Parton-Shower Simulations of R-parity Violating SUSY

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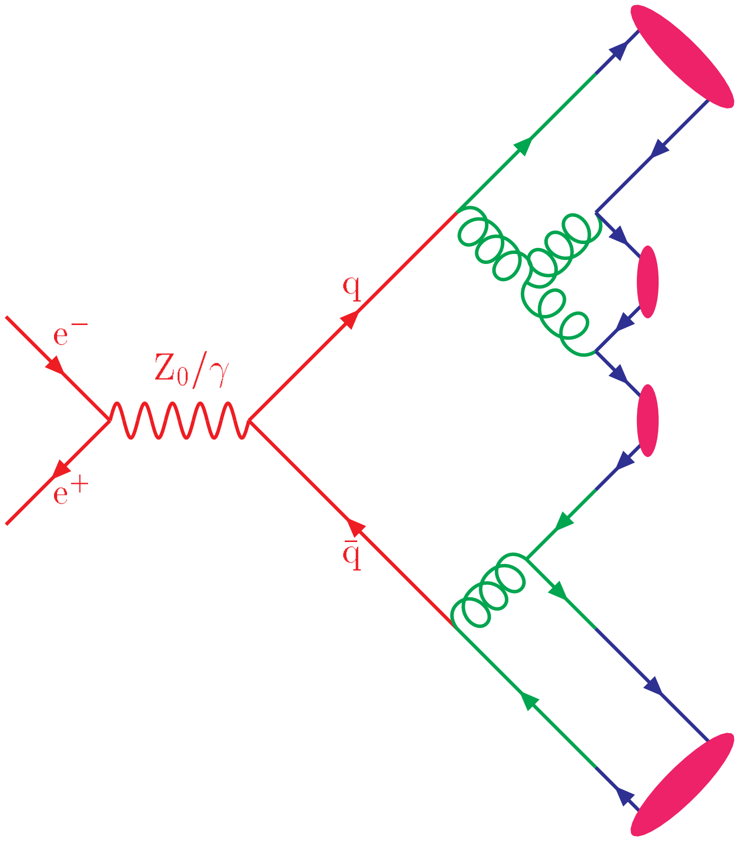
Outline

- Parton-Shower Simulations
- R-Parity Violating Monte Carlo Simulations
- Resonant Slepton Production
- Conclusions

Basic Idea of HERWIG



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

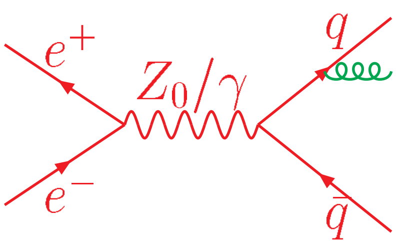
- Main Input
  1. Hard QCD Matrix Element
  2. Angular Ordering in Parton Shower
  3. Preconfinement (clustering of "colour connected" partons)

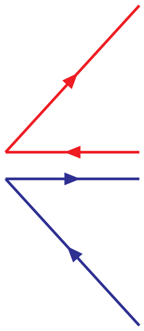
Angular Ordering

- 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



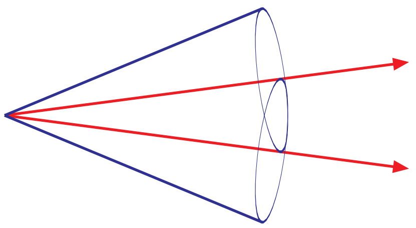


Colour Flow

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

- We then get that
  - q and the g are colour connected
  - $\bar{q}$ and the g are anticolour connected

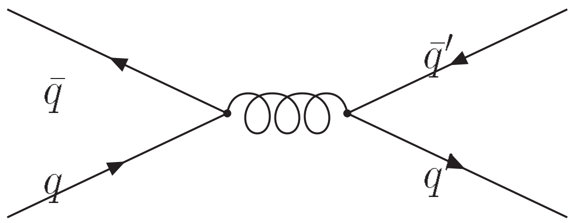
- QCD radiation only occurs in a cone up to the direction of the colour partner (Marchesini & Webber)

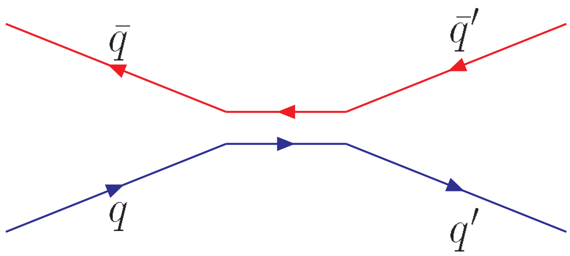


Colour Coherence Effects

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

  CDF Phys. Rev. D50 5562
  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

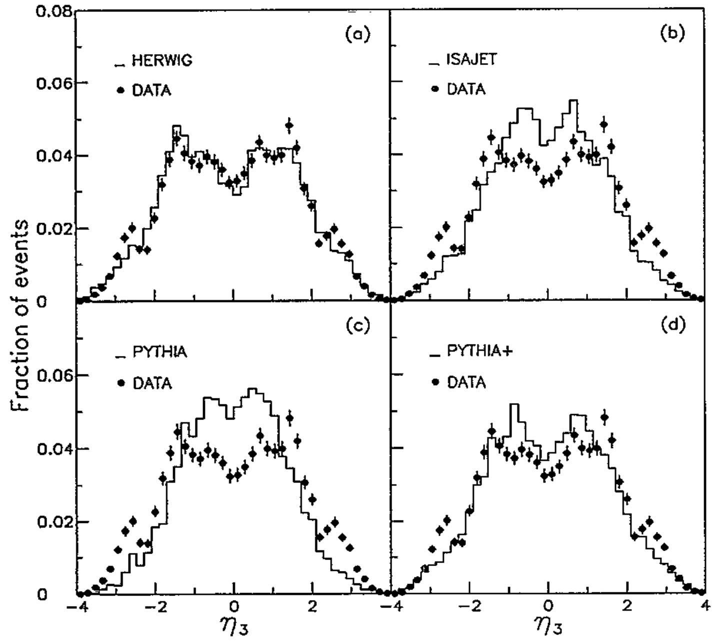


FIG. 13. Observed η_3 distribution compared to the predic-ions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

• α Distributions

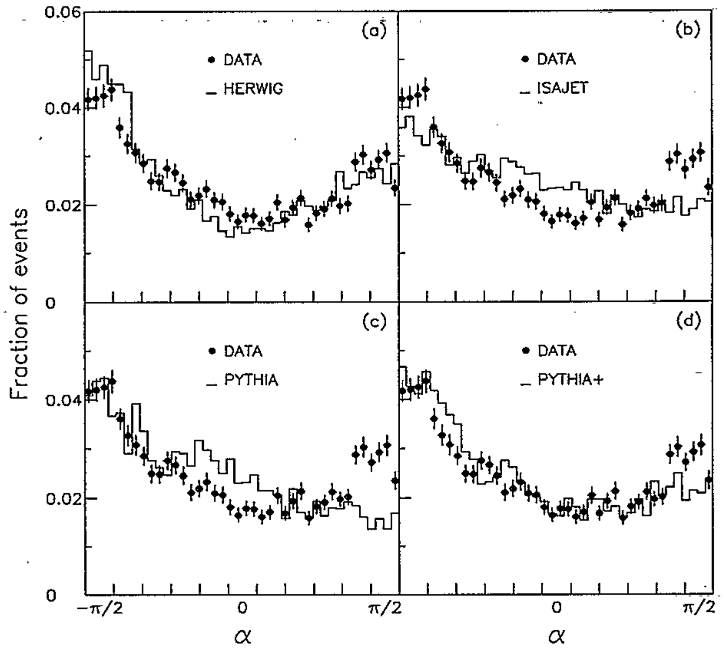
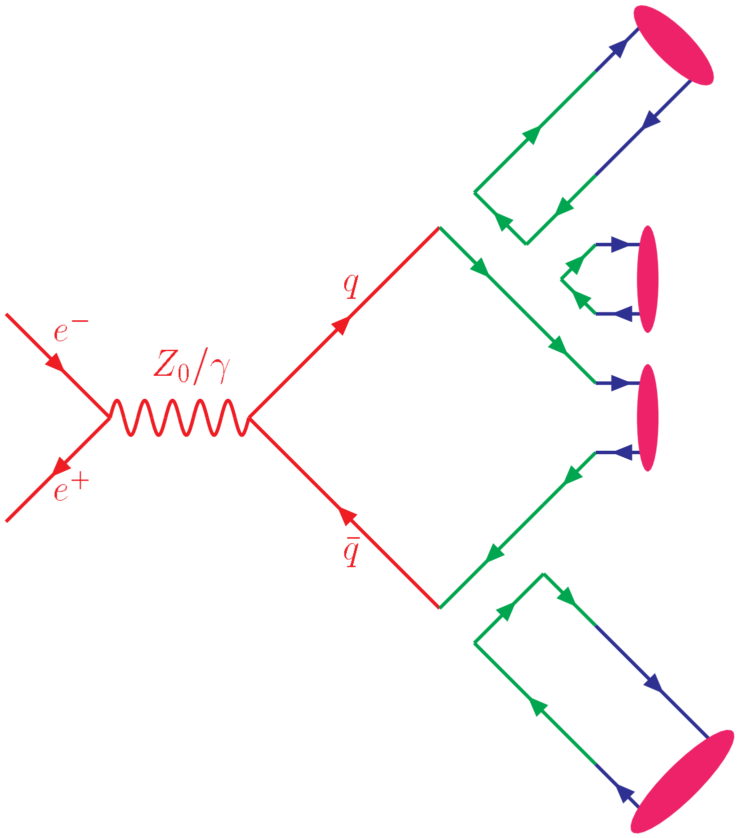


FIG. 15. Observed α distribution compared to the predic-ions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

Cluster Hadronization Model

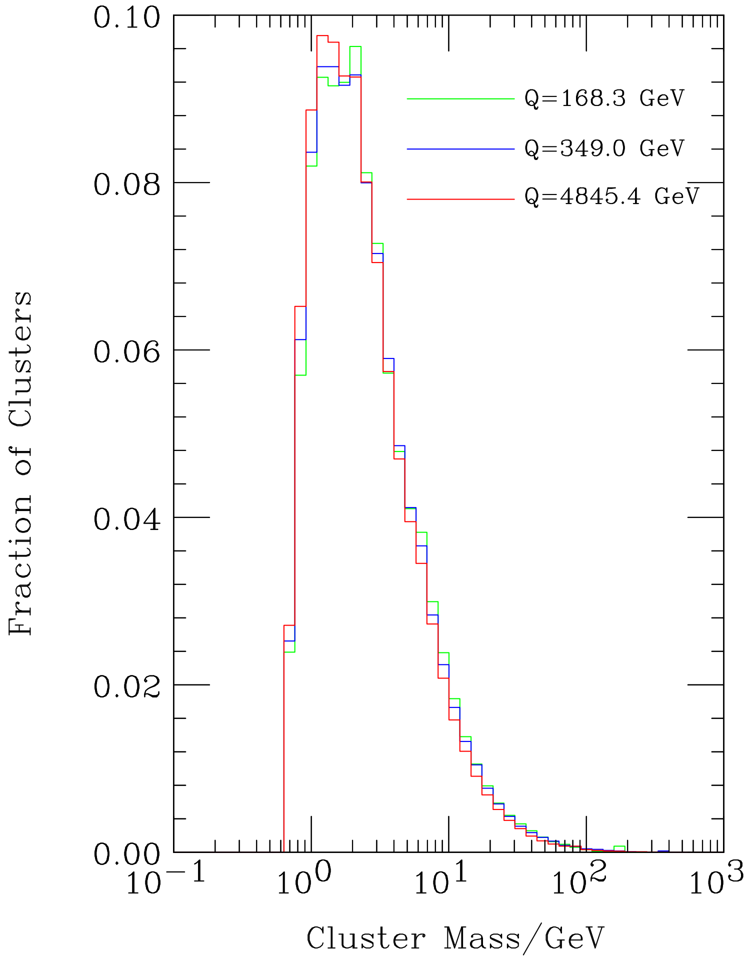
- HERWIG includes angular-ordered parton showers
- The hadronization model is based on one property of this



- First split the gluons into $q\bar{q}$ pairs
- Each quark is then uniquely paired with an antiquark in a colour singlet
- Form these into colour singlet clusters

Cluster Hadronization Model

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



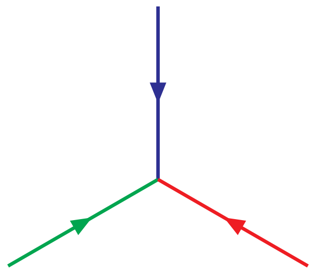
- called colour 'pre-confinement'
- Assume these clusters are superpositions of resonances
- Decay according to phase space to hadrons.

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)
- Will allow full simulation for arbitrary couplings for the first time.
- Particularly of interest to simulate $\not{B}$

Angular Ordering in $\not{R}_{\rm p}$

- **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

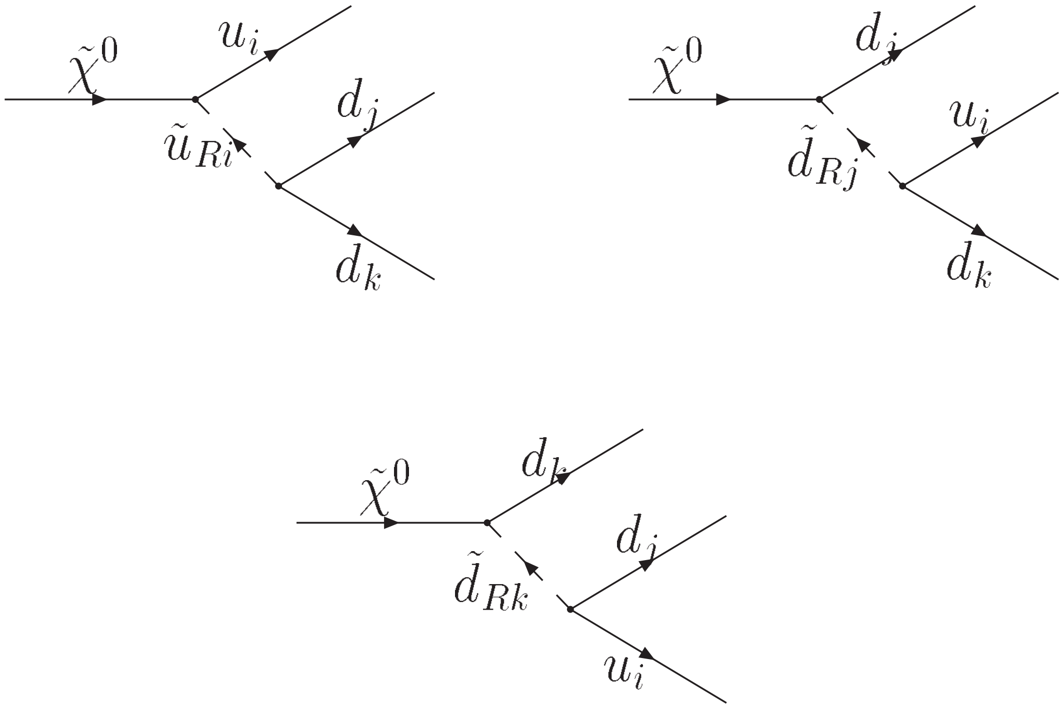


Figure 1: UDD decay of $\tilde{\chi}^0$.

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

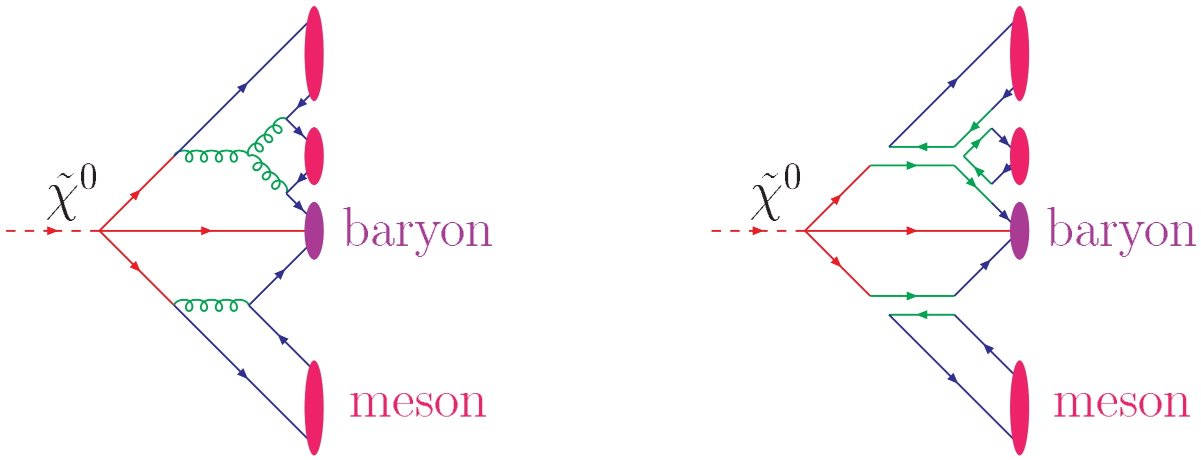


Figure 2: Hadronization of a $\not{B}$ Neutralino Decay

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

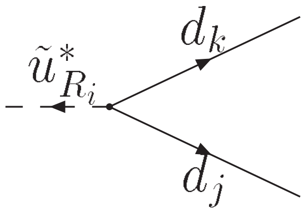


Figure 3: UDD decay of $\tilde{u}^*_R$.

- **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

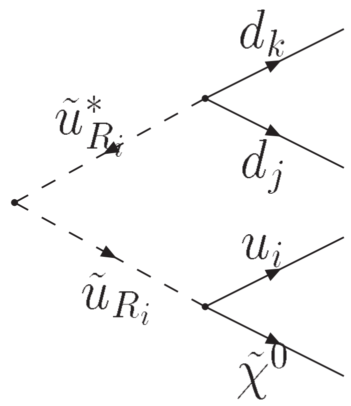


Figure 4: Hadronization with one $\not{B}$ decay.

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

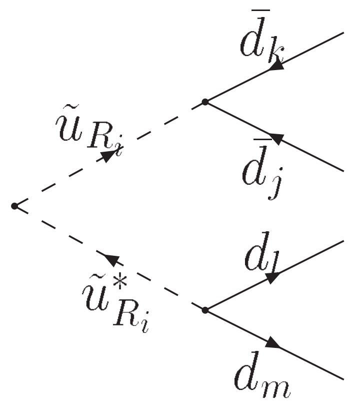


Figure 5: Hadronization with two $\not{B}$ decays.

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

Resonant 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**

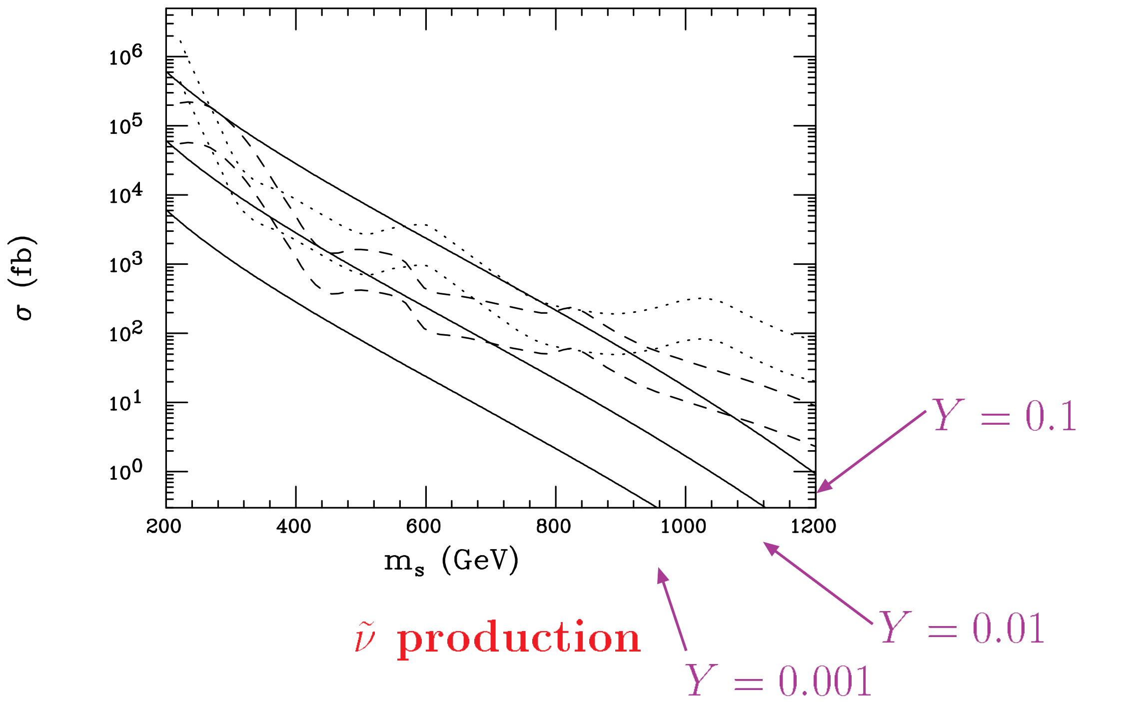
Resonant Slepton Production

- 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.

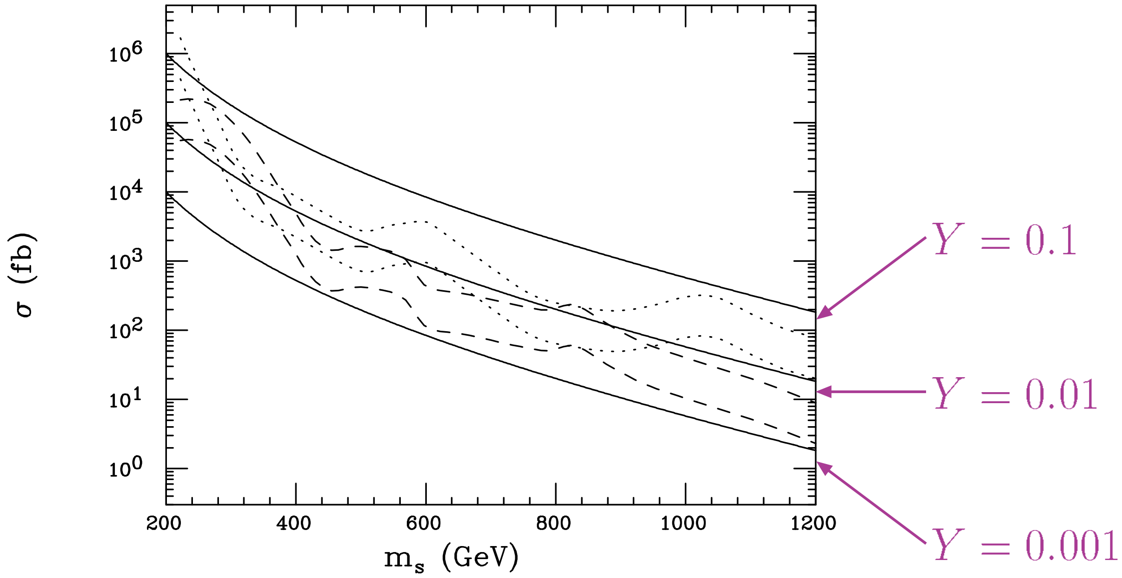
- This does not include the effect of QCD radiation.

- These processes are now included in HERWIG.

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



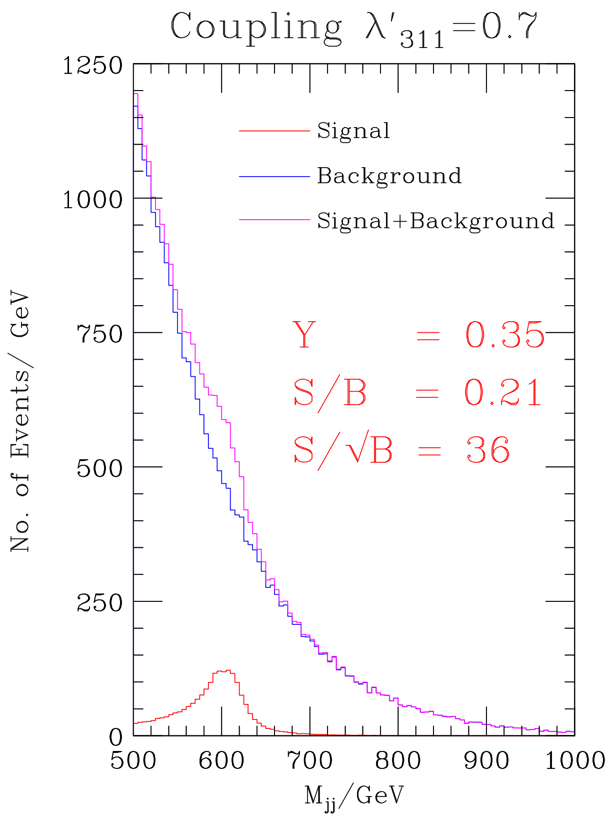
$\tilde{\nu}$ **production**

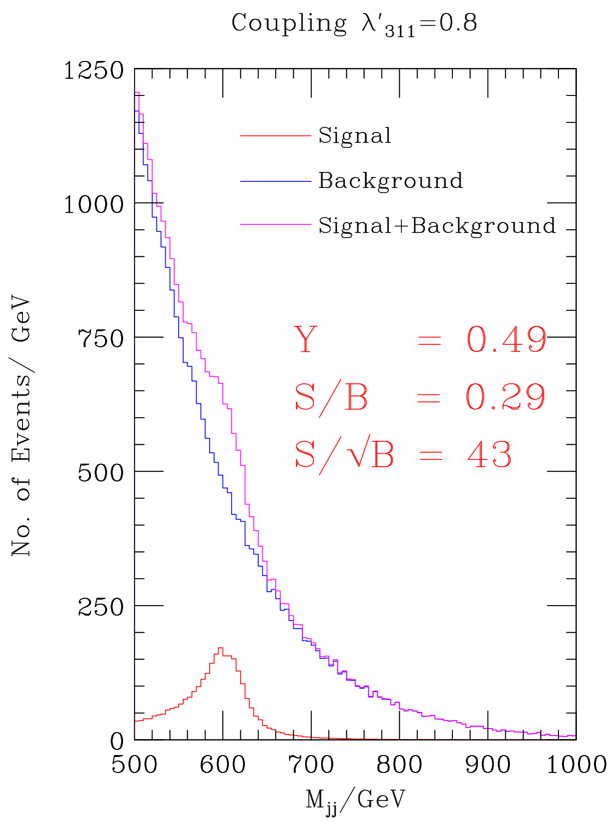


$\tilde{\tau}$ **production**

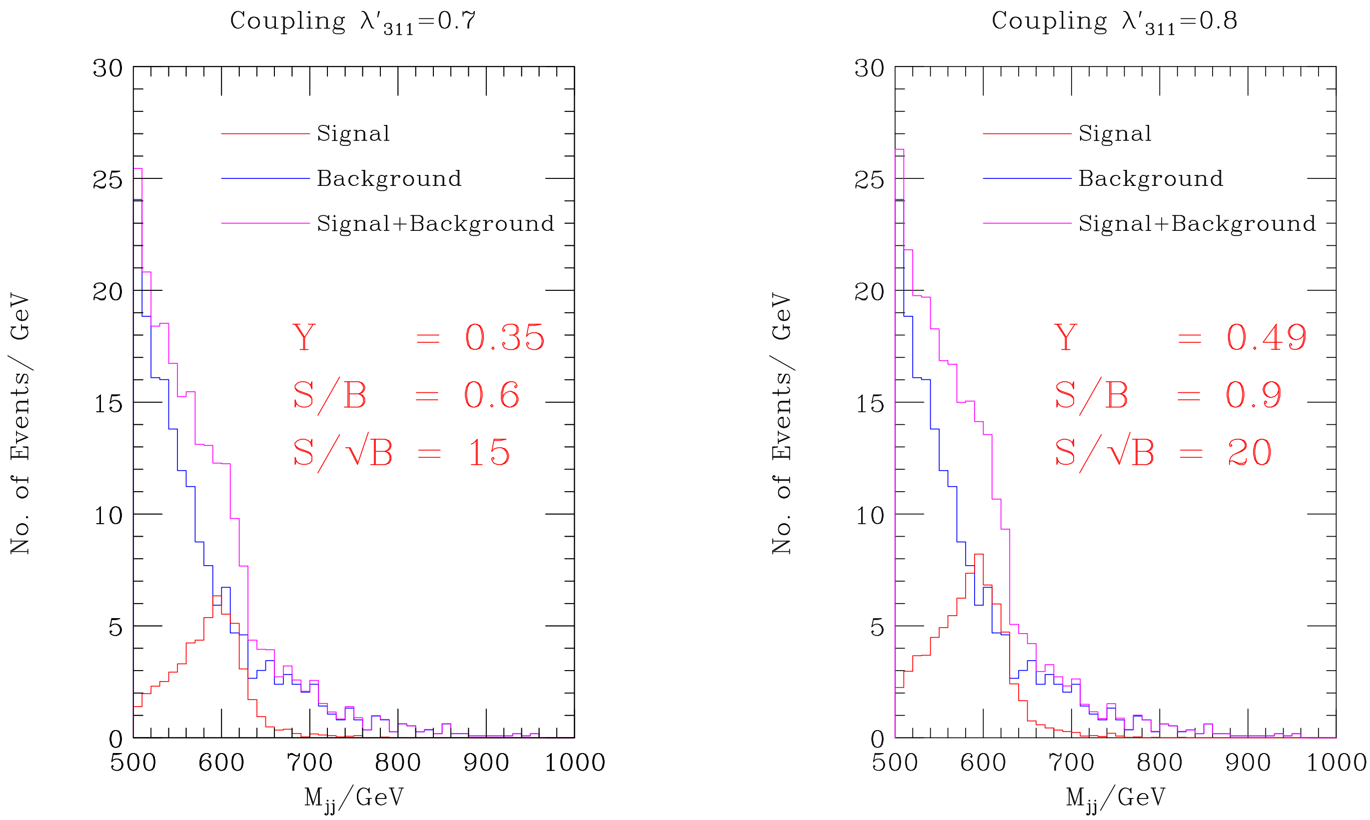
- $Y = \lambda'^2 \times \mathrm{BR}(\tilde{\ell} \to \mathrm{jets})$
- **dots CDF discovery potential at 2 fb^{-1} and 30 fb^{-1}**
- **dashes D0 discovery potential at 2 fb^{-1} and 30 fb^{-1}**

Effect of QCD Radiation





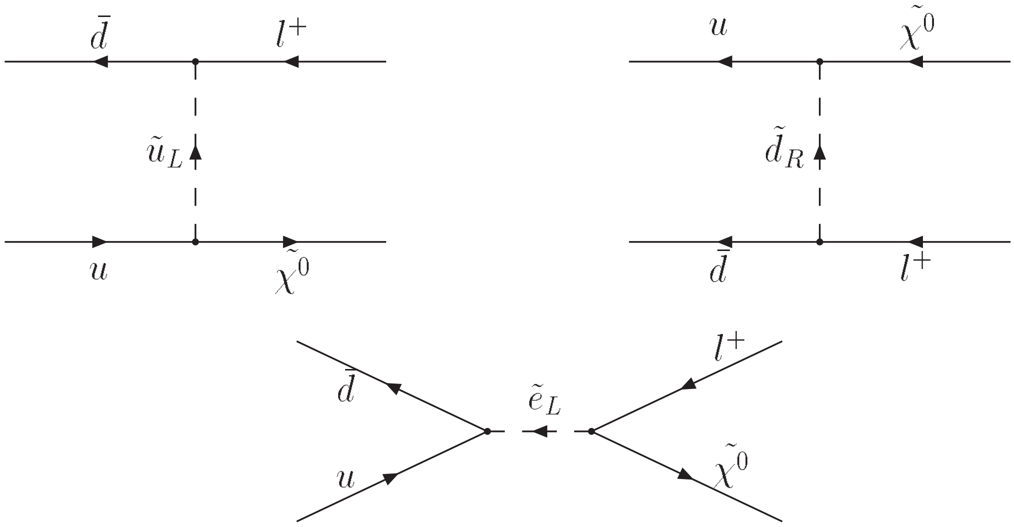
- **SUGRA point** $M_0 = 600$ **GeV**, $M_{1/2} = 200$ **GeV**, $A_0 = 0$ **GeV**, $\tan\beta = 10$, $\mathrm{sgn}\,\mu\ +$.
- **At this point the limit on the coupling in** $\lambda'_{311} < 0.8$
- **Slepton Masses between 600 and 620 GeV**
- **If we consider the region** $580\,\mathrm{GeV} \leq M_{jj} \leq 640\,\mathrm{GeV}$ **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.**



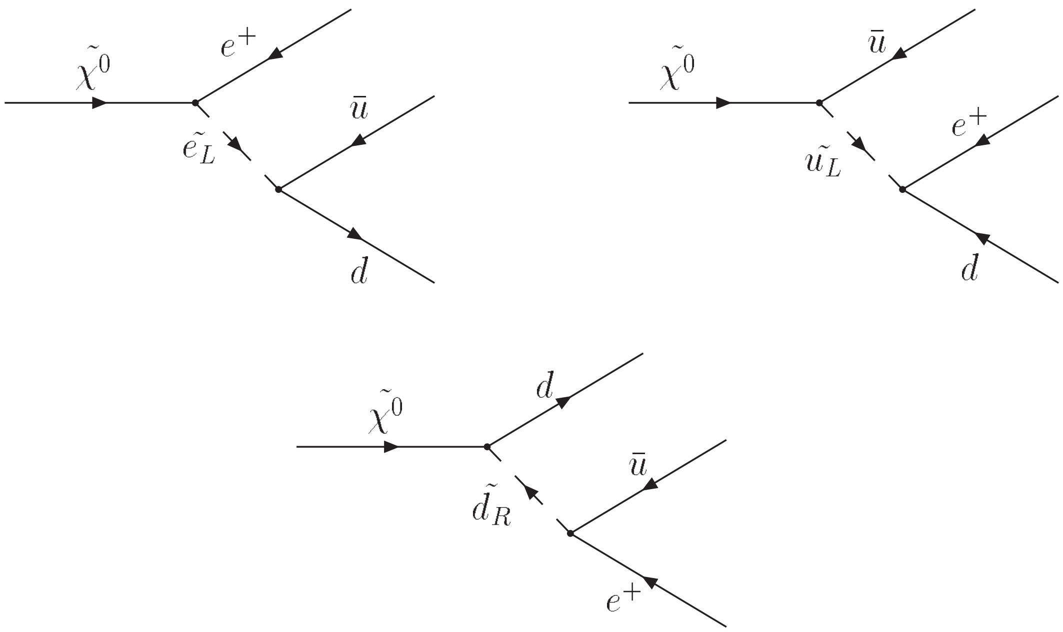
- **Require the presence of a third jet with** $E_T > 10\ GeV$.
- **Pseudo-Rapidity cut** $|\eta_1|,\ |\eta_2| < 0.7$.
- **Require the jets be back-to-back** $||\phi_1 - \phi_2| - \pi| < 20^0$.
- **Cut to avoid overlapping cones** $1.1 < R < \pi$.
- **Require** $|\alpha| < 0.4$
- S/B **is improved at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

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

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

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. $p_T^{\rm lepton} > 20$ 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 $60\,{\rm GeV} < M_T < 85\,{\rm GeV}$.
  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.

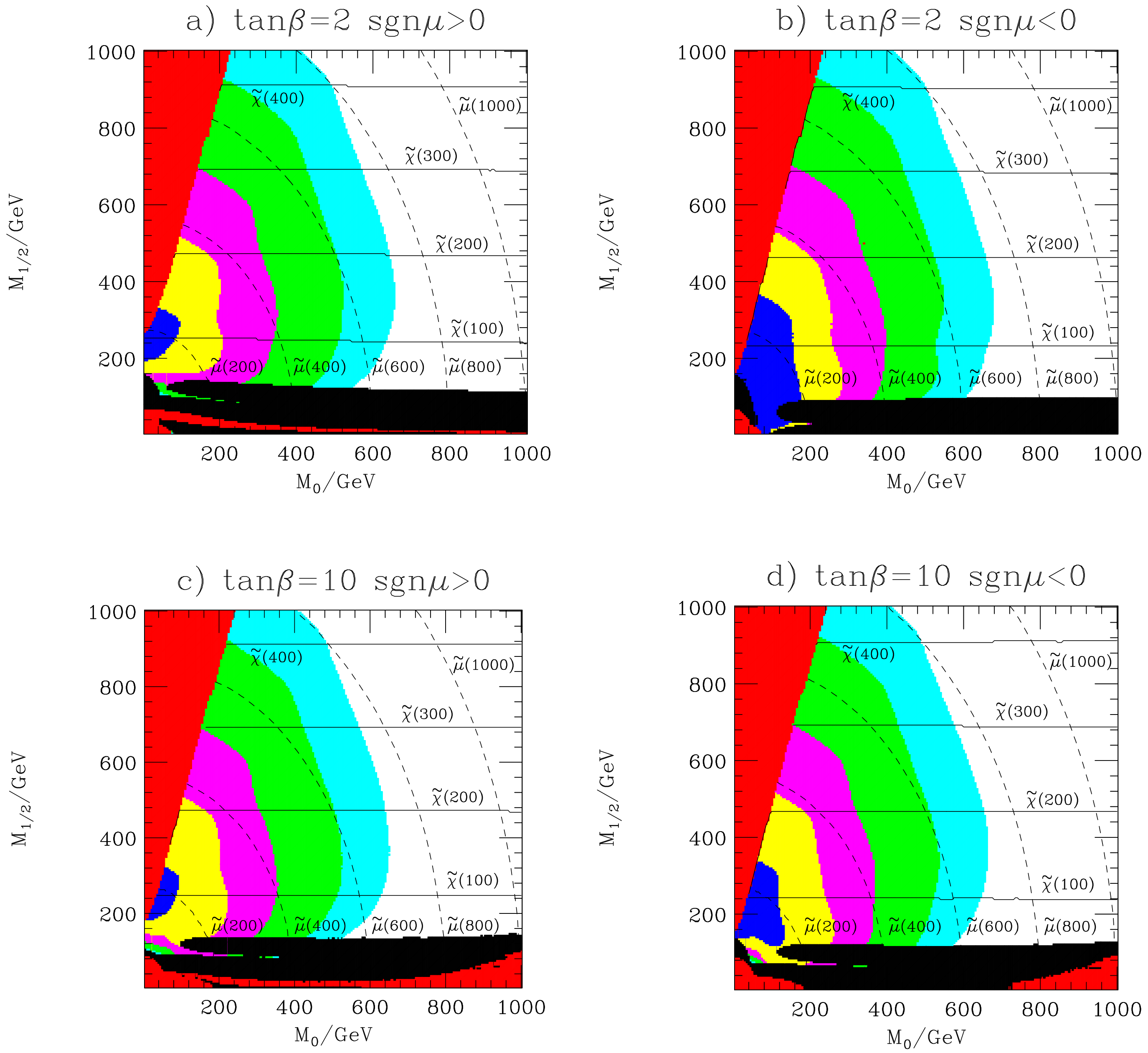
- We have only considered like-sign muon production as the limit on the coupling λ'_{211} is far weaker than that on λ'_{111}.

- The limit is

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

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

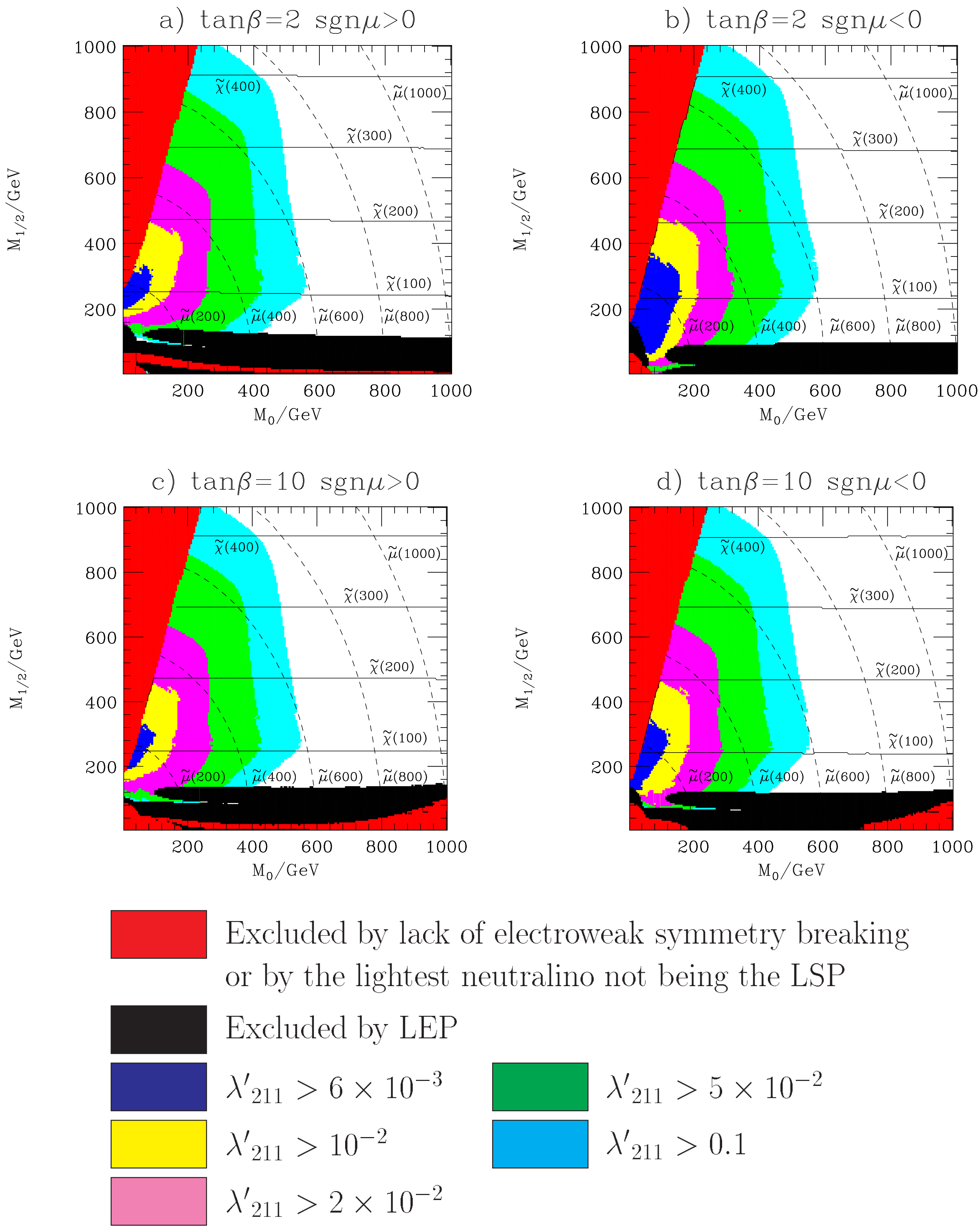
- In addition to the Standard Model backgrounds SUSY particle pair production is a major source of background
- The dominant processes are sparton pair production
- the sparticles then cascade decay to the LSP, provided the $\not{R}_p$ couplings are small.
- the two LSPs produced can then decay to give 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 at 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** $60\,\text{GeV} < M_T < 85\,\text{GeV}$**.**

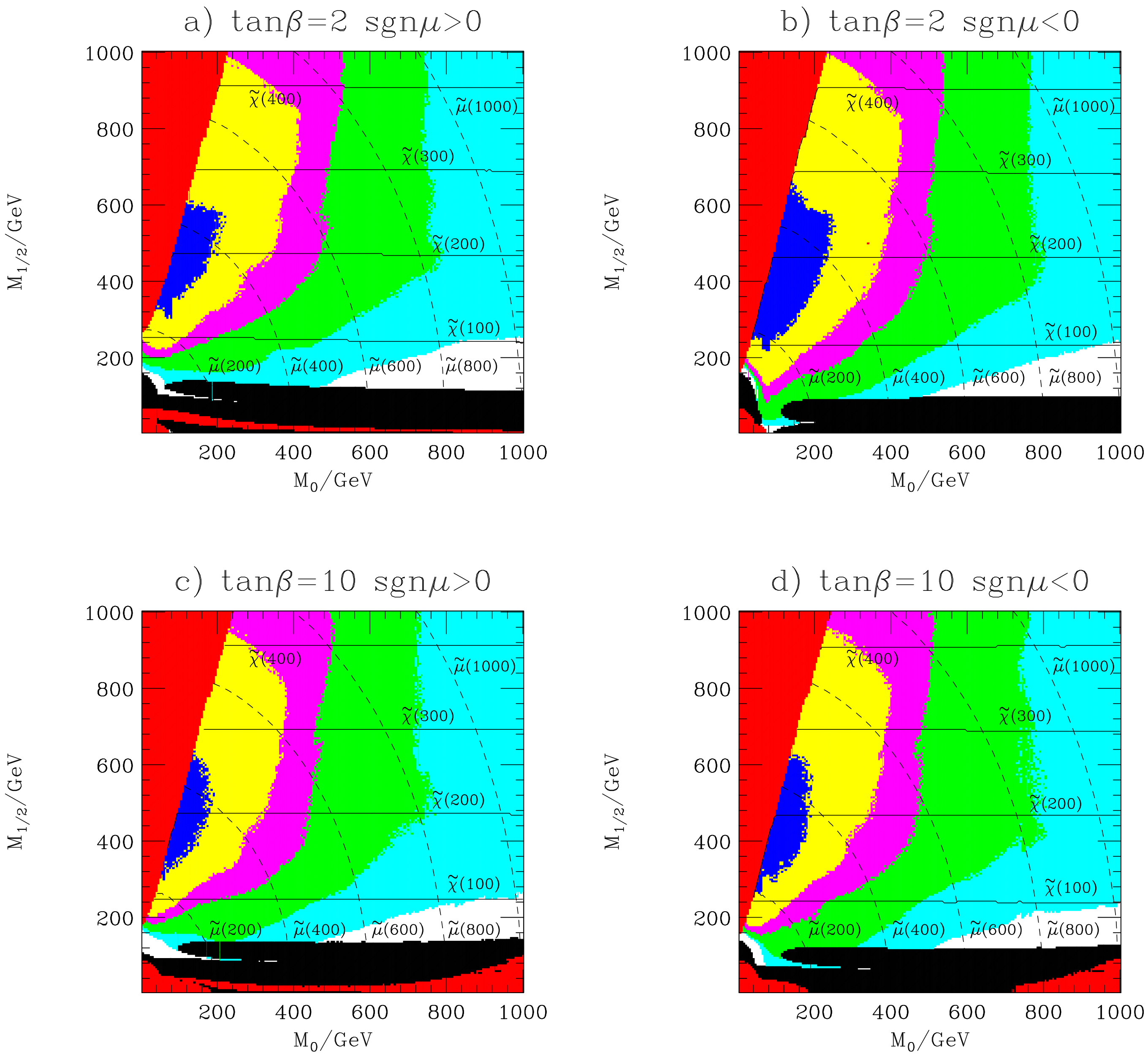
4. **A veto on the presence of a lepton in the event with the same flavour but opposite charge (OSSF) as either of the leptons in the like-sign pair if the lepton has** $p_T > 10$ **GeV and passes the same isolation cut as the like-sign leptons.**

5. **A cut on the missing transverse energy,** $E^T_{miss} < 20$ **GeV.**

6. **For the SUSY backgrounds we imposed a cut requiring at most two jets with** $p_T > 50$ **GeV**

SUSY Backgrounds

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



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

Excluded by LEP

$\lambda'_{211} > 4 \times 10^{-3}$

$\lambda'_{211} > 7 \times 10^{-3}$

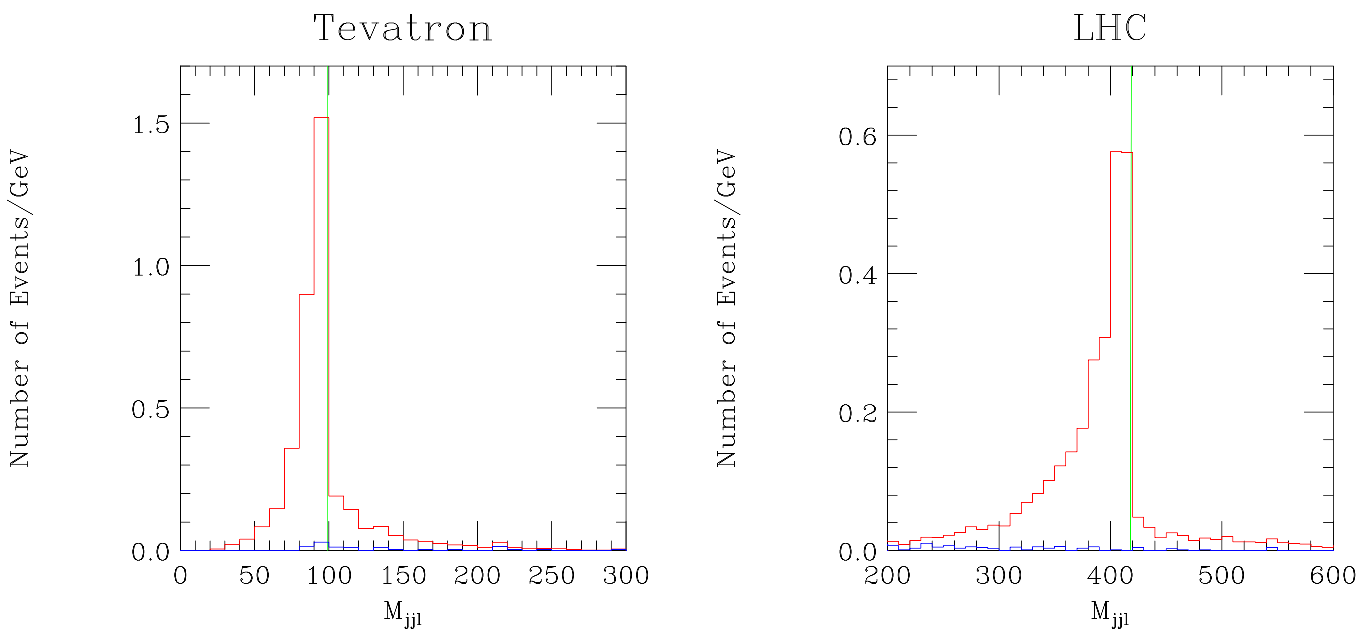
$\lambda'_{211} > 2 \times 10^{-2}$

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

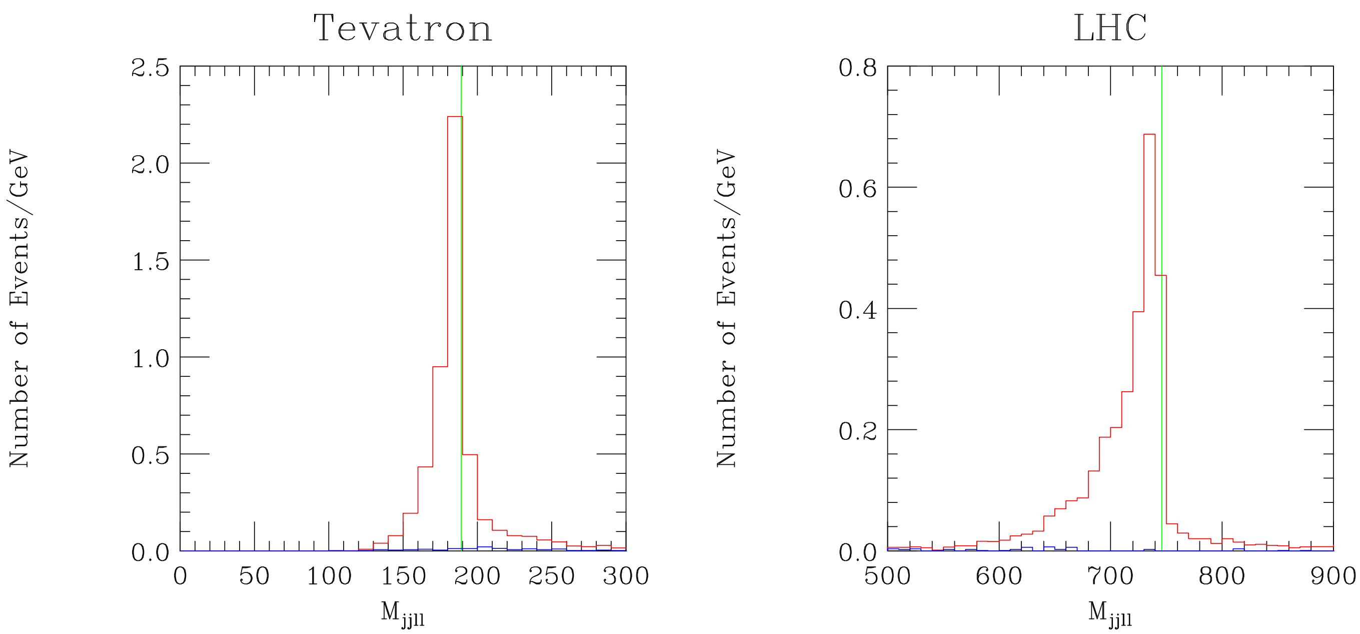
$\lambda'_{211} > 5 \times 10^{-2}$

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



Mass Reconstruction

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

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

Conclusions

- The existing Monte Carlos for $\not{R}_{\mathrm{p}}$ 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 resonant slepton production and and baryon number violation in hadron-hadron collisions for the first time.