Signals for doubly charged Higgsinos at colliders

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M. Frank, K. Huitu, SKR (arXiv:0710.2415) Phys.Rev.D77:015006, 2008

D. Demir, M. Frank, K. Huitu, SKR, I.Turan (arXiv:0805.4202) subm. to Phys.Rev.D

Outline

- *Left-Right Supersymmetry*
- *Higgs Sector and Doubly Charged States*
- *Extended “ino” spectrum*
- *Production & Decay of doubly charged Higgsinos*
- *Collider Signals*
- *Conclusions & Outlook*

Supersymmetry

- *Supersymmetry is by far the most popular option for beyond standard model physics.*
  - *-- solves the gauge hierarchy problem*
  - *-- candidate for cold dark matter and new (s)particles*
  - *-- gauge coupling unification*
- *Neutrino mass generation in its minimal version*
  - -- *R-parity violation* $(-1)^{3(B-L)+2S}$
  - -- *Right-handed neutrinos (seesaw)*
- *No unique supersymmetric field theory to model new physics at the TeV scale.*

Left-Right Supersymmetry

- Supersymmetric left-right theories (LRSUSY) are based on the product group:

  $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- Gauged $U(1)_{B-L}$: R-parity conserving
- This product group is broken to $SU(3)_C \times U(1)_{em}$ by giving vevs to fields in the Higgs sector.

  $SU(2)_R \times U(1)_{B-L} \longrightarrow U(1)_Y$

- Neutrino masses are induced by the see-saw mechanism

  -- Higgs triplet fields with B-L= ±2

Higgs sector

- *The left-right symmetry is broken at a scale $\langle\Delta_R^0\rangle = v_R$*
- *The bi-doublet Higgs fields break the $SU(2)_L \times U(1)_Y$*
- *Supersymmetry requires other Higgs multiplets to cancel chiral anomalies among the fermionic partners*

$$\Phi_1 = \begin{pmatrix} \Phi_{11}^0 & \Phi_{11}^+ \\ \Phi_{12}^- & \Phi_{12}^0 \end{pmatrix} \sim (1,2,2,0)\,, \quad \Phi_2 = \begin{pmatrix} \Phi_{21}^0 & \Phi_{21}^+ \\ \Phi_{22}^- & \Phi_{22}^0 \end{pmatrix} \sim (1,2,2,0)$$

$$\Delta_L = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_L^- & \Delta_L^0 \\ \Delta_L^{--} & -\frac{1}{\sqrt{2}}\Delta_L^- \end{pmatrix} \sim (1,3,1,-2), \quad \delta_L = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta_L^+ & \delta_L^{++} \\ \delta_L^0 & -\frac{1}{\sqrt{2}}\delta_L^+ \end{pmatrix} \sim (1,3,1,2),$$

$$\Delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^- & \Delta_R^0 \\ \Delta_R^{--} & -\frac{1}{\sqrt{2}}\Delta_R^- \end{pmatrix} \sim (1,1,3,-2), \quad \delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta_R^+ & \delta_R^{++} \\ \delta_R^0 & -\frac{1}{\sqrt{2}}\delta_R^+ \end{pmatrix} \sim (1,1,3,2)$$

✷ The matter fields:

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \sim \left(3,2,1,\frac{1}{3}\right), \quad Q^c = \begin{pmatrix} d^c \\ u^c \end{pmatrix} \sim \left(3^*,1,2,-\frac{1}{3}\right),$$

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \sim (1,2,1,-1), \quad L^c = \begin{pmatrix} e^c \\ \nu^c \end{pmatrix} \sim (1,1,2,1),$$

✷ *The most general superpotential one can write is*

$$\begin{aligned} W &= \mathbf{Y}_Q^{(i)} Q^T \Phi_i i\tau_2 Q^c + \mathbf{Y}_L^{(i)} L^T \Phi_i i\tau_2 L^c + i(\mathbf{h}_{ll} L^T \tau_2 \delta_L L + \mathbf{h}_{ll} L^{cT} \tau_2 \Delta_R L^c) \\ &\quad + \mu_3 \left[Tr(\Delta_L \delta_L + \Delta_R \delta_R)\right] + \mu_{ij} Tr(i\tau_2 \Phi_i^T i\tau_2 \Phi_j) + W_{NR} \end{aligned}$$

and the soft terms as

$$\begin{aligned} \mathcal{L}_{soft} &= \Big[\mathbf{A}_Q^i \mathbf{Y}_Q^{(i)} \tilde{Q}^T \Phi_i i\tau_2 \tilde{Q}^c + \mathbf{A}_L^i \mathbf{Y}_L^{(i)} \tilde{L}^T \Phi_i i\tau_2 \tilde{L}^c + i\mathbf{A}_{LR} \mathbf{h}_{ll} (\tilde{L}^T \tau_2 \delta_L \tilde{L} + \tilde{L}^{cT} \tau_2 \Delta_R \tilde{L}^c) \\ &+ m_\Phi^{(ij)2} \Phi_i^\dagger \Phi_j\Big] + \Big[(m_L^2)_{ij} \tilde{l}_{Li}^\dagger \tilde{l}_{Lj} + (m_R^2)_{ij} \tilde{l}_{Ri}^\dagger \tilde{l}_{Rj}\Big] - M_{LR}^2 \left[Tr(\Delta_R \delta_R) + Tr(\Delta_L \delta_L) + h.c.\right] \\ &- [B\mu_{ij} \Phi_i \Phi_j + h.c.] \end{aligned}$$

- The vevs to the different scalar multiplets contributing to the symmetry breaking down to $U(1)_{em}$

$$\langle \delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_{\delta_L} & 0 \end{pmatrix}, \langle \Delta_R \rangle = \begin{pmatrix} 0 & v_{\Delta_R} \\ 0 & 0 \end{pmatrix}, \langle \delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_{\delta_R} & 0 \end{pmatrix}.$$

$$\langle \Phi_1 \rangle = \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_1' e^{i\omega_1} \end{pmatrix}, \langle \Phi_2 \rangle = \begin{pmatrix} \kappa_2' e^{i\omega_2} & 0 \\ 0 & \kappa_2 \end{pmatrix}, \langle \Delta_L \rangle = \begin{pmatrix} 0 & v_{\Delta_L} \\ 0 & 0 \end{pmatrix},$$

Extended “ino” spectrum

Due to the extended Higgs sector, the spectrum has additional higgsinos, both neutral, singly charged and doubly charged.

Δ_L^{++} , Δ_R^{++} , δ_L^{++} , δ_R^{++}

Mass term: $\mathcal{L}_{\tilde{\Delta}} = -M_{\tilde{\Delta}^{--}} \tilde{\Delta}_L^{--} \tilde{\delta}_L^{++} - M_{\tilde{\Delta}^{--}} \tilde{\Delta}_R^{--} \tilde{\delta}_R^{++} + h.c.,$

where $M_{\tilde{\Delta}^{--}} = \mu_3.$

6 charginos: $\tilde{\lambda}_L, \tilde{\lambda}_R, \tilde{\phi}_2, \tilde{\phi}_1, \tilde{\Delta}_L^{\pm}$, and $\tilde{\Delta}_R^{\pm}$.

11 neutralinos: $\tilde{\lambda}_Z, \tilde{\lambda}_{Z'}, \tilde{\lambda}_{B-L}, \tilde{\phi}_{21}^0, \tilde{\phi}_{22}^0, \tilde{\phi}_{11}^0, \tilde{\phi}_{12}^0, \tilde{\Delta}_L^0, \tilde{\Delta}_R^0, \tilde{\delta}_L^0$, and $\tilde{\delta}_R^0$.

Extended "ino" spectrum

For the charginos we have

$$\mathcal{L}_C = -\frac{1}{2}(\psi^{+T}, \psi^{-T}) \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix} \begin{pmatrix} \psi^+ \\ \psi^- \end{pmatrix} + \text{h.c.}$$

with

$$\psi^{+T} = (-i\lambda_L^+, -i\lambda_R^+, \tilde{\phi}_{1d}^+, \tilde{\phi}_{1u}^+, \tilde{\delta}_L^+, \tilde{\delta}_R^+) \qquad \psi^{-T} = (-i\lambda_L^-, -i\lambda_R^-, \tilde{\phi}_{2d}^-, \tilde{\phi}_{2u}^-, \tilde{\Delta}_L^-, \tilde{\Delta}_R^-)$$

the mass eigenstates are given by

$$\tilde{\chi}_i^+ = V_{ij}\psi_j^+, \; \tilde{\chi}_i^- = U_{ij}\psi_j^- \quad (i, j = 1, \ldots 6)$$

Extended "chargino" spectrum

$$X = \begin{pmatrix} M_L & 0 & 0 & g_L\kappa_d & \sqrt{2}g_L v_{\delta_L} & 0 \\ 0 & M_R & 0 & g_R\kappa_d & 0 & \sqrt{2}g_R v_{\delta_R} \\ g_L\kappa_u & g_R\kappa_u & 0 & -\mu_1 & 0 & 0 \\ 0 & 0 & -\mu_1 & 0 & 0 & 0 \\ \sqrt{2}g_L v_{\Delta_L} & 0 & 0 & 0 & -\mu_3 & 0 \\ 0 & \sqrt{2}g_R v_{\Delta_R} & 0 & 0 & 0 & -\mu_3 \end{pmatrix}$$

The mixing matrix is diagonalised by the unitary matrices

$$U^* X V^{-1} = M_D$$

Extended "neutralino" spectrum

$$\mathcal{L}_N = -\frac{1}{2}\psi^{0T} Z \psi^0 + \text{h.c.}$$

with

$$\psi^0 = (-i\lambda_L^0, -i\lambda_R^0, -i\lambda_{B-L}, \tilde{\phi}_{22}^0, \tilde{\phi}_{11}^0, \tilde{\Delta}_L^0, \tilde{\delta}_L^0, \tilde{\Delta}_R^0, \tilde{\delta}_R^0, \tilde{\phi}_{21}^0, \tilde{\phi}_{12}^0)^T$$

and the mass eigenstates in this case are given by

$$\tilde{\chi}_i^0 = N_{ij}\psi_j^0 \quad (i, j = 1, 2, \ldots 11)$$

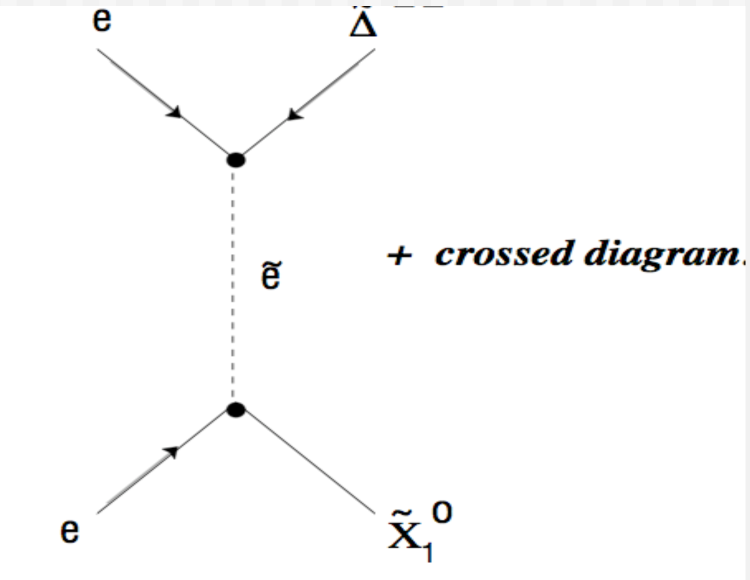
$$
Z = \begin{pmatrix}
M_L & 0 & 0 & -\frac{g_L\kappa_u}{\sqrt{2}} & \frac{g_L\kappa_d}{\sqrt{2}} & -2^{\frac{1}{2}}g_L v_{\Delta_L} & -2^{\frac{1}{2}}g_L v_{\delta_L} & 0 & 0 & 0 & 0 \\
0 & M_R & 0 & \frac{g_L\kappa_u}{\sqrt{2}} & \frac{g_L\kappa_d}{\sqrt{2}} & 0 & 0 & -2^{\frac{1}{2}}g_R v_{\Delta_R} & -2^{\frac{1}{2}}g_R v_{\delta_R} & 0 & 0 \\
0 & 0 & M_{B-L} & 0 & 0 & 2^{\frac{3}{2}}g_V v_{\Delta_L} & 2^{\frac{3}{2}}g_V v_{\delta_L} & 2^{\frac{3}{2}}g_V v_{\Delta_R} & 2^{\frac{3}{2}}g_V v_{\delta_R} & 0 & 0 \\
-\frac{g_L\kappa_u}{\sqrt{2}} & \frac{g_R\kappa_u}{\sqrt{2}} & 0 & 0 & \mu_1 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{g_L\kappa_d}{\sqrt{2}} & -\frac{g_R\kappa_d}{\sqrt{2}} & 0 & \mu_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-2^{\frac{1}{2}}g_L v_{\Delta_L} & 0 & 2^{\frac{3}{2}}g_V v_{\Delta_L} & 0 & 0 & 0 & -\mu_3 & 0 & 0 & 0 & 0 \\
-2^{\frac{1}{2}}g_L v_{\delta_L} & 0 & 2^{\frac{3}{2}}g_V v_{\delta_L} & 0 & 0 & -\mu_3 & 0 & 0 & 0 & 0 & 0 \\
0 & -2^{\frac{1}{2}}g_R v_{\Delta_R} & 2^{\frac{3}{2}}g_V v_{\Delta_R} & 0 & 0 & 0 & 0 & 0 & -\mu_3 & 0 & 0 \\
0 & -2^{\frac{1}{2}}g_R v_{\delta_R} & 2^{\frac{3}{2}}g_V v_{\delta_R} & 0 & 0 & 0 & 0 & -\mu_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mu_1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mu_1 & 0
\end{pmatrix}
$$

The mixing matrix is diagonalised by the unitary matrix

$$
N^* Z N^T = Z_D,
$$

Collider Signals

Single production mode at linear e^- e^- colliders



$$e^- e^- \longrightarrow \tilde{\Delta}^{--} \tilde{\chi}_1^0$$

ideal for production of such doubly charged exotics

allows to probe a large range of masses of the doubly charged Higgsinos

(pair production at e+e- and $\gamma\gamma$)

Single and pair production at LHC

- $pp \longrightarrow \widetilde{\chi}_1^+ \, \widetilde{\Delta}^{--}$
- $pp \longrightarrow \widetilde{\Delta}^{++} \, \widetilde{\Delta}^{--}$

Decay modes

2-body decays

- $\widetilde{\Delta}^{--} \longrightarrow \widetilde{\ell}^- \, \ell^-,$
- $\widetilde{\Delta}^{--} \longrightarrow \Delta^{--} \, \widetilde{\chi}_i^0,$
- $\widetilde{\Delta}^{--} \longrightarrow \widetilde{\chi}_i^- \, \Delta^-,$
- $\widetilde{\Delta}^{--} \longrightarrow \widetilde{\chi}_i^- \, W^-,$

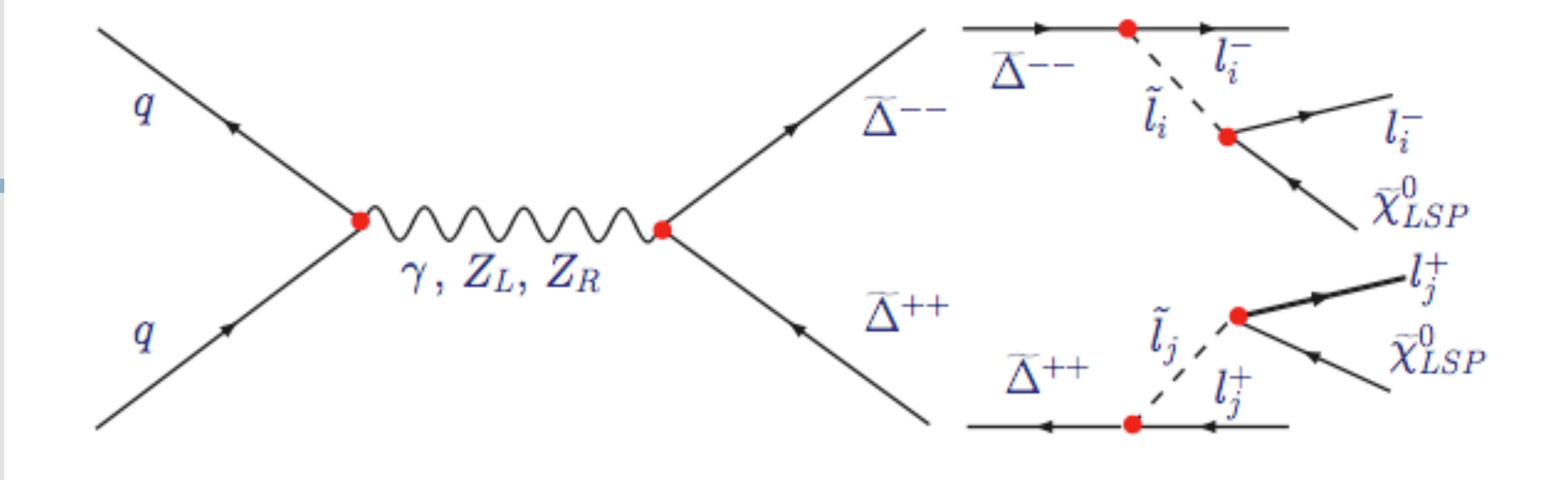
(S2)

favored channel for decay which is $\tilde{\Delta}^{--} \longrightarrow \tilde{\ell}^- \, \ell^-$, provided $m_{\tilde{l}} < M_{\tilde{\Delta}^{--}}$.

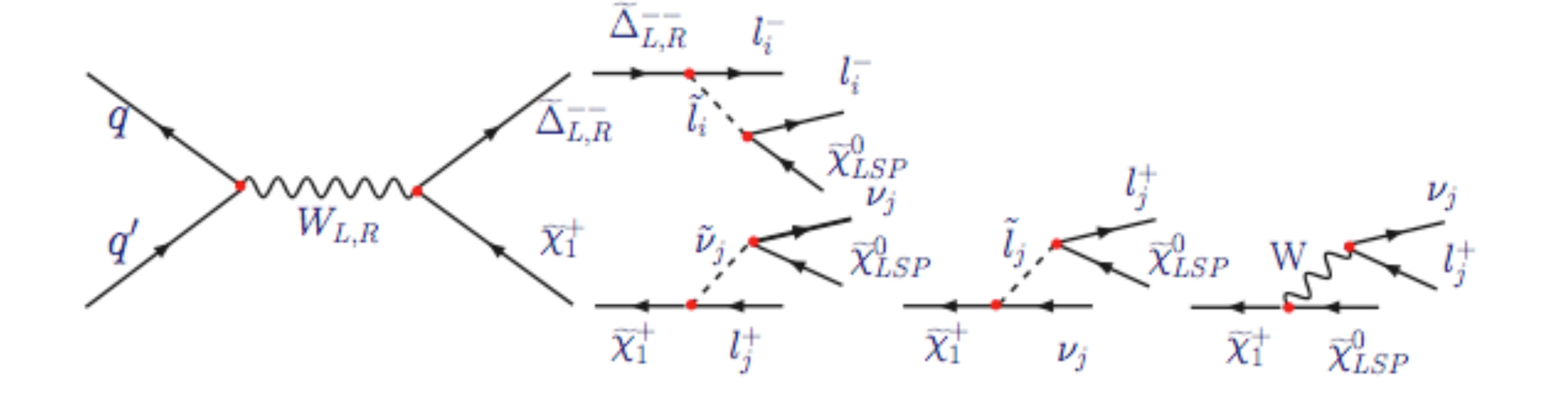
or $\tilde{\Delta}^{--} \to \tilde{\ell}^{*-} \, \ell^- \to \ell^- \ell^- \tilde{\chi}_1^0.$

(S3)

4 lepton signals:



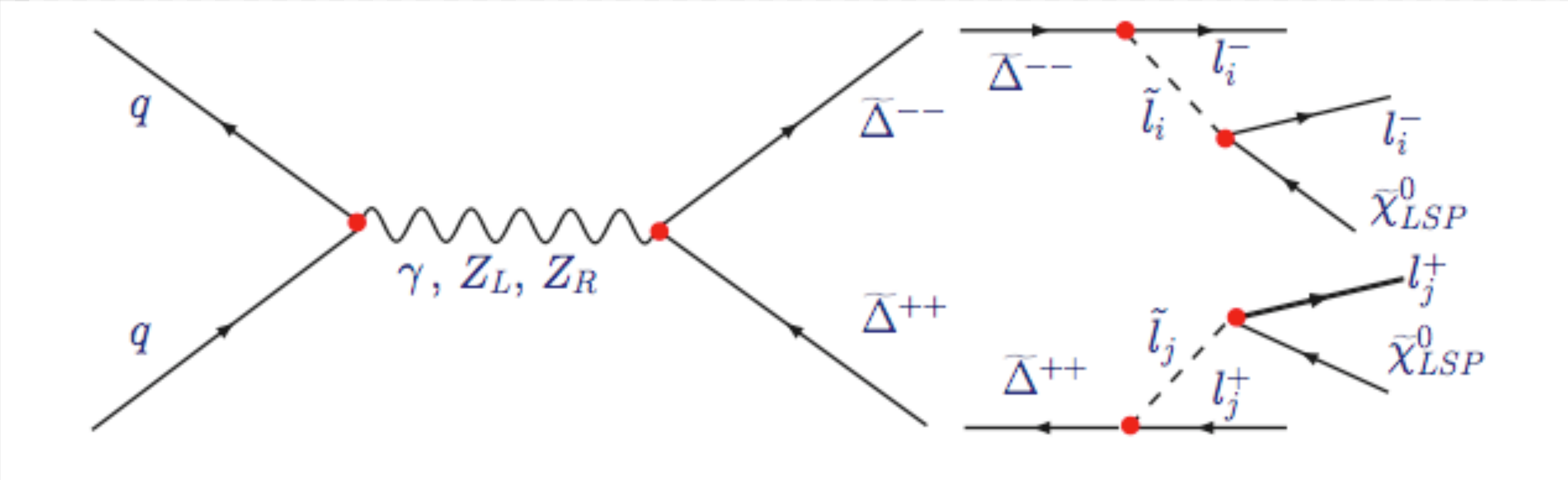
3 lepton signals:



Representative points

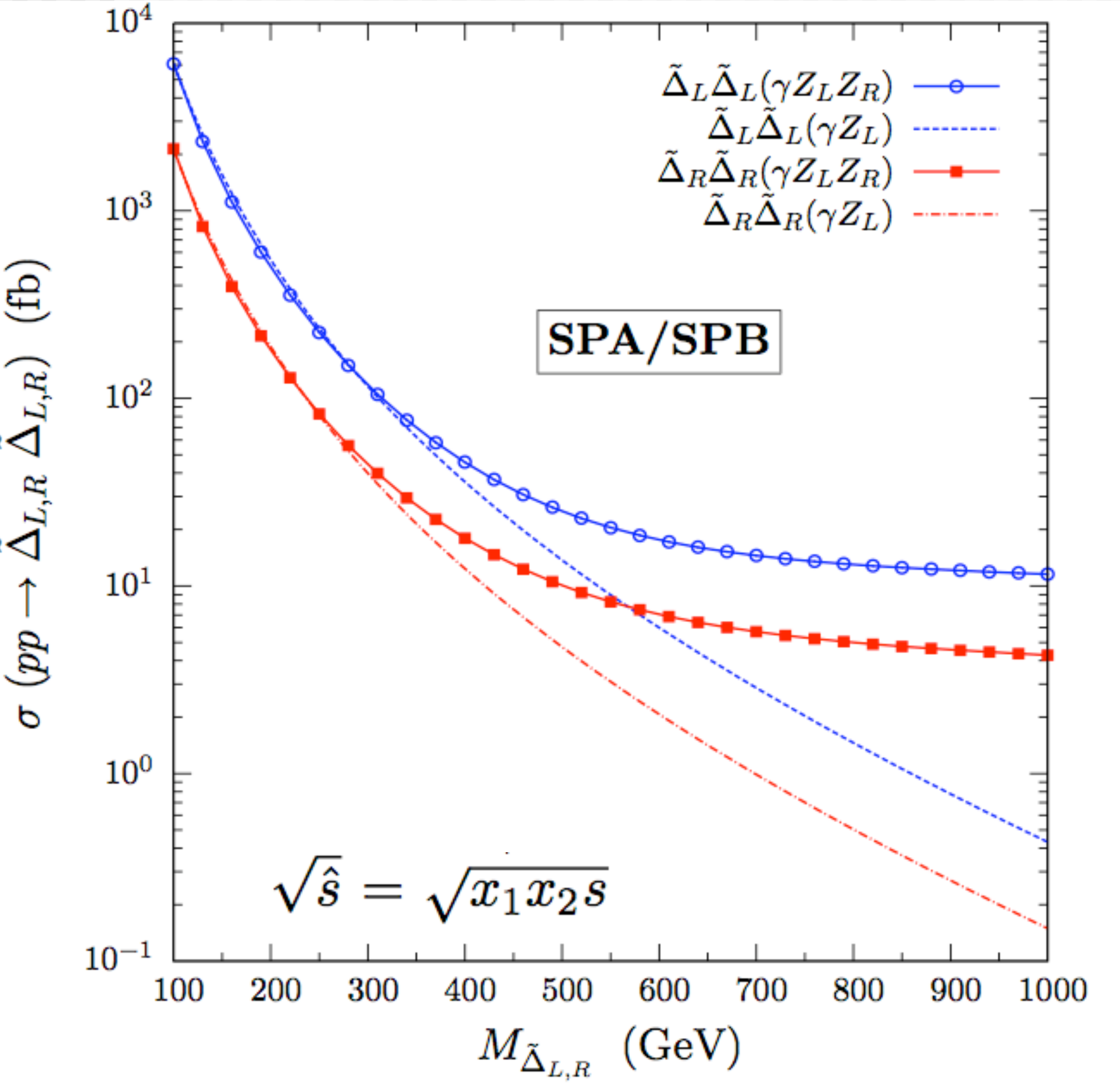
Fields	SPA	SPB
	SPA	**SPB**
	$\tan\beta = 5, M_{B-L} = 25$ GeV	$\tan\beta = 5, M_{B-L} = 100$ GeV
Fields	$M_L = M_R = 250$ GeV	$M_L = M_R = 500$ GeV
	$v_{\Delta_R} = 3000$ GeV, $\mathrm{v}_{\delta_\mathrm{R}} = 1000$ GeV	$v_{\Delta_R} = 2500$ GeV, $\mathrm{v}_{\delta_\mathrm{R}} = 1500$ GeV
	$\mu_1 = 1000$ GeV, $\mu_3 = 300$ GeV	$\mu_1 = 500$ GeV, $\mu_3 = 500$ GeV
$\widetilde{\chi}_i^0$ $(i = 1, 3)$	89.9, 180.6, 250.9 GeV	212.9, 441.2, 458.5 GeV
$\widetilde{\chi}_i^\pm$ $(i = 1, 3)$	250.9, 300.0, 953.9 GeV	459.4, 500.0, 500.0 GeV
$M_{\widetilde{\Delta}}$	300 GeV	500 GeV
W_R, Z_R	2090.4, 3508.5 GeV	1927.2, 3234.8 GeV
	S2 **S3**	**S2** **S3**
$\widetilde{e}_L, \widetilde{e}_R$	(156.9, 155.6 GeV), (402, 402 GeV)	(254.2, 253.4 GeV), (552, 552 GeV)
$\widetilde{\mu}_L, \widetilde{\mu}_R$	(156.9, 155.6 GeV), (402, 402 GeV)	(254.2, 253.4 GeV), (552, 552 GeV)
$\widetilde{\tau}_1, \widetilde{\tau}_2$	(155.4, 159.9 GeV), (401, 406 GeV)	(252.5, 257.9 GeV), (550, 556 GeV)

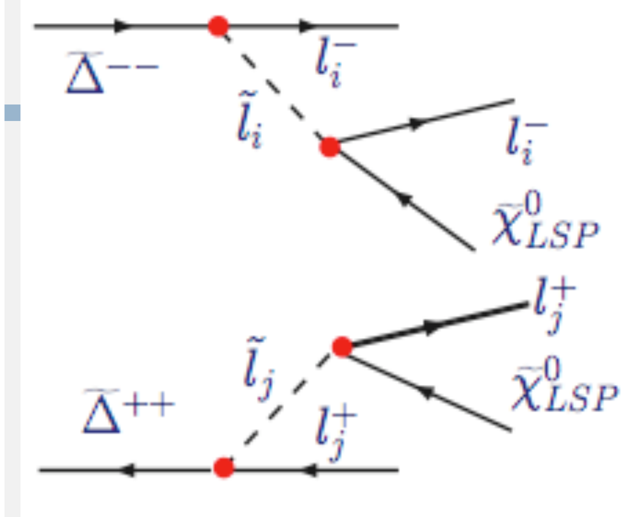
4 lepton signals:



4 lepton signals

$$pp \longrightarrow \widetilde{\Delta}^{++}\widetilde{\Delta}^{--} \longrightarrow (\ell_i^+\ell_i^+) + (\ell_j^-\ell_j^-) + \not{E}_T$$





- *cross section is quite sizeable for sufficiently light doubly charged Higgsinos ~10^4 fb*
- *The $4l$ + **MET** Signal receives contributions from the pair production of both chiral states of Δ.*

4 lepton signals at LHC

♣ *We have a rather clean and robust signal with highly suppressed SM background.*

♣ *For tetralepton signals with a sufficiently large MET, SM background is estimated to be ~10^{-3} fb.*

♣ *This makes this channel highly promising for an efficient and clean disentanglement of LRSUSY effects.*

♣ *Kinematic cuts:*

$p_T^{l} > 25$ GeV ; $|\eta_l| < 2.5$

$\Delta R_{ll} > 0.4$ & $E_T^{miss} > 50$ GeV

4 lepton signals at LHC

- *We use the CalcHEP+Pythia interface for numerical analysis.*
- *For the analysis we choose ($2\mu^- + 2e^+$)+ **MET** final state*
- *SPA:*

$$\sigma(\widetilde{\Delta}_L^{--}\widetilde{\Delta}_L^{++}) = 117.9 \text{ fb}$$

$$\sigma(\widetilde{\Delta}_R^{--}\widetilde{\Delta}_R^{++}) = 44.5 \text{ fb.}$$

After cuts

– **S2** $\sigma(2\mu^-2e^+ + \not{E}_T) = 7.71$ fb,

– **S3** $\sigma(2\mu^-2e^+ + \not{E}_T) = 7.02$ fb.

- *SPB:*

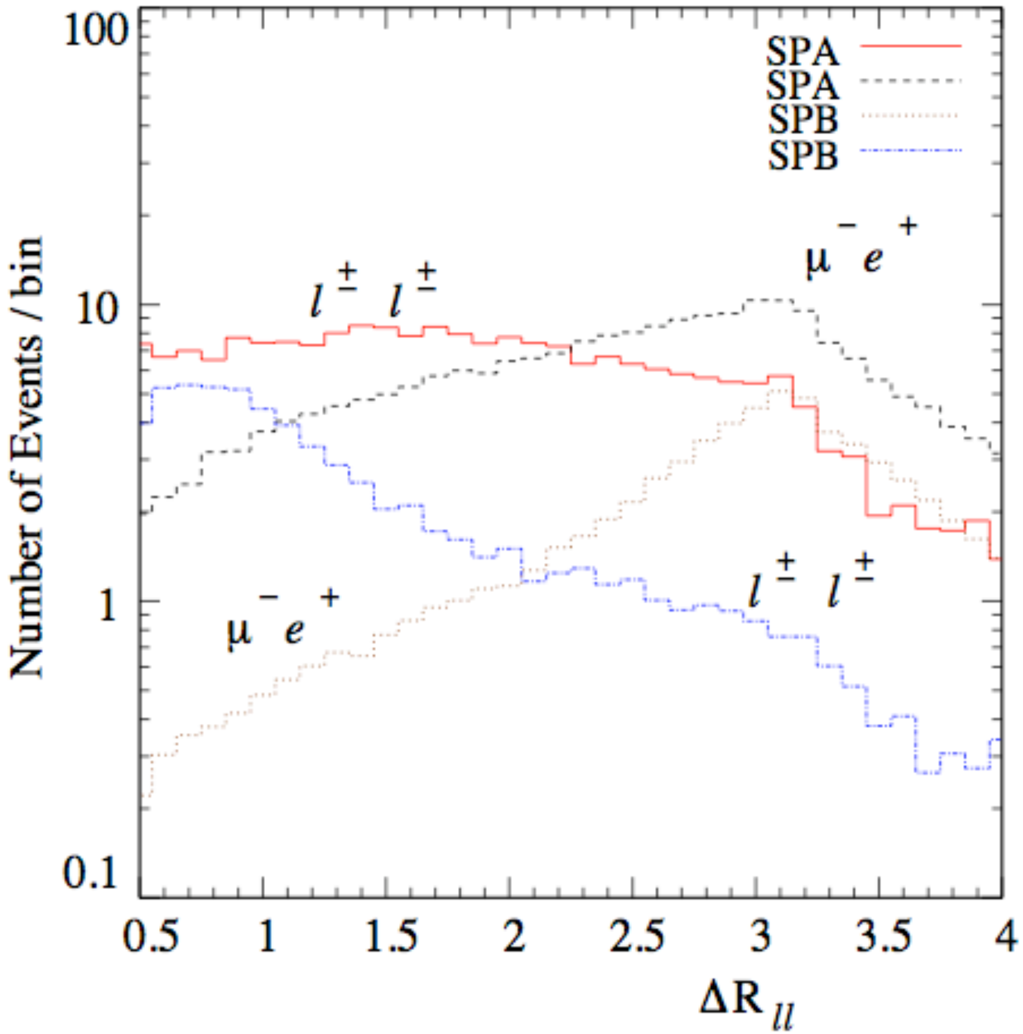
$$\sigma(\widetilde{\Delta}_L^{--}\widetilde{\Delta}_L^{++}) = 32.4 \text{ fb}$$

$$\sigma(\widetilde{\Delta}_R^{--}\widetilde{\Delta}_R^{++}) = 12.95 \text{ fb.}$$

– **S2** $\sigma(2\mu^-2e^+ + \not{E}_T) = 2.43$ fb,

– **S3** $\sigma(2\mu^-2e^+ + \not{E}_T) = 2.66$ fb.

4 lepton signals at LHC



- *SSSF leptons are peaked at lower values* ΔR_{ll}
- *OSDF configurations are formed from two isolated leptons originating from separate cascades.*

For SPA: M_{ll} **=209.6 GeV (S2) , 210.1 GeV (S3)**

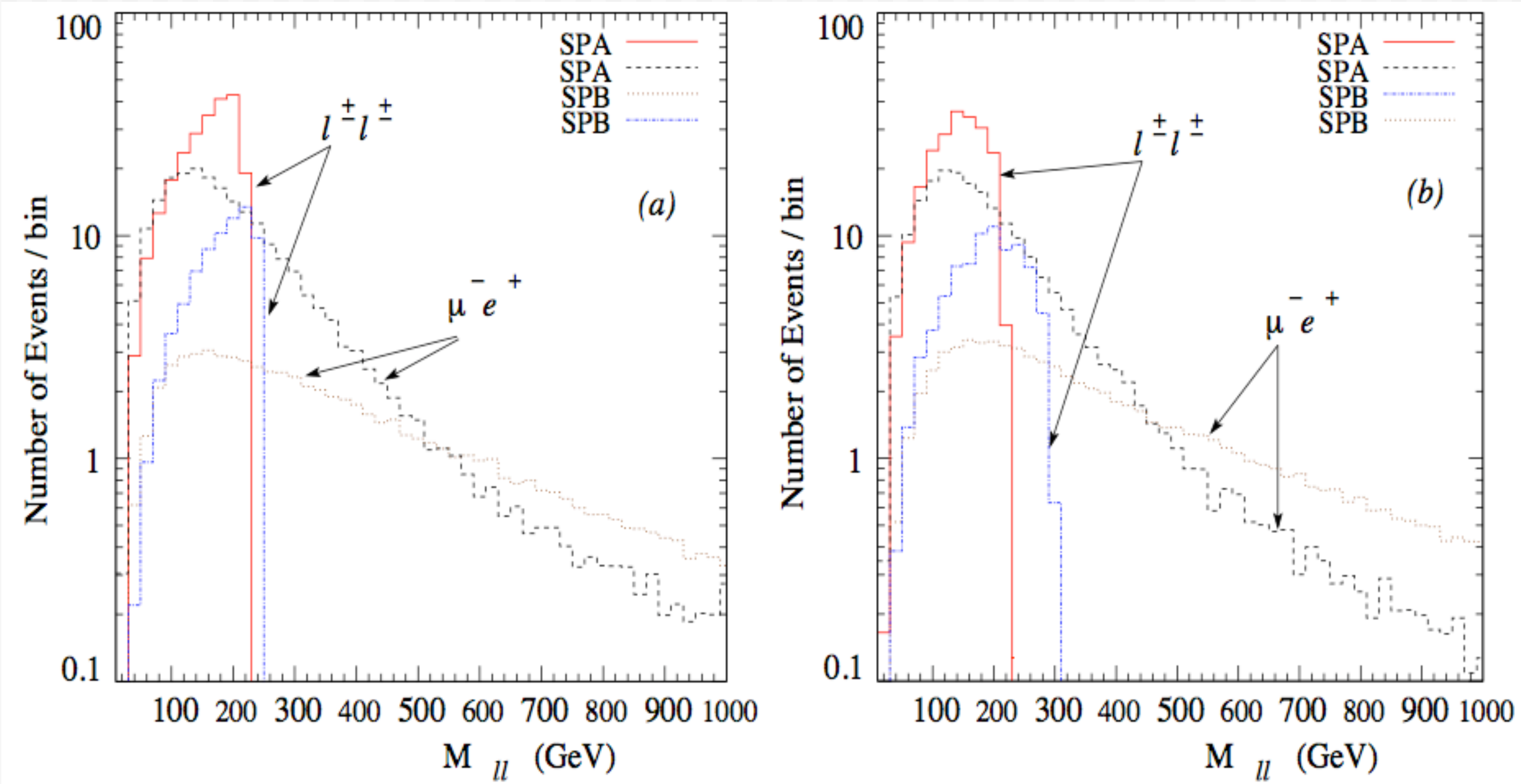
For SPB: M_{ll} **=235.2 GeV (S2) , 287.1 GeV (S3)**

(S2)

$$M^{max}_{\ell^\pm\ell^\pm} = M_{\tilde{\Delta}}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{M_{\tilde{\Delta}}}\right)^2}\sqrt{1-\left(\frac{M_{\tilde{\chi}^0_1}}{m_{\tilde{\ell}}}\right)^2}$$

(S3)

$$M^{max}_{\ell^\pm\ell^\pm} = \sqrt{M^2_{\tilde{\Delta}} + M^2_{\tilde{\chi}^0_1} - 2M_{\tilde{\Delta}}E_{\tilde{\chi}^0_1}} \ ,$$

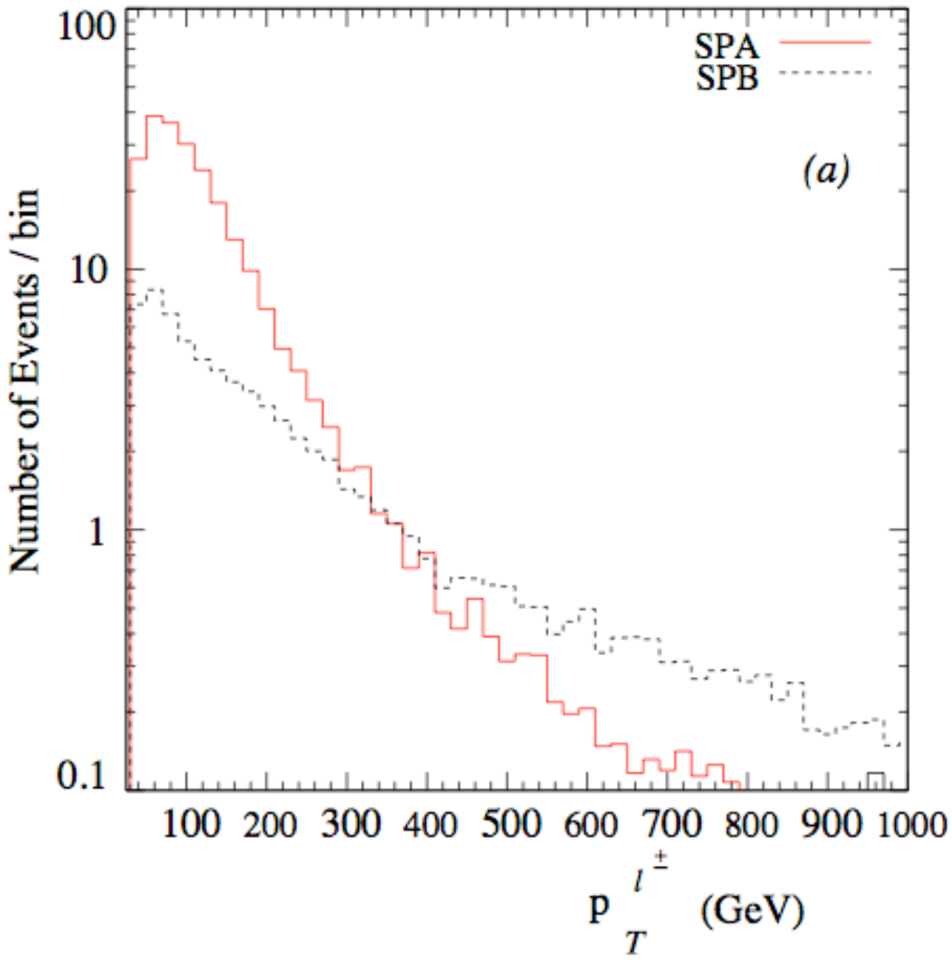


The edge in the SSSF dilepton invariant mass -> hint of a $\Delta L = 2$ *interaction and a doubly charged particle in the underlying model of* ***new physics.***

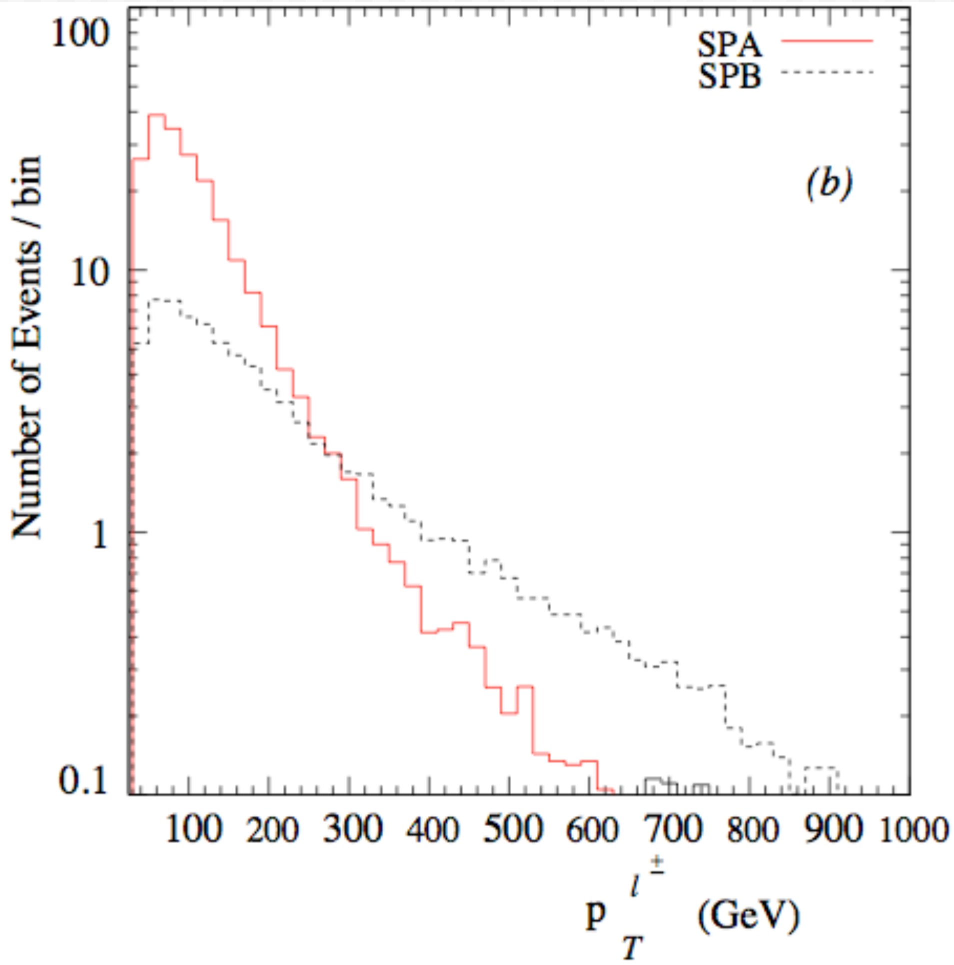
4 lepton signals at LHC

The p_T distribution for the charged leptons

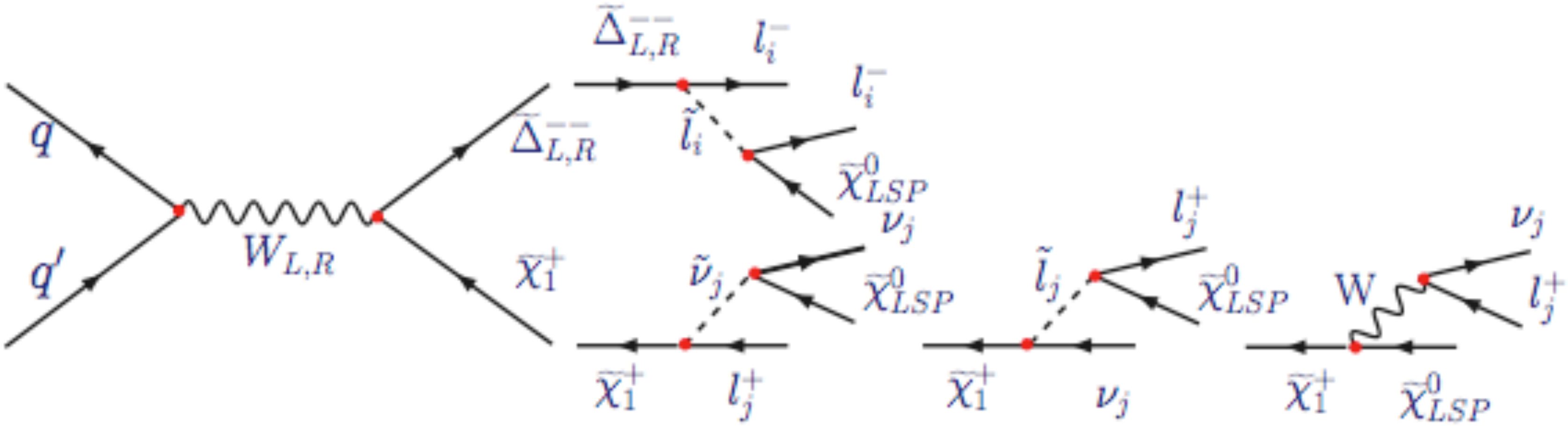
(S2)



(S3)



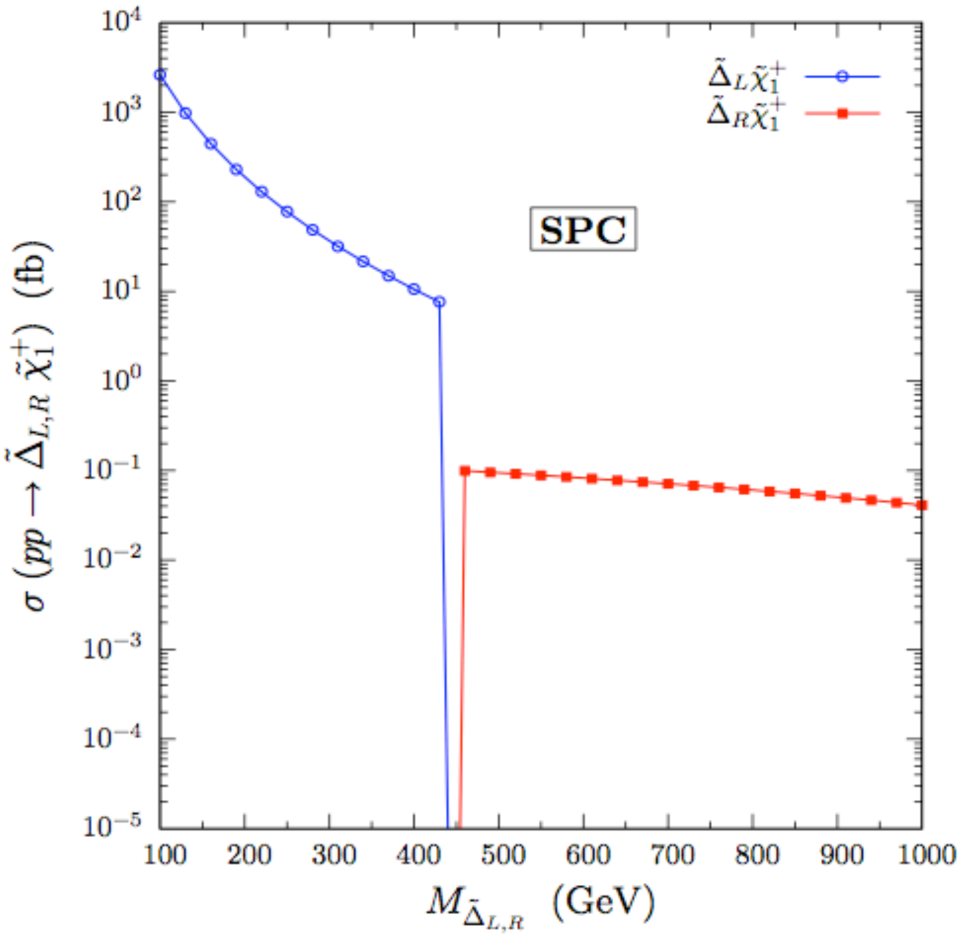
3 lepton signals:



Fields	SPC	
	$\tan\beta = 5, M_{B-L} = 0$ GeV $M_L = M_R = 500$ GeV $v_{\Delta_R} = 2500$ GeV, $v_{\delta_R} = 1500$ GeV $\mu_1 = 500$ GeV, $\mu_3 = 300$ GeV	
$\widetilde{\chi}^0_i$ $(i = 1,3)$	142.5, 265.6, 300.0 GeV	
$\widetilde{\chi}^\pm_i$ $(i = 1,3)$	300.0, 459.3, 500.0 GeV	
$M_{\widetilde{\Delta}}$	300 GeV	
W_R, Z_R	1927.2, 3234.8 GeV	
	S2	**S3**
$\widetilde{e}_L, \widetilde{e}_R$	(214.9, 214.0 GeV),	(402.6, 402.2 GeV)
$\widetilde{\mu}_L, \widetilde{\mu}_R$	(214.9, 214.0 GeV),	(402.6, 402.2 GeV)
$\widetilde{\tau}_1, \widetilde{\tau}_2$	(212.8, 216.2 GeV),	(401.5, 403.3 GeV)

3 lepton signals at LHC

$$pp \longrightarrow \widetilde{\Delta}^{--}\,\widetilde{\chi}_1^{+} \longrightarrow \left(\ell_i^- \ell_i^-\right) + \ell_j^+ + \not{E}_T,$$



- *Cross section small for SPA and SPB.*
- *SPC gives appreciable rates.*
- *Strongly depends on the composition of the lightest chargino.*
- *The dominant decay for chargino is slepton+neutrino~100%*

Couplings:

- $W_L^\mu\ \tilde{\chi}_k^+\ \tilde{\Delta}_L^{--}$: $\quad ig_L\gamma^\mu(V_{k5}^\star P_L + U_{k5}P_R)$
- $W_R^\mu \tilde{\chi}_k^+ \tilde{\Delta}_R^{--}$: $\quad ig_R\gamma^\mu(V_{k6}^\star P_L + U_{k6}P_R)$

3 lepton signals at LHC

- *We use the similar cuts for the numerical analysis.*
- *For the analysis we choose ($\mathbf{2}\mu^-$ + $\boldsymbol{e}^+$)+ **MET** final state*
- *SPC:* *After cuts*

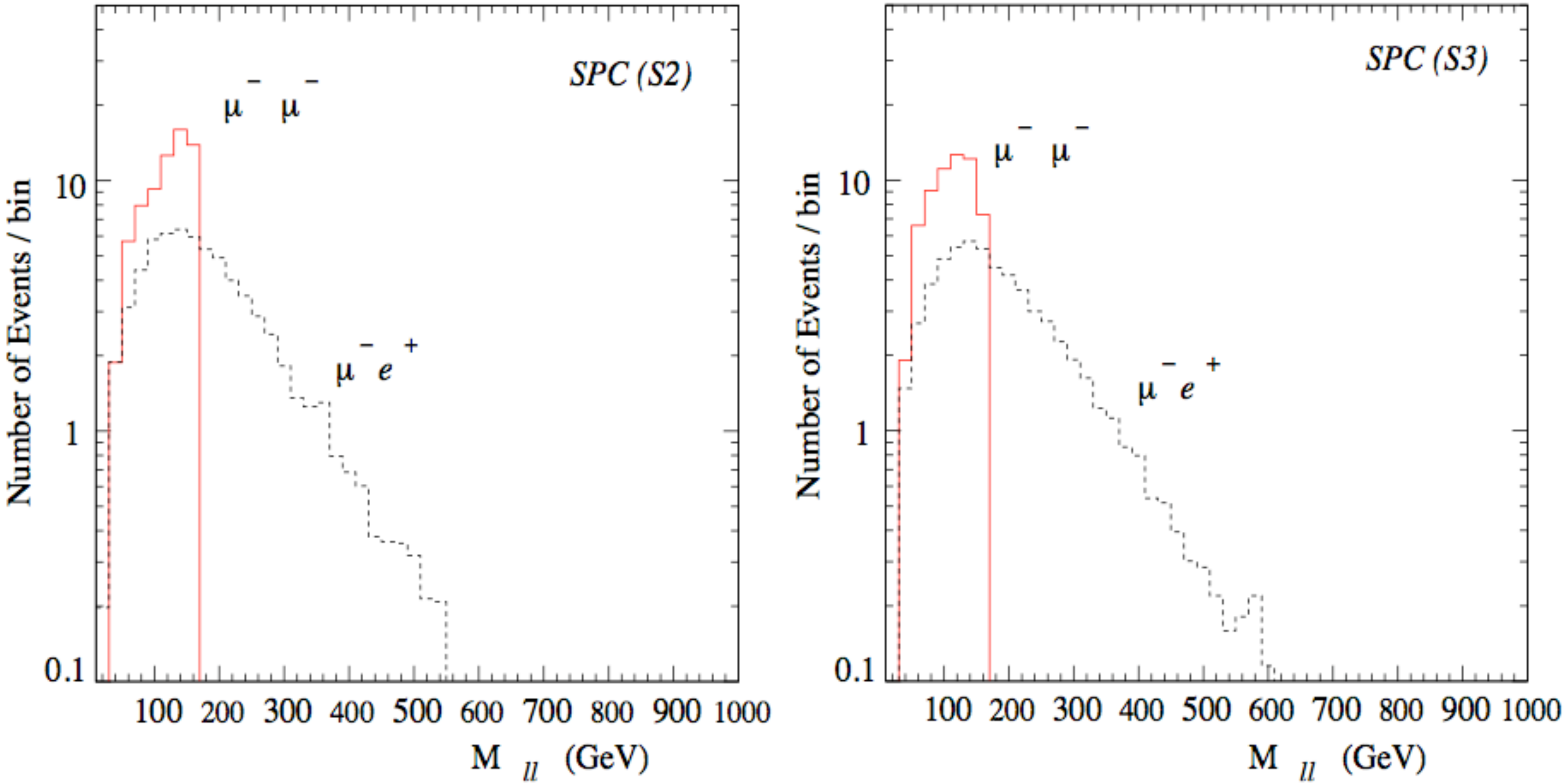
$$\sigma(\widetilde{\Delta}_L^{--}\widetilde{\chi}_1^+) = 36.57 \text{ fb},$$

$$- \textbf{S2} \quad \sigma(2\ell_i^- \ell_j^+ \not{E}_T) = 2.24 \text{ fb},$$
$$- \textbf{S3} \quad \sigma(2\ell_i^- \ell_j^+ \not{E}_T) = 2.03 \text{ fb},$$

- *Relatively similar kinematic distributions for the SSSF and OSDF dilepton pairs.*

3 lepton signals at LHC

For SPC: M_{ll} **=156.7 GeV (S2) , 157.5 GeV (S3)**



Distinguishing power at LHC

♣ *The $4l$+MET signal is an excellent option to achieve this.*

♣ *Once we make the choice $l_i \neq l_j$ we have two pairs SSSF dileptons in the final state. --> ($2\mu^- + 2e^+$)*

hard to think of "standard" SUSY or UED giving this. Possible if all 4 leptons are identical flavour.

The invariant mass distribution for the SSSF dilepton (or OSSF) and the ΔR_{ll} distribution would prove to be a good discriminant.

(In SUSY/UED χ_2 / Z_1 pair production)

Distinguishing power at LHC

♣ *possibilities with two different flavours..*

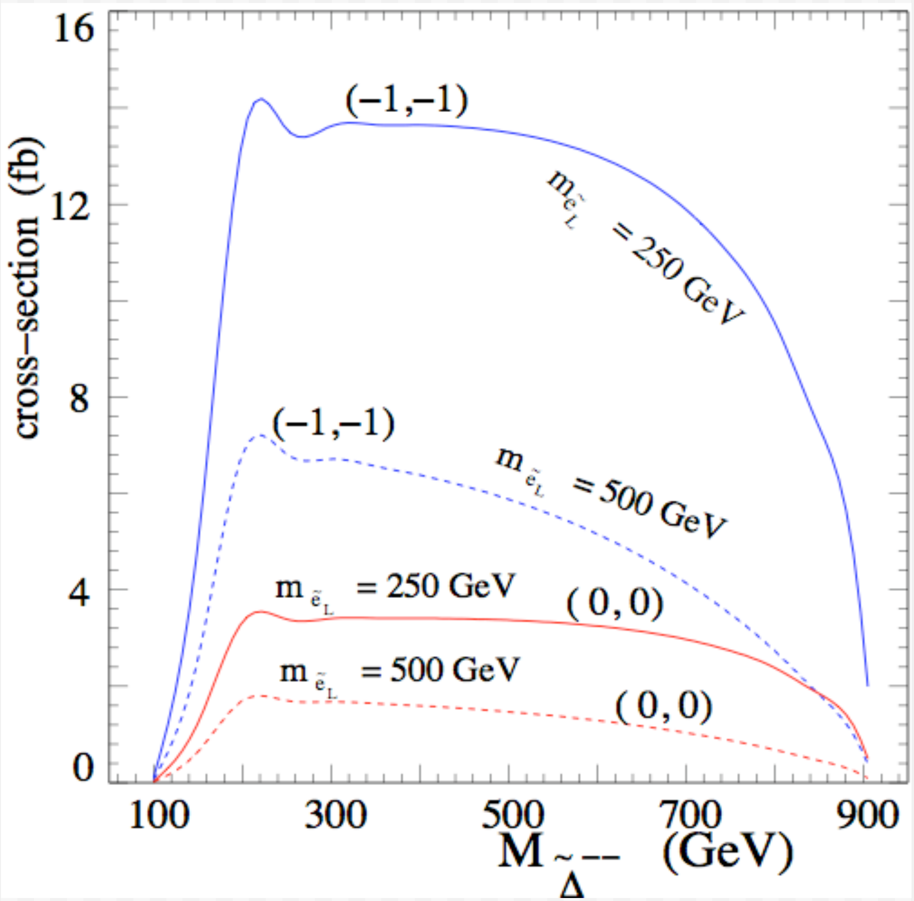
-- *pair production of doubly charged scalar*

(invariant mass distribution for SSSF dilepton should give a sharp peak --> scalar mass)

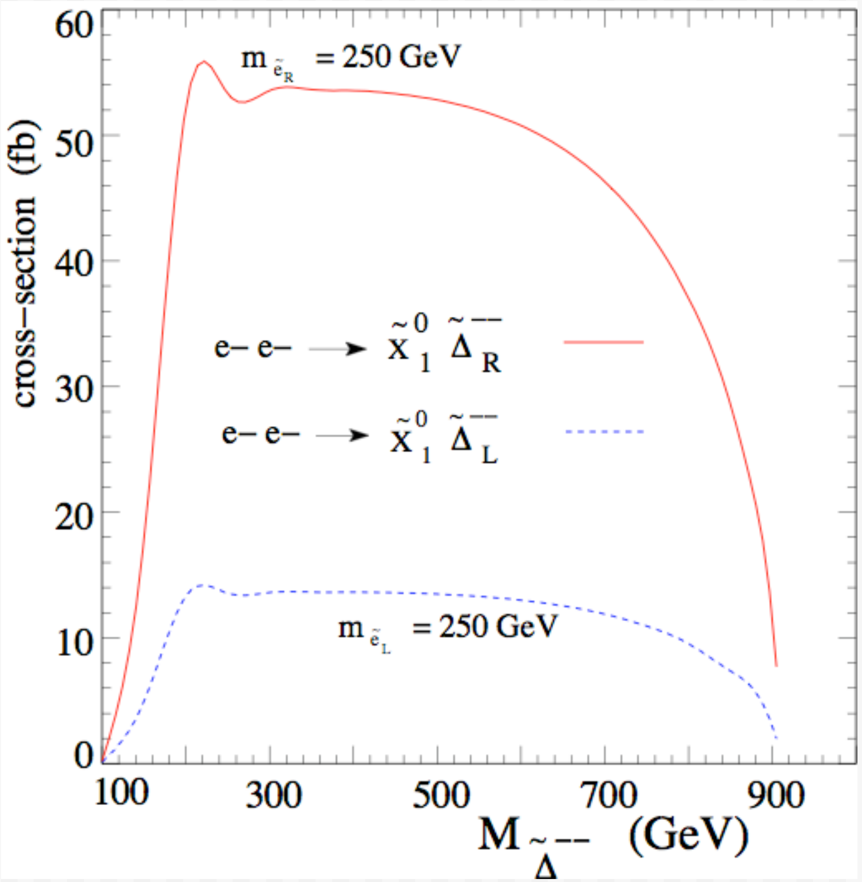
-- *heavy right-handed neutrinos* **($N \to l_i W \to l_i l_j$ +MET)**

♣ *Discrimination also possible for trilepton signals following similar arguments.*

Production cross-section of the left-chiral states at $e^- e^-$ colliders



Production cross-section of the different chiral states at $e^- e^-$ colliders



Sample point: **SPA**

larger selectron mass suppresses the production

production enhanced for polarised beams

polarised cross sections for the two chiral states.

We focus on the 2-body (S2) and 3-body (S3) decay modes of the doubly charged Higgsino and look at the resulting signal events against the most dominant SM background.

We consider the following final states

$$\text{(i)} \quad e^- e^- \not{E}, \qquad \text{(ii)} \quad \mu^- \mu^- \not{E}$$

We assume beam polarisation (-1,-1) for the left-chiral Δ

SM background:

$$e^- + e^- \rightarrow e^- + e^- + \bar{\nu}_l \nu_l$$

$$e^- + e^- \rightarrow \mu^- + \mu^- + \bar{\nu}_\mu \bar{\nu}_\mu + \nu_e \nu_e$$

Kinematic cuts are used which effectively suppress the SM background without losing out much on the signal events.

$E_e > 5$ GeV ; $|\eta_l| < 1.5$; $\Delta R_{ll} > 0.2$ & $E^{miss} > E_{cm}/2$ GeV

		$\sqrt{s} = 500$ GeV		
Cuts Used		SM	signal-1	signal-2
$E_e > 5$ GeV $\not{E} > 10$ GeV	$\lvert\eta_e\rvert < 3.0$ $\Delta R_{ee} > 0.2$	(-,-) 537.7 fb (+,+) 15.1 fb	(-,-) 123.8 fb (+,+) 486.8 fb	(-,-) 19.9 fb (+,+) 78.1 fb
$E_e > 5$ GeV $\not{E} > 100$ GeV	$\lvert\eta_e\rvert < 1.5$ $\Delta R_{ee} > 0.2$	(-,-) 218.0 fb (+,+) 3.8 fb	(-,-) 102.7 fb (+,+) 403.98 fb	(-,-) 16.5 fb (+,+) 65.1 fb
$E_e > 5$ GeV $\not{E} > \sqrt{s}/2$ GeV	$\lvert\eta_e\rvert < 3.0$ $\Delta R_{ee} > 0.2$	(-,-) 280.1 fb (+,+) 3.3 fb	(-,-) 123.8 fb (+,+) 468.8 fb	(-,-) 19.9 fb (+,+) 78.1 fb
$E_e > 5$ GeV $\not{E} > \sqrt{s}/2$ GeV	$\lvert\eta_e\rvert < 1.5$ $\Delta R_{ee} > 0.2$	(-,-) 103.8 fb (+,+) 0.103 fb	(-,-) 102.7 fb (+,+) 403.98 fb	(-,-) 16.5 fb (+,+) 65.1 fb
		$\sqrt{s} = 1$ TeV		
$E_e > 5$ GeV $\not{E} > 10$ GeV	$\lvert\eta_e\rvert < 3.0$ $\Delta R_{ee} > 0.2$	(-,-) 1.13 pb (+,+) 12.6 fb	(-,-) 40.5 fb (+,+) 156.4 fb	(-,-) 14.0 fb (+,+) 53.9 fb
$E_e > 5$ GeV $\not{E} > 100$ GeV	$\lvert\eta_e\rvert < 1.5$ $\Delta R_{ee} > 0.2$	(-,-) 238.9 fb (+,+) 3.1 fb	(-,-) 33.4 fb (+,+) 129.2 fb	(-,-) 11.7 fb (+,+) 45.0 fb
$E_e > 5$ GeV $\not{E} > \sqrt{s}/2$ GeV	$\lvert\eta_e\rvert < 3.0$ $\Delta R_{ee} > 0.2$	(-,-) 605.9 fb (+,+) 0.4 fb	(-,-) 40.5 fb (+,+) 156.4 fb	(-,-) 14.0 fb (+,+) 53.9 fb
$E_e > 5$ GeV $\not{E} > \sqrt{s}/2$ GeV	$\lvert\eta_e\rvert < 1.5$ $\Delta R_{ee} > 0.2$	(-,-) 106.0 fb (+,+) 0.007 fb	(-,-) 33.4 fb (+,+) 129.2 fb	(-,-) 11.7 fb (+,+) 45.0 fb

Table 2: *Signal and SM cross sections for the $e^-e^-\not{E}$ final states with different choice of kinematic cuts for both signal and background at the e^-e^- collider with center-of-mass energies $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV. We also show the beam polarizations in parentheses. The ΔR is defined as $(\Delta R)^2 \equiv (\Delta\phi)^2 + (\Delta\eta)^2$ with $\Delta\eta$ and $\Delta\phi$ respectively denoting the separation in rapidity and azimuthal angle for the pair of particles under consideration.*

Kinematic distributions

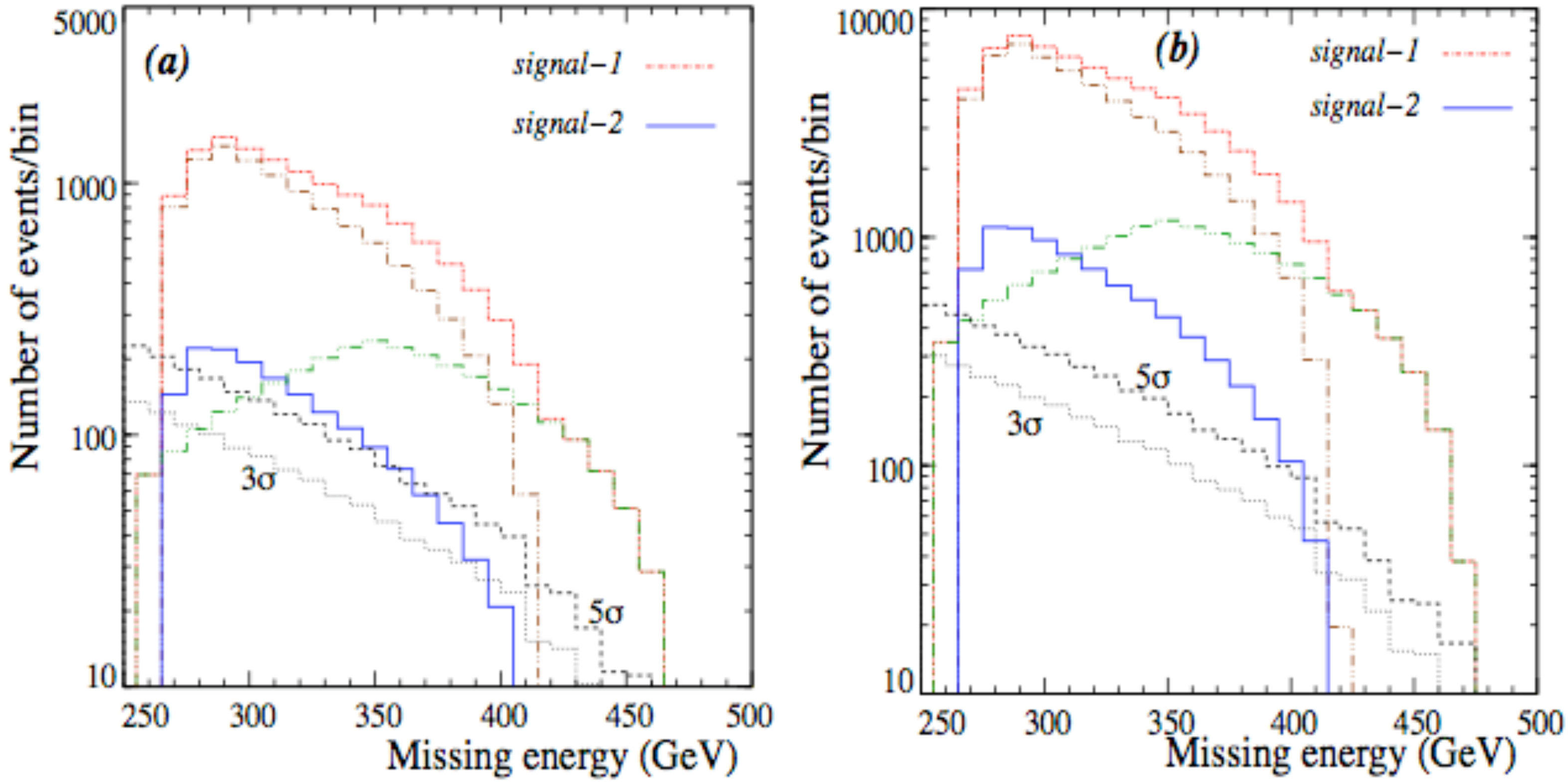


Figure 5: *Binwise distribution of missing energy for both signal-1 and signal-2 for the final states* $e^-e^-\not{E}$ $(\sqrt{s} = 500$ *GeV). The broken* $(- \cdot \cdot -)$ *brown lines correspond to the signal through* $\tilde{\Delta}_L^{--}$ *production while the broken* $(- \cdots -)$ *green lines correspond to the signal events from* $\tilde{e}_L^-$*-pair production. Also shown in dashed and dotted dark lines are the* 5σ *and* 3σ *fluctuations in the SM background. Each binsize is 10 GeV.* (a) $\mathcal{L} = 100 fb^{-1}$, (b) $\mathcal{L} = 500 fb^{-1}$.

$$M^{max}_{\ell^\pm\ell^\pm} = \sqrt{M^2_{\widetilde{\Delta}} + M^2_{\widetilde{\chi}^0_1} - 2M_{\widetilde{\Delta}}E_{\widetilde{\chi}^0_1}} \; ,$$

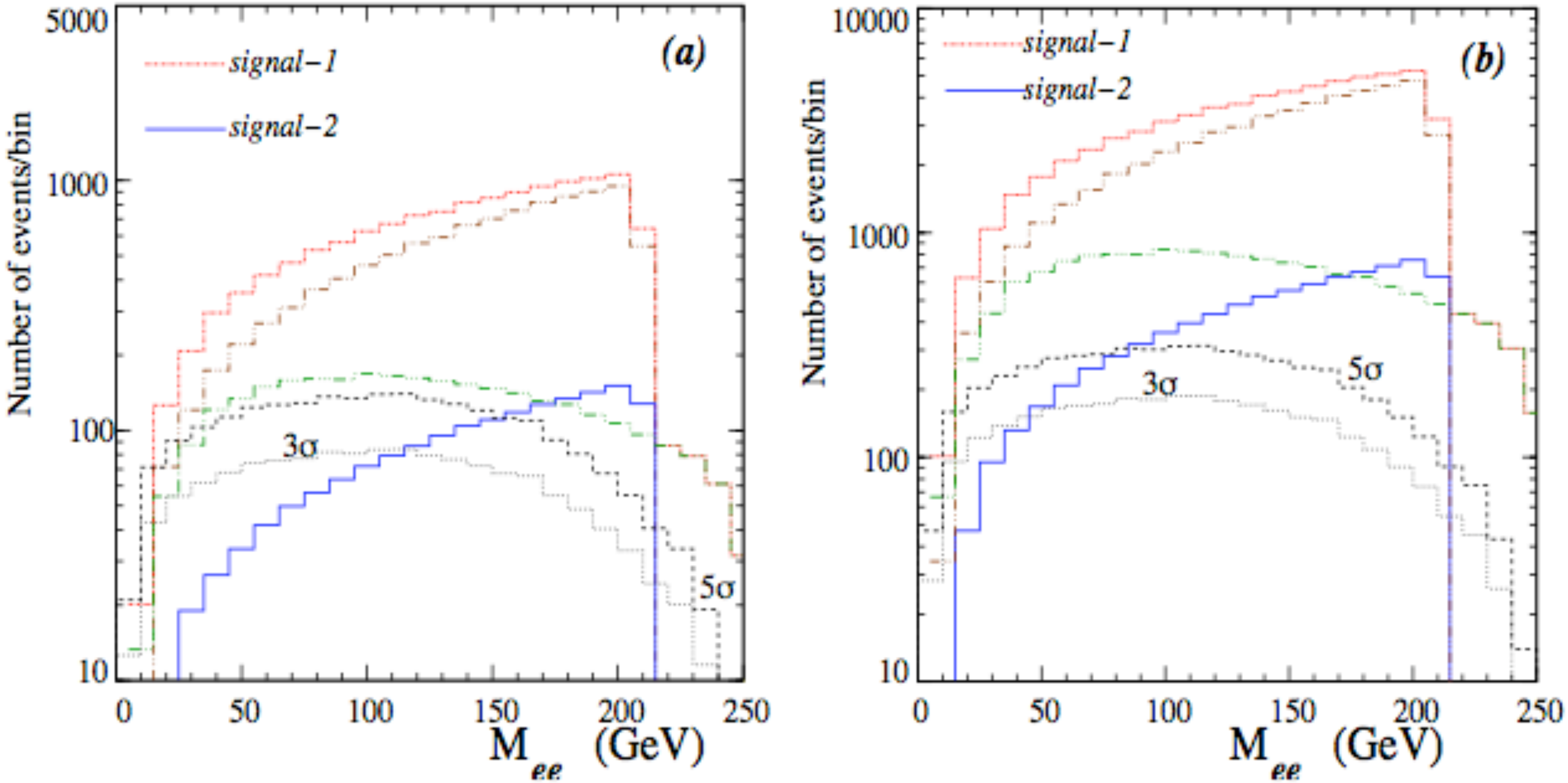


Figure 6: *Binwise distribution of the invariant mass of the visible particles in the final state* $e^-e^-\not{E}$ *for both signal-1 and signal-2* ($\sqrt{s} = 500$ *GeV*)*. The broken* $(- \cdot \cdot -)$ *brown lines correspond to the signal through* $\widetilde{\Delta}_L^{--}$ *production while the broken* $(- \cdot \cdot \cdot -)$ *green lines correspond to the signal events from* $\tilde{e}_L^-$*-pair production. The background follows the notation of Fig 5. Each binsize is 10 GeV.*(a) $\mathcal{L} = 100 fb^{-1}$, (b) $\mathcal{L} = 500 fb^{-1}$.

If one considers

$$|\Delta\eta| = |\eta^1_{e^-} - \eta^2_{e^-}|$$

the signal peaks at |Δη|=0, while for the SM background it peaks beyond |Δη|>1.2

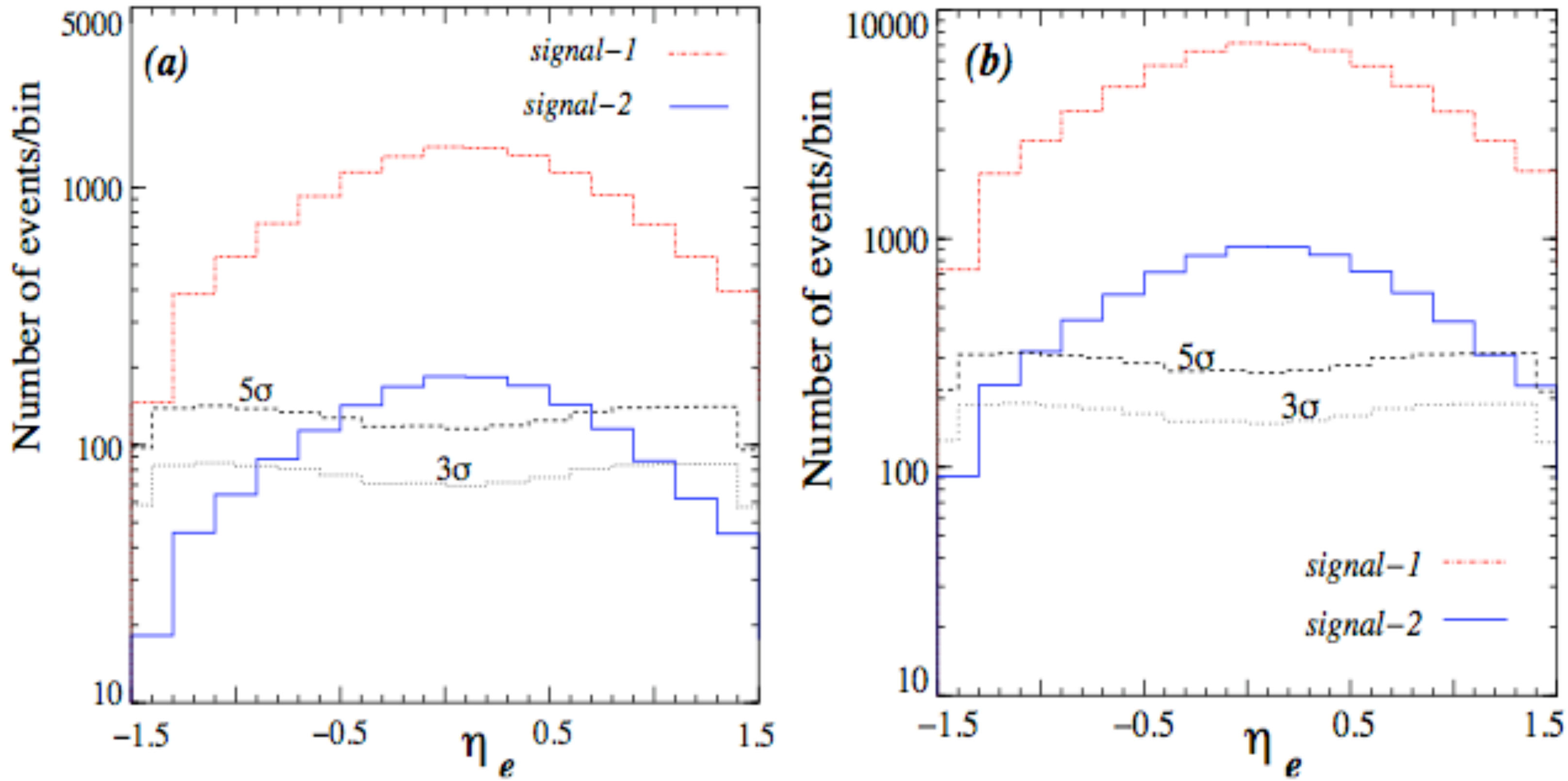


Figure 7: *Binwise distribution of the rapidity of the e^- in the final state $e^-e^-\not{E}$ for both signal-1 and signal-2 ($\sqrt{s}$ = 1 TeV). The background follows the notation of Fig 5. Each binsize is 0.2 radians.* (a) $\mathcal{L} = 100 fb^{-1}$, (b) $\mathcal{L} = 500 fb^{-1}$.

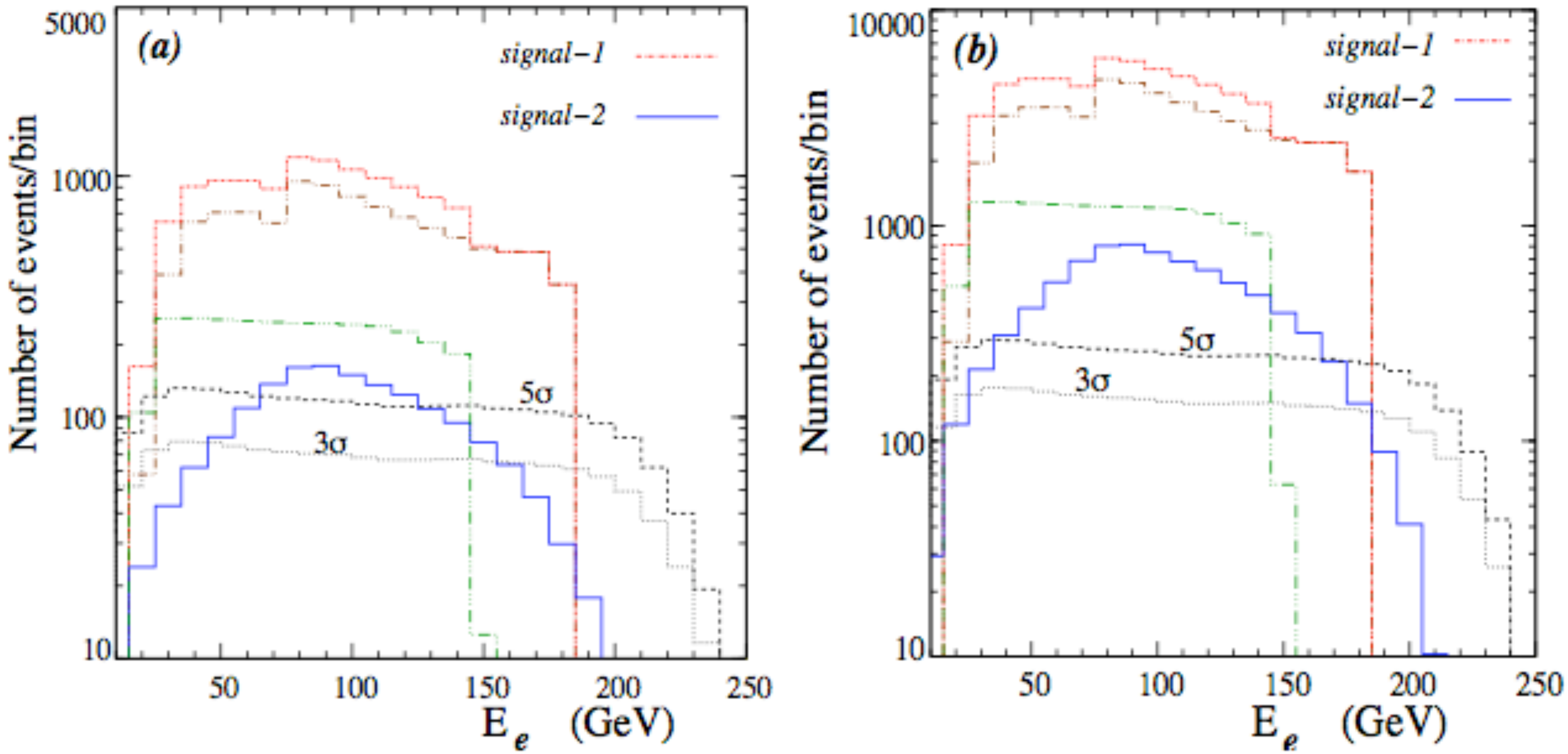


Figure 9: *Binwise distribution of the energy of e^- in the final state $e^-e^-\not{E}$ for both signal-1 and signal-2 ($\sqrt{s} = 500$ GeV). The broken ($- \cdot \cdot -$) brown lines correspond to the signal through $\tilde{\Delta}_L^{--}$ production while the broken ($- \cdot \cdot \cdot -$) green lines correspond to the signal events from $\tilde{e}_L^-$-pair production. The background follows the notation of Fig 5. Each binsize is 10 GeV.* (a) $\mathcal{L} = 100 fb^{-1}$, (b) $\mathcal{L} = 500 fb^{-1}$.

The right-handed higgsino $\widetilde{\Delta}_R^{--}$

- *Cross section enhanced for right-polarised electron beams.*
- *SM background dominated by W-boson exchange is completely suppressed by this choice of beam polarisation*
- *Signal is relatively background free.*
- *Allows to probe much lower $\Delta L=2$ couplings.*

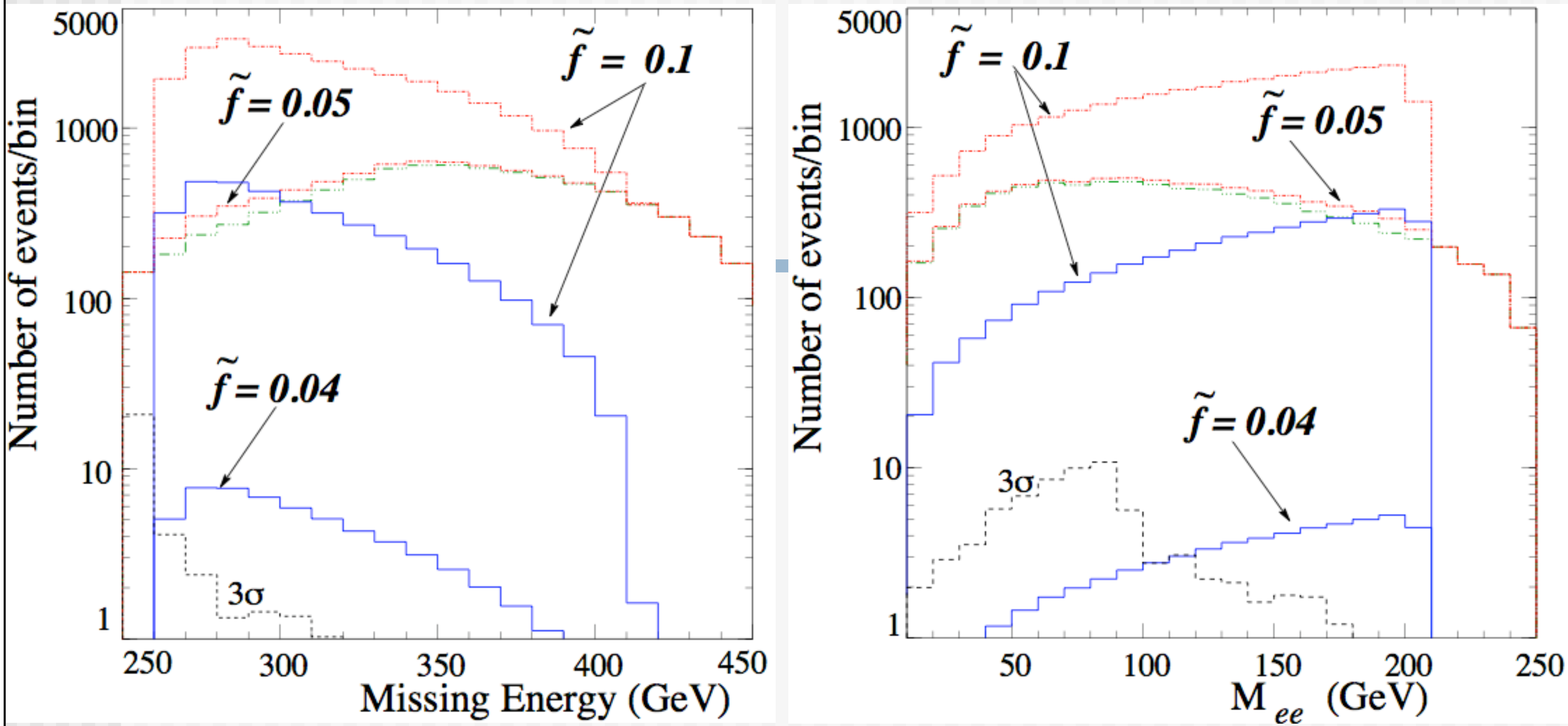


Figure 14: *Binwise distribution of missing energy, invariant mass and energy of e^- for different values of the $\Delta L = 2$ coupling $\tilde{f}_{ee}$. The statistical fluctuations in the SM background is shown at 3σ in black (dashed) lines. Each binsize is 10 GeV while the luminosity is taken as $\mathcal{L} = 500 fb^{-1}$ (final state $e^-e^-\not{E}$). The green $(- \cdot\cdot -)$ line stands for the independent contribution from $\tilde{e}_R^-$-pair production for signal-1. Here $\sqrt{s}$ = 500 GeV and $M_{\tilde{\Delta}_R^{--}}$ =300 GeV. For signal-1 shown in red lines, $m_{\tilde{e}_R}$ =150 GeV and for signal-2 shown in blue lines, $m_{\tilde{e}_R}$ =400 GeV.*

Conclusions

- *The left-right supersymmetric theories predict light doubly charged Higgsinos.*
- *We show that production cross section for doubly charged Higgsinos in LRSUSY framework is large at LHC.*
- ***4l+MET** and **3l+MET** signal at LHC gives robust signatures in the form of SSSF dileptons.*
- *Kinematic distributions prove to be very good discriminants from signals coming from other new physics scenarios.*

Conclusions

- *The presence of $\Delta L=2$ processes in theories beyond the SM can be probed directly at e^-e^- colliders*
- *We show that production cross section for doubly charged Higgsinos in LRSUSY framework is large with polarised initial beams and also helps in distinguish the two chiral states giving the same final state.*
- *The kinematic cuts can be effectively used to limit the SM background and give clear signal for LRSUSY.*
- *Additional charginos and neutralinos in the theory can throw up completely new signals.*

Extra Slides

$\bullet \tilde{\Delta}_L^{--}\ \tilde{l}\ l: \qquad -2h_{ll}\mathcal{C}^{-1}P_L$

$\bullet \tilde{\Delta}_R^{--}\ \tilde{l}\ l: \qquad -2h_{ll}\mathcal{C}^{-1}P_R$

Fermion-Fermion-Z Boson, γ:

$\bullet \gamma^\mu \tilde{\Delta}_{L,R}^{--}\bar{\tilde{\Delta}}_{L,R}^{--}: \qquad 2ie\gamma^\mu$

$\bullet Z_L^\mu \tilde{\Delta}_L^{--}\bar{\tilde{\Delta}}_L^{--}: \qquad i\dfrac{g_L \cos 2\theta_W}{\cos\theta_W}\gamma^\mu$

$\bullet Z_L^\mu \tilde{\Delta}_R^{--}\bar{\tilde{\Delta}}_R^{--}: \qquad -i\dfrac{2g_L \sin^2\theta_W}{\cos\theta_W}\gamma^\mu$

$\bullet Z_R^\mu \tilde{\Delta}_L^{--}\bar{\tilde{\Delta}}_L^{--}: \qquad i\dfrac{g_L \sqrt{\cos 2\theta_W}}{\cos\theta_W}\gamma^\mu$

$\bullet Z_R^\mu \tilde{\Delta}_R^{--}\bar{\tilde{\Delta}}_R^{--}: \qquad -i\dfrac{g_L(1-3\sin^2\theta_W)}{\cos\theta_W\sqrt{\cos 2\theta_W}}\gamma^\mu$

$$\bullet\ \tilde{\chi}_k^0\ \tilde{l}\ \bar{l}: \quad -i\left\{\left[\sqrt{2}g_L\left(\frac{1}{2}N_{k1}-\frac{1}{2}\left(\frac{\cos 2\theta_W}{\cos^2\theta_W}+\tan^2\theta_W\right)N_{k2}-\frac{\sin\theta_W\sqrt{\cos 2\theta_W}}{\cos^2\theta_W}N_{k3}+\frac{m_l}{2M_W\cos\beta}N_{k5}\right)\right]P_L\right.$$
$$\left.-\left[\sqrt{2}g_R\left(\left(\frac{\cos 2\theta_W}{2\cos^2\theta_W}-\tan^2\theta_W\right)N_{k2}-\frac{\sin\theta_W\sqrt{\cos 2\theta_W}}{\cos^2\theta_W}N_{k3}+\frac{m_l}{2M_W\cos\beta}N_{k5}^\star\right)\right]P_R\right\}$$

$$\bullet\ \tilde{\chi}_k^0\ \tilde{\nu}\ \bar{\nu}: \quad -i\left\{\left[\sqrt{2}g_L\left(\frac{1}{2}N_{k1}+\frac{1}{2}\left(\frac{\cos 2\theta_W}{\cos^2\theta_W}-\tan^2\theta_W\right)N_{k2}-\frac{\sin\theta_W\sqrt{\cos 2\theta_W}}{\cos^2\theta_W}N_{k3}+\frac{m_l}{2M_W\cos\beta}N_{k5}\right)\right]P_L\right.$$
$$\left.-\left[\sqrt{2}g_R\left(\frac{\cos 2\theta_W}{2\cos^2\theta_W}N_{k2}-\frac{\sin\theta_W\sqrt{\cos 2\theta_W}}{2\cos^2\theta_W}N_{k3}+\frac{m_l}{2M_W\cos\beta}N_{k5}^\star\right)\right]P_R\right\}$$

Bounds on the Yukawa couplings

$$h_{e\mu}h_{ee} < 3.2 \times 10^{-11}\,\mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}} \quad \text{from } \mu \to \bar{e}ee,$$

$$h_{e\mu}h_{\mu\mu} < 2 \times 10^{-10}\,\mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}} \quad \text{from } \mu \to e\gamma,$$

$$h^2_{ee} < 9.7 \times 10^{-6}\,\mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}} \quad \text{from Bhabha scattering},$$

$$h^2_{\mu\mu} < 2.5 \times 10^{-5}\,\mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}} \quad \text{from} \quad (g-2)_\mu,$$

$$h_{ee}h_{\mu\mu} < 2.0 \times 10^{-7}\,\mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}} \quad \text{from muonium} - \text{antimuonium transition}.$$

We choose h_{ll} = 0.1 which is consistent with the bounds.
Larger values allowed with a large mass for Δ^{--}

The mixing matrix for sleptons

$$\mathcal{M}_L^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ M_{RL}^2 & M_{RR}^2 \end{pmatrix}$$

where the different entries correspond to

$$\begin{aligned} M_{LL}^2 &= M_L^2 + m_\ell^2 + m_Z^2 (T_{3\ell} + \sin^2\theta_{\rm W}) \cos 2\beta, \\ M_{LR}^2 &= M_{RL}^{2\,\dagger} = m_\ell (A + \mu \tan\beta), \\ M_{RR}^2 &= M_R^2 + m_\ell^2 - m_Z^2 \sin^2\theta_{\rm W} \cos 2\beta \end{aligned}$$