Monte Carlo Simulations of R-parity Violating Supersymmetry Models

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Outline

- Introduction to $\not{R}_p$ SUSY
- Differences in Phenomenology
- R-Parity Violating Monte Carlo Simulations
- Resonant Slepton Production
- Baryon Number violating Neutralino Decays
- Conclusions

Introduction to $\not{R}_p$

- Most SUSY studies have been of the Minimal Supersymmetric Standard Model (MSSM)
- Simplest SUSY extension of the Standard Model

SM particle	Spin	Sparticle	Spin	
Electron	1/2	Selectron	0	
Neutrino	1/2	Sneutrino	0	
Up	1/2	Sup	0	
Down	1/2	Sdown	0	
Gluon	1	Gluino	1/2	
Photon	1	Photino	1/2	
Z	1	Zino	1/2	Neutralinos
Higgs	0	Higgsino	1/2	
W^+	1	Wino	1/2	Charginos
H^+	0	Higgsino	1/2	

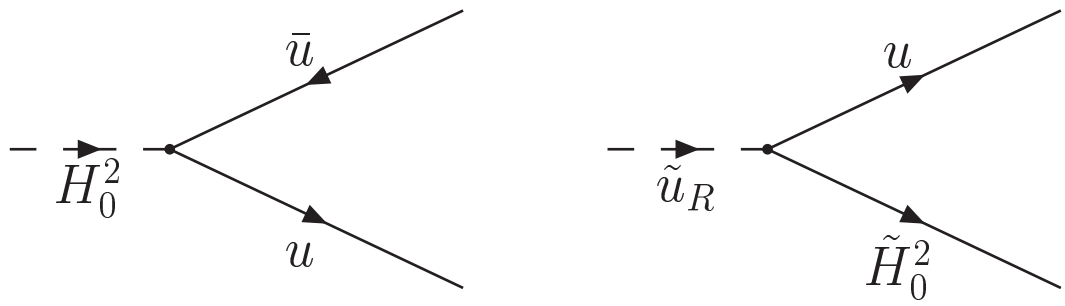
Introduction to $\not{R}_p$

- **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**

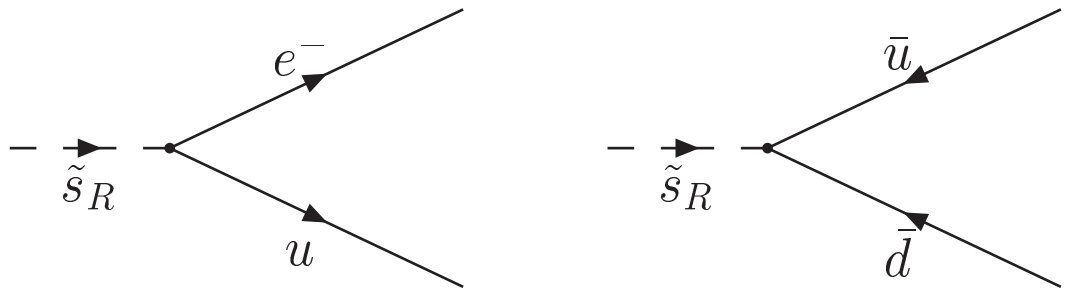
$$\mathbf{W} = \mathbf{W_{MSSM}} + \mathbf{W_{\not{R}_p}}$$

where

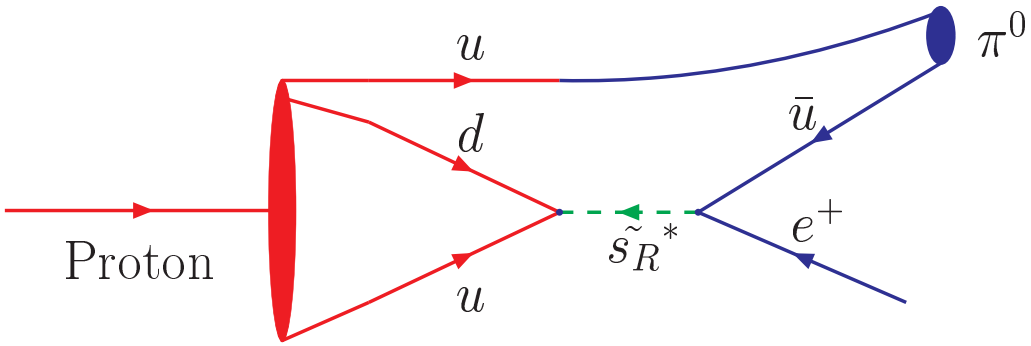
$$\begin{aligned}\mathbf{W_{MSSM}} &= h^E_{ij}\varepsilon^{ab}L^i_a H^1_b \overline{E}^j + h^D_{ij}\varepsilon^{ab}Q^i_a H^1_b \overline{D}^j \\ &\quad + h^U_{ij}\varepsilon^{ab}Q^i_a H^2_b \overline{U}^j + \mu\varepsilon^{ab}H^1_a H^2_b\end{aligned}$$



$$\begin{aligned}\mathbf{W_{\not{R}_p}} &= \lambda_{ijk}\varepsilon^{ab}L^i_a L^j_b \overline{E}^k + \lambda'_{ijk}\varepsilon^{ab}L^i_a Q^j_b \overline{D}^k \\ &\quad + \lambda''_{ijk}\varepsilon^{\alpha\beta\gamma}\overline{U}^i_\alpha \overline{D}^j_\beta \overline{D}^k_\gamma + \kappa_i \varepsilon^{ab}L^i_a H^2_b\end{aligned}$$



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



- **Limits on the proton lifetime give**

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

- **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**

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

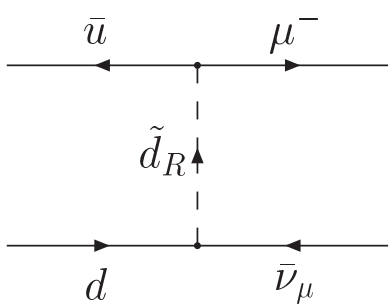
Limits on the Couplings

- **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 which should be investigated

Differences in Phenomenology

- Provided the $\not{R}_p$ coupling is small the main effect is the decay of the LSP
- 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

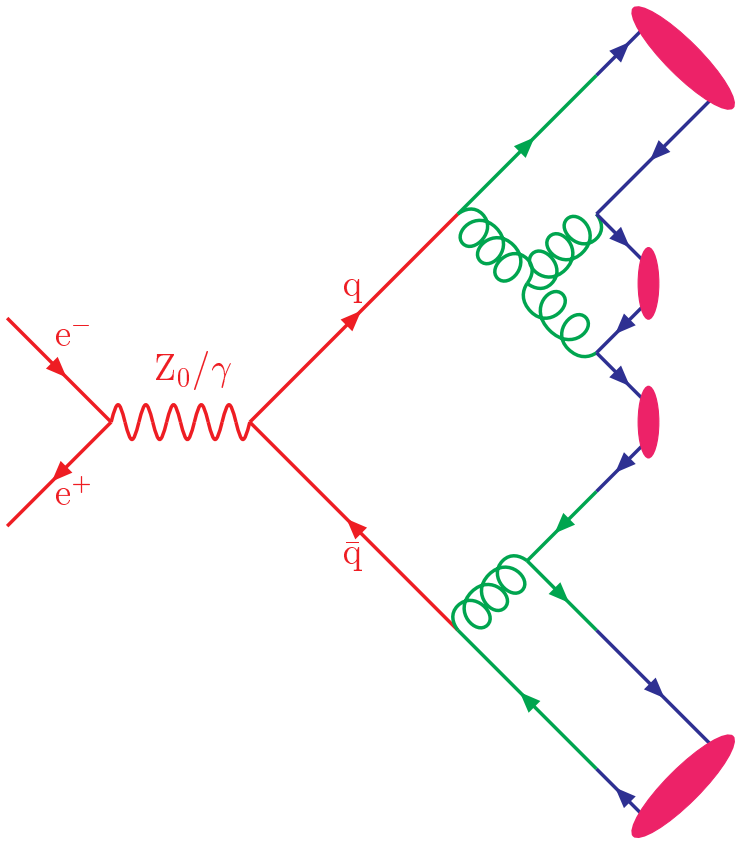
    Again Multi-lepton signatures which should be visible above the background and the possibility of reconstructing the $\tilde{\chi}_1^0$ mass
  - UDD LSP decays to quarks.

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

R-Parity Violating Monte Carlo Simulations

- To study $\not{R}_p$ we need a Monte Carlo simulation which includes these processes
- Previously the only $\not{R}_p$ Monte Carlo simulation in hadron-hadron collisions was ISAJET, with forced decays.
- HERWIG 6.1 now includes a full simulation of $\not{R}_p$ in hadron-hadron collisions
- We include full matrix element calculations of the $\not{R}_p$ decay rates and hard processes.
- All 2 body squark and slepton decays
- All 3 body gaugino and gluino decays
- All resonant sparticle production mechanisms (in hadron-hadron or lepton-antilepton)
- Will allow full simulation for arbitrary couplings for the first time.
- Particularly of interest to simulate $\not{B}$

Basic Idea of HERWIG



- There are three phases
  1. Hard Process
  2. Parton Shower
  3. Cluster Hadronization Model

- Main Input
  1. Hard QCD Matrix Element
  2. Angular Ordering in Parton Shower
  3. Preconfinement (clustering of "colour connected" partons)

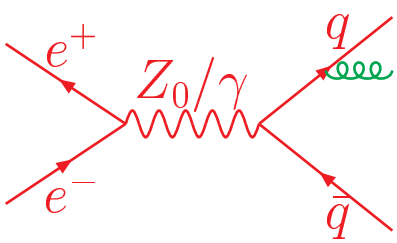
Angular Ordering

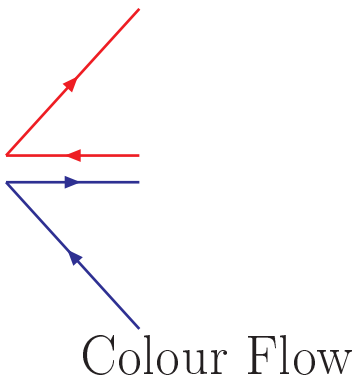
- **Two regions where the emission of QCD radiation is enhanced**

  1. **Collinear Emission**
  2. **Soft Emission**

- **Consider the emission using the eikonal current**

  e.g. $e^- e^+ \longrightarrow q\bar{q}g$ **with radiation of an extra gluon**





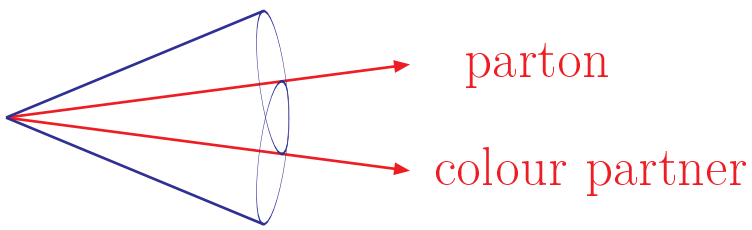
$$\mathcal{M}^{e^+e^-\to q\bar{q}gg}(p_q, p_{\bar{q}}, p_g, k) = g_s m^{e^+e^-\to q\bar{q}g}(p_q, p_{\bar{q}}, p_g)\mathbf{J}(k)$$

- **We then get that**

  – **q and the g are colour connected**

  – **$\bar{\text{q}}$ and the g are anticolour connected**

- **QCD radiation only occurs in a cone up to the direction of the colour partner (Marchesini & Webber)**



Colour Coherence Effects

- **There have been a number of studies of colour coherence effects**

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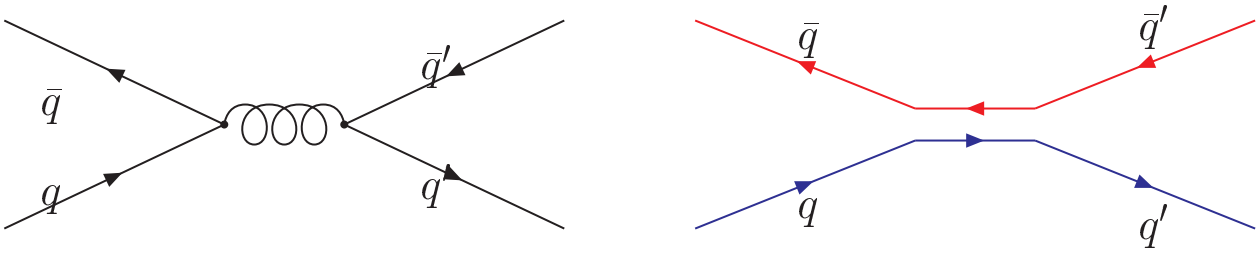
  D0 Phys. Lett. B414 419



- **If we define the jets in the order of their E_t**

  η_3 is the pseudo-rapidity of the third jet.

  $\Delta\eta = \eta_3 - \eta_2$ **pseudo-rapidity difference**

  $\Delta\phi = \phi_3 - \phi_2$ **azimuthal difference**

  $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ **distance in** (η, ϕ)**.**

  $\Delta H = sgn(\eta_2)\Delta\eta$

  $\alpha = \tan^{-1}(\Delta H/|\Delta\phi|)$ **azimuthal angle in** $(|\Delta\phi|, \Delta H)$

- **Consider three jet events where the leading jet has** $E_T > 110$ **GeV**

• η_3 Distributions

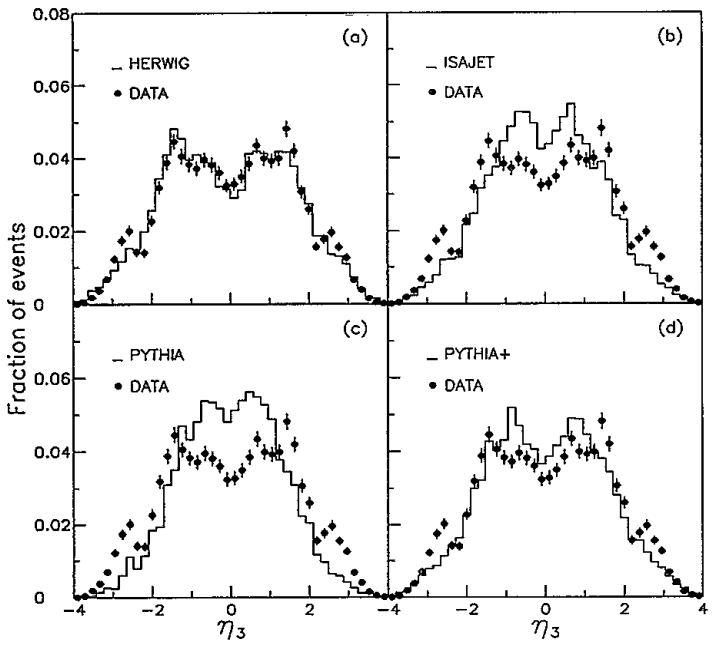


FIG. 13. Observed η_3 distribution compared to the predictions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

• α Distributions

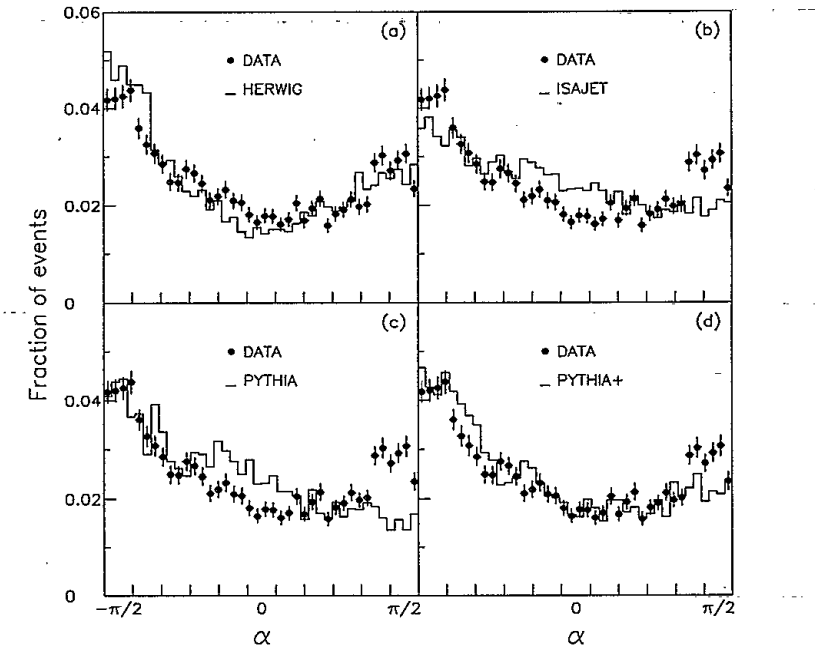
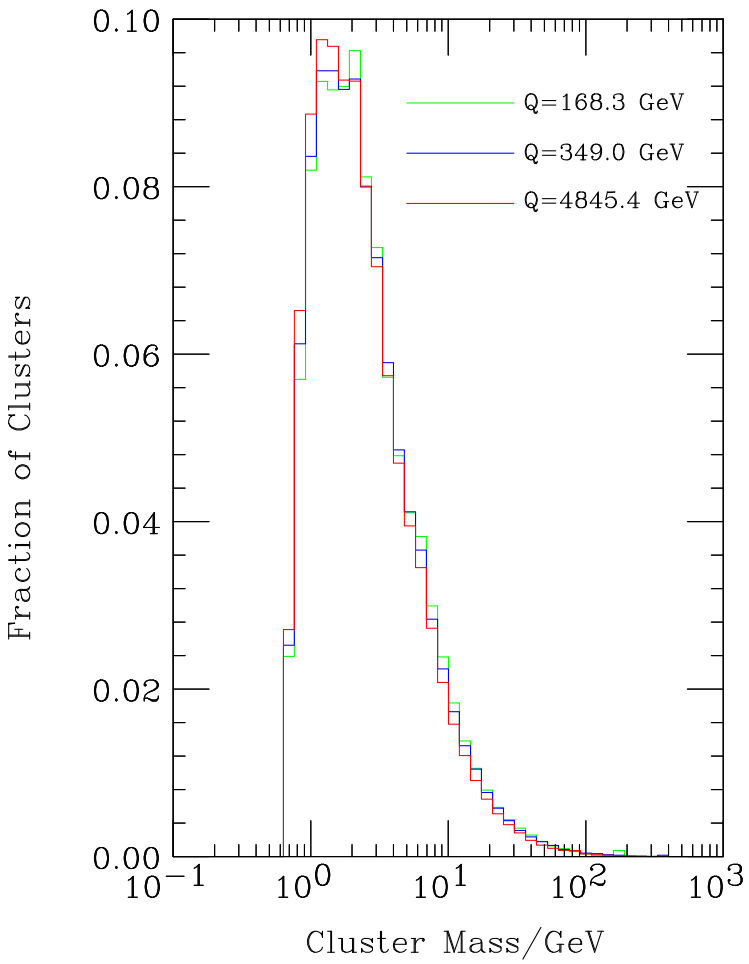


FIG. 15. Observed α distribution compared to the predictions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

Cluster Hadronization Model

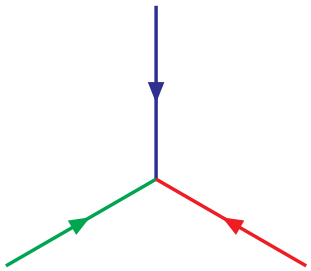
- The mass spectrum of pairs of colour singlet clusters after gluon splitting



- called colour 'pre-confinement'
- Assume these clusters are superpositions of resonances
- Decay according to phase space to hadrons.

Angular Ordering in $\not{R}_p$

- Angular ordering in $\not{L}$ as in the MSSM.
- Angular Ordering in $\not{B}$ is more complicated.
- The colour flow is non-trivial at the UDD vertex.
- Three coloured objects form a singlet.



- There are no obvious pairs.

1. Neutralino Decay

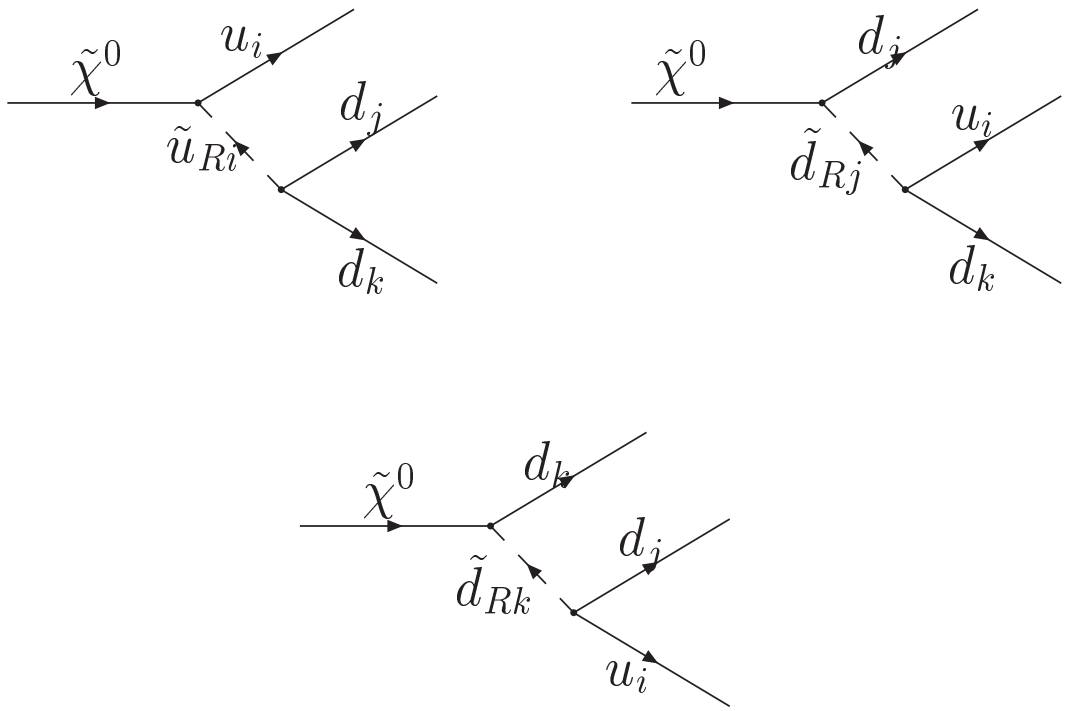


Figure 1: UDD decay of $\tilde{\chi^0}$.

- **The angular ordering procedure is to randomly colour connect a quark to either of the other quarks.**

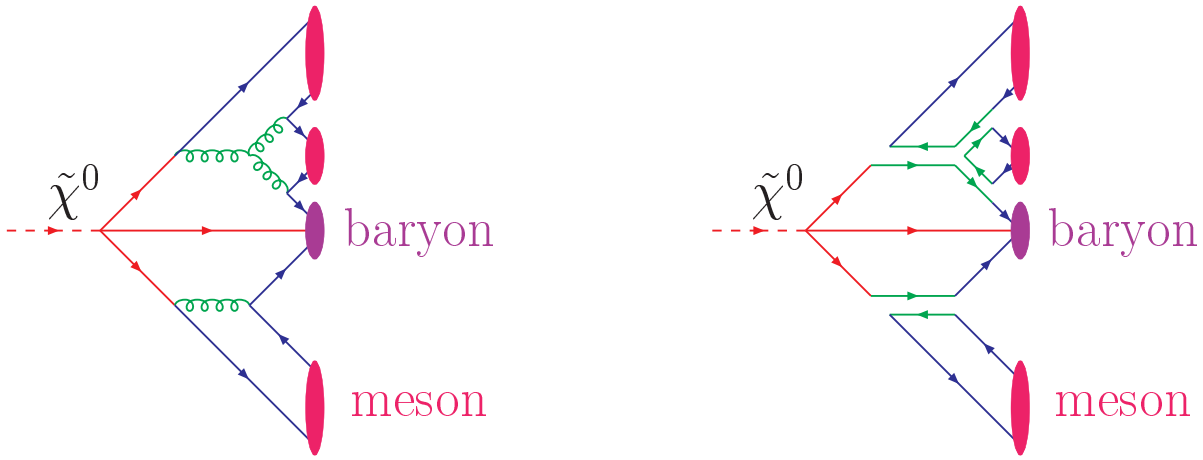


Figure 2: Hadronization of a $\not{B}$Neutralino Decay

Hadronization

The hadronization is done by forming two of the quarks left after the parton shower phase into a diquark. This is then formed into a colour singlet cluster with the remaining quark from the $\not{B}$

2. Squark Decays

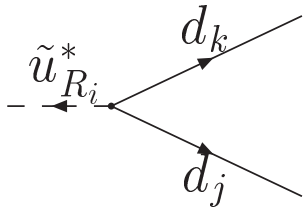


Figure 3: UDD decay of $\tilde{u}^*_R$.

- **Here we randomly take the other quark or the decaying antisquark to be the colour partner of the quark.**
- **The hadronization is more difficult**

Hadronization of $\not{B}$ squark decays

- **There are two possibilities**
- **The squark is connected to a standard model particle or a SUSY particle which decays via a baryon number conserving mode**

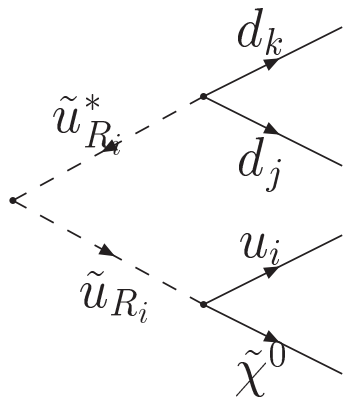


Figure 4: Hadronization with one $\not{B}$ decay.

- **The three quarks are formed into a baryonic cluster as before**
- **The squark is connected to a second $\not{B}$ decay**

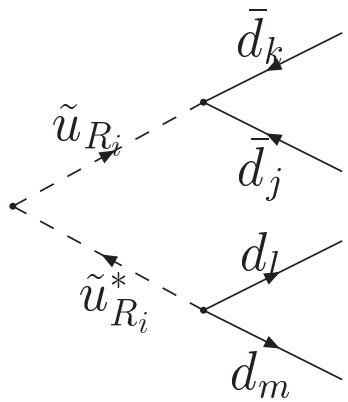


Figure 5: Hadronization with two $\not{B}$ decays.

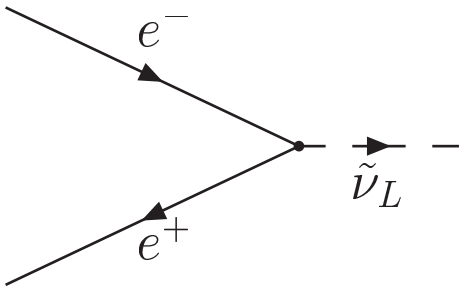
- **Here we need to form the quarks and antiquarks into two mesonic clusters at random**

Resonant Sparticle Production

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

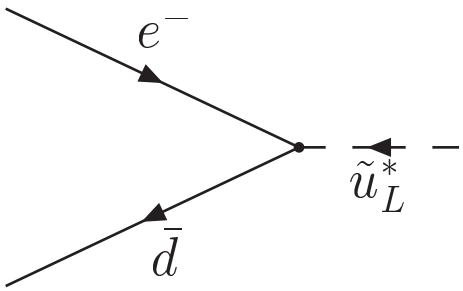
- **In e^+e^- collisions**

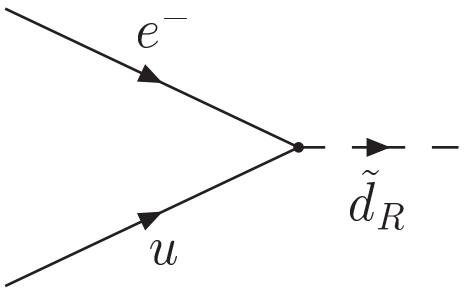
LLE



- **In electron-proton collisions**

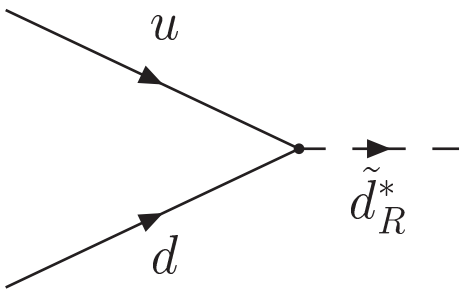
LQD

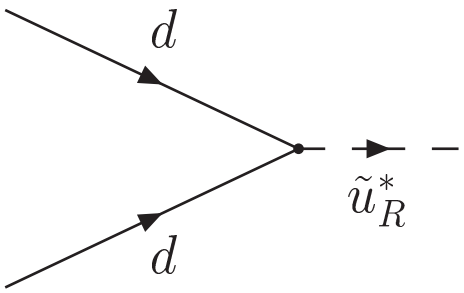




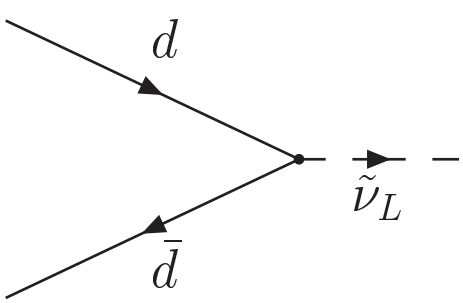
- **In hadron-hadron collisions**

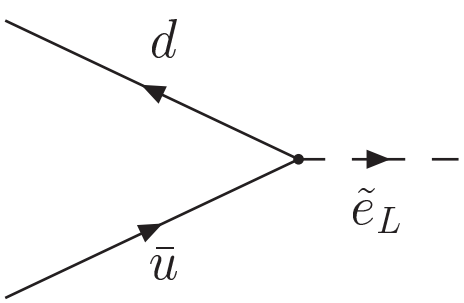
UDD





LQD





Resonant Slepton Production

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

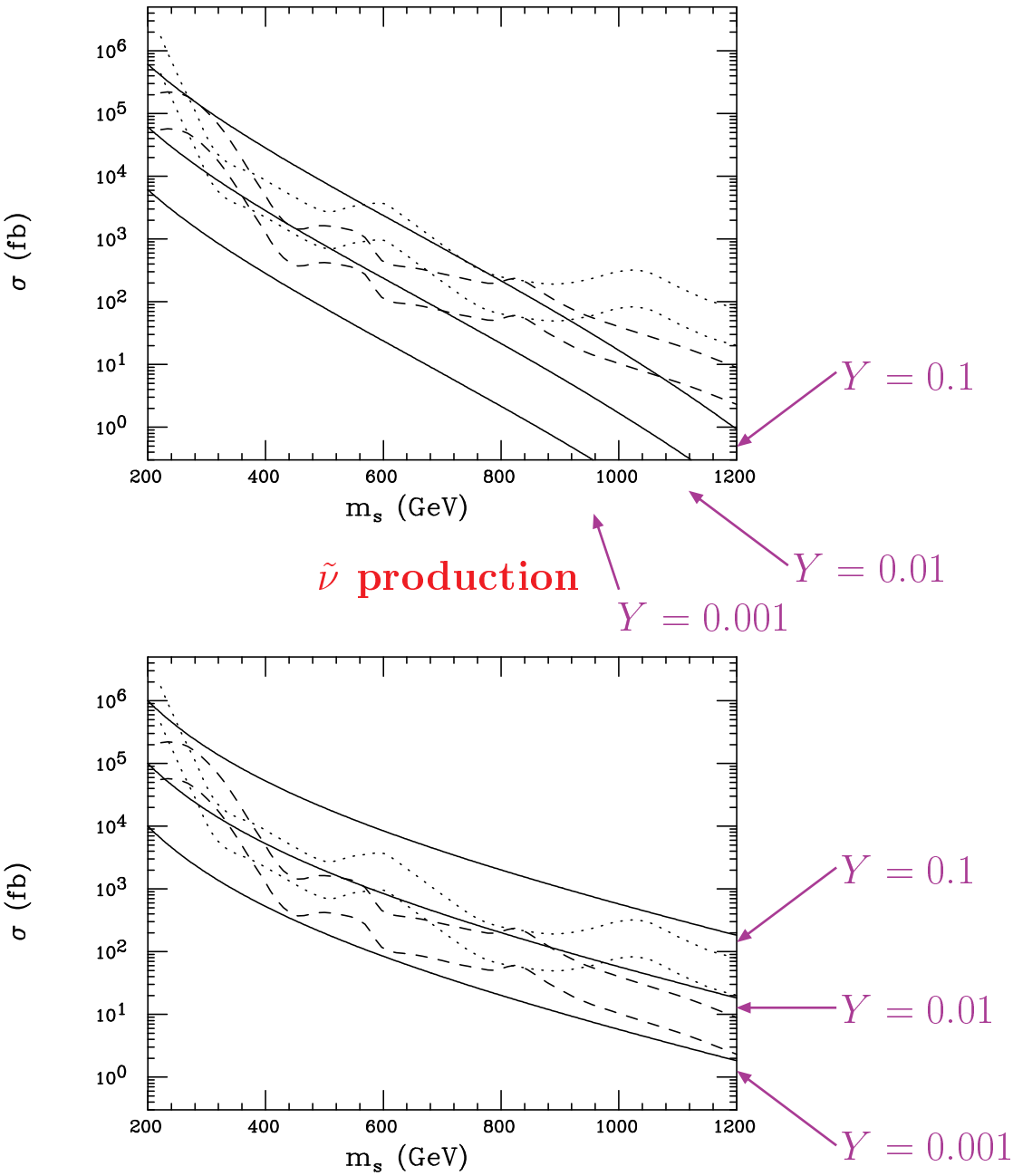
	Charged Sleptons	Sneutrinos
Gauge Decays	$\tilde{\ell}_{i\alpha} \to \ell_i^- \tilde{\chi}^0$	$\tilde{\nu}_i \to \nu_i \tilde{\chi}^0$
	$\tilde{\ell}_{i\alpha} \to \nu_i \tilde{\chi}^-$	$\tilde{\nu}_i \to \ell_i^- \tilde{\chi}^+$
$\not{R}_p$ Decays	$\tilde{\ell}_{i\alpha} \to \bar{u}_j d_k$	$\tilde{\nu}_i \to \bar{d}_j d_k$
	$\tilde{\ell}_{i\alpha} \to \bar{\nu}_j \ell_k^-$	$\tilde{\nu}_i \to \ell_j^+ \ell_k^-$
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 $\not{R}_p$ decays**
  - **LLE gives new resonances in Drell-Yan Production**
  - **LQD gives new resonances in di-jet Production**

Resonant Slepton Production

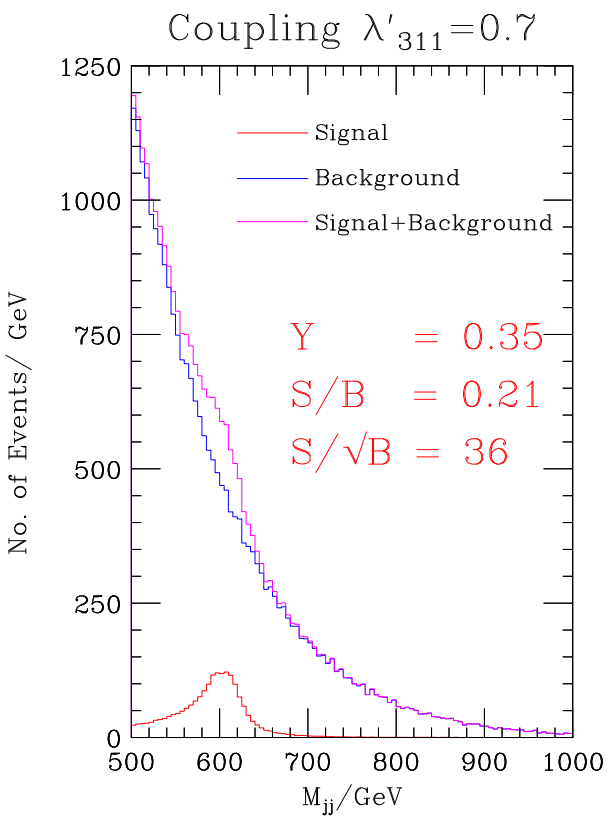
- Studies based on the parton-level cross section (narrow width approximation) suggest that di-jet production can be used to search for resonance production to fairly small couplings.
- This does not include the effect of QCD radiation.
- These processes are now included in HERWIG.

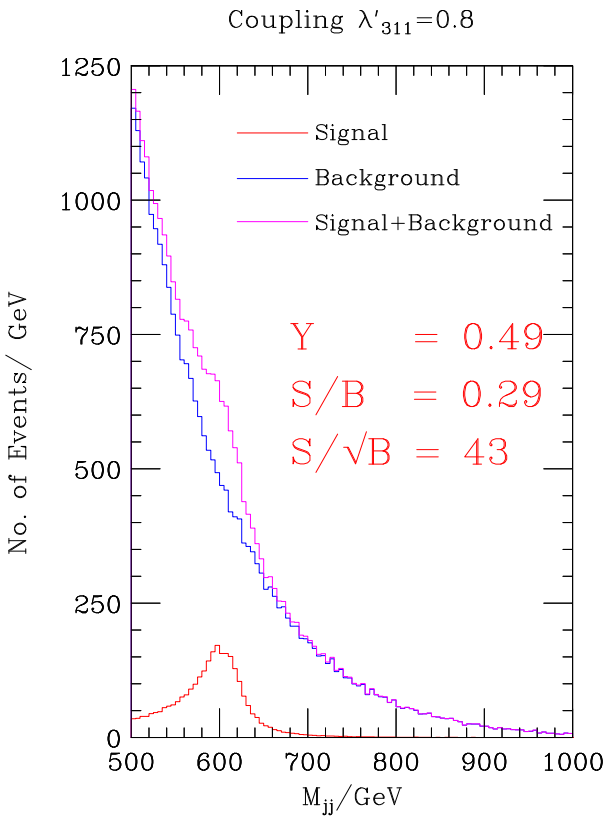
- **Taken from hep-ph/9809525, J. Hewett and T. Rizzo.**



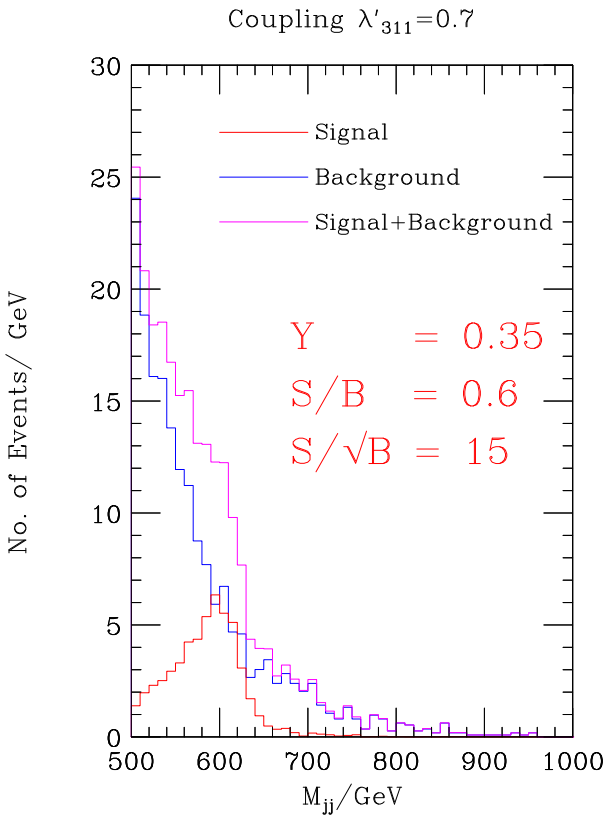
- $Y = \lambda'^2 \times \mathrm{BR}(\tilde{\ell} \to \mathrm{jets})$
- **dots CDF discovery potential at 2 fb^{-1} and 30 fb^{-1}**
- **dashes D0 discovery potential at 2 fb^{-1} and 30 fb^{-1}**

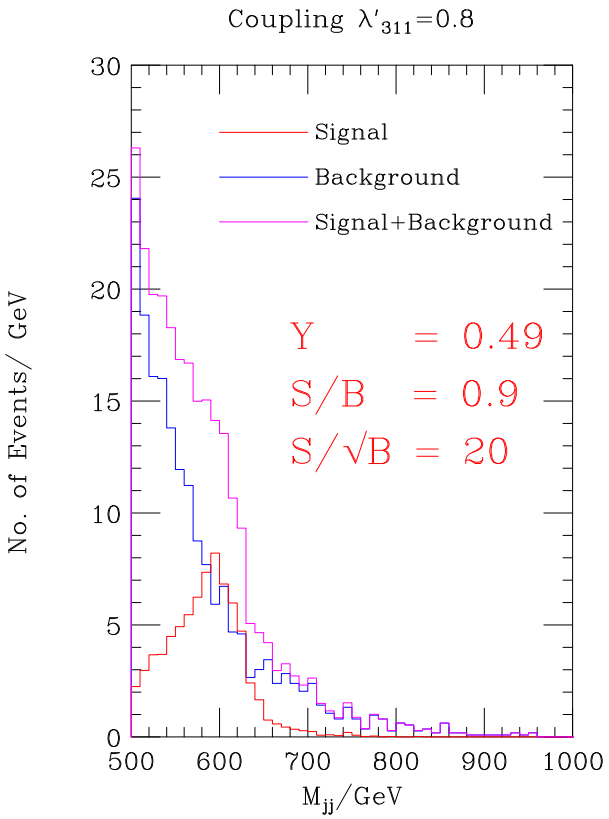
Effect of QCD Radiation





- **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** $580\,\mathrm{GeV} \leq M_{jj} \leq 640\,\mathrm{GeV}$ **which contains the resonance the** $S/\sqrt{B} > 35$ **at both points.**
- **However the** S/B **is between 20 and 30%.**
- **This can be improved by applying cuts using the different QCD radiation patterns for the signal and the QCD background.**

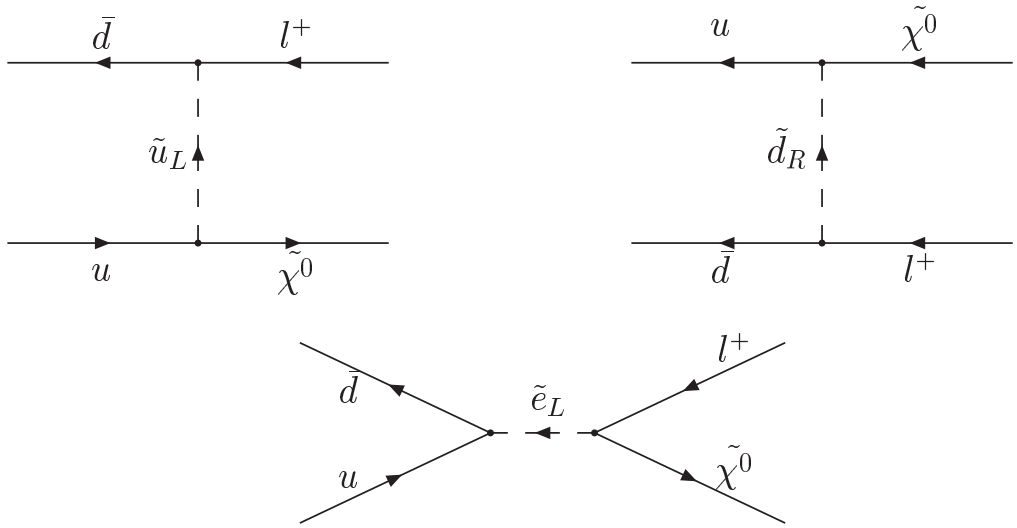




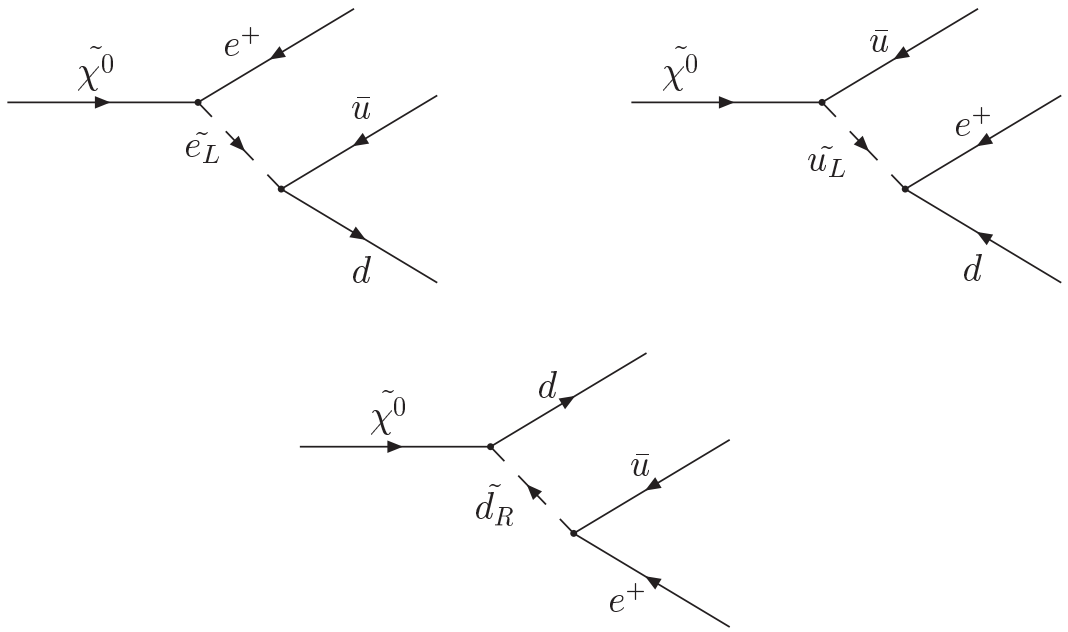
- **Require the presence of a third jet with** $E_T > 10\ GeV$**.**
- **Pseudo-Rapidity cut** $|\eta_1|,\ |\eta_2| < 0.7$**.**
- **Require the jets be back-to-back** $||\phi_1 - \phi_2| - \pi| < 20^0$**.**
- **Cut to avoid overlapping cones** $1.1 < R < \pi$**.**
- **Require** $|\alpha| < 0.4$
- S/B **is improved at the expense of a reduced** $S/\sqrt{B}$

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

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

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

Standard Model Backgrounds

- Gauge Boson pair production
- $b\bar{b}$ production
- $t\bar{t}$ production
- single top 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,** $E_{miss}^T < 20$ **GeV.**

Summary of Tevatron Backgrounds

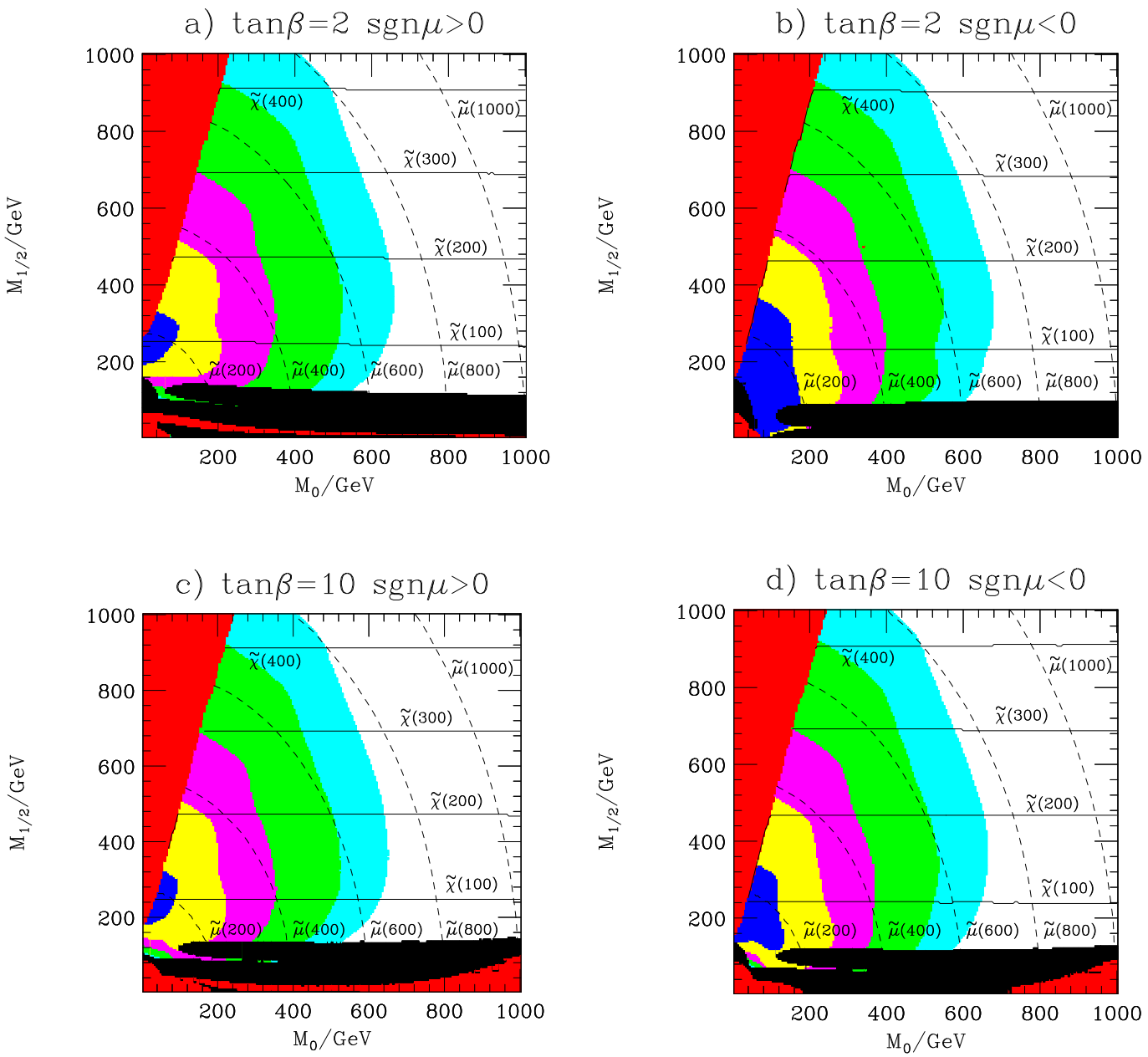
Background Process	Number of Events		
	After p_T cut	After isolation and p_T cuts	After all cuts
WW	0.23 ± 0.02	0.0 ± 0.003	0.0 ± 0.003
WZ	9.96 ± 0.09	7.93 ± 0.08	0.21 ± 0.01
ZZ	2.05 ± 0.03	1.61 ± 0.02	0.069 ± 0.005
$t\bar{t}$	34.1 ± 1.6	0.028 ± 0.002	0.0032 ± 0.0006
$b\bar{b}$	$(3.4 \pm 1.3) \times 10^3$	0.15 ± 0.16	0.15 ± 0.16
Single Top	1.77 ± 0.01	0.0014 ± 0.0003	0.0001 ± 0.0001
Total	$(3.4 \pm 1.3) \times 10^3$	9.72 ± 0.18	0.43 ± 0.16

- **All the numbers are for** $2\ \mathrm{fb}^{-1}$ **integrated luminosity**
- **We have only considered like-sign muon production as the limit on the coupling** λ'_{211} **is far weaker than that on** λ'_{111}**.**
- **The limit is**

$$\boldsymbol{\lambda'_{211} < 0.059 \times \left(\frac{M_{\tilde{d}_R}}{100\mathrm{GeV}} \right)}$$

Results

- **We used 2 fb^{-1} integrated luminosity**



Excluded by lack of electroweak symmetry breaking or by the lightest neutralino not being the LSP

Excluded by LEP

$\lambda'_{211} > 5 \times 10^{-3}$

$\lambda'_{211} > 5 \times 10^{-2}$

$\lambda'_{211} > 10^{-2}$

$\lambda'_{211} > 0.1$

$\lambda'_{211} > 2 \times 10^{-2}$

SUSY backgrounds

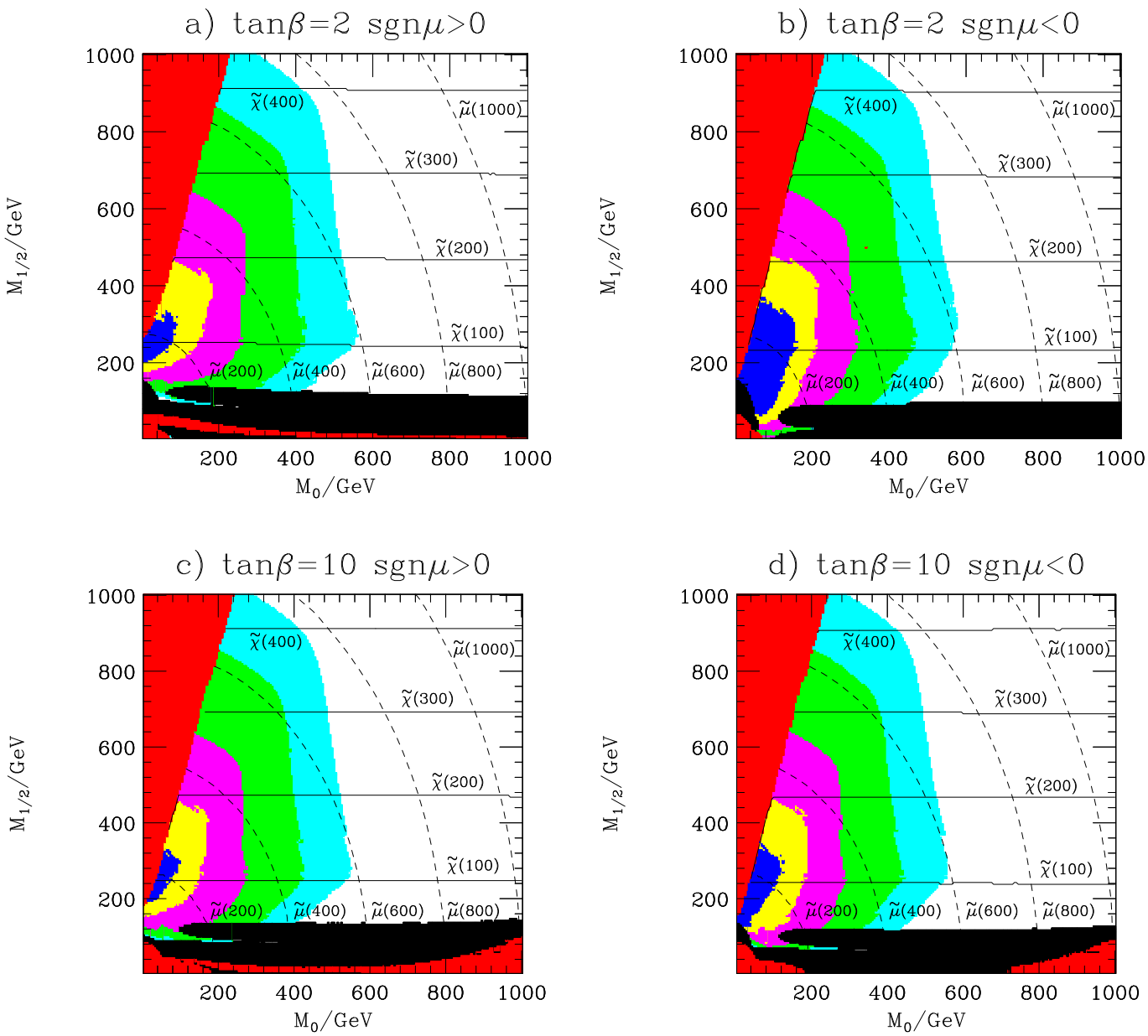
- In addition to the Standard Model backgrounds SUSY particle pair production is a major source of background
- The dominant processes are sparton pair production
- the sparticles then cascade decay to the LSP, provided the $\not{R}_{\rm p}$ couplings are small.
- the two LSPs produced can then decay to give like-sign leptons.

  $\tilde{q}_L \to \tilde{\chi}^0\ q \to \ell^+\ d\ \bar{u}\ q$

  $\tilde{g} \to \tilde{q}_L\ \bar{q} \to \tilde{\chi}^0\ \bar{q}q \to \ell^+\ d\ \bar{u}\ \bar{q}q$
- These processes contain more jets than the signal.
- Therefore we require that there are at most two jets with $E_T > 20$ GeV.

SUSY backgrounds

- **We used 2 fb^{-1} integrated luminosity**

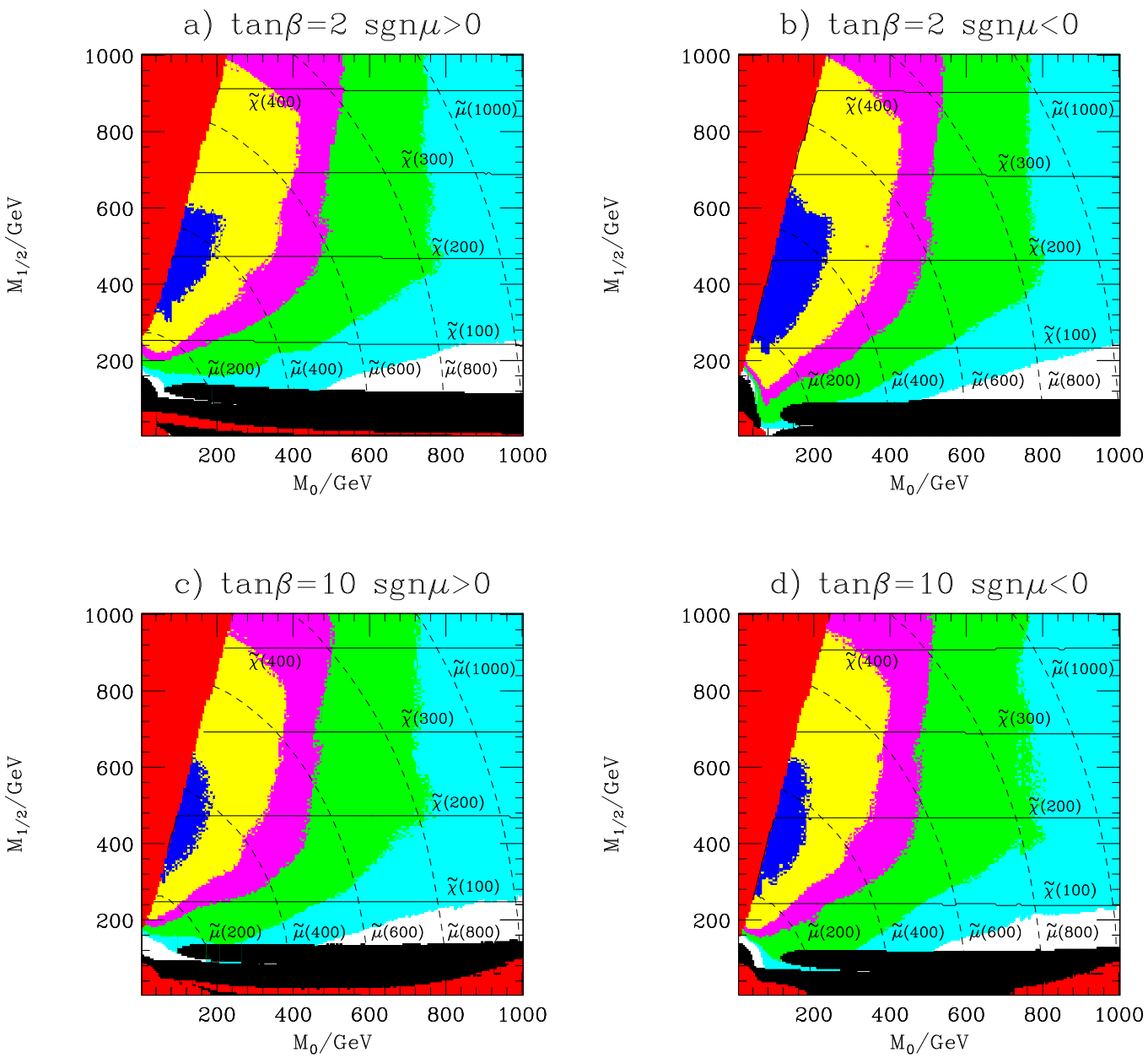


LHC

- **We have performed a similar analysis for the LHC**
- **We impose the following cuts**
  1. $p_T^{\text{lepton}} > 50$ **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,** $E_{miss}^T < 20$ **GeV.**
  6. **For the SUSY backgrounds we imposed a cut requiring at most two jets with** $p_T > 50$ **GeV**

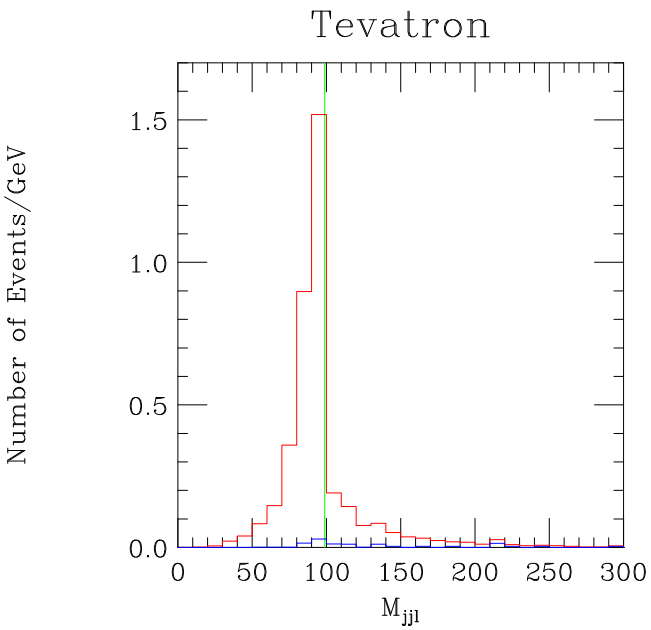
Results including SUSY Backgrounds

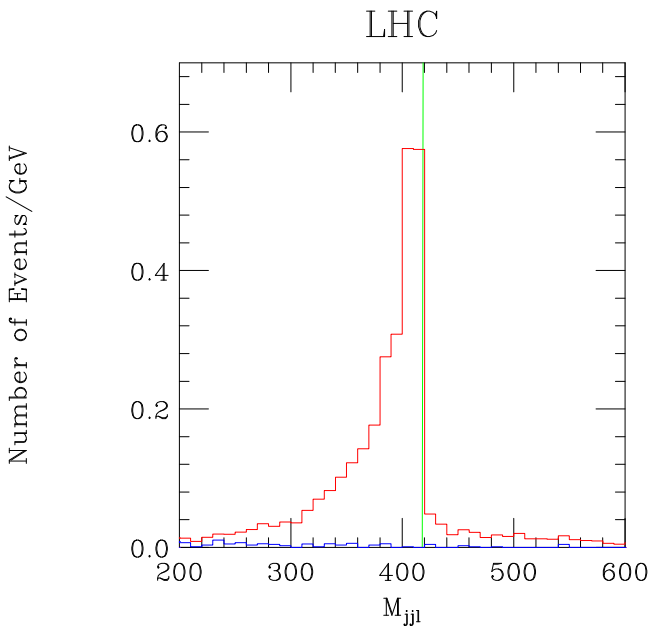
- **We used 10 fb^{-1} integrated luminosity**



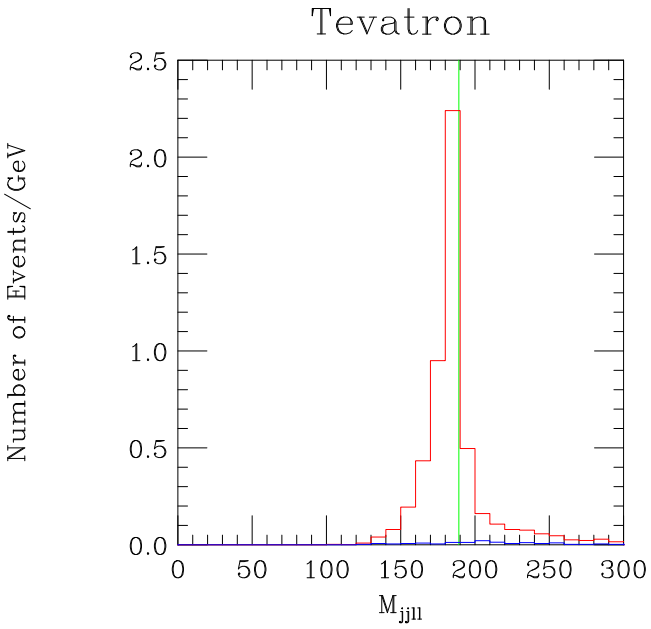
Mass Reconstruction

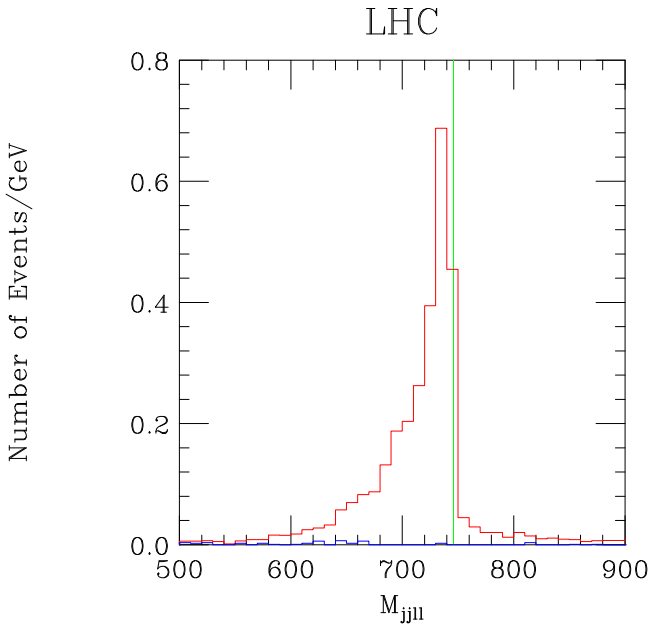
- **We can reconstruct the neutralino and slepton masses**
- **Neutralino: Combine the lepton closest in (η, ϕ) with the two hardest jets in the event**





- **Slepton: Combine both leptons and the two hardest jets**





Mass Reconstruction

- **Tevatron Results were generated for $M_0 = 50$ GeV, $M_{1/2} = 250$ GeV, $\tan\beta = 2$, $\mathrm{sgn}\,\mu > 0$, $A_0 = 0$ GeV**

- **LHC Results were generated for $M_0 = 350$ GeV, $M_{1/2} = 950$ GeV, $\tan\beta = 10$, $\mathrm{sgn}\,\mu < 0$, $A_0 = 0$ GeV**

Experiment	Neutralino Mass		Slepton Mass	
	Simulated	Reconstructed	Simulated	Reconstructed
Tevatron	98.9	90.3	189.1	181.6
LHC	418	404.1	745	734.1

- **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.**

Baryon Number Violating Neutralino Decays at LHC

Work by Cambridge ATLAS-HERWIG SUSY Working Group
in particular A. Barr, L. Drage, D. Morgan, and A. Parker

- **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** $\tilde{\chi}_1^0$ **decays to three quarks**
- **As the coloured sparticles are predominantly produced the jet multiplicities are large**

  $\tilde{q}_R \longrightarrow \tilde{\chi}_1^0 q \longrightarrow qqq \Rightarrow$ **8 jets in** $\tilde{q}_R\tilde{q}_R$ **production.**

  gives 9.2 jets after gluon radiation

  $\tilde{q}_L\tilde{q}_L$ **gives 10.7 jets after gluon radiation**

  $\tilde{g}\tilde{g}$ **gives 12.8 jets after gluon radiation**

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**

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

  where a and b are the neutralino candidates.
- **Only consider** $8 \leq N_{\text{jet}} \leq 10$.
- **Transverse sphericity**> 0.2, **thrust**< 0.9.
- $m_{T,\text{cent}} > 1000$ **GeV where** $m_{T,\text{cent}} = \sum \left[p_T^{\text{jet}} + p_T^{\text{lept}} \right]$.
- **at least 2 leptons with** $p_T > 15$ **GeV &** $|\eta| < 2$.
- **the following cuts on the jet momenta(all in GeV) were also used**

  1. $100 < p_T^{a1}$; $17.5 < p_T^{a2} < 300$; $15.0 < p_T^{a3} < 150$

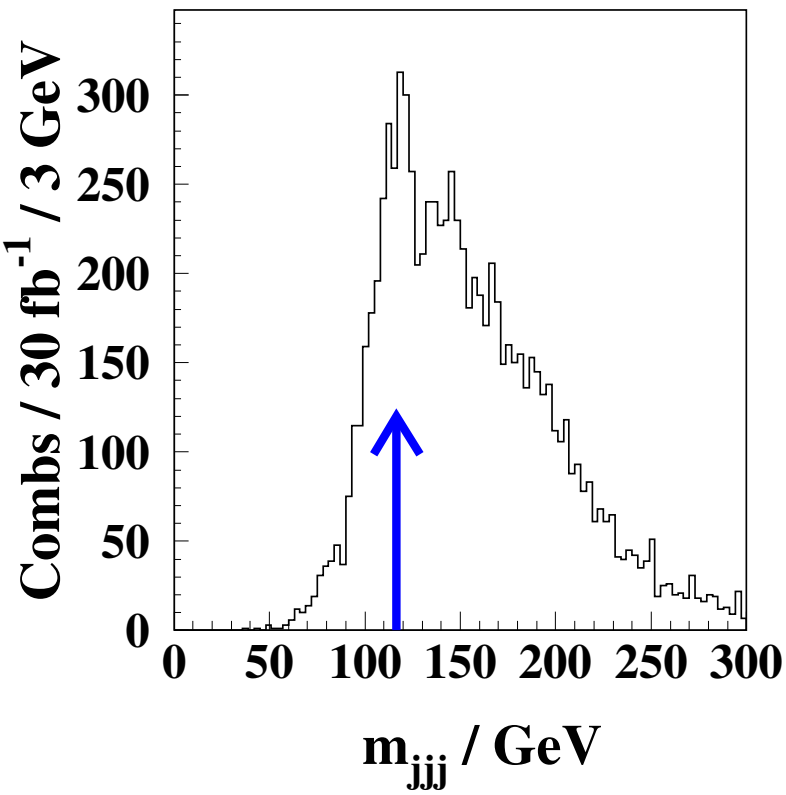
  2. $17.5 < p_T^{b1} < 300$; $17.5 < p_T^{a2} < 150$; $15.0 < p_T^{a3} < 75$
- **Since the cross section is dominated by squark and gluino production** $\approx 95\%$ **of the events contain hard jets from squark decays. Require**

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

  and only consider the other jets to reduce combinatorics

Results

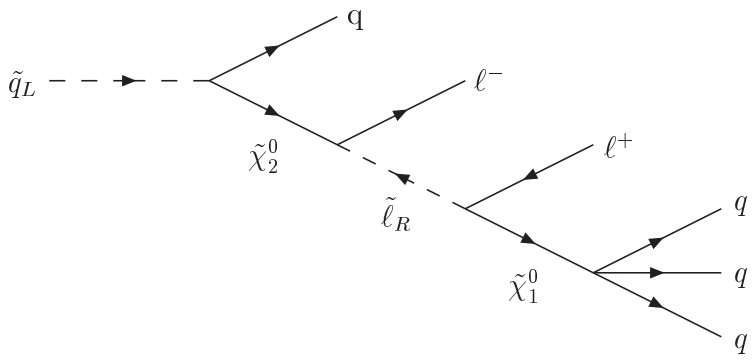
- Reconstructed $\tilde{\chi}_1^0$ masses for $30\ fb^{-1}$



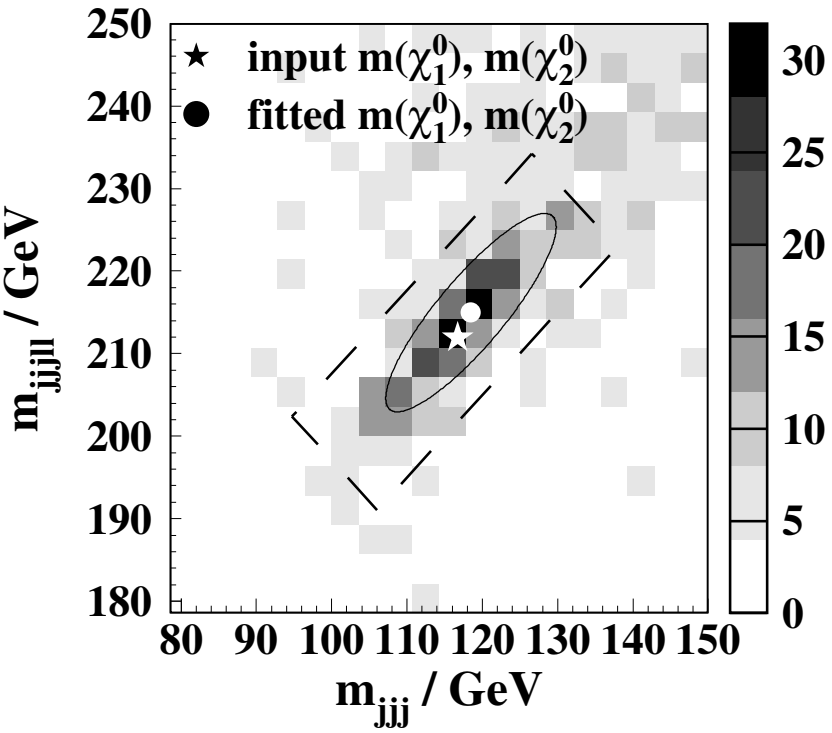
- There is a combinatoric background below the peak
- The shape of this background is defined by the cuts

Results

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



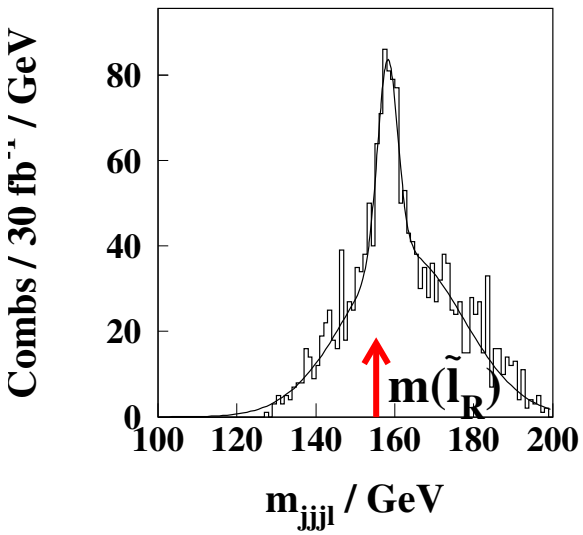
- Use these leptons to reconstruct the $\tilde{\chi}_2^0$ mass.



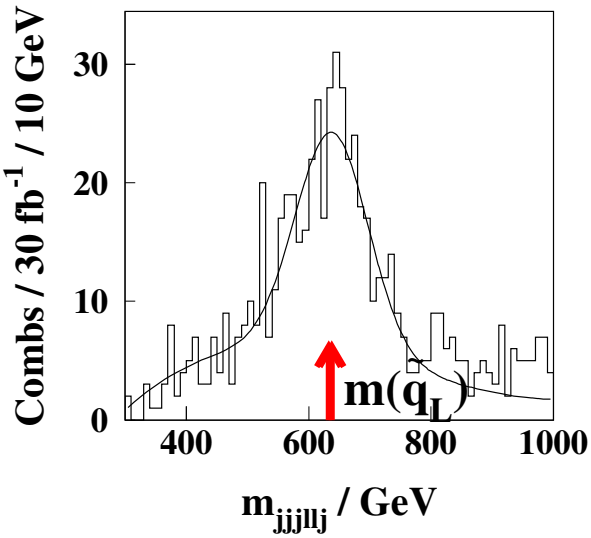
- We can then cut around the peak peak at the $\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$ masses in the mass plane.

Results

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



- and $\tilde{q}_L$ masses



Conclusions

- $\not{R}_p$ models should be studied if we are to explore all possible channels for discovering SUSY.

- The existing Monte Carlos for $\not{R}_p$ in hadron-hadron collisions include no hard processes and only include the decays via FORCE

- We have produced a Monte Carlo Simulation which
  1. Includes all the 2 and 3 body decays
  2. All the resonant hard processes
  3. Full treatment of the colour coherence effects in the production and decay

- This has allowed the full simulation of $\not{B}$ in hadron-hadron collisions for the first time.

- A first analysis shows that a neutralino which decays via baryon number violation can be detected and its mass reconstructed