# Distinguishing MSSM and Dirac neutralinos at the ILC
## Majorana (MSSM)        Dirac (MRSSM)

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Motivation

Minimal R-symmetric model (MRSSM)
as a viable model for Dirac neutralinos

Distinguishing MSSM vs. Dirac at the 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
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◆ 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

$S = 1/2$
Majorana     Dirac

Neutralinos at ILC
(Gluinos at LHC)

$$\boxed{\text{Majorana} \quad\quad \text{Dirac Fermion}}$$

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

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

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

$$\updownarrow$$

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

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

◆ 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

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

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

**Chiral**

— matter

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

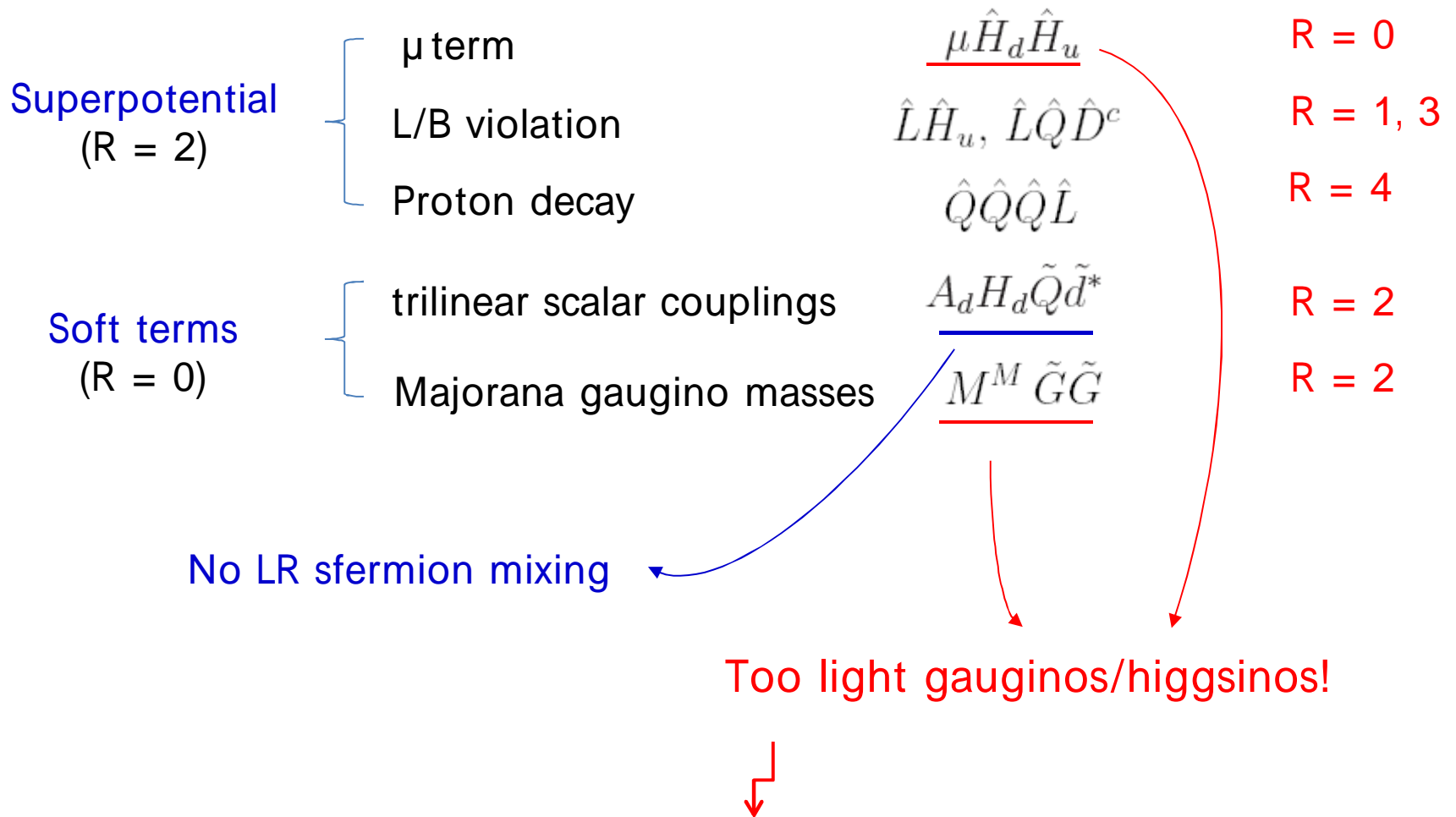$$\boxed{R(\hat{f}) = +1} \quad \Rightarrow \quad R(\tilde{f}) = +1, \quad R(f) = 0$$

— 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 Terms

**Superpotential**
**(R = 2)**

- μ term $\qquad\qquad\qquad \underline{\mu \hat{H}_d \hat{H}_u}$ $\qquad$ R = 0
- L/B violation $\qquad\quad \hat{L}\hat{H}_u, \ \hat{L}\hat{Q}\hat{D}^c$ $\qquad$ R = 1, 3
- Proton decay $\qquad\quad \hat{Q}\hat{Q}\hat{Q}\hat{L}$ $\qquad$ R = 4

**Soft terms**
**(R = 0)**

- trilinear scalar couplings $\qquad \underline{A_d H_d \tilde{Q} \tilde{d}^*}$ $\qquad$ R = 2
- Majorana gaugino masses $\qquad \underline{M^M \tilde{G}\tilde{G}}$ $\qquad$ R = 2

No LR sfermion mixing

Too light gauginos/higgsinos!
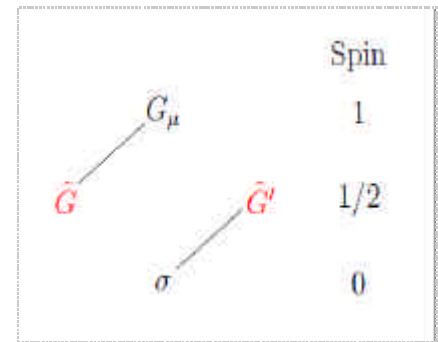
Two extensions for R-symmetric gaugino/higgsino masses required

Massive gauginos (+ adjoint scalars)

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

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

to build a R-symmetric Dirac gaugino mass $M^D \tilde{G}\tilde{G}'$

(and also to contain adjoint scalars).

| | Spin |
|---|---|
| $G_\mu$ | 1 |
| $\tilde{G}$ $\tilde{G}'$ | 1/2 |
| $\sigma$ | 0 |

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 terms $\lambda_d^i \hat{H}_d \cdot \hat{\Sigma}^i \hat{R}_d + \lambda_u^i \hat{H}_u \cdot \hat{\Sigma}^i \hat{R}_u$
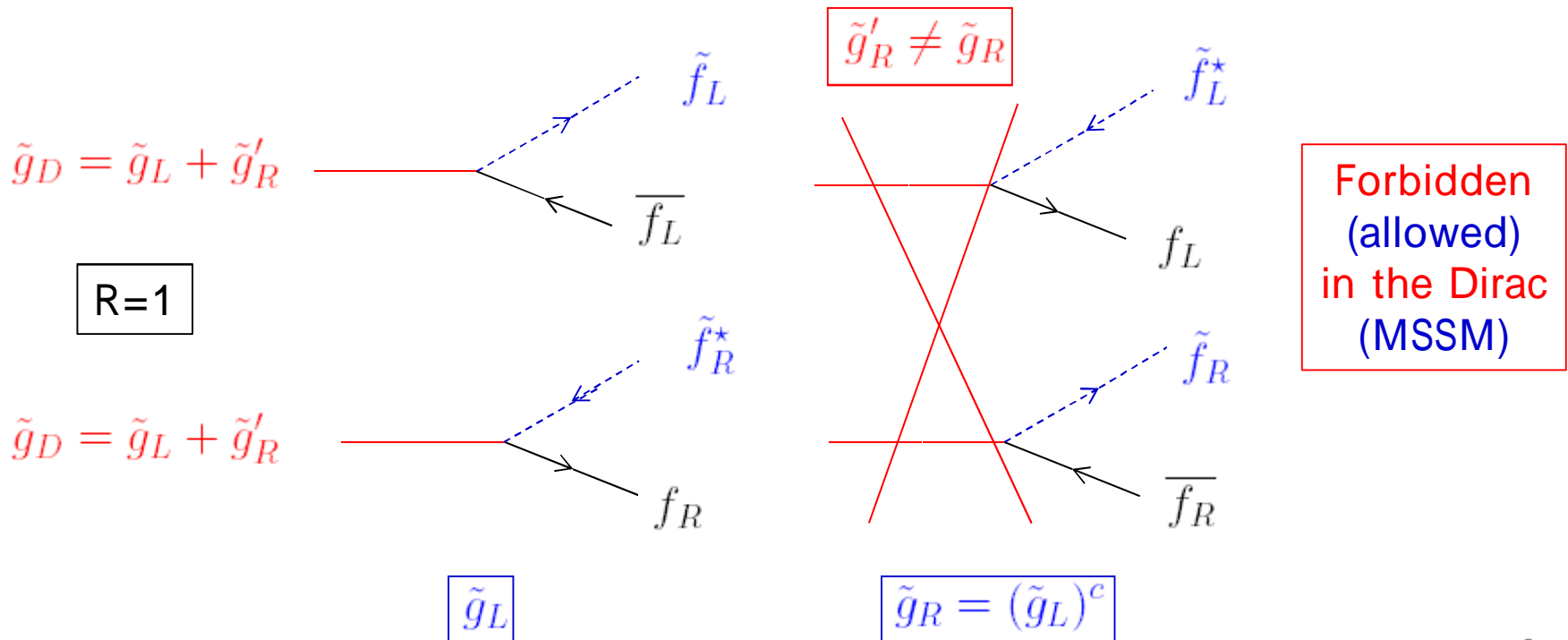
$$N=2 \text{ SUSY} \quad \text{——} \quad \begin{aligned} \lambda_u^I &= -\lambda_d^I = \;\; g/\sqrt{2} \\ \lambda_u^Y &= \;\; \lambda_d^Y = -g'/\sqrt{2} \end{aligned}$$

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## Couplings

◆ Both the MSSM and new gauginos are coupled minimally to gauge bosons

◆ Only the MSSM gauginos and H-higgsinos interact with sfermions carrying definite R charges.

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

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



$\tilde{g}_D = \tilde{g}_L + \tilde{g}'_R$

$\tilde{g}_D = \tilde{g}_L + \tilde{g}'_R$

R= 1

$\tilde{f}_L$

$\overline{f_L}$

$\tilde{f}^\star_R$

$f_R$

$\tilde{g}'_R \neq \tilde{g}_R$

$\tilde{f}^\star_L$

$f_L$

$\tilde{f}_R$

$\overline{f_R}$

Forbidden (allowed) in the Dirac (MSSM)

$\tilde{g}_L$

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

# 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 | $G_\mu$ | 0 | $\tilde{G}$ | +1 |
| Gauge Chiral | $\hat{\Sigma}$ | 0 | $\sigma$ | 0 | $\tilde{G}'$ | −1 |

MSSM matter, gauge and H-Higgs fields

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

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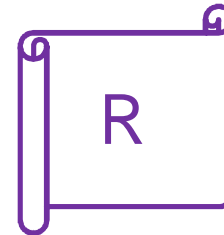
[Kribs ea, SYC ea, Nojiri ea, Plehn ea, Han ea, Hsieh, EJChun ea, Belanger ea, Kumar ea, Benakli ea, Fox ea, Davies ea, Sanz, …]

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

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

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
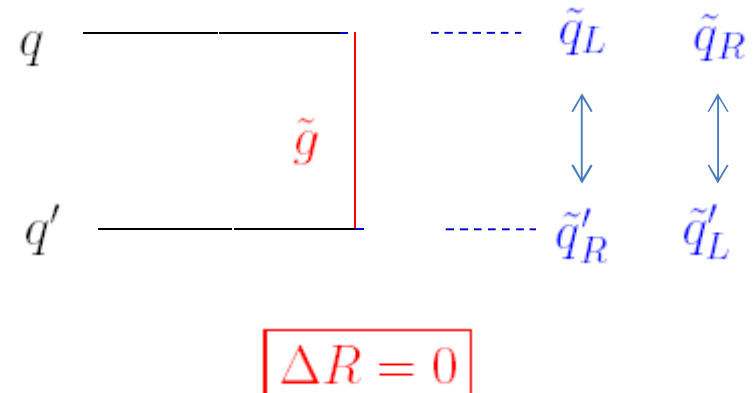
**MRSSM**

4 Dirac
Neutralinos

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

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]      10

# Squark pair production in pp collisions at the LHC



$q$ --------- $\tilde{q}_L$     $\tilde{q}_R$

$\tilde{g}$     $\updownarrow$     $\updownarrow$

$q'$ --------- $\tilde{q}'_L$     $\tilde{q}'_R$

$$\boxed{\Delta R = 2}$$

$q$ --------- $\tilde{q}_L$     $\tilde{q}_R$

$\tilde{g}$     $\updownarrow$     $\updownarrow$

$q'$ --------- $\tilde{q}'_R$     $\tilde{q}'_L$

$$\boxed{\Delta R = 0}$$
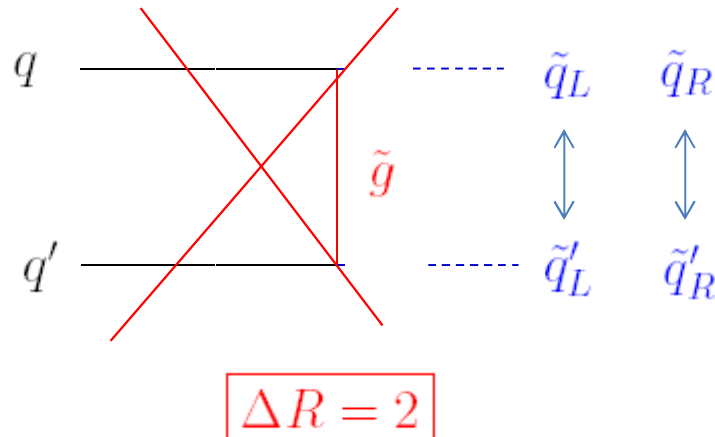
R- charge conservation in the Dirac (MRSSM) case kills the same chirality squark pair production in qq' collisions

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

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

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

Many other channels involved

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

D M discrimination at 10.5 with systematics for 300 fb$^{-1}$ (SPS1a')

[SYC, Drees, Freitas , Zerwas, 2008]

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

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## Squark cascade decays at the LHC (SPS1a')

Dirac $\Rightarrow$ Conserved R-charge

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

### Neutralino path

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



| | | hard | | 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

# Selectron pair production in e⁻e⁻ /e⁻e⁺ collisions



$$e^- \quad \tilde{e}_L^- \quad \tilde{e}_R^-$$
$$\tilde{\chi}^0 \quad \updownarrow \quad \updownarrow \quad \boxed{\Delta R = 2}$$
$$e^- \quad \tilde{e}_L^- \quad \tilde{e}_R^-$$

$$e^- \quad \tilde{e}_L^-$$
$$\tilde{\chi}^0 \quad \boxed{\Delta R = 0}$$
$$e^- \quad \tilde{e}_R^-$$

$$e^- \quad \tilde{e}_L^-$$
$$e^+ \quad \tilde{e}_R^+$$

$$e^- \quad \tilde{e}_L^- \quad \tilde{e}_R^-$$
$$\updownarrow \quad \updownarrow$$
$$e^+ \quad \tilde{e}_L^+ \quad \tilde{e}_R^+$$
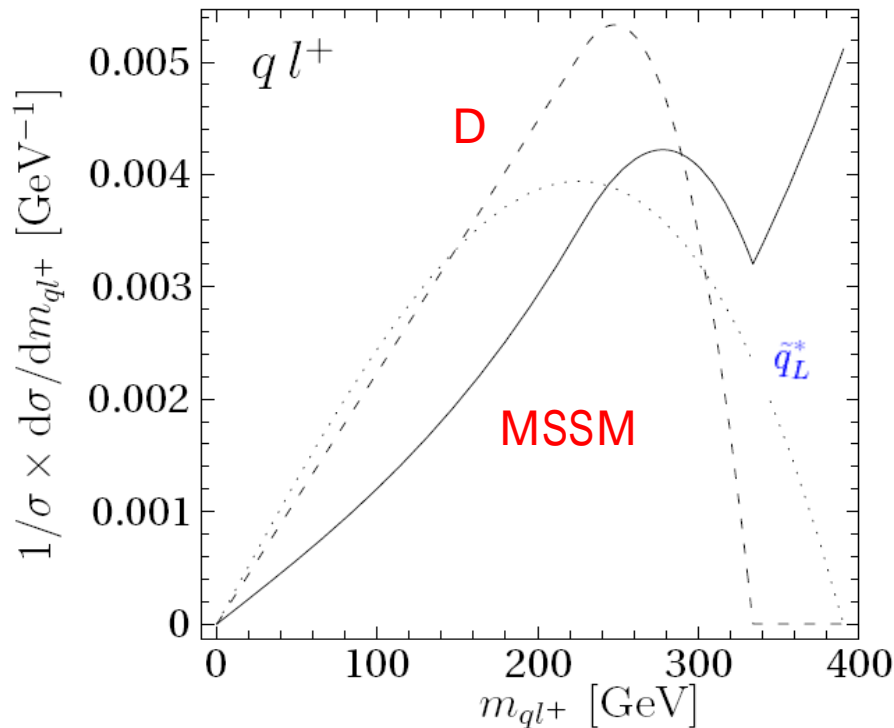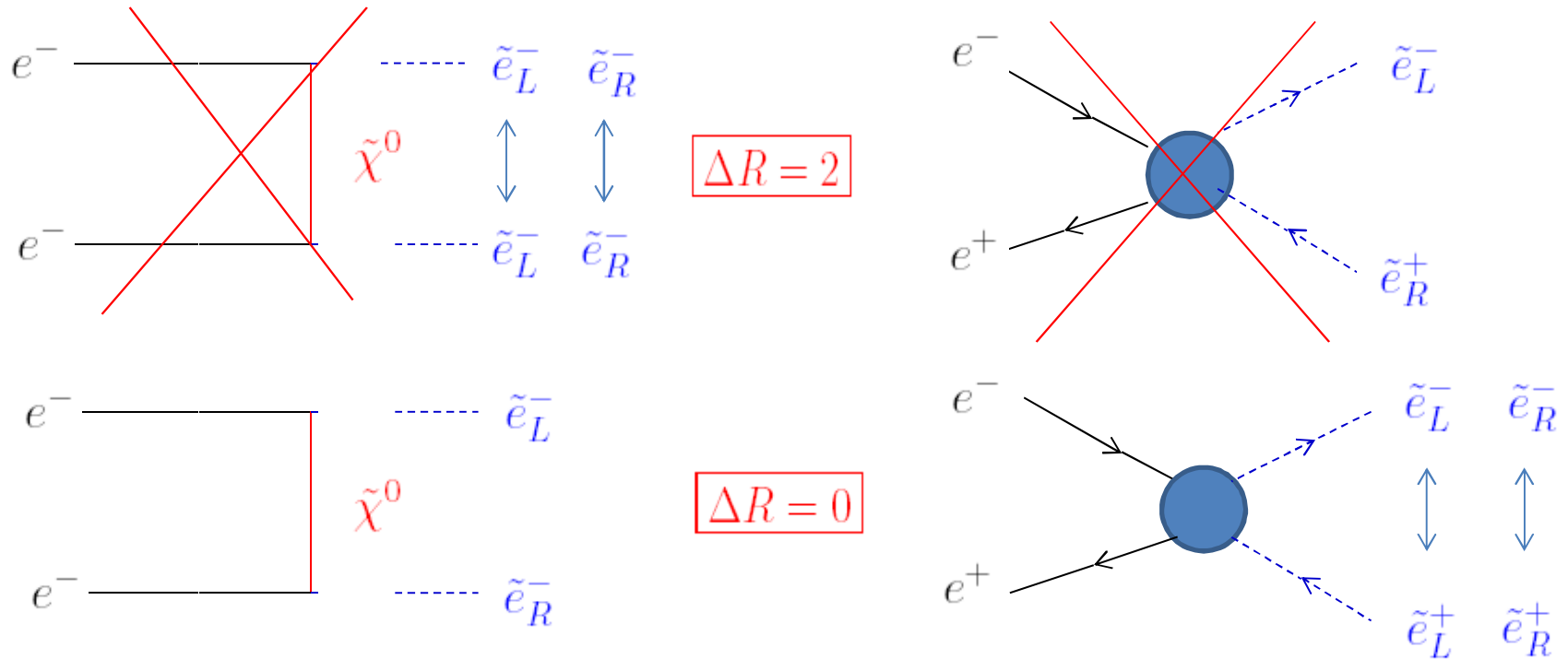
## Dirac (MRSSM)

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

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# Neutralino pair production and 3-body decays



**s**  **t**  **u**
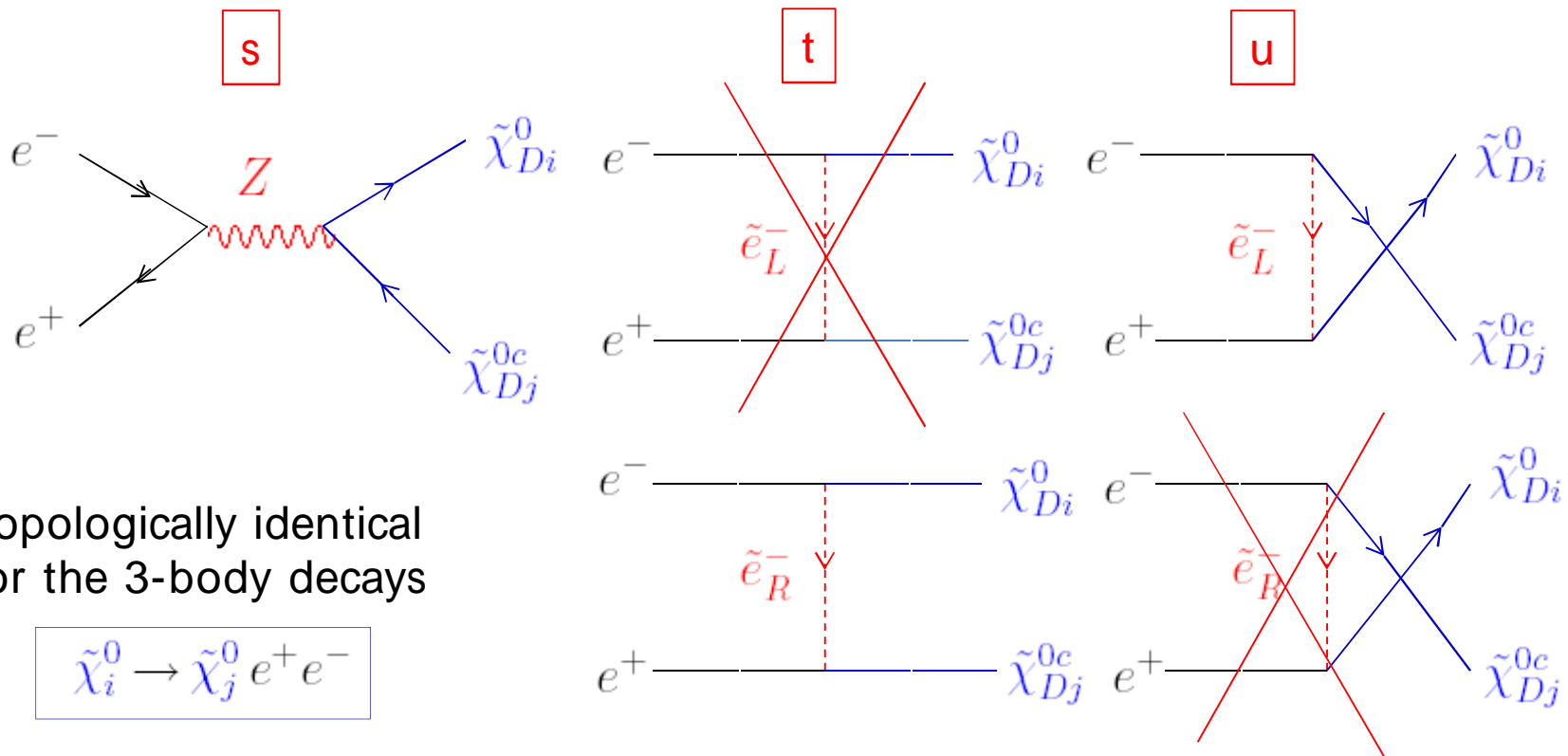
Topologically identical
for the 3-body decays

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

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

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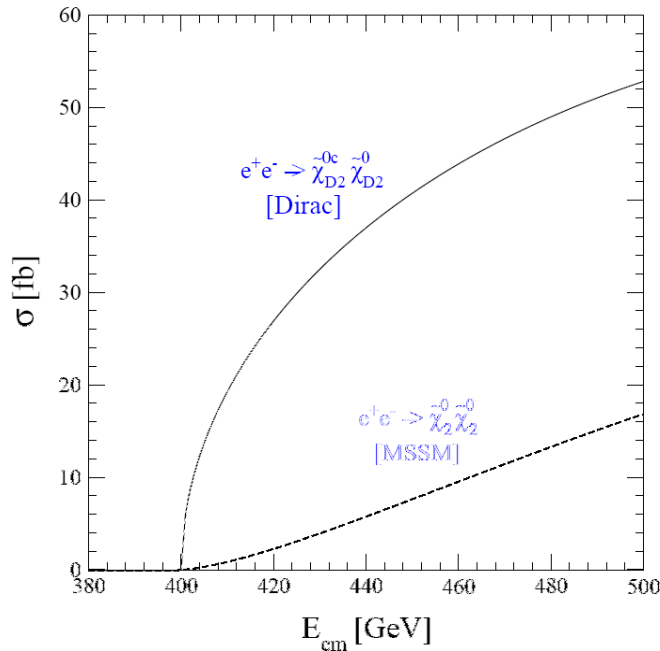
**P**   **D**

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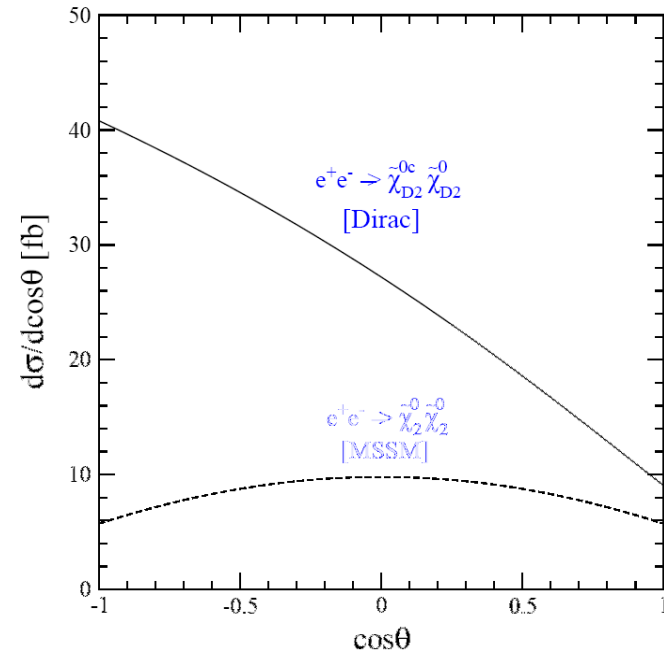
# Neutralino diagonal pair production

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

$$M_l = 200 \text{ GeV}, \; m_{\tilde{e}_L} = 400 \text{ GeV}$$



P-wave in MSSM

S-wave in Dirac

FB symmetric in MSSM
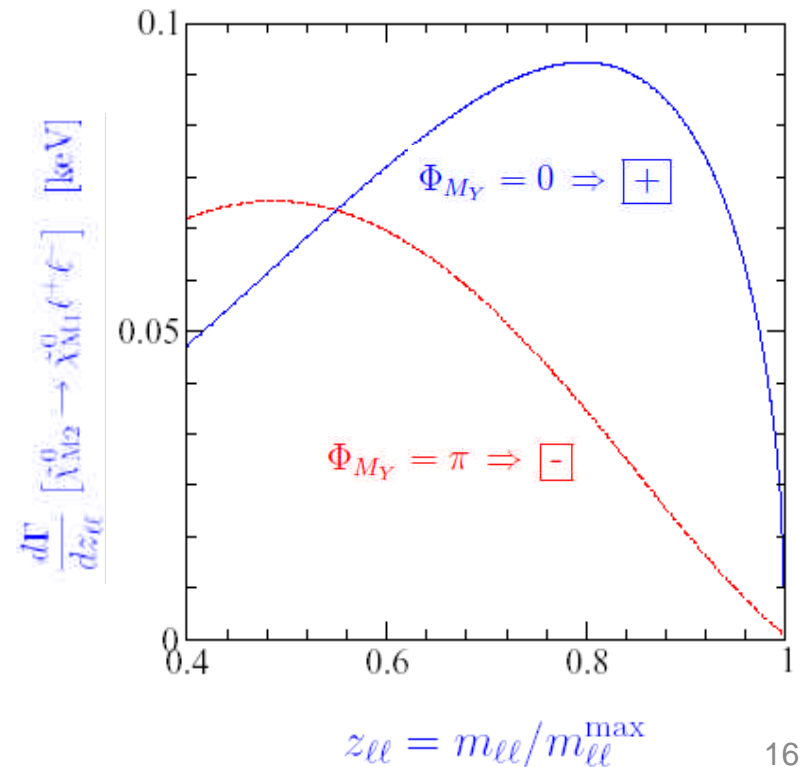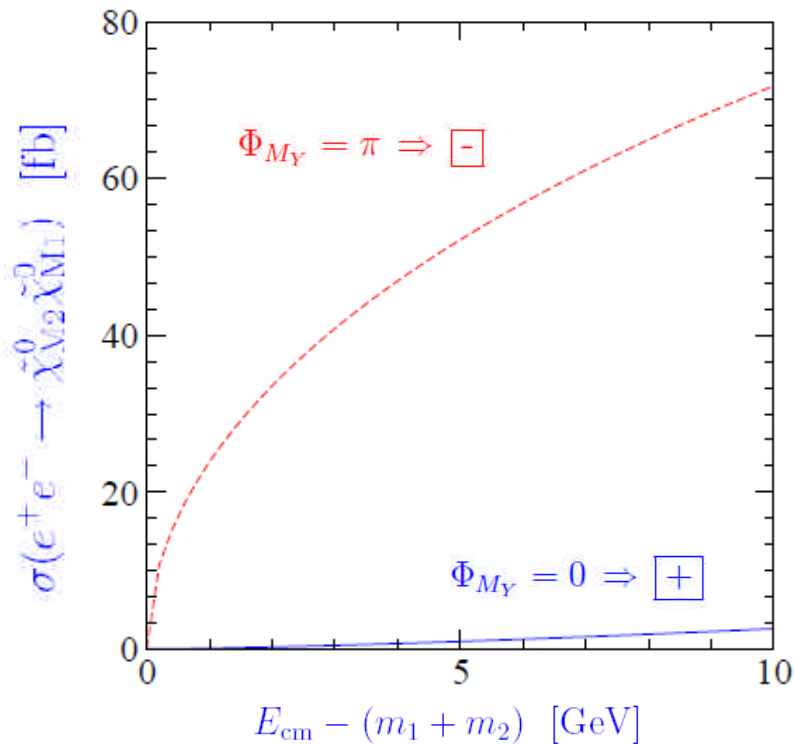
FB asymmetric in Dirac

Dirac     no t-/u-channel L/R selectron exchanges
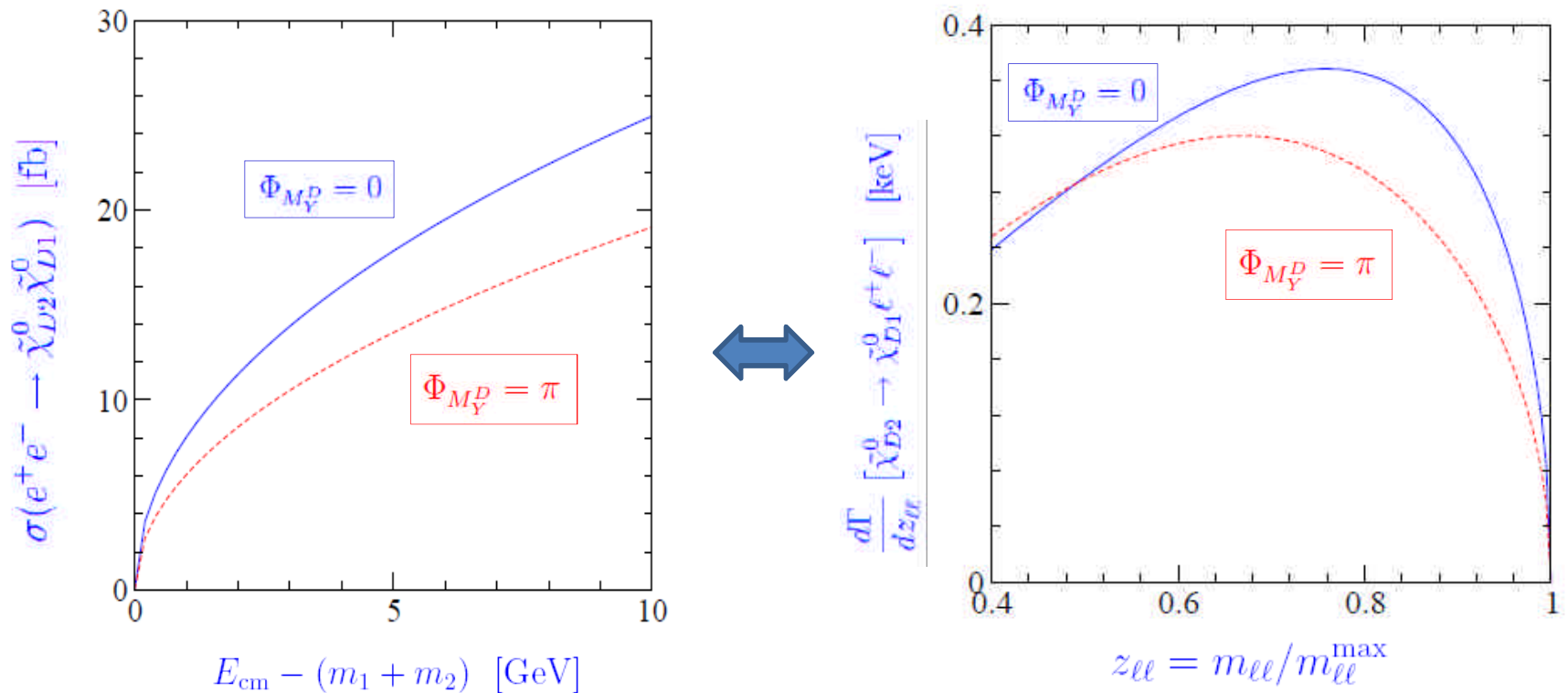
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## Nondiagonal pair production    3-body decays (MSSM)

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

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



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Nondiagonal pair production    3-body decays  (Dirac)

✠ Non-diagonal $D$ pair $\Rightarrow$ both $V$ and $A$ couplings $\Rightarrow$ always $S$-wave excitation



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# M

Summary

# D

◆ <u>Same (opposite)</u> chirality sfermion pair production in the <u>e-e- (e+e-)</u> mode

◆ <u>P-wave</u> excitation of neutralino <u>diagonal pair</u> production in the e+e- mode

◆ <u>Perfect P/S correlations</u> of neutralino non-diagonal pair <u>production</u> in the e+e- mode and its corresponding neutralino 3-body <u>decays</u>

◆      ---

◆ <u>Only opposite (same)</u> chirality sfermion pair production in the <u>e-e- (e+e-)</u> mode

◆ <u>S-wave</u> excitation for every neutralino pair <u>production</u> in the e+e- mode and of every neutralino 3-body <u>decays</u>

◆      ---

## Characteristic M vs. D neutralino signatures at the ILC
(Full realistic simulations required)