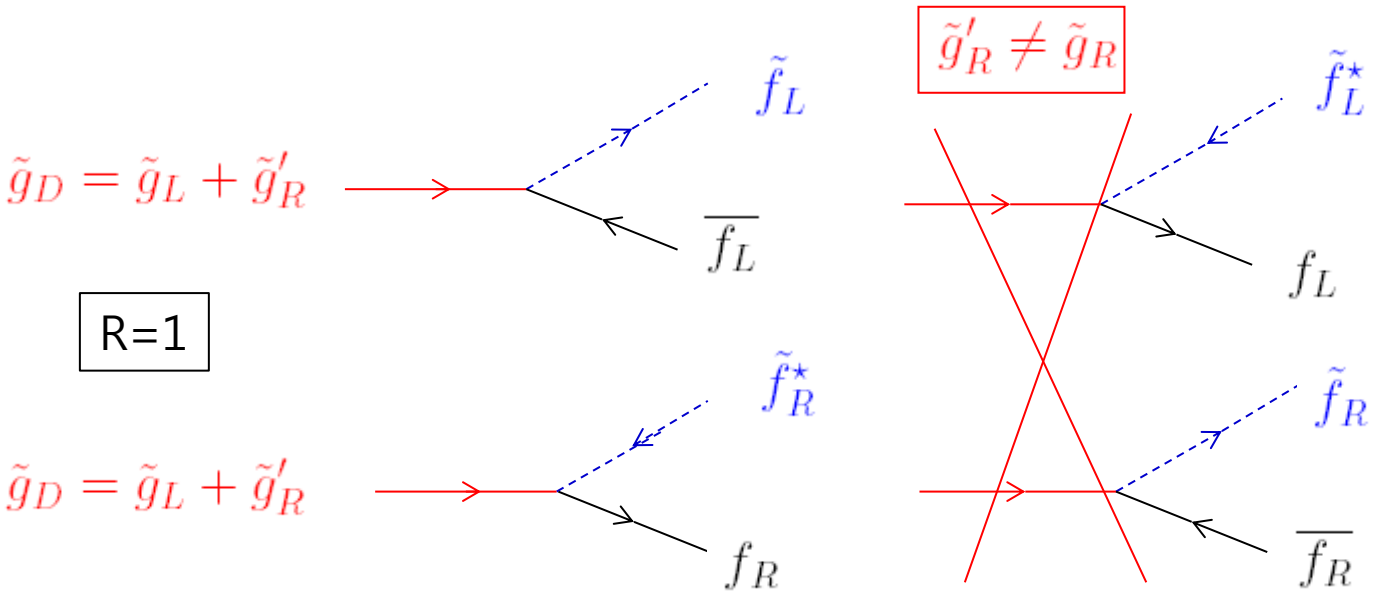
$$\lambda_u^I = -\lambda_d^I = g/\sqrt{2}$$
$$\lambda_u^Y = \lambda_d^Y = -g'/\sqrt{2}$$

Couplings

- Both the MSSM and new gauginos are coupled minimally to gauge bosons
- However, only the MSSM gauginos and H-higgsinos interact with sfermions carrying definite R charges.

$$R(\tilde{f}_L) = -R(\tilde{f}_R) = +1$$

(Note that the couplings of the H-higgsinos to the 1st and 2nd sfermions are practically negligible due to their small Yukawa couplings).



Forbidden (allowed) in the Dirac (MSSM)

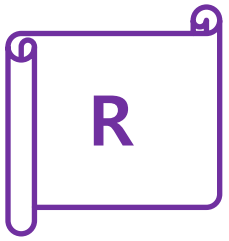
$\tilde{g}_M = \tilde{g}_L + \tilde{g}_R$ $\tilde{g}_L$ $\tilde{g}_R = (\tilde{g}_L)^c$

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

MSSM matter, gauge and H-Higgs fields

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



[Kribs ea, SYC ea, Nojiri ea, Plehn ea, Han ea, Hsieh, EJChun ea, Belanger ea, Kumar ea, Benakli ea, Fox ea, Davies ea, Sanz, …]

MSSM Majorana ⇔ MRSSM Dirac neutralinos

The MRSSM contains new gauginos and R-higgsinos and the EW gauginos and H/R-higgsinos with identical R-charge mix after EWSB

MSSM

4 Majorana Neutralinos

$$\mathcal{M}^0_{\rm MSSM} = \begin{bmatrix} M_Y & 0 & g'v_u/2 & -g'v_d/2 \\ 0 & M_I & -gv_u/2 & gv_d/2 \\ g'v_u/2 & -gv_u/2 & 0 & -\mu \\ -g'v_d/2 & gv_d/2 & -\mu & 0 \end{bmatrix}$$

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

MRSSM

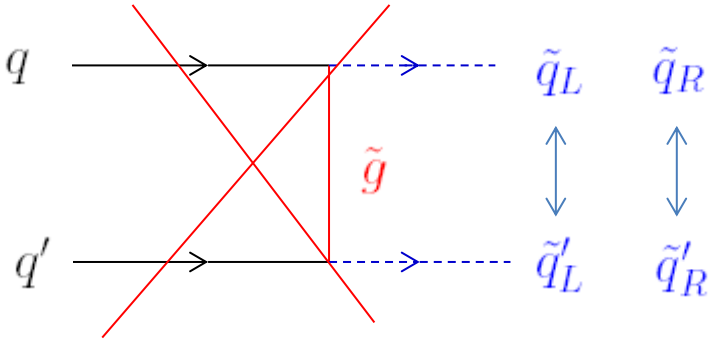
4 Dirac Neutralinos

$$\mathcal{M}^0_{\rm MRSSM} = \begin{bmatrix} M^D_Y & 0 & -\lambda^Y_u v_u/\sqrt{2} & \lambda^Y_d v_d/\sqrt{2} \\ 0 & M^D_I & -\lambda^I_u v_u/\sqrt{2} & -\lambda^I_d v_d/\sqrt{2} \\ g'v_u/2 & -gv_u/2 & -\mu_u & 0 \\ -g'v_d/2 & gv_d/2 & & \mu_d \end{bmatrix}$$

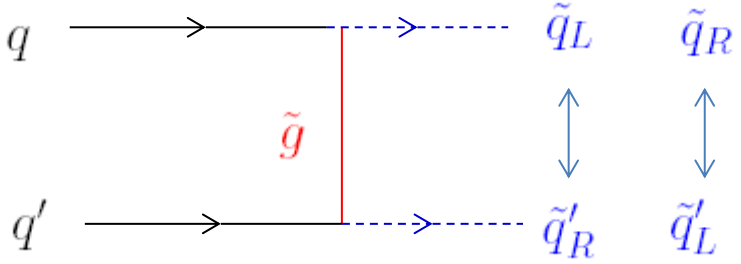
in the $(\tilde{B}', \tilde{W}'^0, \tilde{H}^0_u, \tilde{H}^0_d)_R/(\tilde{B}, \tilde{W}^0, \tilde{R}^0_u, \tilde{R}^0_d)_L$ basis

[symmetric in N=2 SUSY]

Squark pair production in pp collisions at the LHC



$\Delta R = 2$



$\Delta R = 0$

R- charge conservation in the Dirac (MRSSM) case kills the same chirality squark pair production in qq′ collisions

$$f_{u/p} > f_{d/p}$$

$$\tilde{u}_L \to d\tilde{\chi}^+ \to d\,\ell^+\,\nu_\ell\tilde{\chi}_1^0$$

$$\tilde{d}_L \to u\tilde{\chi}^- \to u\,\ell^-\,\bar{\nu}_\ell\tilde{\chi}_1^0$$

Many other channels involved

MSSM and Dirac gluinos lead to different rates of l^-l^-, l^+l^+, l^+l^-

D⇔M discrimination at 10.5σ with systematics for 300 fb^{-1} (SPS1a′)

[SYC, Drees, Freitas , Zerwas, 2008]

[Nojiri, Takeuchi, 2007; Heikinheimo ea, 2011, ...]

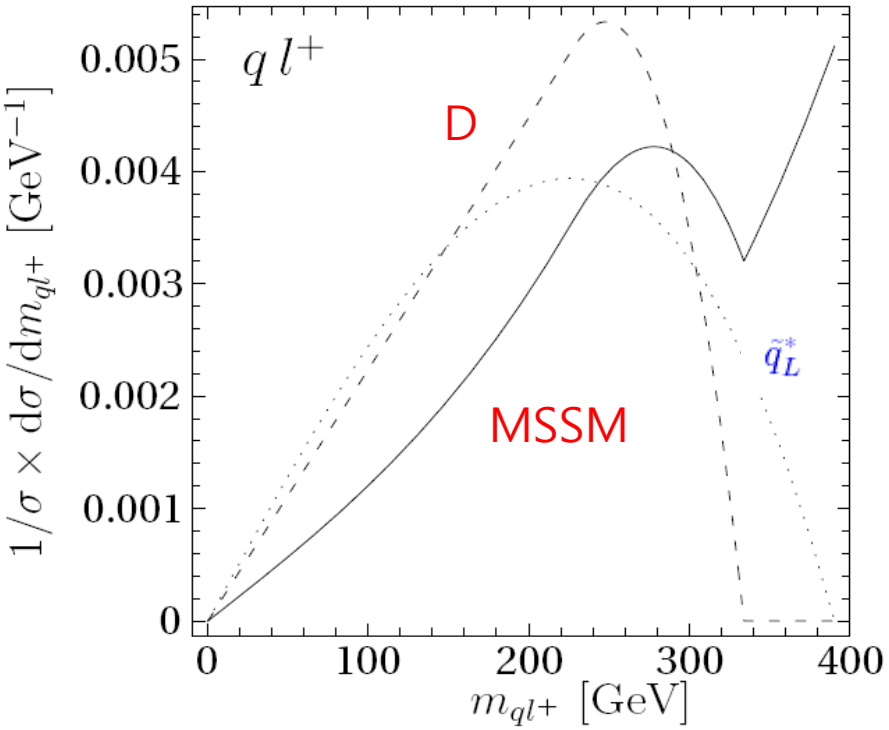
Squark cascade decays at the LHC (SPS1a')

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

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



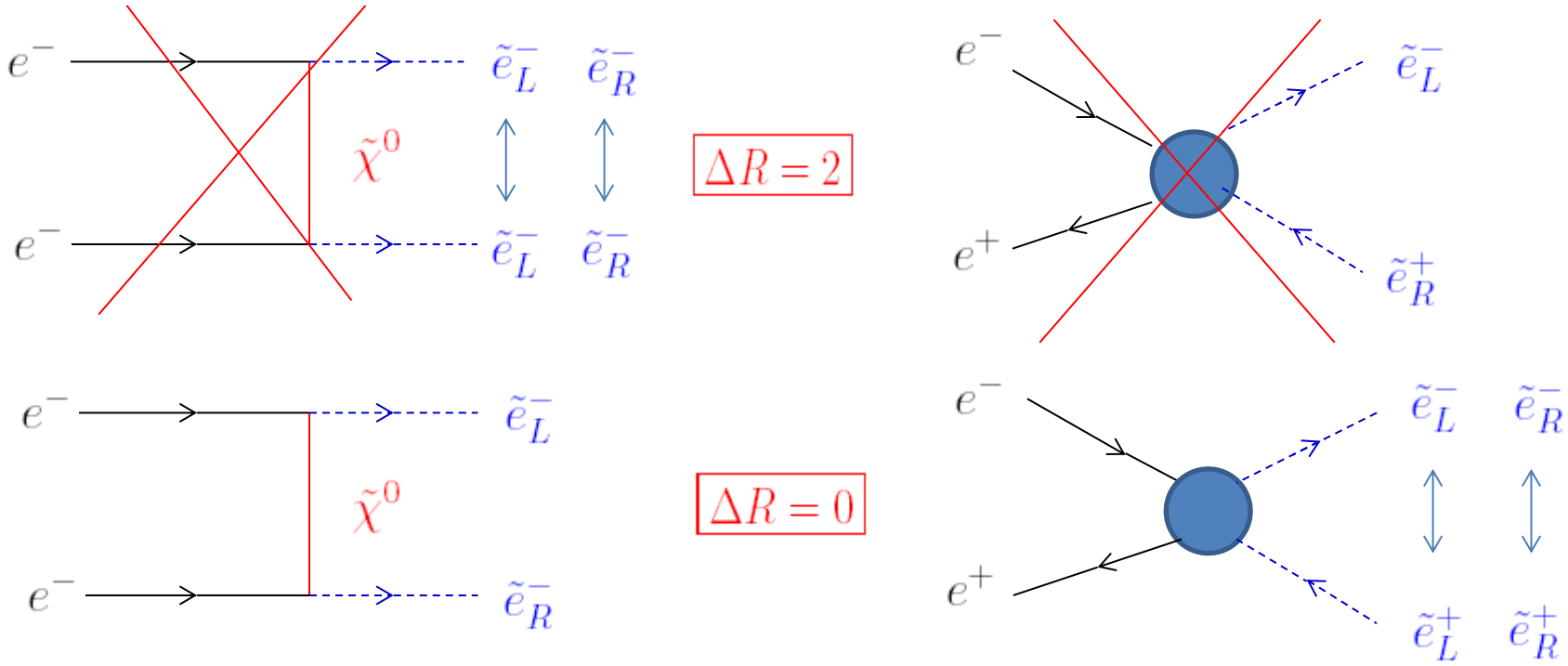
hard

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

Similar striking M ⇔D difference expected in slepton cascade decays at an LC, too

$\tilde{q}_L \Rightarrow \tilde{\ell}_L$

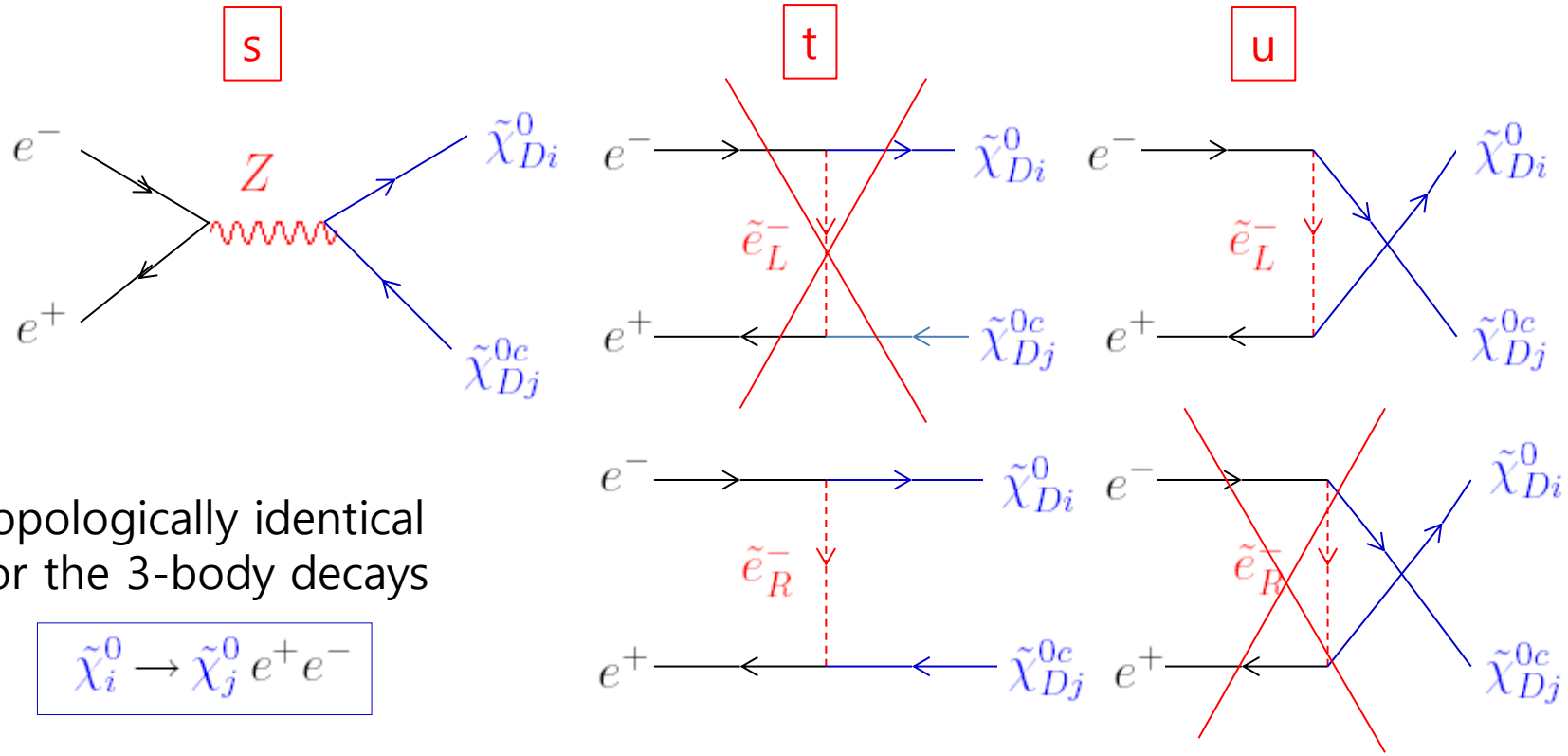
Selectron pair production in e^-e^- /e^-e^+ collisions



Dirac (MRSSM)

R- charge conservation kills the same (opposite) sign and chirality selectron pair production in e^-e^- (e^-e^+) collisions

Neutralino pair production and 3-body decays



Topologically identical
for the 3-body decays

$$\tilde{\chi}^0_i \to \tilde{\chi}^0_j\, e^+ e^-$$

✠ Diagonal Majorana pair $\Rightarrow$ $\bar{u}\,[\gamma_\nu\gamma_5]\,v$ on threshold : P-wave excitation

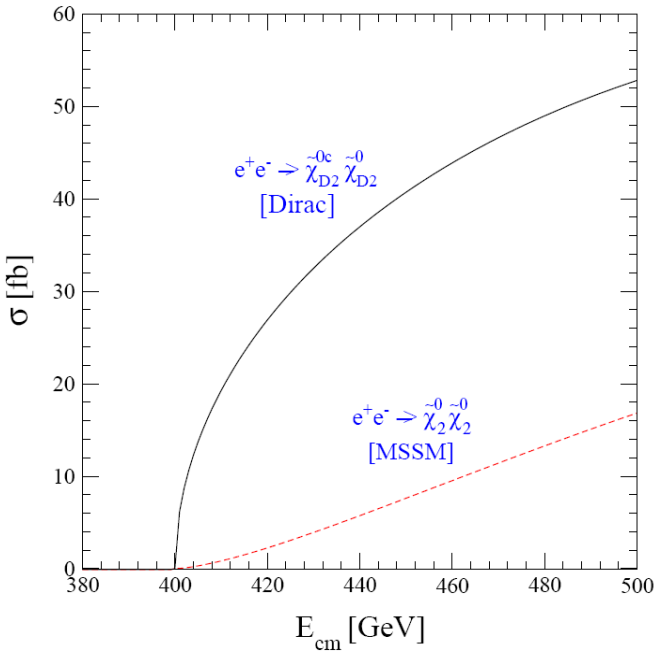
✠ Non-diagonal M pair $\Rightarrow$
$$\begin{cases} \bar{u}_i\,[\gamma_u\gamma_5]\,v_j \Leftrightarrow \bar{u}_j\,[\gamma_u\gamma_5]\,u_i & : P \Leftrightarrow S \text{ for } \eta_i = +\eta_j \\ \bar{u}_i\,[\ \gamma_u\ ]\,v_j \Leftrightarrow \bar{u}_j\,[\ \gamma_u\ ]\,u_i & : S \Leftrightarrow P \text{ for } \eta_i = -\eta_j \end{cases}$$

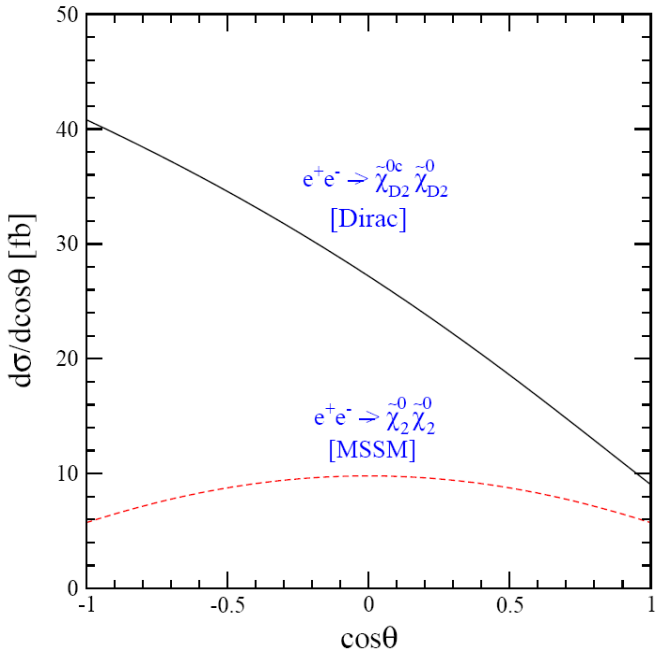
P D

Neutralino diagonal pair production

✠ Diagonal Majorana pair $\Rightarrow \bar{u}\,[\gamma_\nu\gamma_5]\,v$ on threshold : P-wave excitation

$M_I = 200\,\mathrm{GeV},\ m_{\tilde{e}_L} = 400\,\mathrm{GeV}$





P-wave in MSSM ↕ S-wave in Dirac

FB symmetric in MSSM ↕ FB asymmetric in Dirac

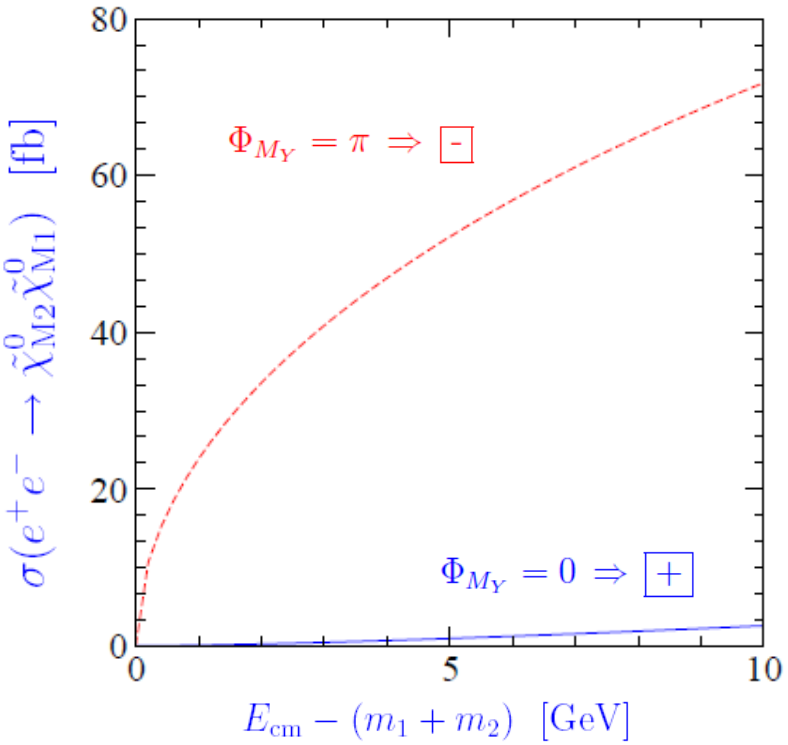
Dirac ⇒ no t-/u-channel L/R selectron exchanges

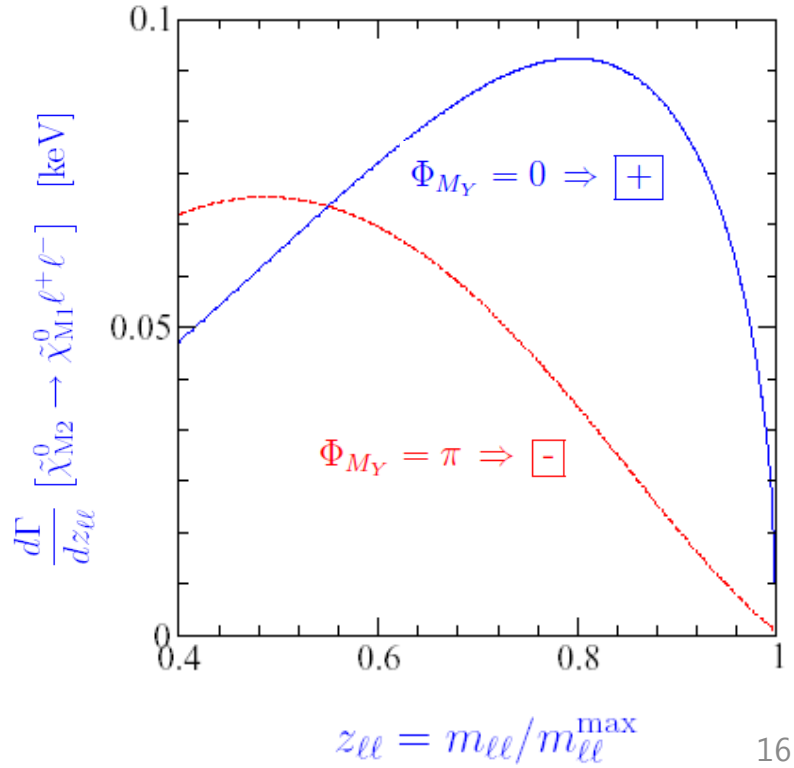
Nondiagonal pair production ⇔ 3-body decays (MSSM)

✠ Non-diagonal M pair ⇒

$$\begin{cases} \bar{u}_i\,[\gamma_u\gamma_5]\,v_j \;\Leftrightarrow\; \bar{u}_j\,[\gamma_u\gamma_5]\,u_i & : P \Leftrightarrow S \text{ for } \eta_i = +\eta_j \\ \bar{u}_i\,[\ \gamma_u\ ]\,v_j \;\Leftrightarrow\; \bar{u}_j\,[\ \gamma_u\ ]\,u_i & : S \Leftrightarrow P \text{ for } \eta_i = -\eta_j \end{cases}$$

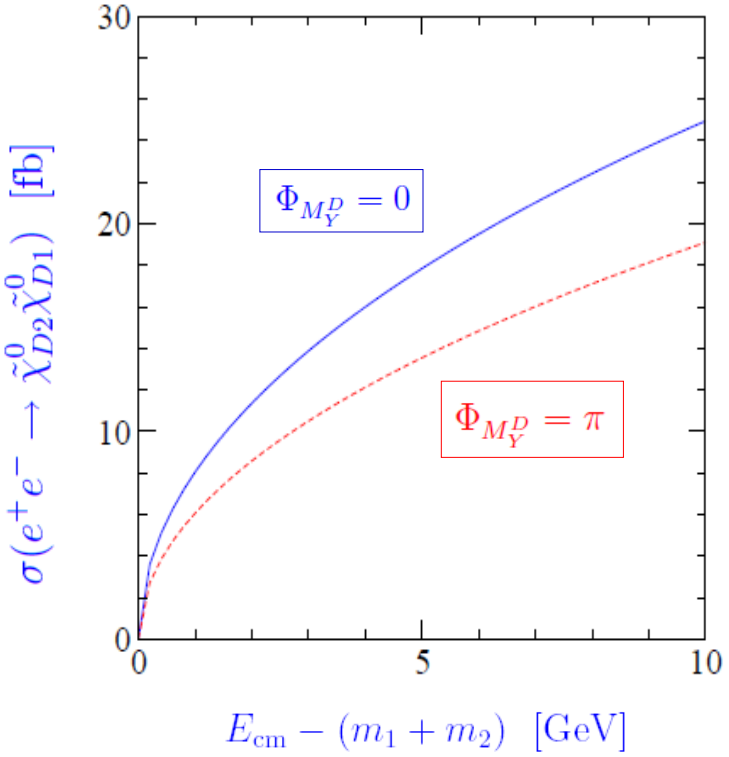
$M_Y = 100\,\text{GeV},\ M_I = 150\,\text{GeV},\ m_{\tilde{e}_L} = 250\,\text{GeV},\ m_{\tilde{e}_R} = 200\,\text{GeV}$

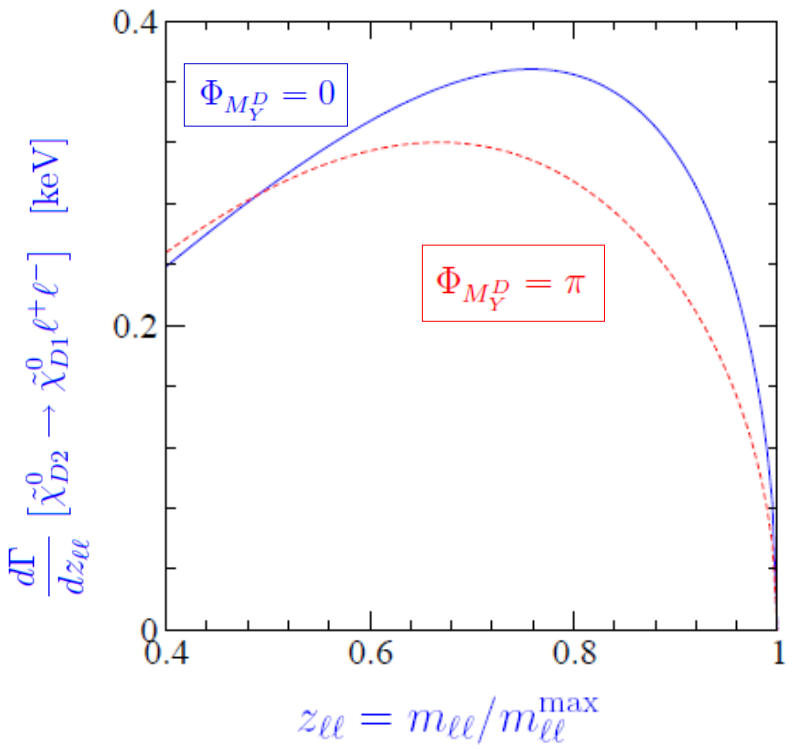




Nondiagonal pair production ⇔ 3-body decays (Dirac)

✠ Non-diagonal D pair ⇒ both V and A couplings ⇒ always S-wave excitation





Summary

M

- Same (opposite) chirality sfermion pair production in the e-e- (e+e-) mode
- Slow P-wave excitation of neutralino diagonal pair production in the e+e- mode
- Perfect P/S correlations of neutralino non-diagonal pair production in the e+e- mode and its corresponding neutralino 3-body decays
- ---

D

- Only opposite (same) chirality sfermion pair production in the e-e- (e+e-) mode
- Sharp S-wave excitation for every neutralino pair production in the e+e- mode and of every neutralino 3-body decays
- ---

Characteristic M vs. D neutralino signatures at the ILC

(Full realistic simulations required)