R-parity Violating Supersymmetry

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Outline

- Introduction to $\not{R}_p$ SUSY
- Differences in Phenomenology
- Resonant Sparticle Production
  - Resonant Slepton Production at the Tevatron
- MSSM production with LSP decays
  - LLE Decays at the LHC
  - LQD Decays at the LHC
  - UDD Decays at the LHC
- Conclusions

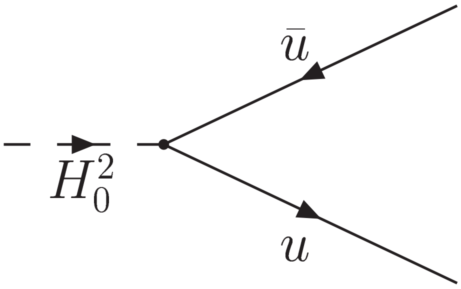
Introduction to $\not{R}_p$

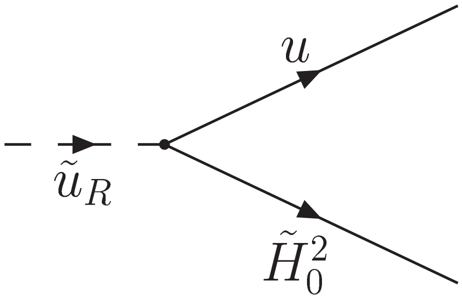
- **If we wish to write down a SUSY version of the Standard Model we should include all terms consistent with the symmetries, and renormalizablity.**
- **If we consider the superpotential of this theory**

$$\mathbf{W} = \mathbf{W}_{\mathbf{MSSM}} + \mathbf{W}_{\not{\mathbf{R}}_\mathbf{p}}$$

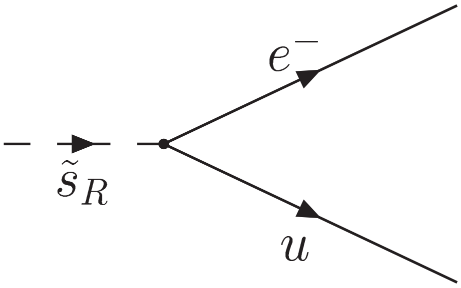
where

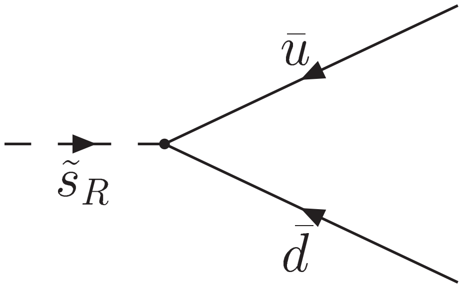
$$\begin{aligned}\mathbf{W}_{\mathbf{MSSM}} &= h^E_{ij}\varepsilon^{ab}L^i_aH^1_b\overline{E}^j + h^D_{ij}\varepsilon^{ab}Q^i_aH^1_b\overline{D}^j \\ &\quad + h^U_{ij}\varepsilon^{ab}Q^i_aH^2_b\overline{U}^j + \mu\varepsilon^{ab}H^1_aH^2_b\end{aligned}$$



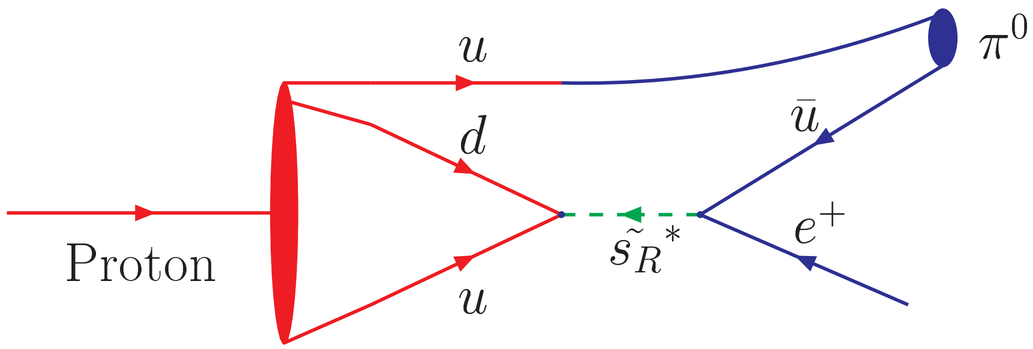


$$\begin{aligned}\mathbf{W}_{\not{\mathbf{R}}_\mathbf{p}} &= \lambda_{ijk}\varepsilon^{ab}L^i_aL^j_b\overline{E}^k + \lambda'_{ijk}\varepsilon^{ab}L^i_aQ^j_b\overline{D}^k \\ &\quad + \lambda''_{ijk}\varepsilon^{\alpha\beta\gamma}\overline{U}^i_\alpha\overline{D}^j_\beta\overline{D}^k_\gamma + \kappa_i\varepsilon^{ab}L^i_aH^2_b\end{aligned}$$





- **However these terms lead to proton decay**



- **Limits on the proton lifetime lead to**

$$\lambda'_{11k} \cdot \lambda''_{11k} \lesssim 2 \times 10^{-27} \left(\frac{M_{\tilde{d}_{kR}}}{100 \ \mathrm{GeV}} \right)^2$$

- **Only natural way is if the LHS is zero**

- **In the MSSM R-parity is imposed by hand. It is a discrete multiplicative symmetry.**

$$\mathbf{R_p} = (-1)^{3B+L+2S}$$

- **SM particles $R_p = +1$, SUSY Particles $R_p = -1$**

- R_p **prevents proton decay by forbidding both terms**

- **Instead impose a symmetry forbidding lepton or baryon number violating terms**

$$\text{e.g. Baryon Parity} \begin{array}{lcl} \{Q_i, U_i, D_i\} & \longrightarrow & -\{Q_i, U_i, D_i\} \\ \{L_i, E_i\} & \longrightarrow & \{L_i, E_i\} \end{array}$$

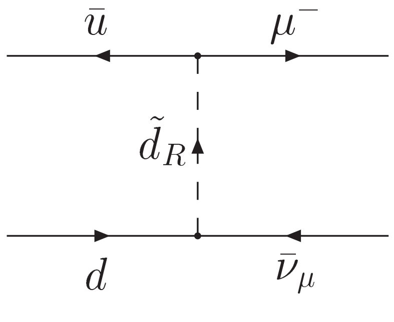
Limits on the Couplings

- **There are limits on the couplings from low energy processes**

ijk	λ_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ''_{ijk}
121	0.049	111	5.2×10^{-4}	211	0.059	311	0.11	112	2×10^{-4}
122	0.049	112	0.021	212	0.059	312	0.11	113	10^{-4}
123	0.049	113	0.021	213	0.059	313	0.11	123	1.23
131	0.062	121	0.043	221	0.18	321	0.52	212	1.23
132	0.062	122	0.043	222	0.21	322	0.52	213	1.23
133	0.006	123	0.043	223	0.21	323	0.52	223	1.23
231	0.070	131	0.019	231	0.18	331	0.45	312	0.50
232	0.070	132	0.28	232	0.56	332	0.45	313	0.50
233	0.070	133	1.4×10^{-3}	233	0.15	333	0.45	323	0.50

- **Taken from hep-ph/9906209 Allanach, Dedes, Dreiner**
- **The couplings on the higher generation couplings are weaker and some (shown in red) are only limited by perturbativity.**
- *e.g.* **limit on λ'_{211} from**

$$R_\pi = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$$



Differences in Phenomenology

- R_p conservation means that
  1. Sparticles are only produced in pairs
  2. The LSP is stable, and neutral (cosmology)
  3. Therefore a major signature is missing transverse energy

- However if R_p is violated
  1. Single Sparticles can be produced
  2. LSP can decay and need not be neutral
  3. Lepton or Baryon Number is Violated

- Different phenomenology to the MSSM

Bi-linear RPV

- The last term in the superpotential is bilinear in the fields
- This gives mixing between

  the neutralinos and neutrinos
  the charginos and the charged leptons

- There is also mixing between

  The Higgs bosons and sleptons

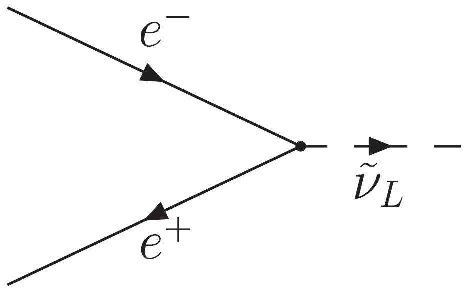
- This mixing gives mass to the neutrinos
- Bi-linear $\not{R}_{\mathrm{p}}$ is one possible explanation of neutrino masses
- Gives predictions for collider phenomenology, *e.g.* the decay modes of SUSY particles

Resonant Sparticle Production

- **The different terms in the $\not{R}_p$ superpotential give different possible resonant production mechanisms**

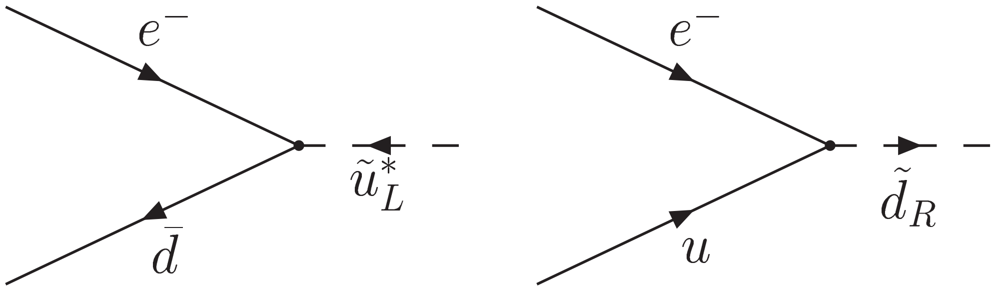
- **In e^+e^- collisions**

LLE



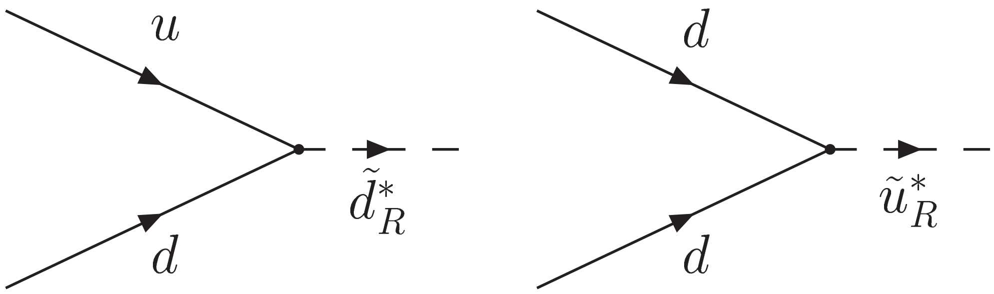
- **In electron-proton collisions**

LQD

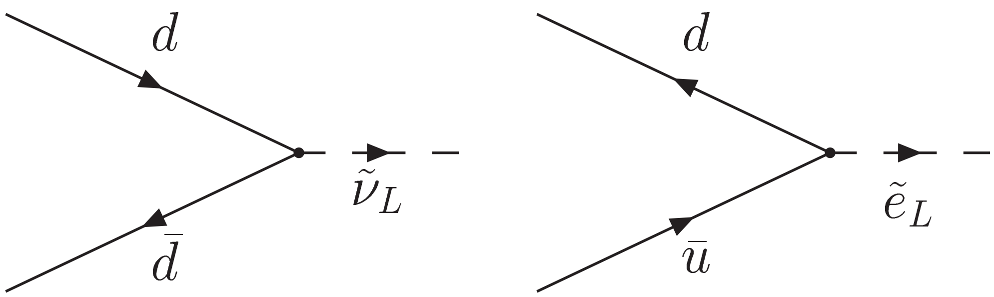


- **In hadron-hadron collisions**

UDD



LQD



Resonant Sparticle Production

- The cross sections for resonant sparticle production depend on the RPV couplings
- Therefore they are only important for relatively large couplings
- However as only one sparticle is produced they can be kinematically favoured over MSSM pair production.

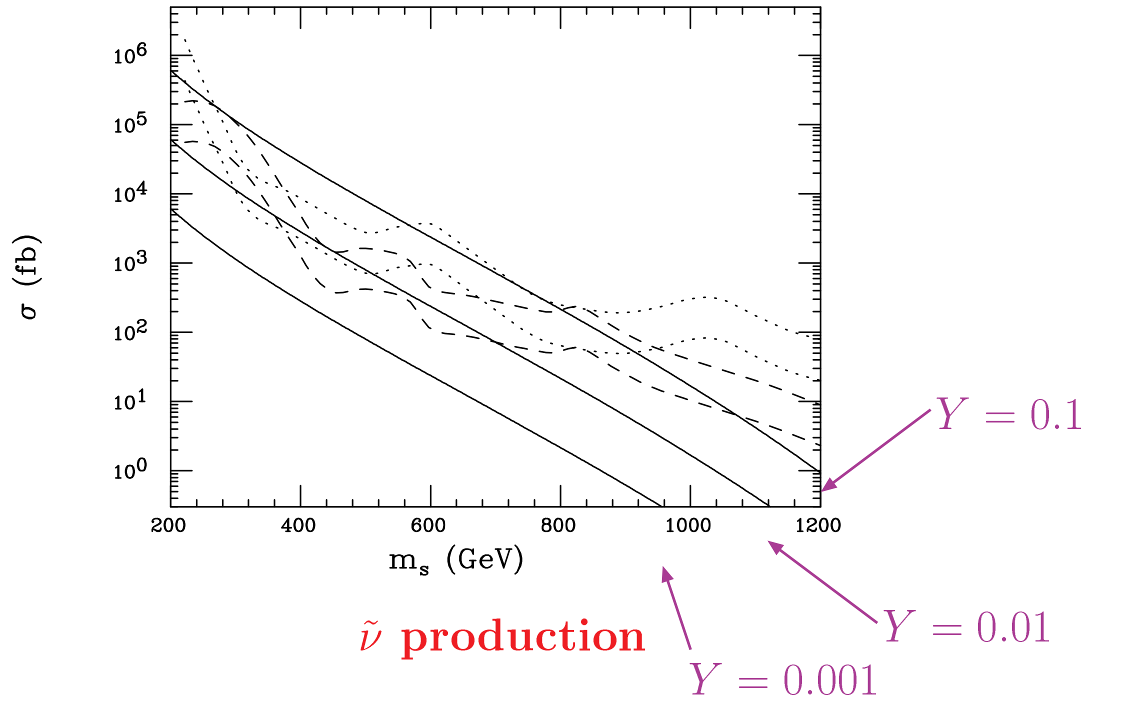
Resonant Slepton Production

- **The experimental signature of resonant slepton production depends on the decay mode of the slepton**

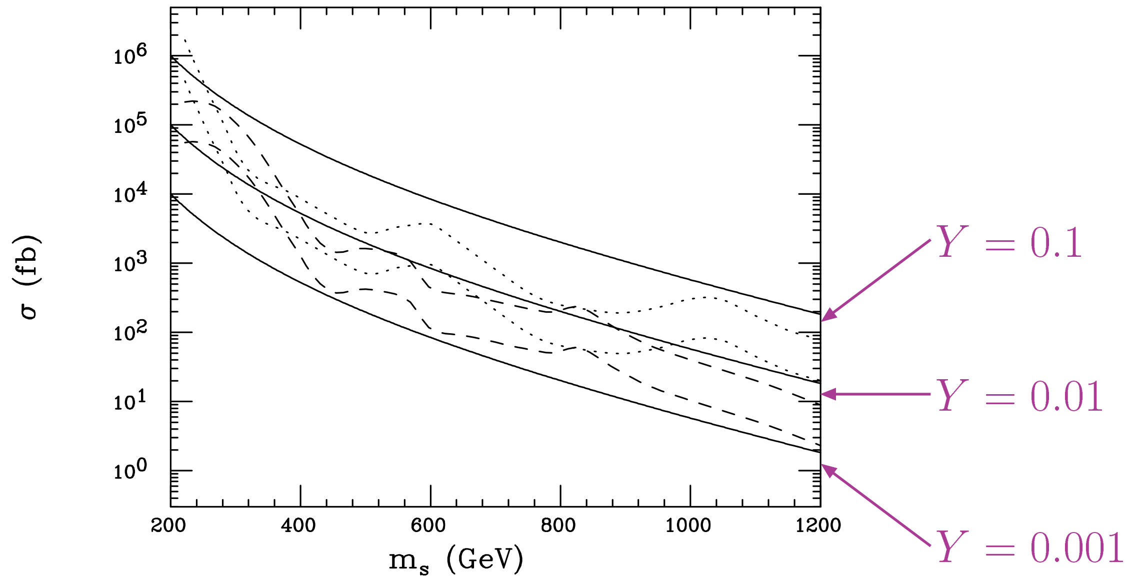
	Charged Sleptons	Sneutrinos
Gauge Decays	$\tilde{\ell}_{i\alpha} \to \ell^-_i \tilde{\chi}^0$	$\tilde{\nu}_i \to \nu_i \tilde{\chi}^0$
	$\tilde{\ell}_{i\alpha} \to \nu_i \tilde{\chi}^-$	$\tilde{\nu}_i \to \ell^-_i \tilde{\chi}^+$
$R\!\!\!/_p$ Decays	$\tilde{\ell}_{i\alpha} \to \bar{u}_j d_k$	$\tilde{\nu}_i \to \bar{d}_j d_k$
	$\tilde{\ell}_{i\alpha} \to \bar{\nu}_j \ell^-_k$	$\tilde{\nu}_i \to \ell^+_j \ell^-_k$
Weak Decays	$\tilde{\ell}_{i\alpha} \to \tilde{\nu}_i W^-$	$\tilde{\nu}_i \to \tilde{\ell}_{i\alpha} W^+$
	$\tilde{\ell}_{i2} \to \tilde{\ell}_{i1} Z_0$	
Higgs Decays	$\tilde{\ell}_{i\alpha} \to \tilde{\nu}_i H^-$	$\tilde{\nu}_i \to \tilde{\ell}_{i\alpha} H^+$
	$\tilde{\ell}_{i2} \to \tilde{\ell}_{i1} h_0, H_0, A_0$	

- **Most of the studies have been of the $R\!\!\!/_p$ decays**
  - **LLE gives new resonances in Drell-Yan Production**
  - **LQD gives new resonances in di-jet Production**

- **Taken from hep-ph/9809525, J. Hewett and T. Rizzo.**



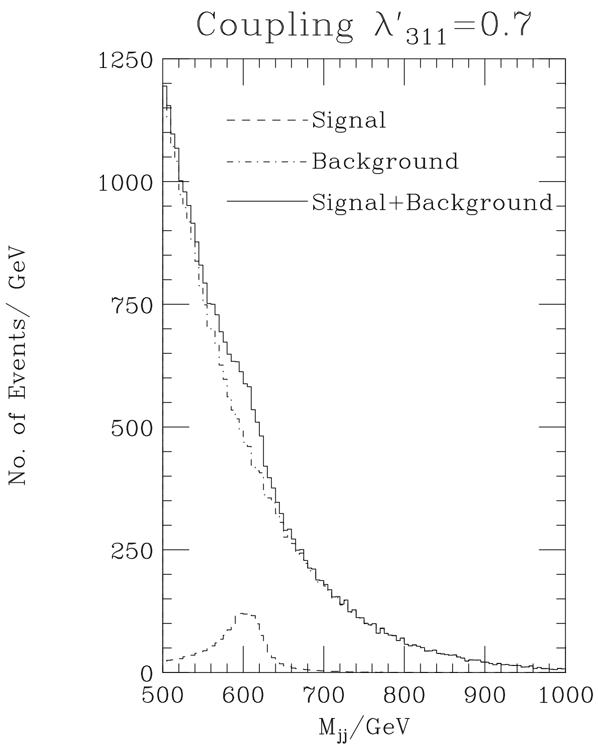
$\tilde{\nu}$ **production**

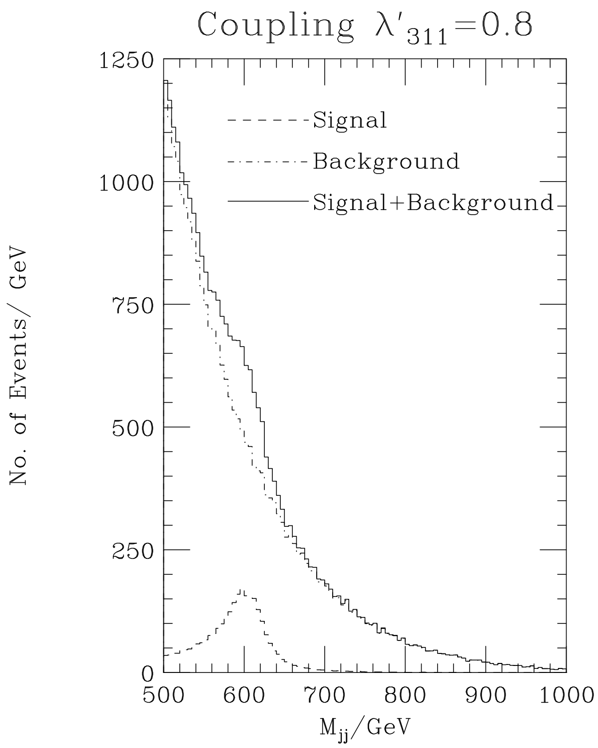


$\tilde{\tau}$ **production**

- $Y = \lambda'^2 \times \mathrm{BR}(\tilde{\ell} \to \mathrm{jets})$
- **dots CDF discovery potential at 2 fb^{-1} and 30 fb^{-1}**
- **dashes D0 discovery potential at 2 fb^{-1} and 30 fb^{-1}**

Effect of QCD Radiation

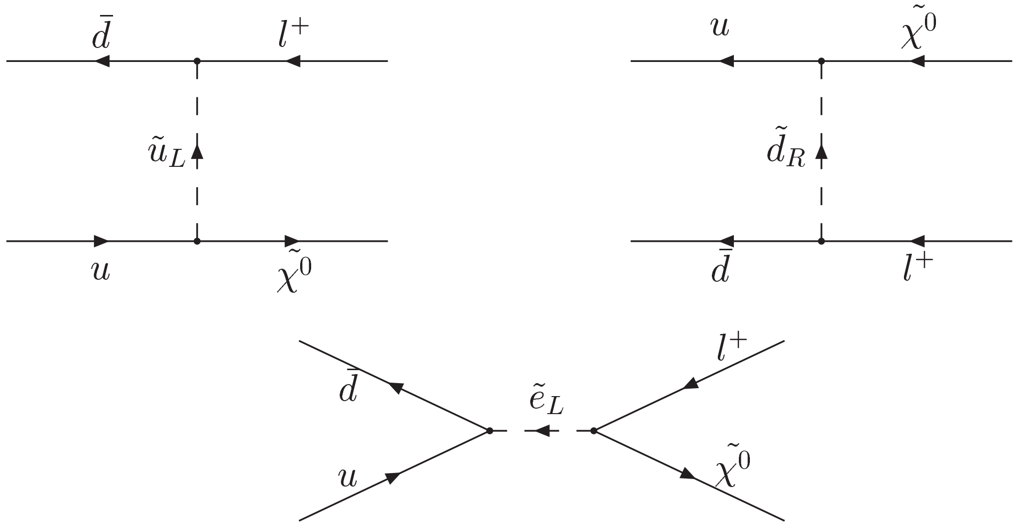




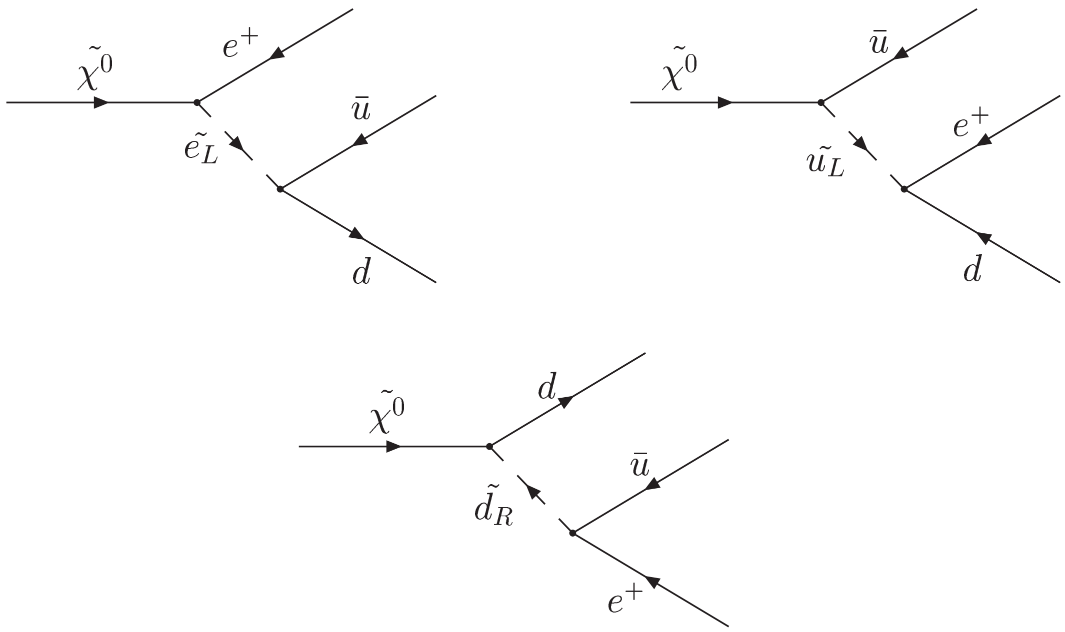
- **SUGRA point** $M_0 = 600$ **GeV,** $M_{1/2} = 200$ **GeV,** $A_0 = 0$ **GeV,** $\tan\beta = 10$**,** $\mathrm{sgn}\,\mu\ +$**.**
- **At this point the limit on the coupling in** $\lambda'_{311} < 0.8$
- **Slepton Masses between 600 and 620 GeV**
- **If we consider the region** $580\,\mathrm{GeV} \le M_{jj} \le 640\,\mathrm{GeV}$ **which contains the resonance the** $S/\sqrt{B} > 35$ **at both points.**
- **However the** S/B **is between 20 and 30%.**

Gauge Decays

- **Consider the decay** $\tilde{\ell}^+ \longrightarrow \ell^+ \tilde{\chi}^0$



- **The neutralino can then decay by the crossed process**



- **This gives a signature of two like-sign leptons**
- **Other processes also contribute**

  $\tilde{\ell}^+ \rightarrow \tilde{\chi}_1^+ \nu_\ell$ **followed by** $\tilde{\chi}_1^+ \rightarrow \ell^+ \nu_\ell \tilde{\chi}_1^0$

  $\tilde{\nu} \rightarrow \ell^- \tilde{\chi}_1^+$ **followed by** $\tilde{\chi}_1^+ \rightarrow q\bar{q}' \tilde{\chi}_1^0$

Standard Model Backgrounds

- **Gauge Boson pair production**
- $b\bar{b}$ **production**
- $t\bar{t}$ **production**
- **single top production**
- **SUSY pair production**
- **There will also be non-physics backgrounds, which we ignore here, but should be included in an experimental search.**

  1. **Charge misidentification in Drell-Yan**
  2. **Fake leptons, from misidentifying an isolated hadron as a lepton in W+jet production.**

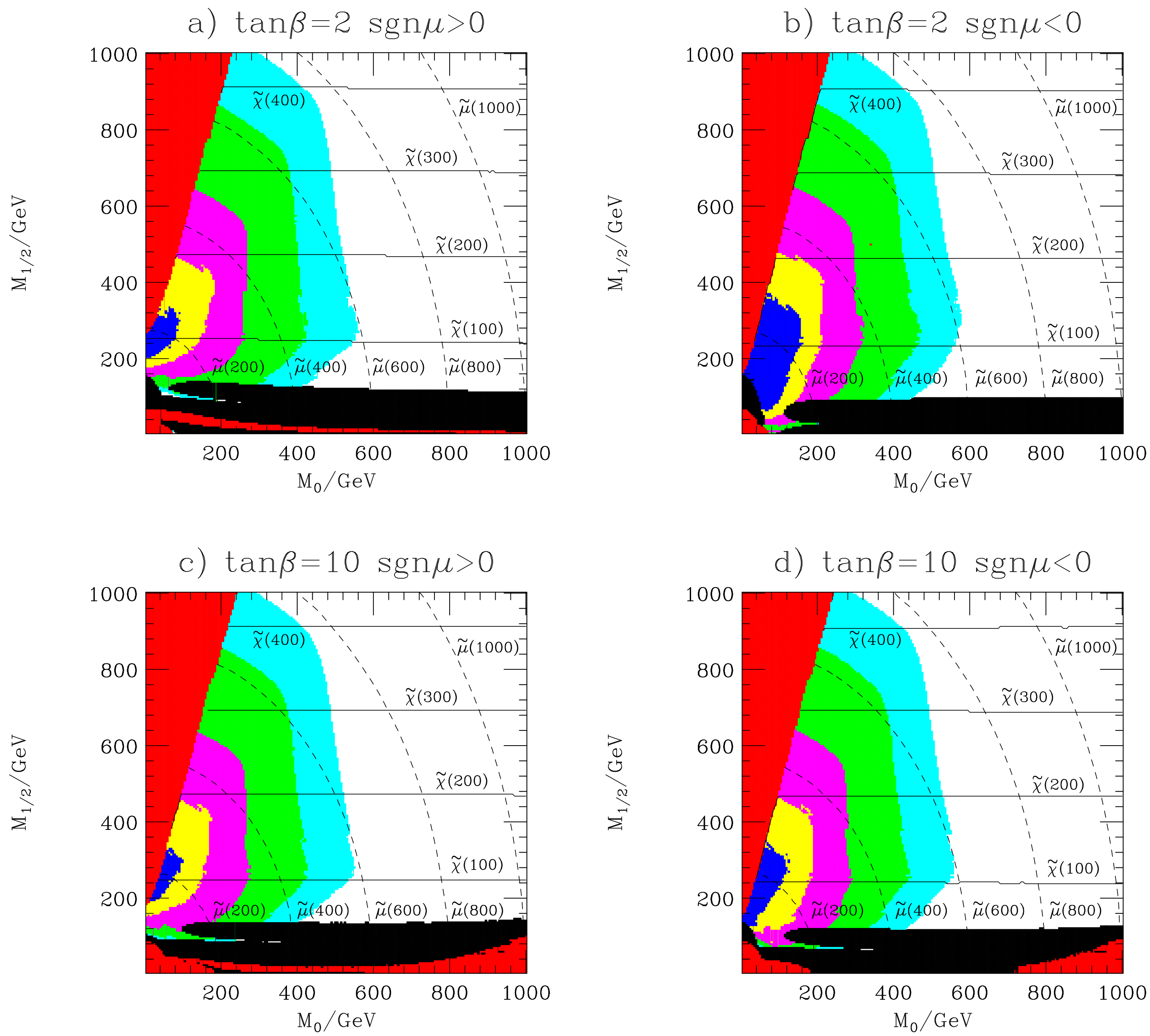
Tevatron

- **We impose the following cuts**

  1. $p_T^{\text{lepton}} > 20$ **GeV**
  2. **An isolation cut on the like-sign leptons so that the transverse energy in a cone about the direction of the lepton is less than** 5 **GeV.**
  3. **We cut the region** $60\,\text{GeV} < M_T < 85\,\text{GeV}$**.**
  4. **A veto on the presence of a lepton in the event with the same flavour but opposite charge (OSSF) as either of the leptons in the like-sign pair if the lepton has** $p_T > 10$ **GeV and passes the same isolation cut as the like-sign leptons.**
  5. **A cut on the missing transverse energy,** $E^T_{miss} < 20$ **GeV.**
  6. **At most two jets with** $E_T > 20$ **GeVto remove SUSY background.**

Results

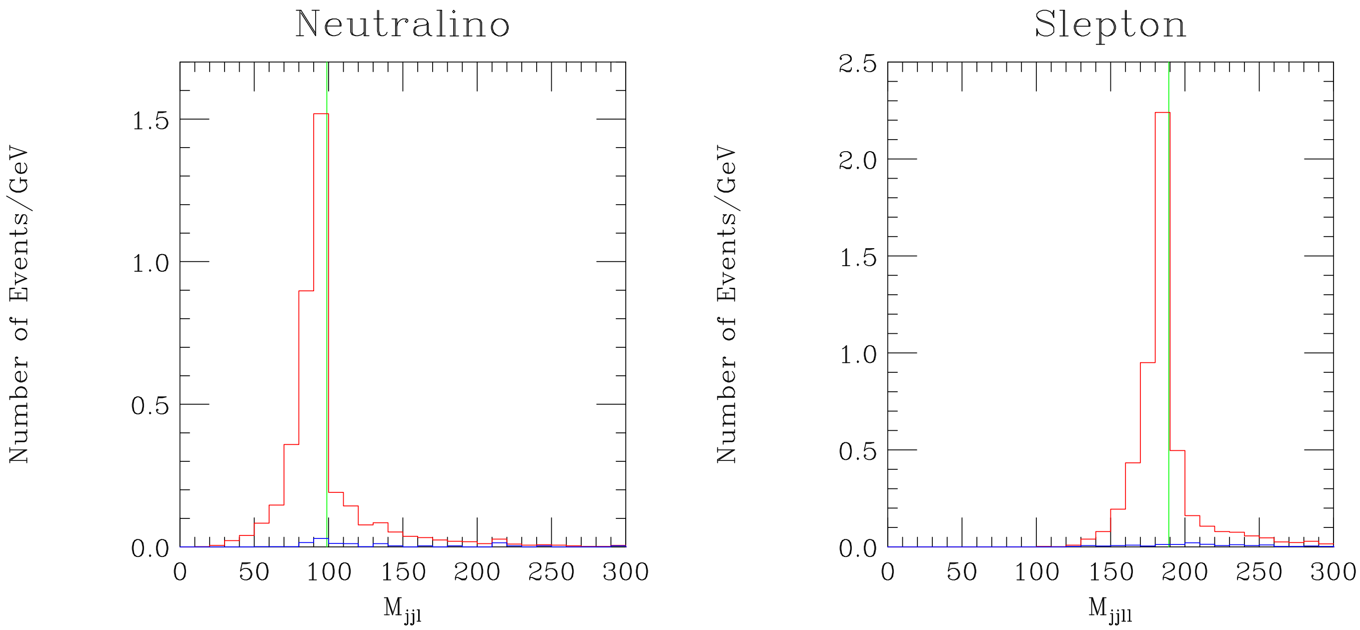
- **For 2 fb^{-1} integrated luminosity**



- Red: Excluded by lack of electroweak symmetry breaking or by the lightest neutralino not being the LSP
- Black: Excluded by LEP
- Blue: $\lambda'_{211} > 6 \times 10^{-3}$
- Green: $\lambda'_{211} > 5 \times 10^{-2}$
- Yellow: $\lambda'_{211} > 10^{-2}$
- Cyan: $\lambda'_{211} > 0.1$
- Pink: $\lambda'_{211} > 2 \times 10^{-2}$

Mass Reconstruction

- We can reconstruct the neutralino and slepton masses
- Neutralino: Combine the lepton closest in (η, ϕ) with the two hardest jets in the event
- Slepton: Combine both leptons and the two hardest jets



- The reconstructed masses are lower by $5 \sim 10$ GeV

- This is due to the loss of some of the hadrons from the jets produced in the neutralino decay.

MSSM Production with RPV decays

- **Provided the $\not{R}_p$ coupling is small the main effect is the decay of the LSP**
- **If the coupling is $\lesssim 10^{-6}$ the LSP decays outside the detector**
- **If the LSP is neutral and decays outside the detector the signatures are the same as the MSSM**
- **If the LSP is charged it acts like a muon in the detector but gives more ionization**
- **If the coupling is $\gtrsim 10^{-6}$ the LSP decays inside the detector**
- **The MSSM decay chains are largely unaffected, but at the end the LSP decays.**
- **The signature depends on the nature of the $\not{R}_p$ coupling**

- Most analyses have assumed the $\tilde{\chi}_1^0$ is the LSP although it can be any sparticle

  – LLE LSP decays to leptons

    Multi-lepton signatures which are visible above the background and the possibility of reconstructing the $\tilde{\chi}_1^0$ mass

  – LQD LSP decays to lepton or neutrino and jets

    Again Multi-lepton signatures which should be visible above the background and the possibility of reconstructing the $\tilde{\chi}_1^0$ mass

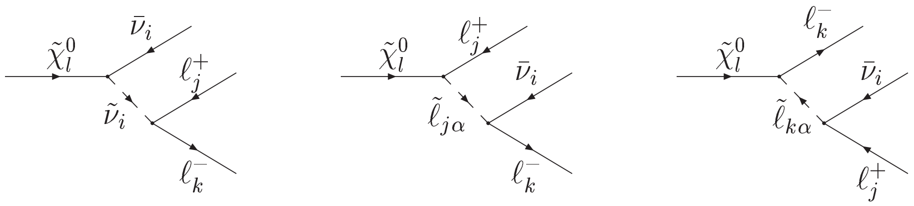
  – UDD LSP decays to quarks.

    This is a potential 'worst case' for the discovery of SUSY at the Tevatron/LHC

LLE Decays at the LHC

- In this model the neutralino decays

$$\tilde{\chi}_1^0 \longrightarrow \ell^+ \ell^- \nu$$



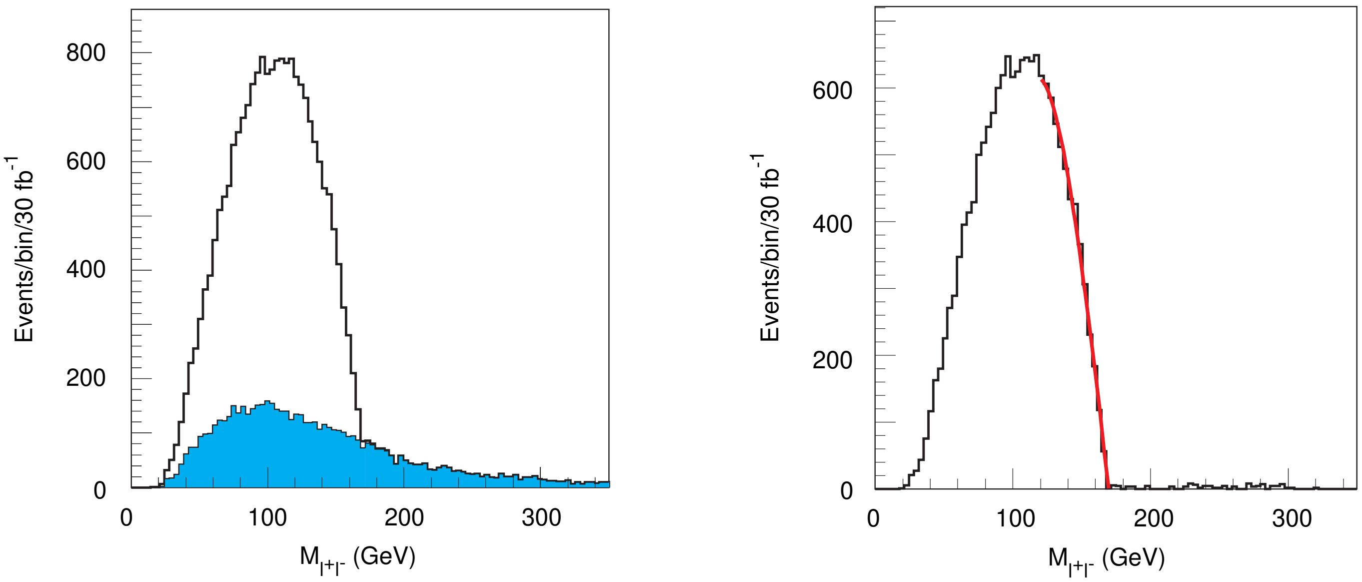
- In these events two neutralinos are produced
- This gives at least 4 charged leptons
- These events are therefore easy to see above the SM background
- Require

  4 isolated leptons with $P_T > 10\,\text{GeV}$

  $\cos\alpha_{ll'} > 0.5$, where $\alpha_{ll'}$ is the angle between leptons in an OSDF pair.

  $E^T_{\text{miss}} > 50\,\text{GeV}$

- **The edge in the OSDF lepton mass distribution gives the $\tilde{\chi}_1^0$ mass.**

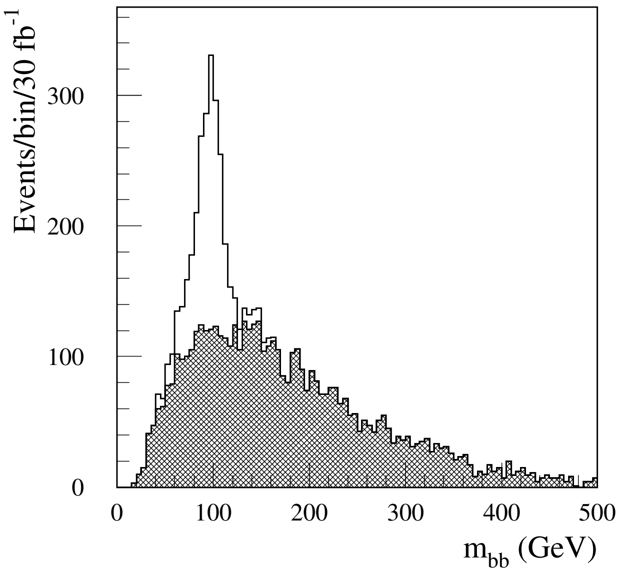


- **Graph shows the result for λ_{122} at SUGRA point 1.**
- **At the point studied the decay $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ occurs**
- **Therefore can reconstruct the $\tilde{\chi}_2^0$ mass by requiring**

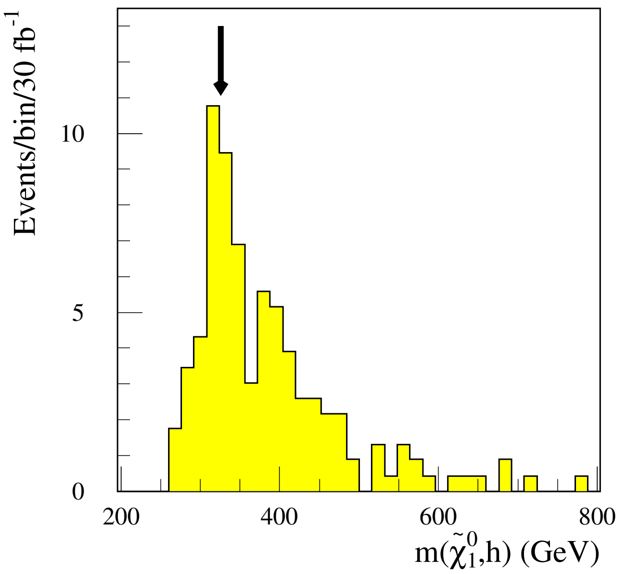
  2 b-jets with $p_T > 30\,\mathrm{GeV}$ and $p_T < 300\,\mathrm{GeV}$

  $\cos\alpha_{bb} > 0.4$ where α_{bb} is the angle between the b-jets

- **Can reconstruct the Higgs in these events**



- **by adding the leptons to the b jets can reconstruct the $\tilde{\chi}_2^0$**



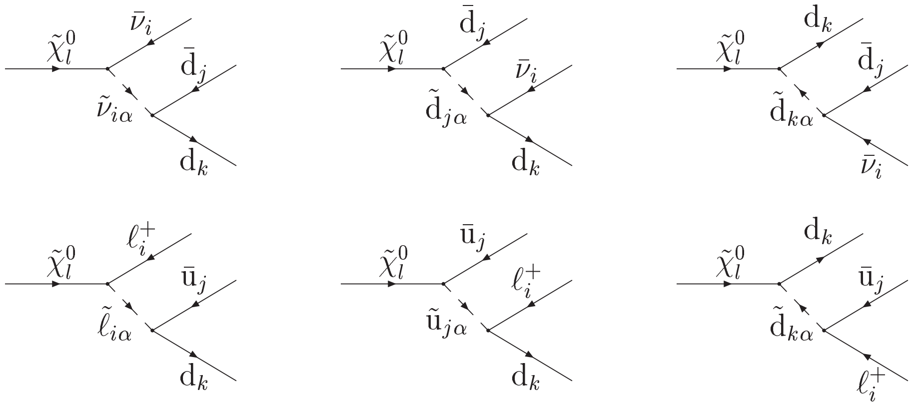
- **In this study**

$$
\begin{aligned}
M_{\tilde{\chi}_1^0} &= 169.8 \pm 0.18\,\mathrm{GeV} \\
M_{\tilde{\chi}_2^0} &= 326.2 \pm 4.8\,\mathrm{GeV}
\end{aligned}
$$

- **Can also reconstruct squarks and charginos**

LQD Neutralino Decays at the LHC

- **In this case the neutralino decay gives two jets and a lepton**



- **Therefore events contain at least four jets and 2 leptons**
- **Apply the following cuts to reduce the SM background**

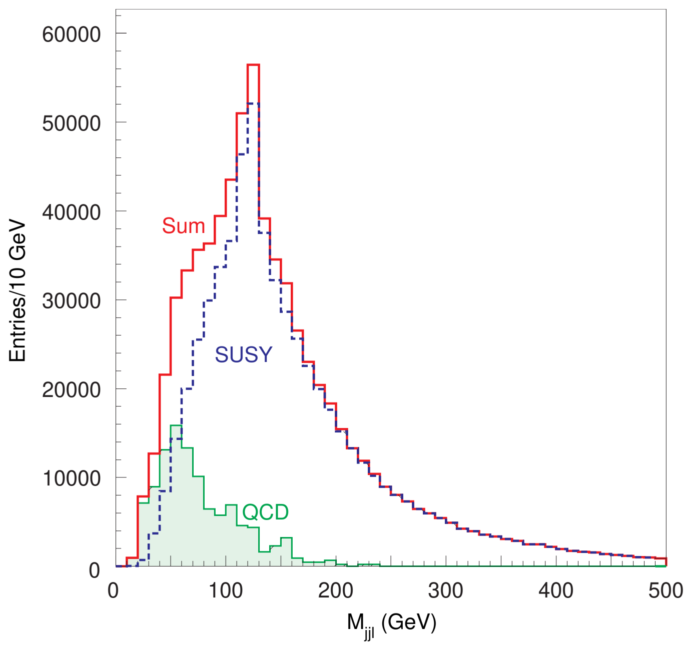
  6 jets with $P_T > 20\,\mathrm{GeV}$ **and 1 with** $p_T > 250\,\mathrm{GeV}$**,**

  1 lepton with $p_T > 20\mathrm{GeV}$**,**

  sphericity > 0.2 **and thrust**< 0.9

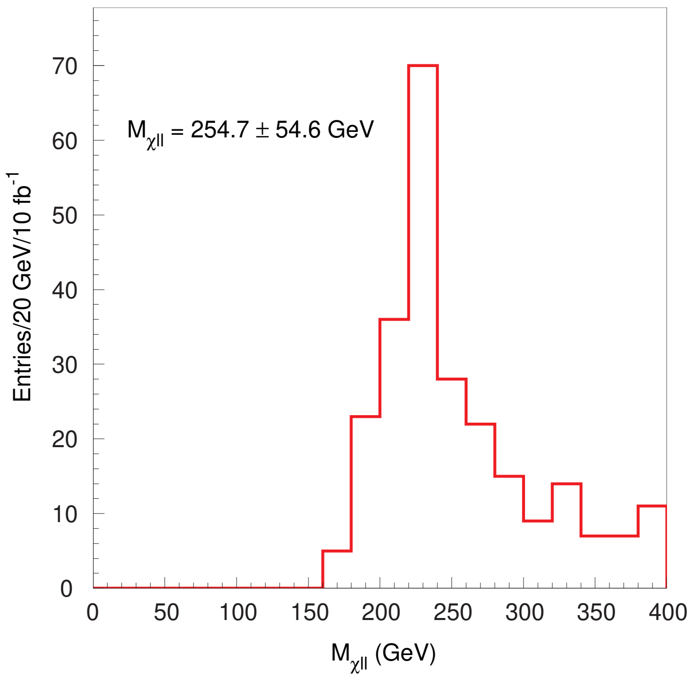
- **Cuts are then applied to find the right combination of jets and a lepton to reconstruct the neutralino**

- **The $\tilde{\chi}_1^0$ mass can be reconstruct from a charged lepton and 2 jets**

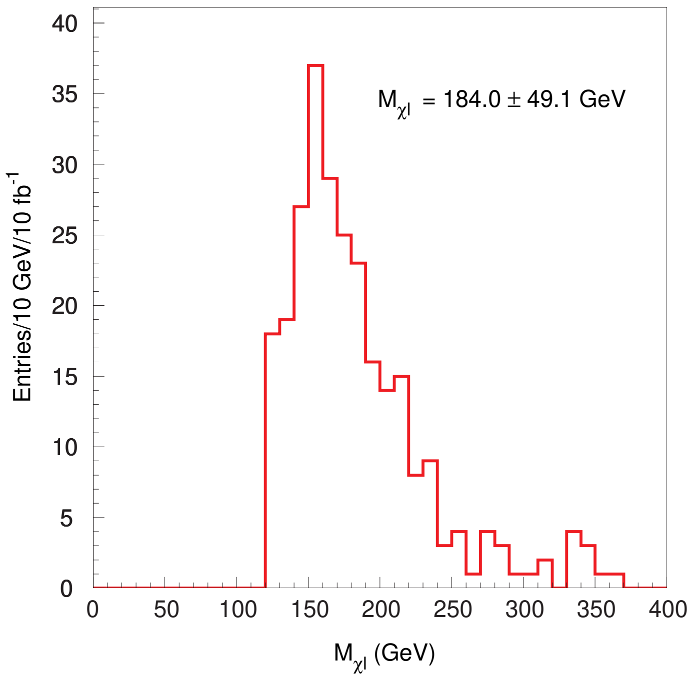


- **The error is $\pm 3\,\mathrm{GeV}$ on the neutralino mass**
- **This is at SUGRA point 5**
- **At this point the $\tilde{\chi}_2^0$ decays via the mode** $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0 \ell^+ \ell^- \tilde{\chi}_1^0$.

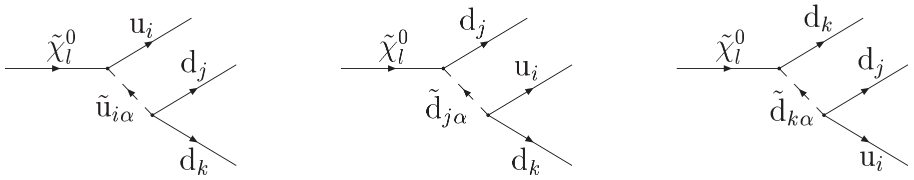
- Therefore by looking for events with 2 more leptons and combining these with nearest $\tilde{\chi}_1^0$ candidate the $\tilde{\chi}_2^0$ can be reconstructed



- By combined the $\tilde{\chi}_1^0$ candidate with the nearest lepton the $\tilde{\ell}_R$ mass can also be reconstructed



UDD Neutralino Decays at the LHC



- **This is the most experimentally challenging channel for the discovery of SUSY**
- **This analysis was performed at SUGRA Point 5, i.e.**

$$M_0 = 100\ \textbf{GeV},\ M_{1/2} = 300\ \textbf{GeV},$$
$$A_0 = 300\ \textbf{GeV},\ \tan\beta = 2.1,\ \mathrm{sgn}\,\mu\ +$$
$$\lambda''_{212} = 0.005$$

- λ''_{212} **was chosen as it is only limited by perturbativity and is one of the harder signatures,** *i.e.* **no b tagging**
- **Each** $\tilde{\chi}^0_1$ **decays to three quarks**
- **As the coloured sparticles are predominantly produced the jet multiplicities are large**

Detection of the $\tilde{\chi}_1^0$

- **When λ''_{212} is small two $\tilde{\chi}_1^0$s are produced.**
- **So search for two combinations of three jets with**

  $$\delta m_{jjj} = |m^a_{jjj} - m^b_{jjj}| < 20 \ \textbf{GeV}$$

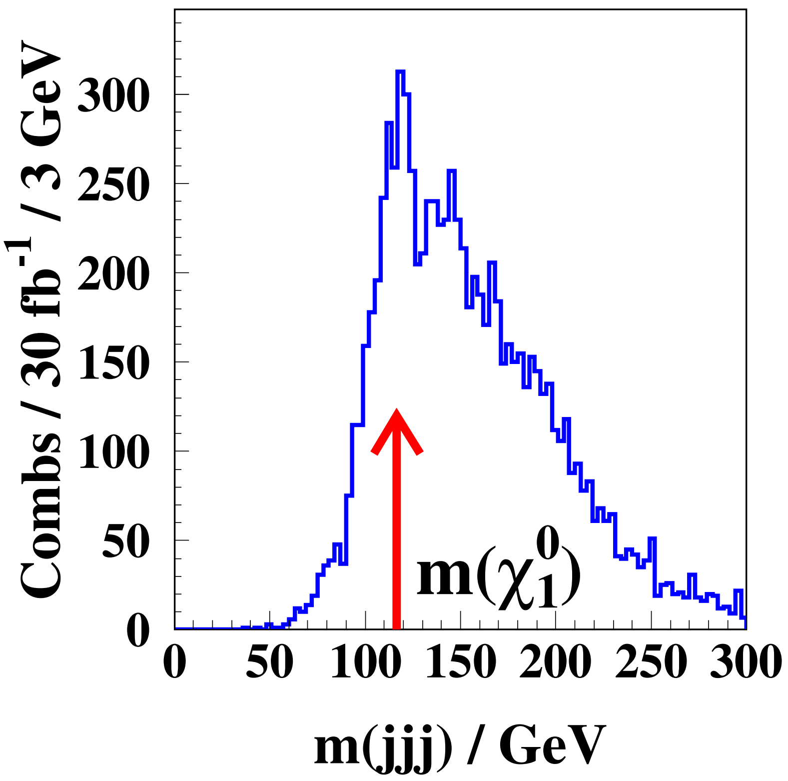
  where a and b are the neutralino candidates.
- **Only consider $8 \le N_{\rm jet} \le 10$.**
- **Transverse sphericity> 0.2, thrust< 0.9.**
- $m_{T,\rm cent} > 1000$ **GeV where** $m_{T,\rm cent} = \sum \left[p_T^{\rm jet} + p_T^{\rm lept} \right]$.
- **at least 2 leptons with $p_T > 15$ GeV & $|\eta| < 2$.**
- **Since the cross section is dominated by squark and gluino production $\approx 95\%$ of the events contain hard jets from squark decays. Require**

  $$E_T^{h1} > 200 \ \textbf{GeV and } E_T^{h2} > 100 \ \textbf{GeV}$$

  and only consider the other jets to reduce combinatorics

Results

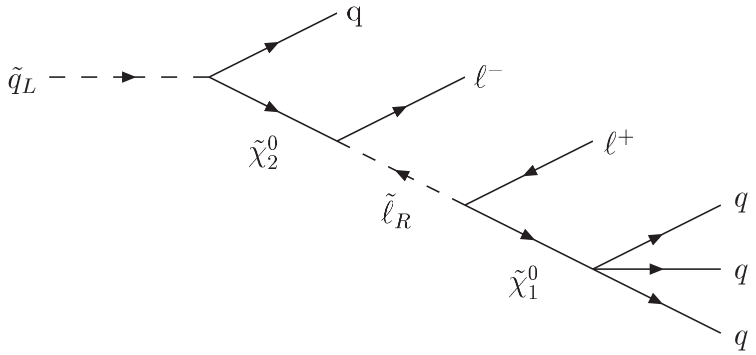
- **Reconstructed $\tilde{\chi}_1^0$ masses for $30\ fb^{-1}$**



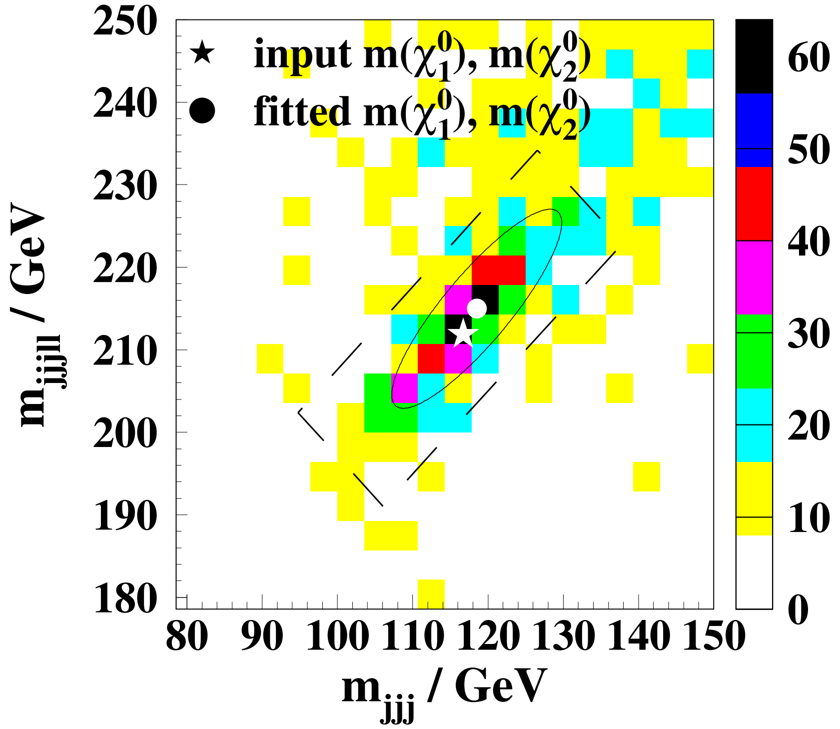
- **There is a combinatoric background below the peak**
- **The shape of this background is defined by the cuts**

Results

- The requirement that the events contain two leptons preferentially selects the decay chain $\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R l q \to \tilde{\chi}_1^0 llq \to qqqllq$



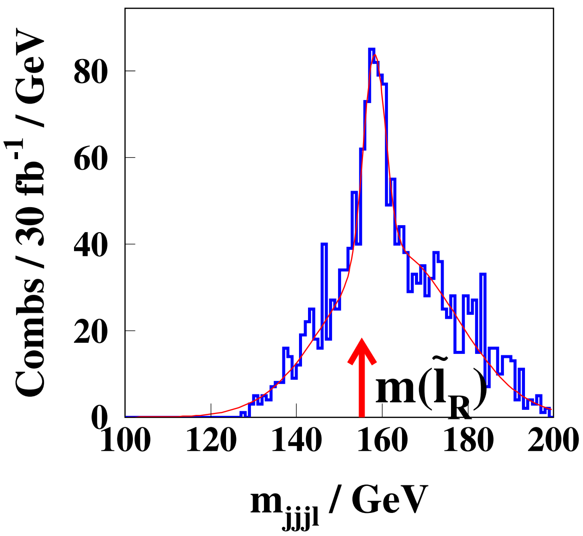
- Use these leptons to reconstruct the $\tilde{\chi}_2^0$ mass.



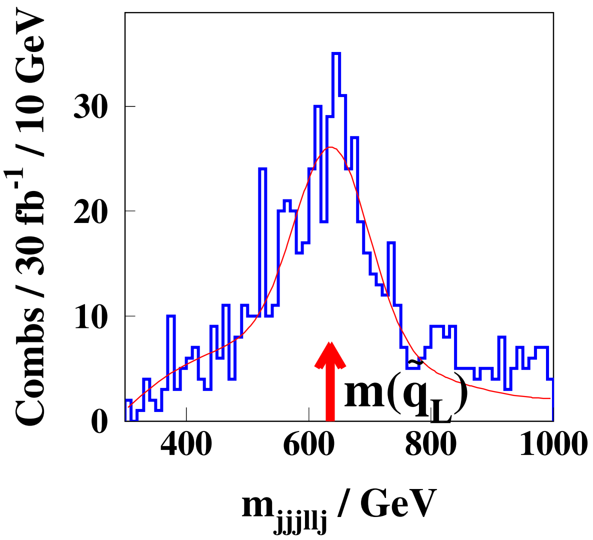
- We can then cut around the peak peak at the $\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$ masses in the mass plane.

Results

- Can also reconstruct the $\tilde{\ell}_R$



- and $\tilde{q}_L$ masses



Conclusions

- **R-parity can be violated**
- $\not{R}_{\mathrm{p}}$ **models should be studied if we are to explore all possible channels for discovering SUSY.**
- **These models give VERY different experimental signatures**
- **Often more information can be extracted than in models in which R_p is conserved**