Doubly charged higgsinos at LHC

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M. Frank, K. H., S.K. Rai (arXiv:0710.2415) Phys.Rev.D77:015006, 2008
D. Demir, M. Frank, K. H., S.K. Rai, I.Turan (arXiv:0805.4202) Phys.Rev.D78:035013, 2008
D. Demir, M. Frank, K. H., S.K. Rai, I.Turan, in preparation

Outline

Motivation for left-right supersymmetry

Higgs sector and doubly charged states

Extended fermion spectra

Production and decay of doubly charged higgsinos at LHC

Conclusions

Motivation

Left-right model is based on the symmetry group

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

- Right-handed neutrinos included in the model

→ Neutrino mass generation through see-saw mechanism

Mohapatra, Senjanovic, PRL 44, 1980, PRD23, 1981
Gell-Mann, Ramond, Slansky, 1980
Yanagida, 1979; Glashow, 1980

Higgs sector problematic as in the SM → supersymmetrize

Gauged $\mathbf{U(1)_{B-L}}$: R-parity conservation, $R_p=(-1)^{3(B-L)+2s}$

- LSP stable and a dark matter candidate

LR-model can be included in SO(10) GUT

The left-right symmetry is broken at a scale **$\langle\Delta_R^0\rangle = v_R$:**

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

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

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

- Δ_L because of LR-symmetry;
- $\delta_{L,R}$ because of anomaly cancellation

The bi-doublet Higgs fields break the

$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{em}$

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

Possible triplet vevs:

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

Neutrino masses are induced by the see-saw mechanism

- triplet fields with |B-L| = 2

$$m_\nu = Y_{LR} v_{\delta_L} - \frac{\left(Y_L^{(\nu)}\right)^2 \kappa_1^2}{Y_{LR} v_{\Delta_R}}$$

→ δ_L vev small, Δ_R vev large

Possible bidoublet vevs:

$$\langle \phi_1 \rangle = \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_1' \end{pmatrix}, \langle \phi_2 \rangle = \begin{pmatrix} \kappa_2' & 0 \\ 0 & \kappa_2 \end{pmatrix},$$

κ_1, κ_2 → masses to quarks and leptons, contribute to gauge boson masses

κ_1',κ_2'→contribute to W_L-W_R mixing → choose to be zero

The matter fields:

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

The most general superpotential 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 possible soft terms are

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

Yukawa coupling constraints:

$h_{e\mu}h_{ee} < 3.2 \times 10^{-11}\ \mathrm{GeV}^{-2}\ M_{\Delta--}^{2}$ ($\mu \rightarrow eee$)

$h_{e\mu}h_{\mu\mu} < 2 \times 10^{-10}\ \mathrm{GeV}^{-2}\ M_{\Delta--}^{2}$ ($\mu \rightarrow e\gamma$)

$h_{ee}^{2} < 9.7 \times 10^{-6}\ \mathrm{GeV}^{-2}\ M_{\Delta--}^{2}$ (Bhabha)

$h_{\mu\mu}^{2} < 2.5 \times 10^{-5}\ \mathrm{GeV}^{-2}\ M_{\Delta--}^{2}$ ($(g-2)_{\mu}$)

$h_{ee}h_{\mu\mu} < 2.0 \times 10^{-7}\ \mathrm{GeV}^{-2}\ M_{\Delta--}^{2}$ (muonium-antimuonium)

For doubly charged Higgs, from LEP
$m_{\Delta} > 100$ GeV for $h_{ij} > 10^{-7}$, $i,j = e,\mu,\tau$

Note that the third generation couplings are restricted only by direct collider limits.

Assume here that Yukawa couplings are diagonal.

Extended 'ino' spectra

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

Doubly charged higgsinos:

$$\tilde{\Delta}_L^{++}, \tilde{\Delta}_R^{++}, \tilde{\delta}_L^{++}, \tilde{\delta}_R^{++}$$

Mass term:

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

where $M_{\tilde{\Delta}^{--}} \equiv \mu_3$

Six charginos:

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

Mass terms for the charginos:

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

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

The mass eigenvalues and eigenstates are given by

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

Eleven neutralinos:

$$\psi^{+T} = \left(-i\lambda_L^0, -i\lambda_R^0, -i\lambda_{B-L}^0, \tilde{\phi}_{1u}^0, \tilde{\phi}_{2d}^0, \tilde{\Delta}_L^0, \tilde{\delta}_L^0, \tilde{\Delta}_R^0, \tilde{\delta}_R^0, \tilde{\phi}_{1d}^0, \tilde{\phi}_{2u}^0\right)$$

Mass terms for the charginos: $\mathcal{L}_N = -\frac{1}{2}\psi^{0T} Z \psi^0 + \text{h.c.}$

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

The mass eigenvalues and eigenstates are given by

$$N^* Z N^T = Z_D \qquad \tilde{\chi}_i^0 = N_{ij}\psi_j^0 \quad (i, j = 1, 2, \ldots 11)$$

Single and pair production at LHC

$$pp \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$$

$$pp \to \tilde{\chi}_1^{+}\tilde{\Delta}^{--}$$

Decay modes for two body decays (S2):

$$\tilde{\Delta}^{--} \to \tilde{\ell}^{-}\ell^{-},\ \Delta^{--}\tilde{\chi}_i^{0},\ \Delta^{-}\tilde{\chi}_i^{-},\ \tilde{\chi}_i^{-}W^{-}$$

If $m_{\tilde{\Delta}^{--}} > m_{\tilde{\ell}^{-}}$ then $\tilde{\Delta}^{--} \to \tilde{\ell}^{-}\ell^{-}$ can be a favoured mode (scalar triplet, chargino+W heavier).

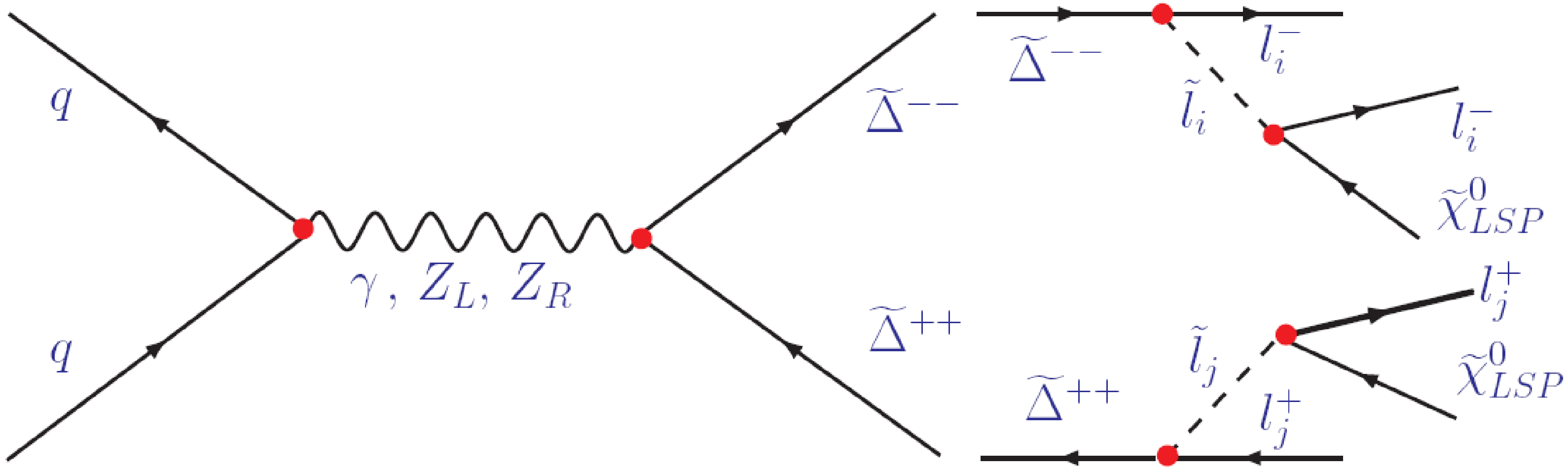
Thus,

$$\tilde{\Delta}^{--} \to \tilde{\ell}^{-}\ell^{-} \to \ell^{-}\ell^{-}\tilde{\chi}_1^{0}$$

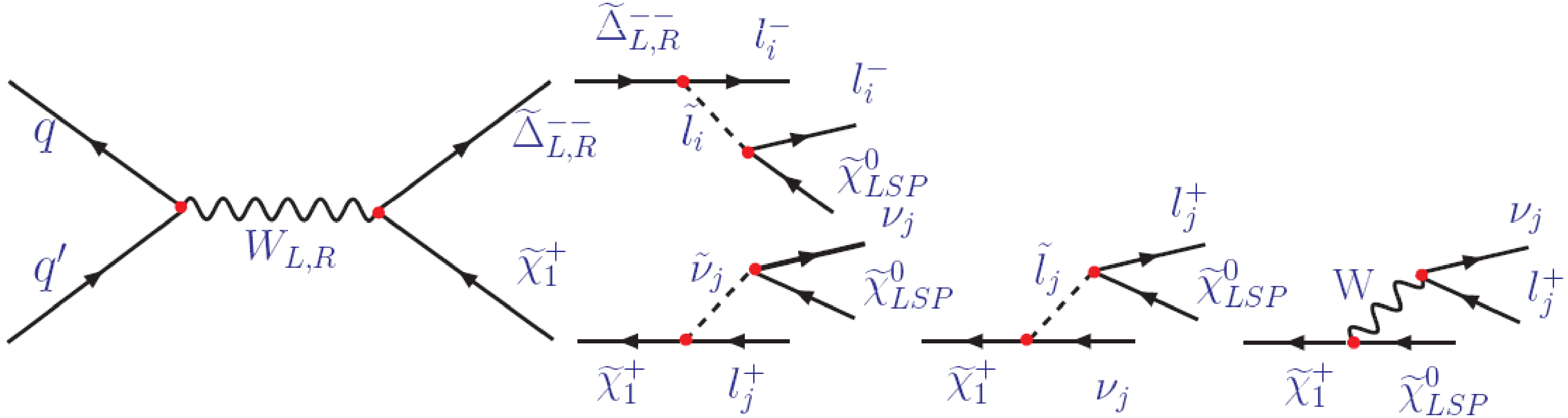
Three body decay, if $m_{\tilde{\Delta}^{--}} < m_{\tilde{\ell}^{-}}$ (S3):

$$\tilde{\Delta}^{--} \to \ell^{-}\ell^{-}\tilde{\chi}_1^{0}$$

Four lepton signals:



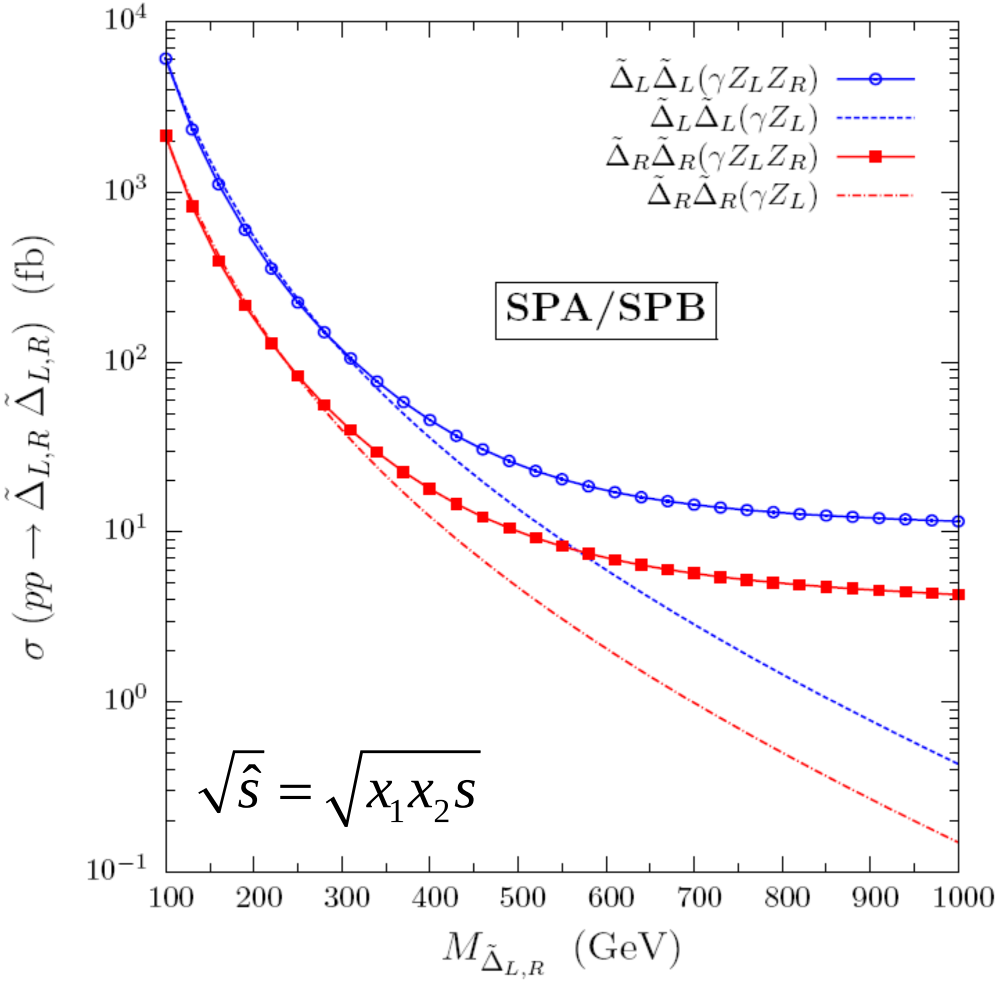
Three lepton signals:



Representative points, four lepton signal

Fields	SPA		SPB	
	SPA $\tan\beta = 5, M_{B-L} = 25$ GeV $M_L = M_R = 250$ GeV $v_{\Delta_R} = 3000$ GeV, $v_{\delta_R} = 1000$ GeV $\mu_1 = 1000$ GeV, $\mu_3 = 300$ GeV		**SPB** $\tan\beta = 5, M_{B-L} = 100$ GeV $M_L = M_R = 500$ GeV $v_{\Delta_R} = 2500$ GeV, $v_{\delta_R} = 1500$ 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)

Four lepton signal $pp \to \tilde{\Delta}^{++}\tilde{\Delta}^{--} \to \left(\ell_i^+\ell_i^+\right) + \left(\ell_j^-\ell_j^-\right) + \not{E}_T$



Used cuts:

$$|\eta_\ell| < 2.5,\ p_{T,lepton} > 25\ \text{GeV},$$

$$\not{E}_T > 50\ \text{GeV},$$

$$\Delta R_{\ell\ell} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.4$$

- cross section is large for light doubly charged higgsinos ~10^4 fb

- the $4\ell + \not{E}_T$ signal receives contributions from the pair production of both $\tilde{\Delta}_L, \tilde{\Delta}_R$.

- with the used missing energy cut, the SM background is estimated to be ~10^{-3} fb

CalcHEP → event files

PYTHIA → ISR, FSR

$$2\mu^- + 2e^+ + \not{E}_T$$

SPA

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

$$\sigma\left(\tilde{\Delta}_R^{--}\tilde{\Delta}_R^{++}\right) = 44.5 \text{ fb}$$

After cuts →

S2 $\sigma\left(2\mu^- 2e^+ + \not{E}_T\right) = 7.71 \text{ fb}$

S3 $\sigma\left(2\mu^- 2e^+ + \not{E}_T\right) = 7.02 \text{ fb}$

SPB

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

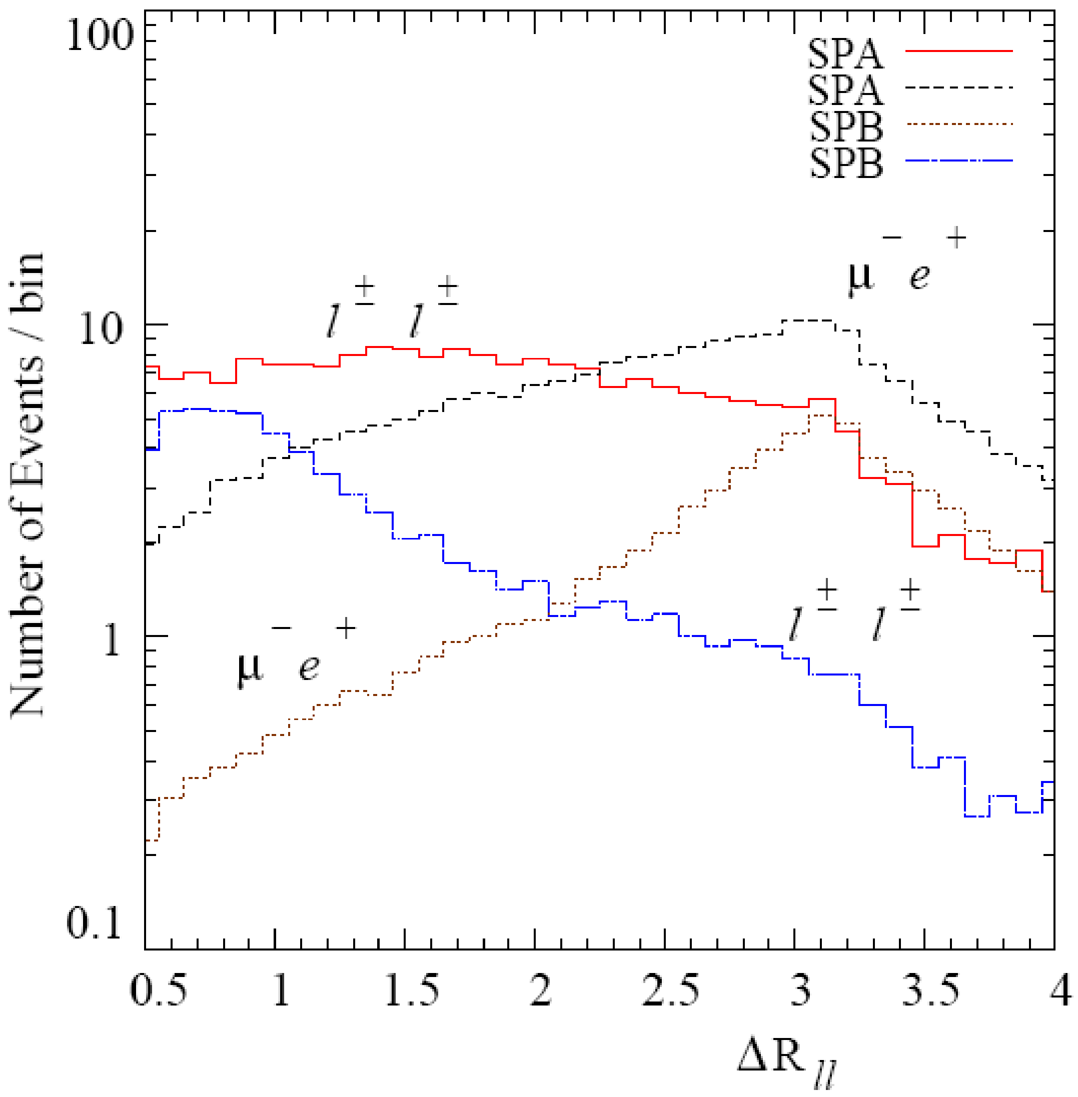
$$\sigma\left(\tilde{\Delta}_R^{--}\tilde{\Delta}_R^{++}\right) = 12.95 \text{ fb}$$

After cuts →

S2 $\sigma\left(2\mu^- 2e^+ + \not{E}_T\right) = 2.43 \text{ fb}$

S3 $\sigma\left(2\mu^- 2e^+ + \not{E}_T\right) = 2.66 \text{ fb}$

Angular separation of lepton pairs

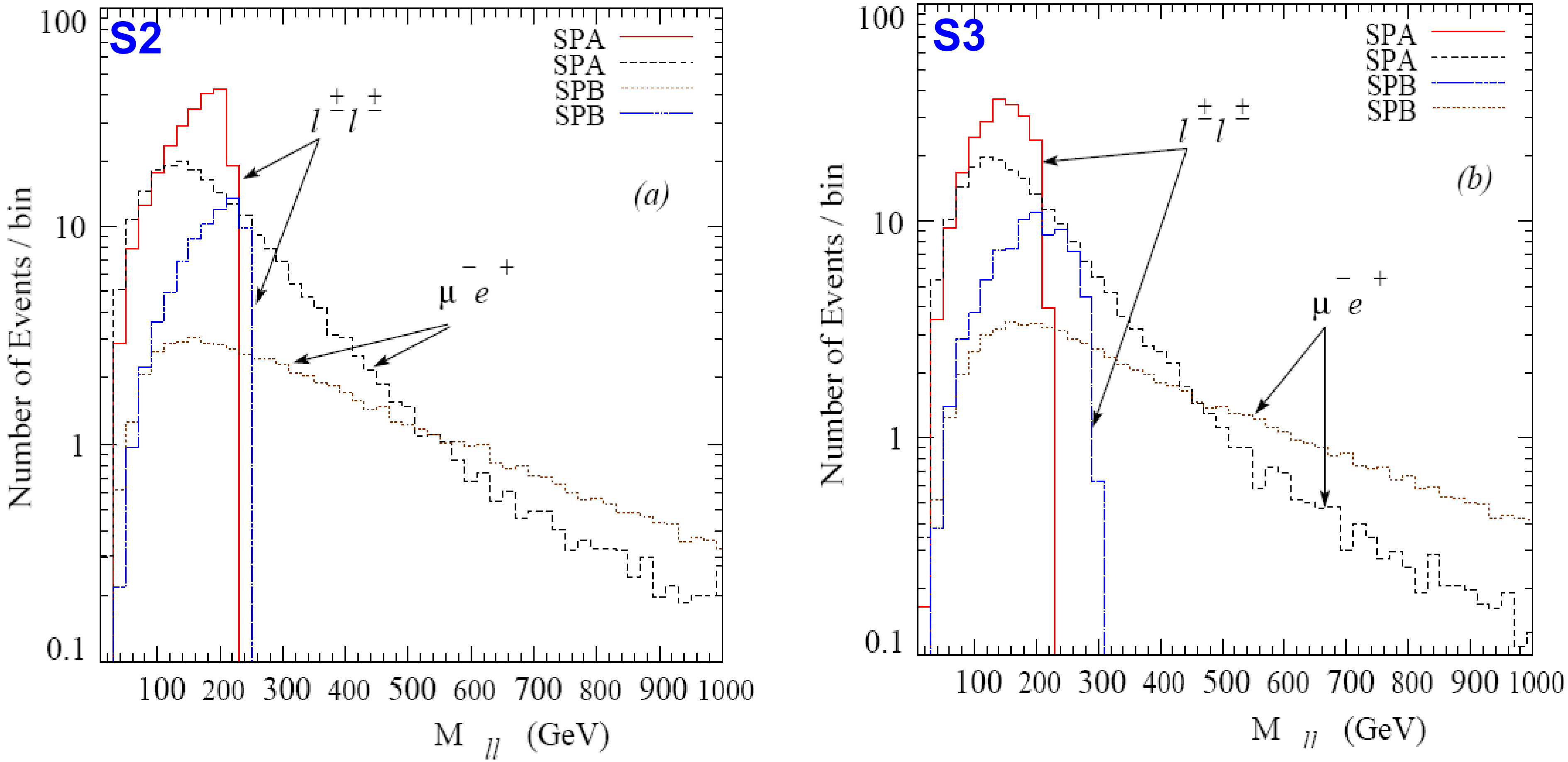


- SSSF lepton pairs are peaked at lower values of ΔR_{ll} than OSDF

- OSDF lepton pairs contain leptons originating from different doubly charged higgsinos

Sharp edge in SSSF lepton pair invariant mass

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

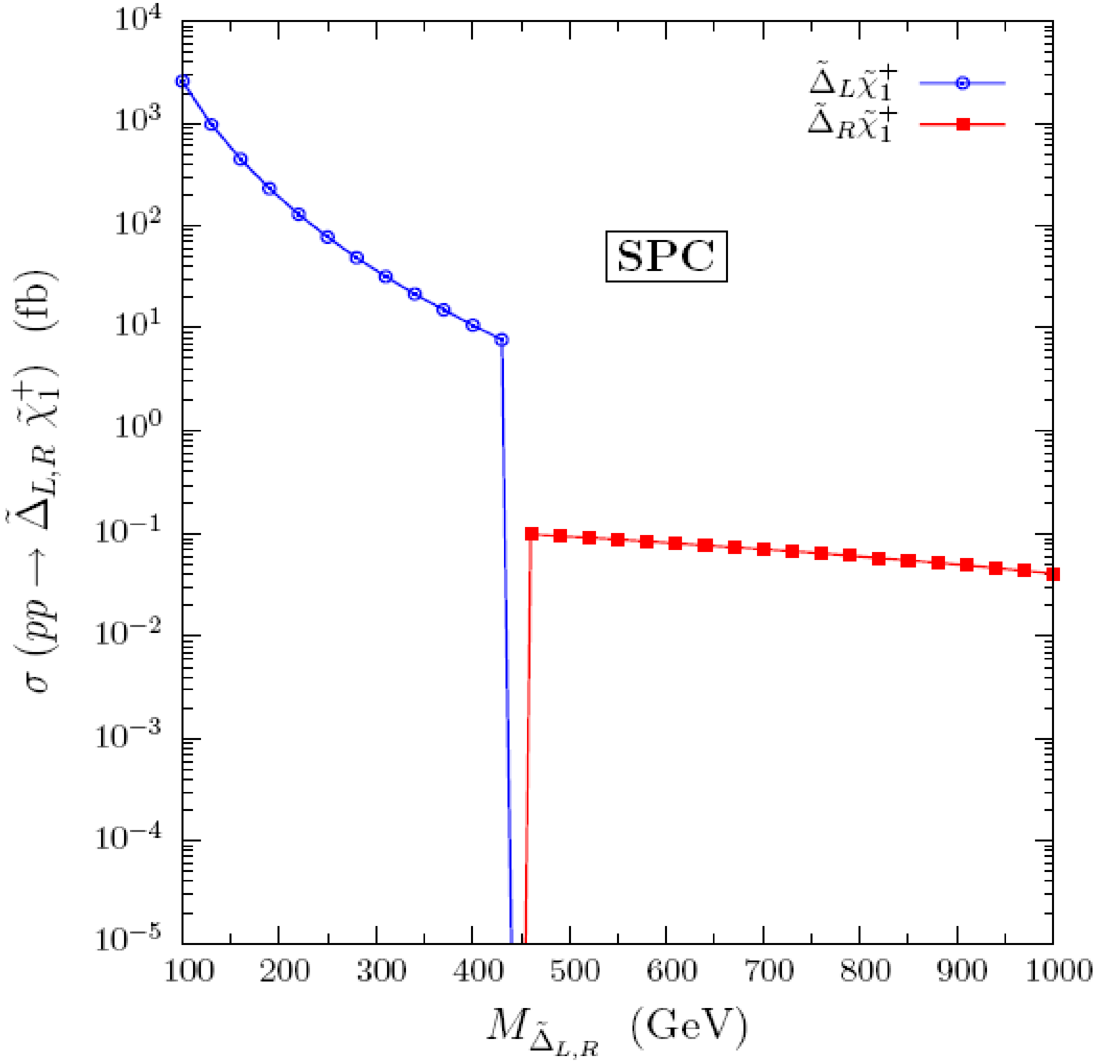


Sharp edge: hint of a $\Delta L = 2$ interaction and a doubly charged particle in the underlying model of new physics.

Representative point, three lepton signal

Fields	SPC	
	$\tan\beta = 5, M_{B-L} = 0$ GeV	
	$M_L = M_R = 500$ GeV	
	$v_{\Delta_R} = 2500$ GeV$, \mathrm{v}_{\delta_\mathrm{R}} = 1500$ GeV	
	$\mu_1 = 500$ GeV$, \mu_3 = 300$ GeV	
$\widetilde{\chi}_i^0$ $(i = 1, 3)$	142.5, 265.6, 300.0 GeV	
$\widetilde{\chi}_i^\pm$ $(i = 1, 3)$	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)

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



- 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%

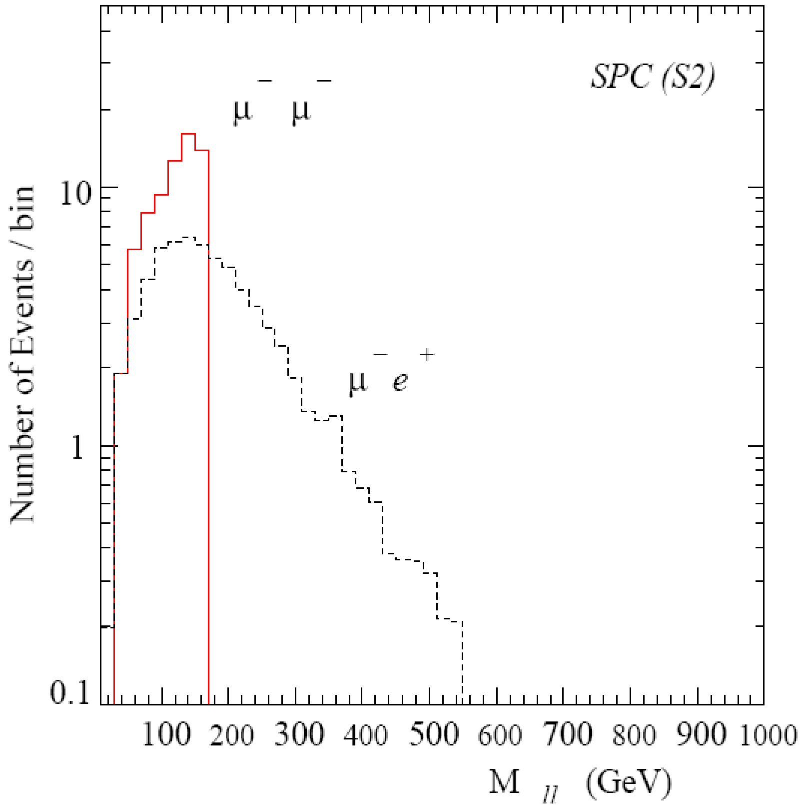
SPC $2\mu^- + e^+ + \not{E}_T$

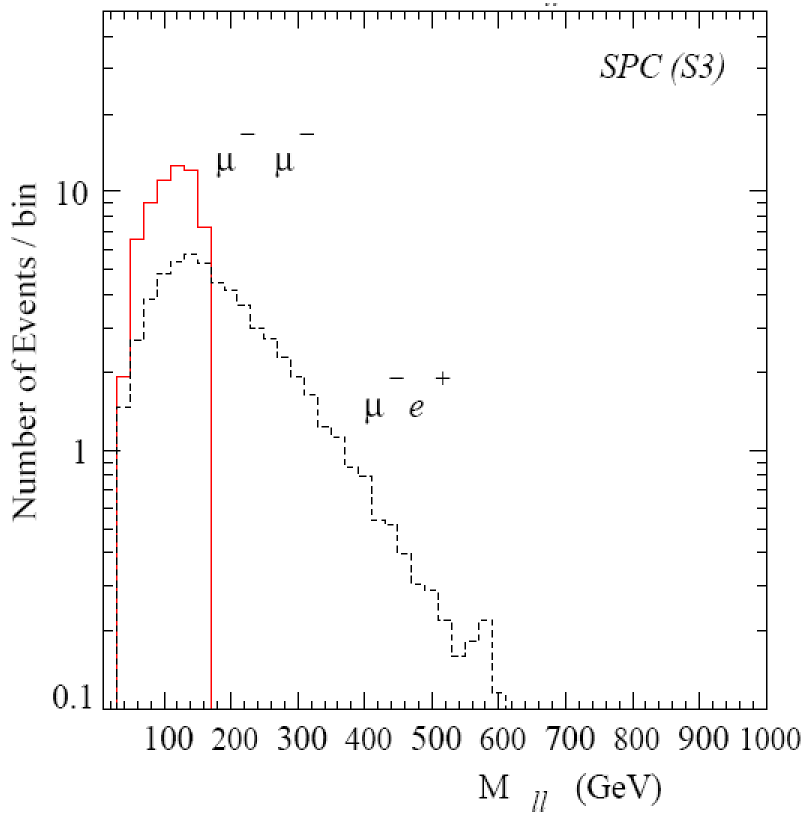
$\sigma(\tilde{\Delta}_L^{--}\tilde{\chi}_1^+) = 36.57$ fb

After cuts

S2 $\sigma(2\ell_i^-\ell_j^+ + \not{E}_T) = 2.24$ fb

S3 $\sigma(2\ell_i^-\ell_j^+ + \not{E}_T) = 2.03$ fb





The edge is seen again. Different from MSSM trilepton signal.

Conclusion

- Studied pair and single production of doubly charged higgsinos in LRSUSY model.
- Production cross section large.
- Decay to leptons: signals $2\ell_i^- 2\ell_j^+ + \not{E}_T, \quad 2\ell_i^- \ell_j^+ + \not{E}_T$
- For $\ell_i \neq \ell_j$, SSSF dileptons have narrow spatial extension and sharp edge in invariant mass – contrary to MSSM (or UED).

➡ Testing ground for underlying SUSY model

- Production at Tevatron?
  - in favourable parameter region for the four lepton signal and suitable cuts, σ ~ 6 fb for $2\mu 2e + \not{E}_T$ and M_Δ=200 GeV seems possible.
- Production at a linear collider?
  - good possibilities to study wide range of masses e.g. with $e^- e^- \to \tilde{\Delta}^{--} \tilde{\chi}_1^0$