Signals for doubly charged Higgsinos at colliders

Santosh Kumar Rai

Helsinki Institute of Physics

Finland

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*

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

and the soft terms as

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

- *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.

$$\Delta_L^{++}, \Delta_R^{++}, \delta_L^{++}, \delta_R^{++}$$

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

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

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

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

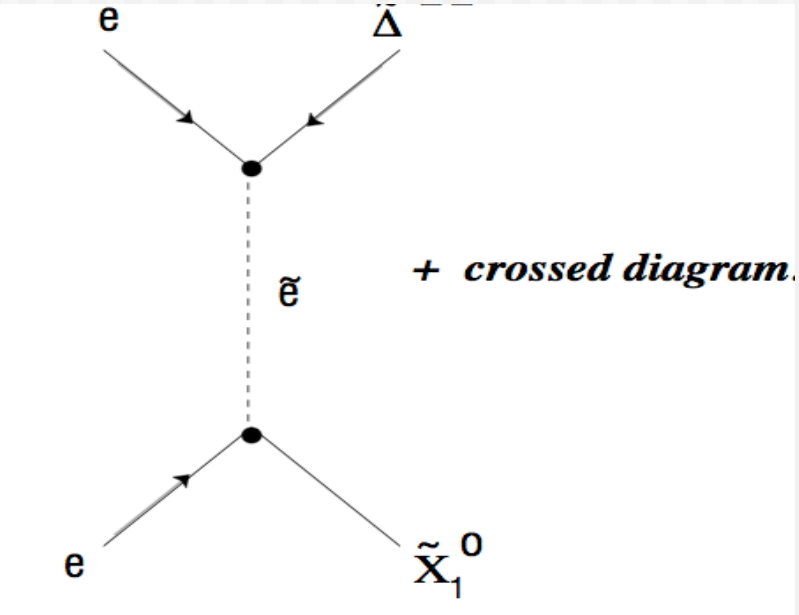
$$\tilde{\chi}_i^0 = N_{ij}\psi_j^0 \quad (i, j = 1, 2, \ldots 11)$$

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 $\gamma\gamma$)

M. Frank, K. Huitu, SKR

Single and pair production at LHC

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

Decay modes

2-body decays

(S2)

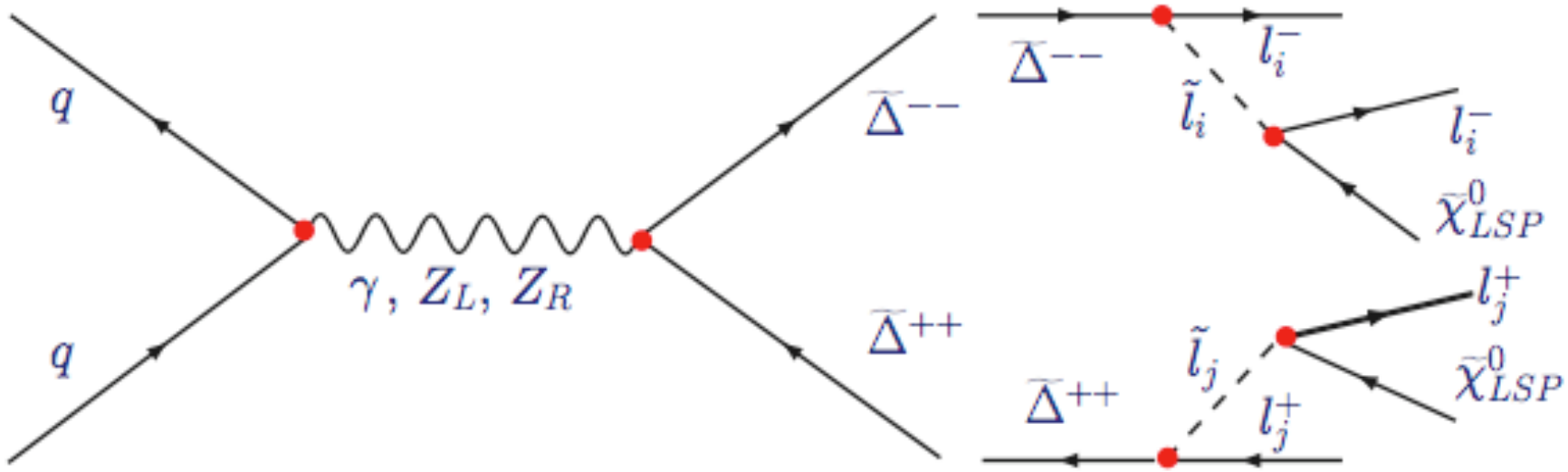
- $\widetilde{\Delta}^{--} \longrightarrow \widetilde{\ell}^- \ell^-,$
- $\widetilde{\Delta}^{--} \longrightarrow \Delta^{--} \widetilde{\chi}_i^0,$
- $\widetilde{\Delta}^{--} \longrightarrow \widetilde{\chi}_i^- \Delta^-,$
- $\widetilde{\Delta}^{--} \longrightarrow \widetilde{\chi}_i^- W^-,$

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

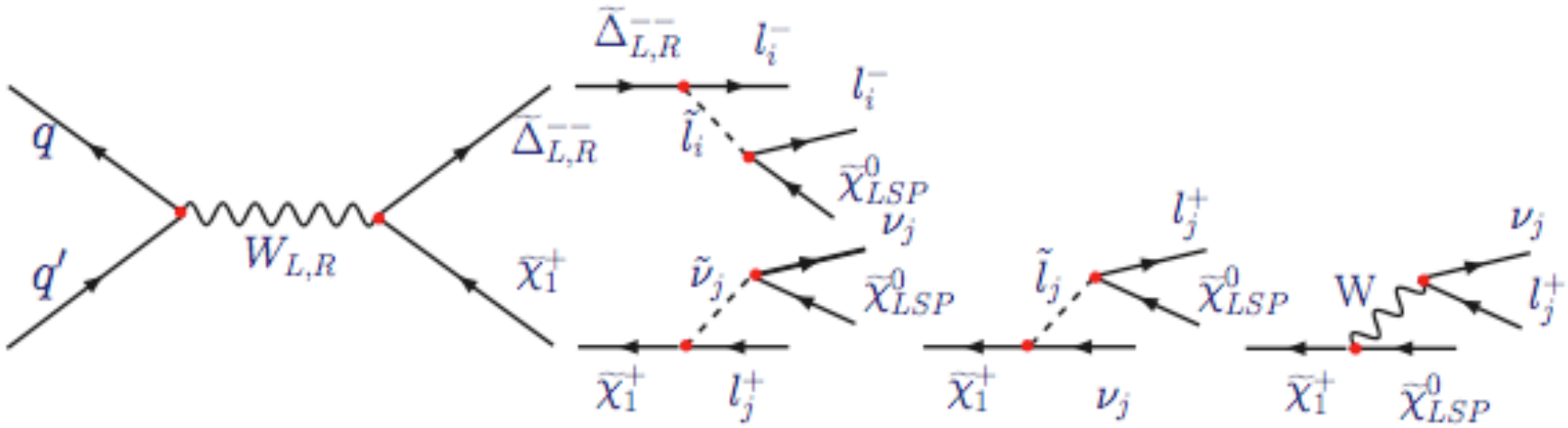
or $\widetilde{\Delta}^{--} \rightarrow \widetilde{\ell}^{*-} \ell^- \rightarrow \ell^- \ell^- \widetilde{\chi}_1^0.$

(S3)

4 lepton signals:



3 lepton signals:



Representative points

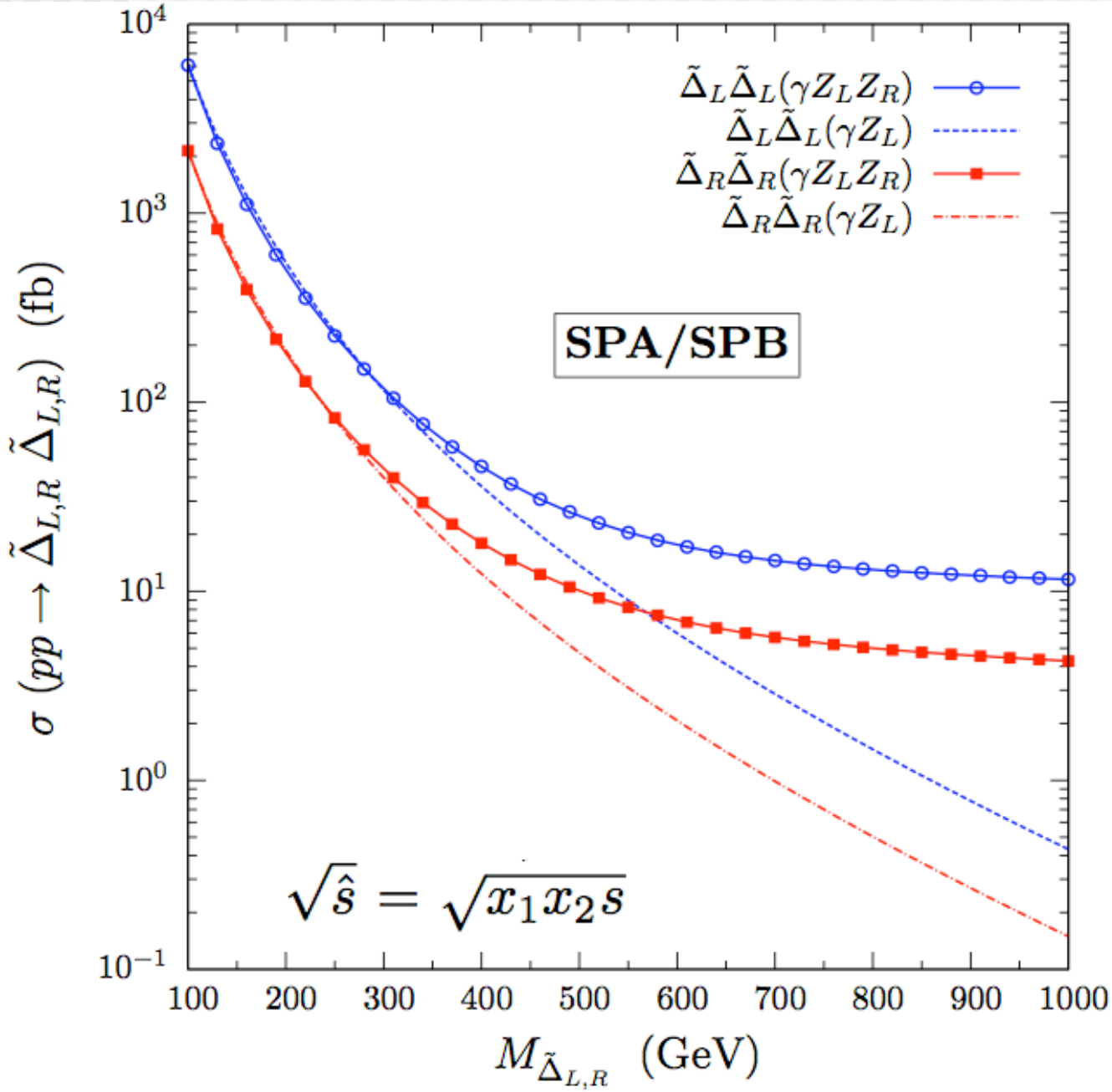
Fields	SPA $\tan\beta = 5, M_{B-L} = 25$ GeV $M_L = M_R = 250$ GeV $v_{\Delta_R} = 3000$ GeV, $v_{\delta_R} = 1000$ GeV $\mu_1 = 1000$ GeV, $\mu_3 = 300$ GeV		SPB $\tan\beta = 5, M_{B-L} = 100$ GeV $M_L = M_R = 500$ GeV $v_{\Delta_R} = 2500$ GeV, $v_{\delta_R} = 1500$ GeV $\mu_1 = 500$ GeV, $\mu_3 =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

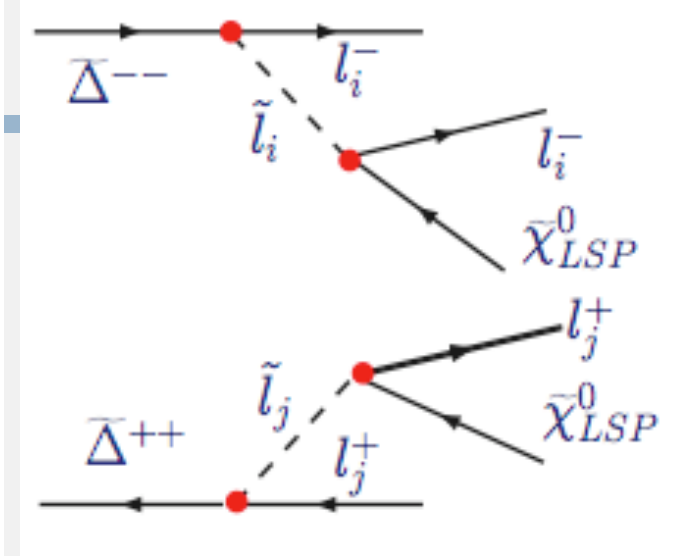
$h_{ee} h_{\mu\mu} < 2.0 \times 10^{-7}\ GeV^{-2}\ M^2_{\Delta^{--}}$

from muonium-antimuonium transitions

4 lepton signals

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





- *cross section is quite sizeable for sufficiently light doubly charged Higgsinos ~10^4 fb*
- *The $4l$ + $\boldsymbol{MET}$ 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.

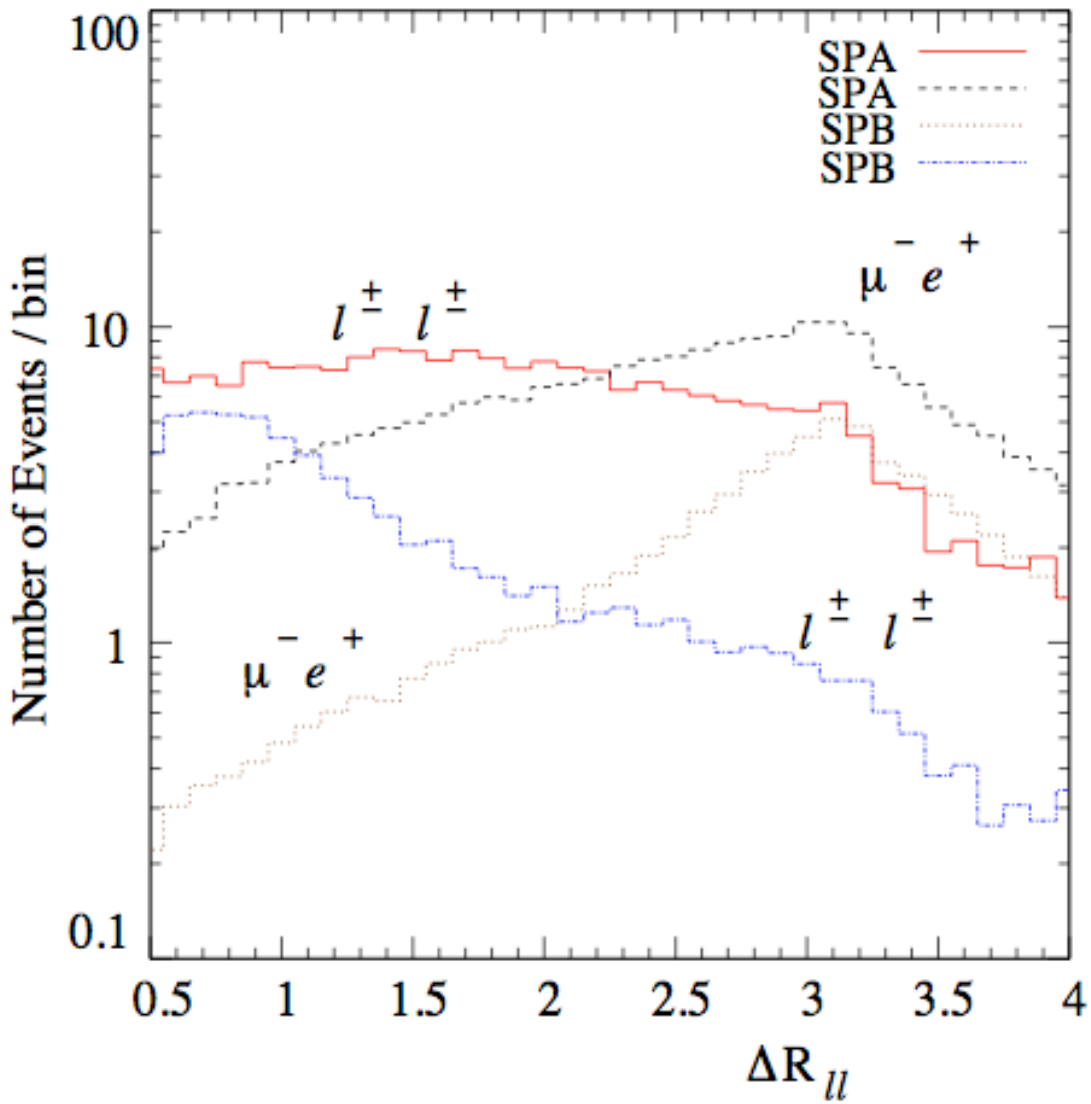
- *SPB:*

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

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

- **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



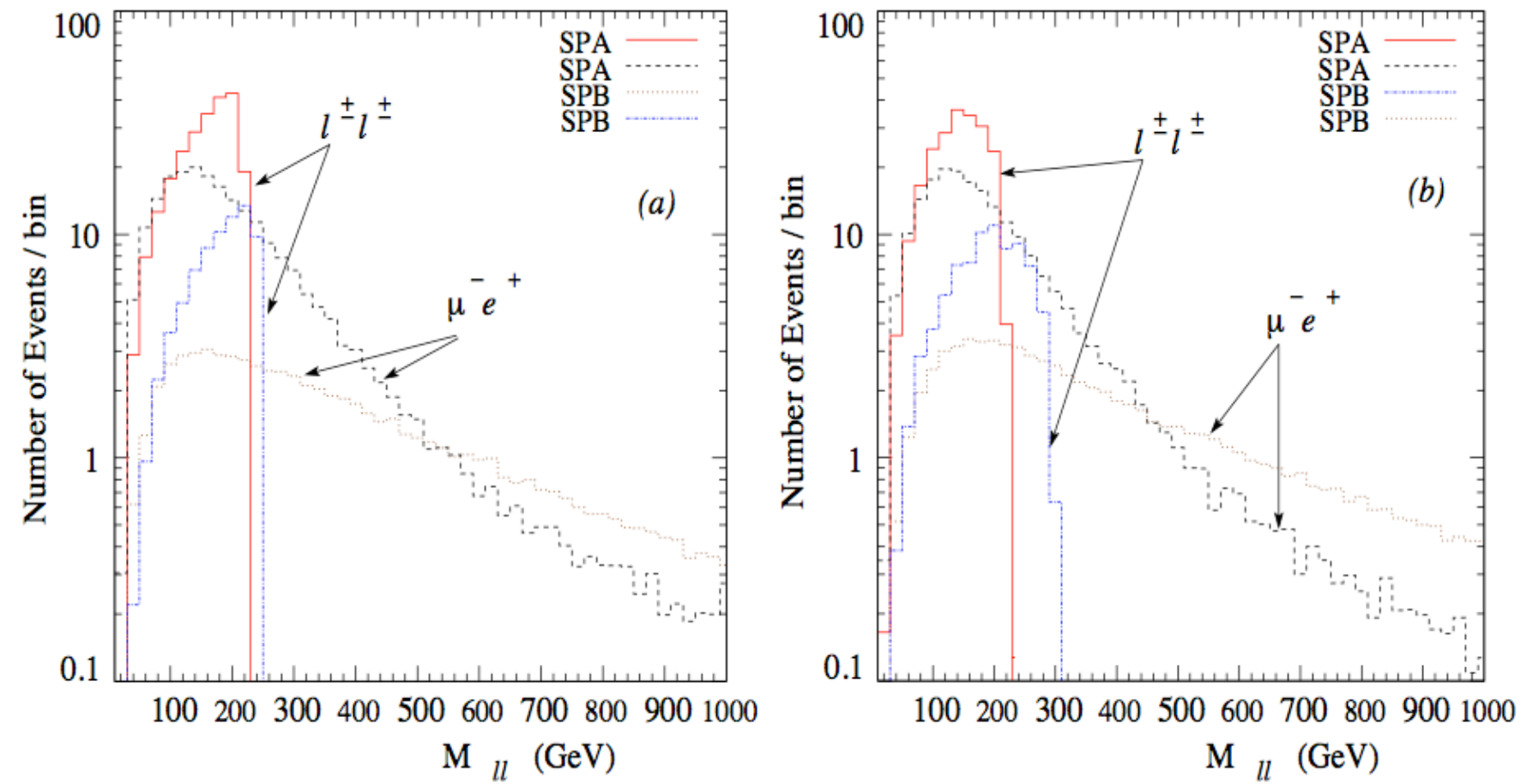
- *SSSF leptons are peaked at lower values* ΔR_{ll}
- *OSDF configurations are formed from two isolated leptons originating from separate cascades.*

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

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

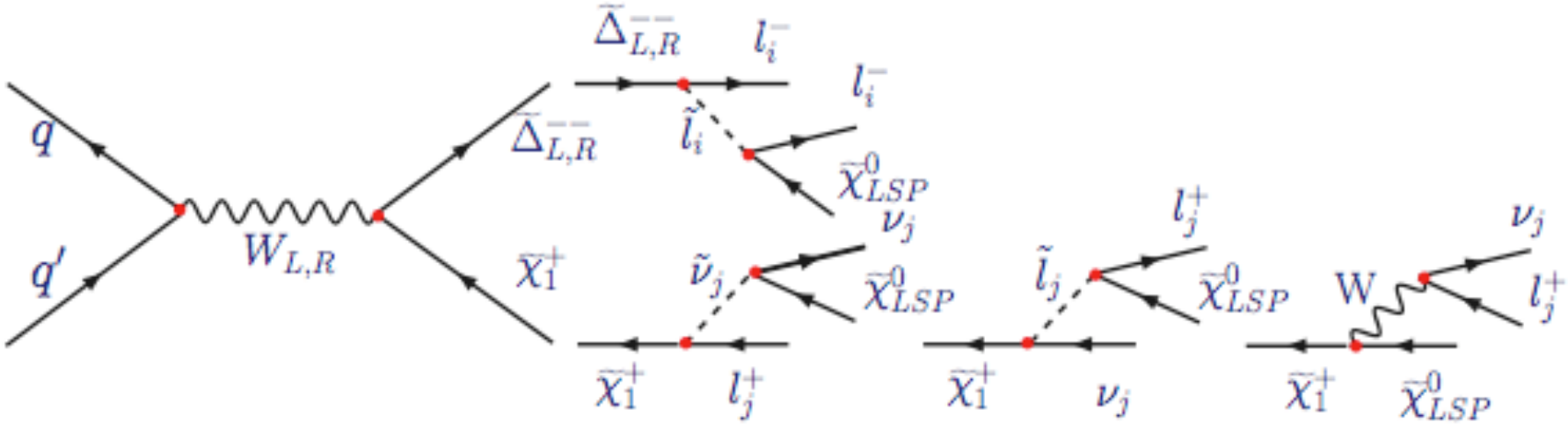
(S2) $$M_{\ell^\pm\ell^\pm}^{max} = M_{\tilde{\Delta}}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{M_{\tilde{\Delta}}}\right)^2}\sqrt{1-\left(\frac{M_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$

(S3) $$M_{\ell^\pm\ell^\pm}^{max} = \sqrt{M_{\tilde{\Delta}}^2 + M_{\tilde{\chi}_1^0}^2 - 2M_{\tilde{\Delta}}E_{\tilde{\chi}_1^0}}\ ,$$



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.***

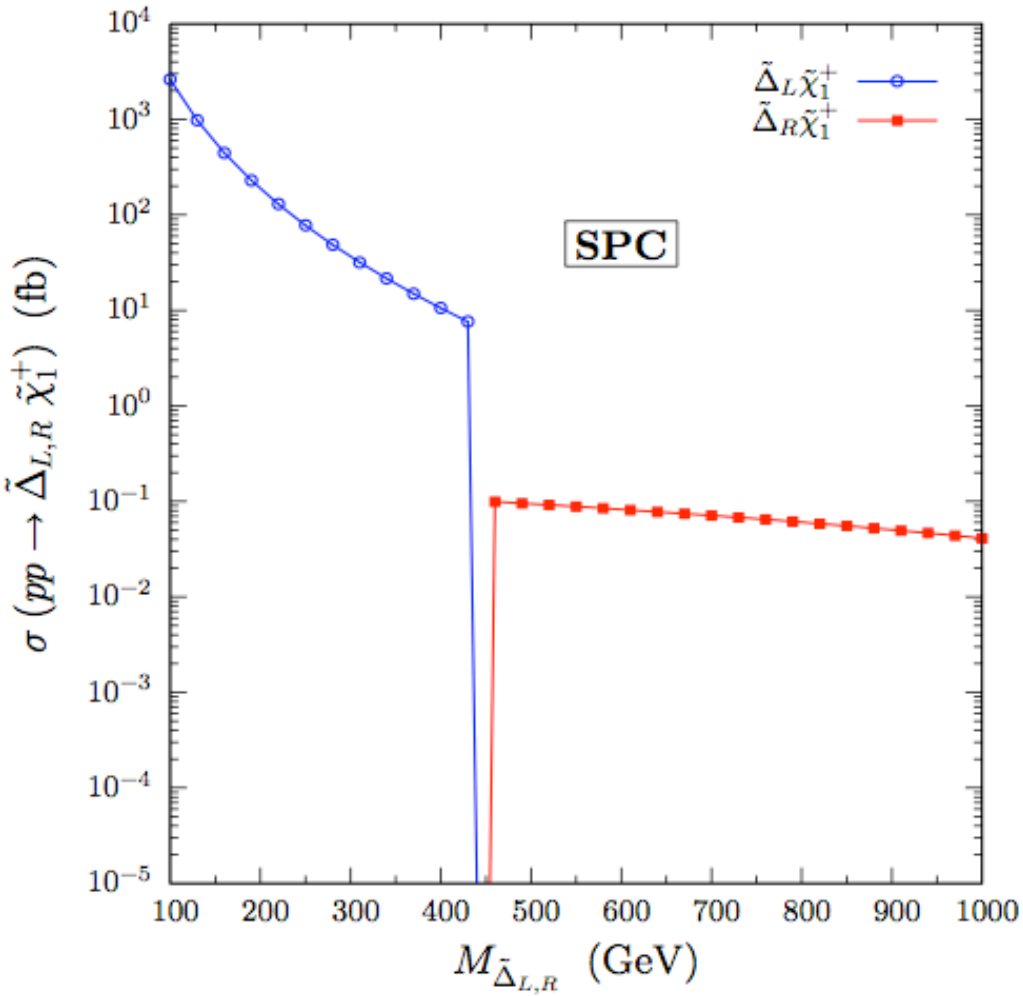
3 lepton signals:



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
$\tilde{\chi}^0_i$ $(i = 1, 3)$	142.5, 265.6, 300.0 GeV
$\tilde{\chi}^\pm_i$ $(i = 1, 3)$	300.0, 459.3, 500.0 GeV
$M_{\tilde{\Delta}}$	300 GeV
W_R, Z_R	1927.2, 3234.8 GeV
	S2 **S3**
$\tilde{e}_L, \tilde{e}_R$	(214.9, 214.0 GeV), (402.6, 402.2 GeV)
$\tilde{\mu}_L, \tilde{\mu}_R$	(214.9, 214.0 GeV), (402.6, 402.2 GeV)
$\tilde{\tau}_1, \tilde{\tau}_2$	(212.8, 216.2 GeV), (401.5, 403.3 GeV)

3 lepton signals at LHC

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



- *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:

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

3 lepton signals at LHC

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

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

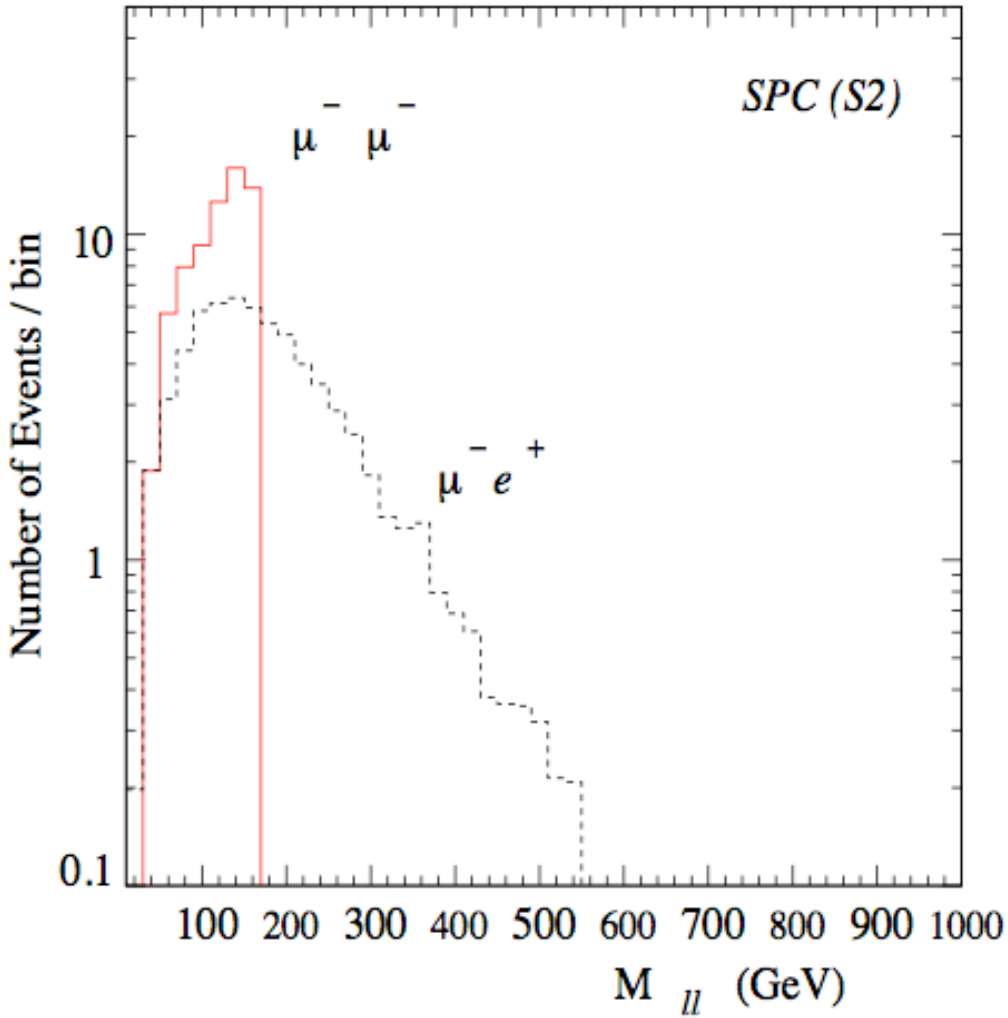
After cuts

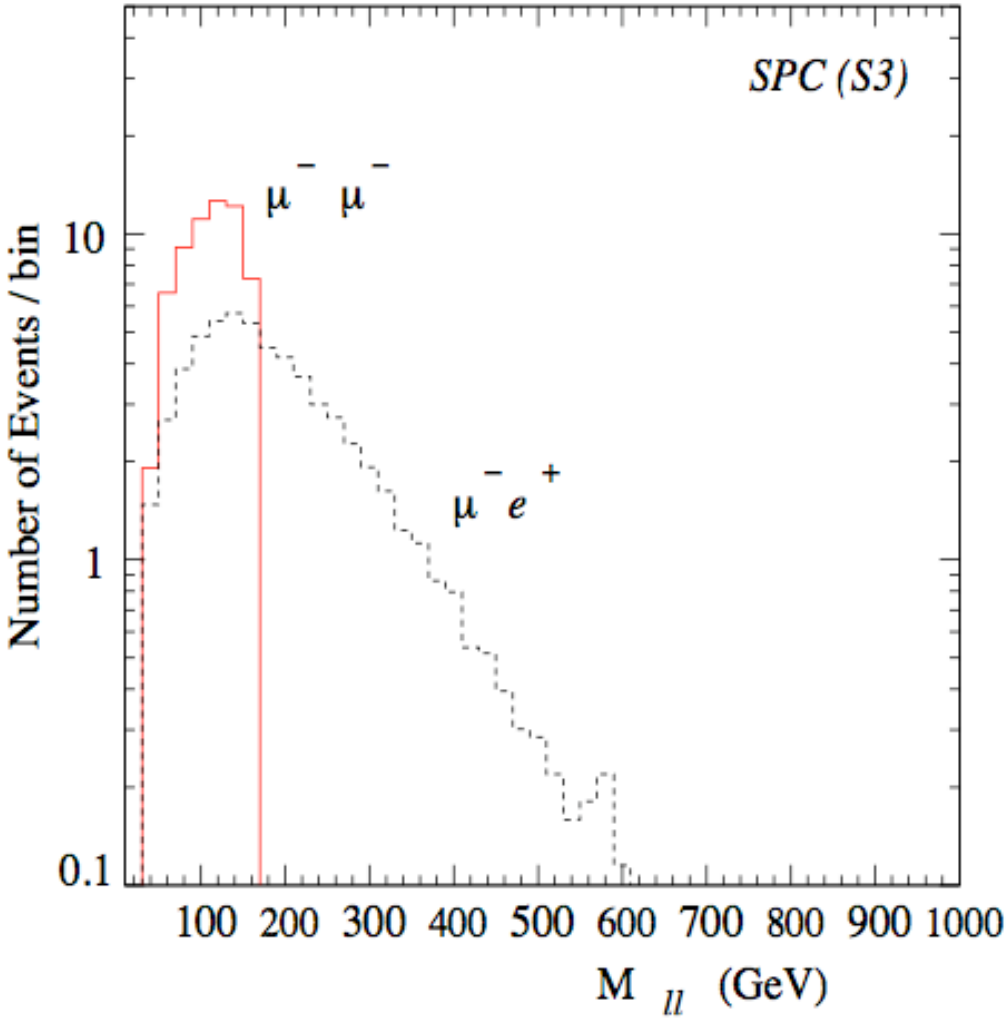
- **S2** $\sigma(2\ell_i^-\ell_j^+\not{E}_T) = 2.24$ fb,
- **S3** $\sigma(2\ell_i^-\ell_j^+\not{E}_T) = 2.03$ fb,

- *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 flavor.

(In SUSY/UED χ_2 / Z_1 *pair production)*

$$\chi_2 \text{-->} \chi_1 l^+ l^- \; ; Z_1 \text{-->} \gamma_1 l^+ l^-$$

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

Distinguishing power at LHC

♣ *possibilities with two different flavours..*

-- *pair production of doubly charged scalars*

(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.*

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 at colliders.*

- *Extended gauge and Higgs sector gives more interesting possibilities for collider searches in the LRSUSY model.*

Extra Slides

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

Fermion-Fermion-Z Boson, γ:

- $\gamma^\mu \tilde{\Delta}_{L,R}^{--}\bar{\tilde{\Delta}}_{L,R}^{--}: \qquad 2ie\gamma^\mu$
- $Z_L^\mu \tilde{\Delta}_L^{--}\bar{\tilde{\Delta}}_L^{--}: \qquad i\frac{g_L\cos 2\theta_W}{\cos\theta_W}\gamma^\mu$
- $Z_L^\mu \tilde{\Delta}_R^{--}\bar{\tilde{\Delta}}_R^{--}: \qquad -i\frac{2g_L\sin^2\theta_W}{\cos\theta_W}\gamma^\mu$
- $Z_R^\mu \tilde{\Delta}_L^{--}\bar{\tilde{\Delta}}_L^{--}: \qquad i\frac{g_L\sqrt{\cos 2\theta_W}}{\cos\theta_W}\gamma^\mu$
- $Z_R^\mu \tilde{\Delta}_R^{--}\bar{\tilde{\Delta}}_R^{--}: \qquad -i\frac{g_L(1-3\sin^2\theta_W)}{\cos\theta_W\sqrt{\cos 2\theta_W}}\gamma^\mu$

- $\tilde{\chi}_k^0\ \tilde{l}\ \bar{l}:$

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

- $\tilde{\chi}_k^0\ \tilde{\nu}\ \bar{\nu}:$

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

Bounds on the Yukawa couplings

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

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

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

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

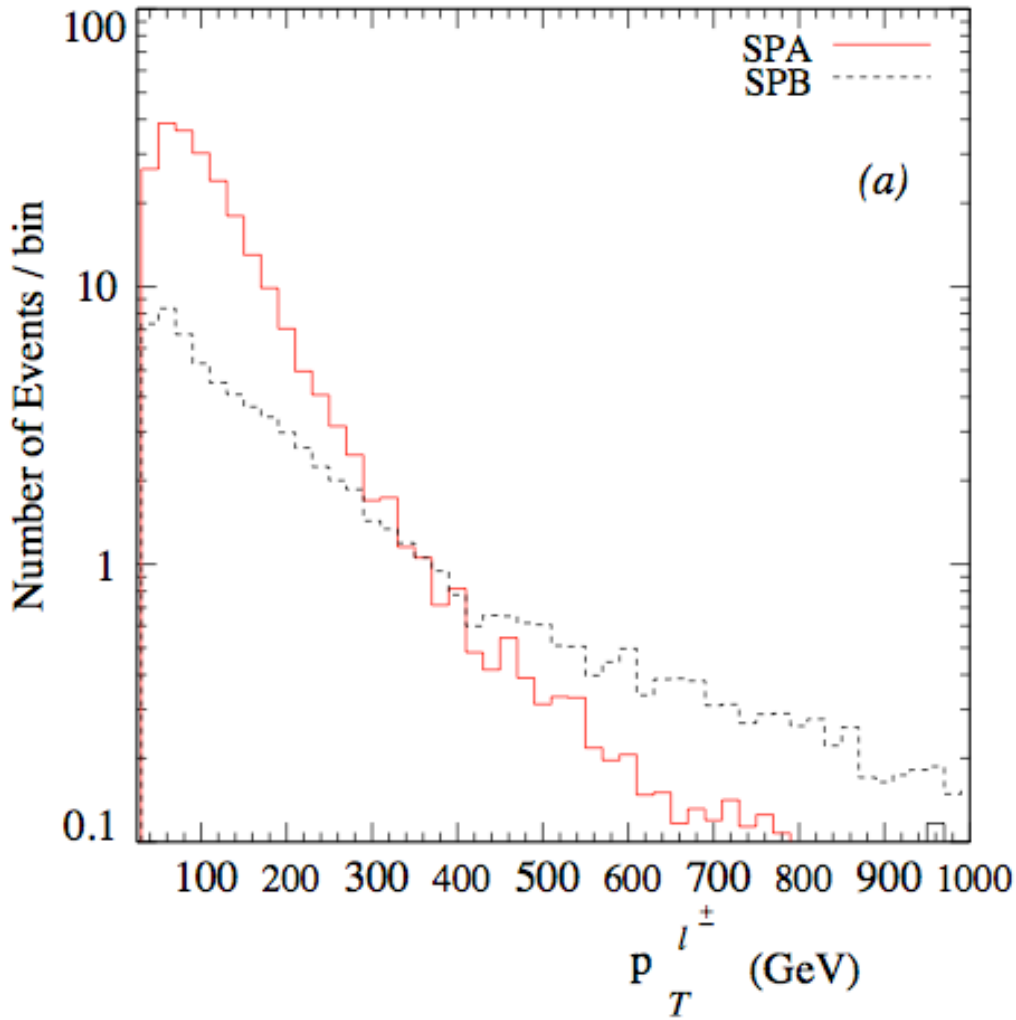
$$h_{ee}h_{\mu\mu} < 2.0 \times 10^{-7}\,\mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}} \quad \text{from muonium} - \text{antimuonium transition}.$$

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

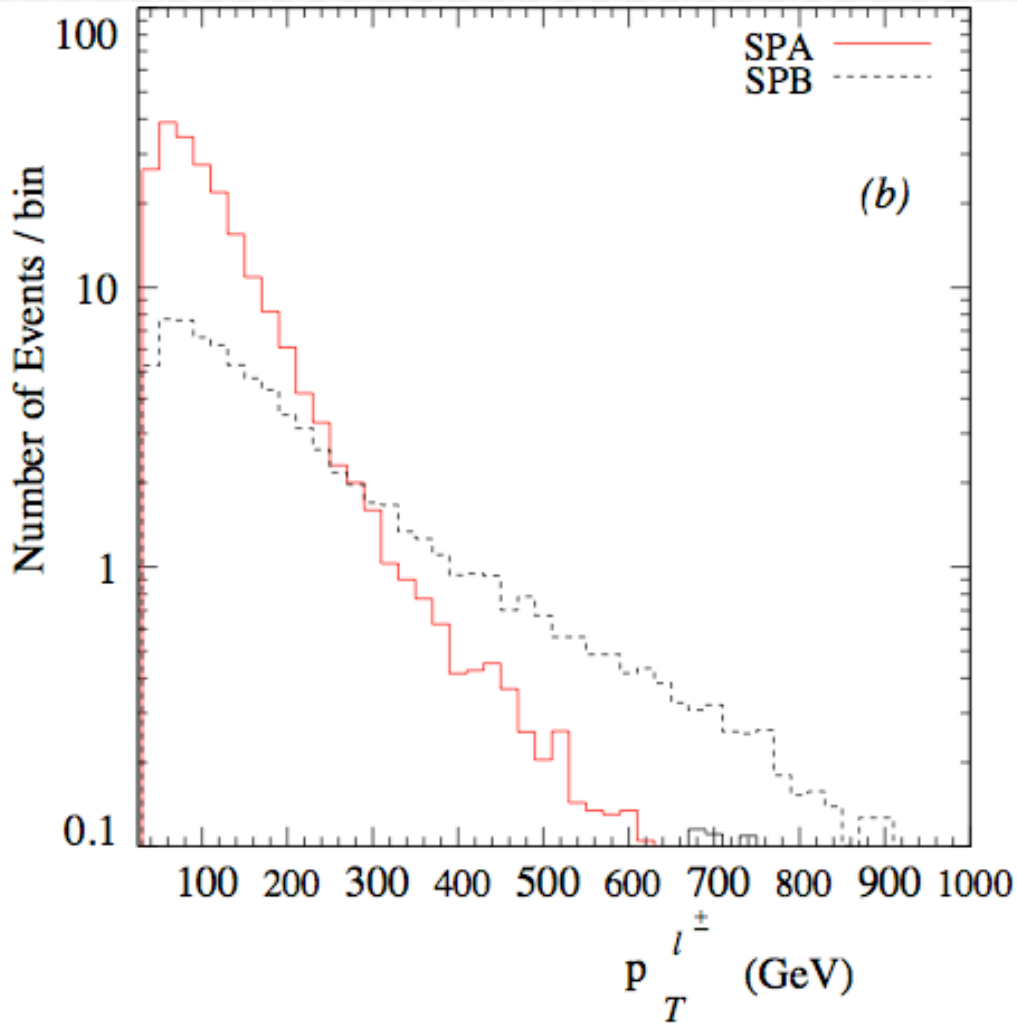
4 lepton signals at LHC

The p_T distribution for the charged leptons

(S2)



(S3)



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

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