Resonant Slepton Production in Hadron-Hadron Collisions

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Outline

- **Introduction to $\not R_p$ SUSY**
- **Resonant Sparticle Production**
- **Resonant Sparticle Production with $\not R_p$ Decays**
- **Resonant Sparticle Production with gauge 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	SUSY particle	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

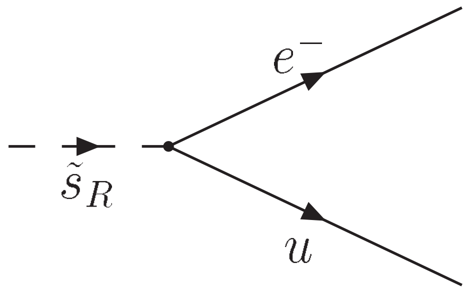
- In the MSSM R-parity is imposed by hand. It is a discrete multiplicative symmetry.

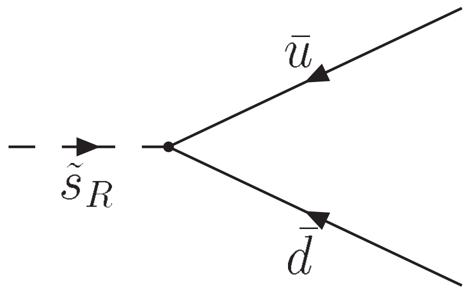
$$\mathbf{R_p} = (-1)^{3B+L+2S}$$

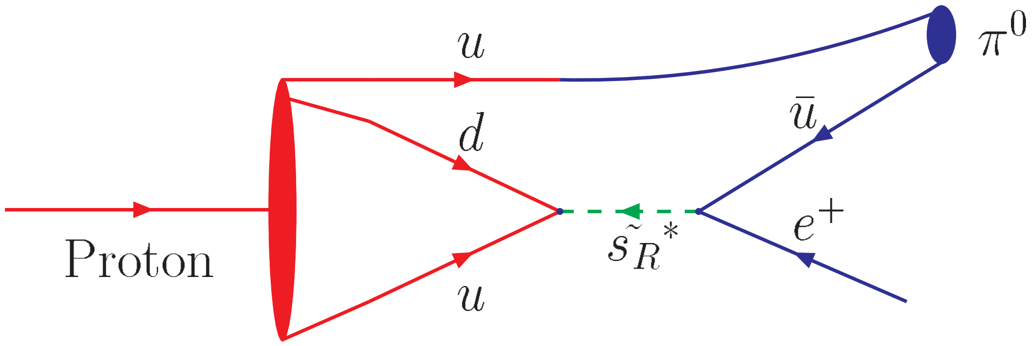
- SM particles $R_p = +1$, SUSY Particles $R_p = -1$

- This means that
  1. Sparticles are only produced in pairs
  2. The LSP is stable, and neutral (cosmology)
- Using the minimal particle content
  we can however violate R-parity

$$\mathbf{W}_{\not{R}_p} = \lambda_{ijk}\varepsilon^{ab}L_a^i L_b^j \overline{E}^k + \lambda'_{ijk}\varepsilon^{ab}L_a^i Q_b^j \overline{D}^k + \lambda''_{ijk}\varepsilon^{\alpha\beta\gamma}\overline{U}_\alpha^i \overline{D}_\beta^j \overline{D}_\gamma^k$$







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

$$\lambda'_{11k} \cdot \lambda''_{11k} \lesssim 2 \cdot 10^{-27}$$

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

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

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

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

- **This means that**

  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**

Limits from Low Energy Experiments

- **There are strict limits on the $\not{R}_p$ couplings from low energy experiments.**
- **The latest summary is hep-ph/9906209, Allanach, Dedes, Dreiner.**
- **On the coupling λ'_{111} from neutrinoless decay beta decay.**

$$\lambda'_{111} < 5.2 \times 10^{-4} \left(\frac{M_{\tilde{\ell}}}{100\,\mathrm{GeV}}\right)^2 \left(\frac{M_{\tilde{\chi}^0}}{100\,\mathrm{GeV}}\right)^{1/2}$$

- **On the coupling λ'_{211} from the ratio $R_\pi = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$.**

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

- **On the coupling λ'_{311} from the ratio $R_{\tau\pi} = \Gamma(\tau \to \pi\nu_\tau)/\Gamma(\pi \to \mu\nu)$.**

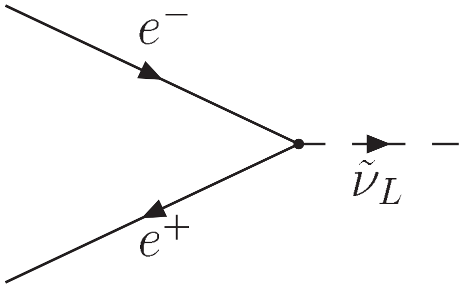
$$\lambda'_{311} < 0.11 \left(\frac{M_{\tilde{\mathrm{d}}_R}}{100\,\mathrm{GeV}}\right)$$

Resonant Sparticle Production

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

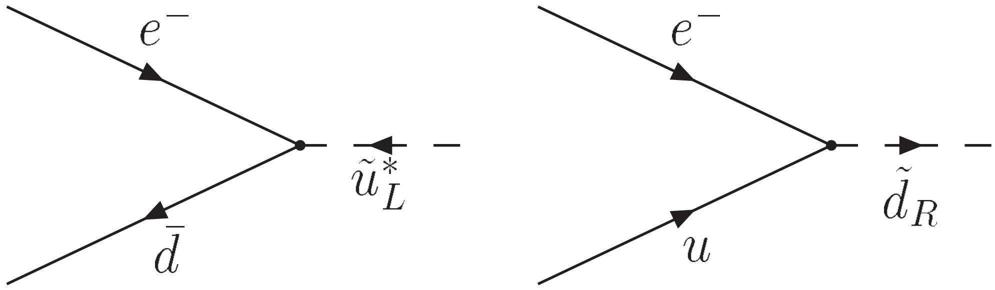
- In e^+e^- collisions

LLE



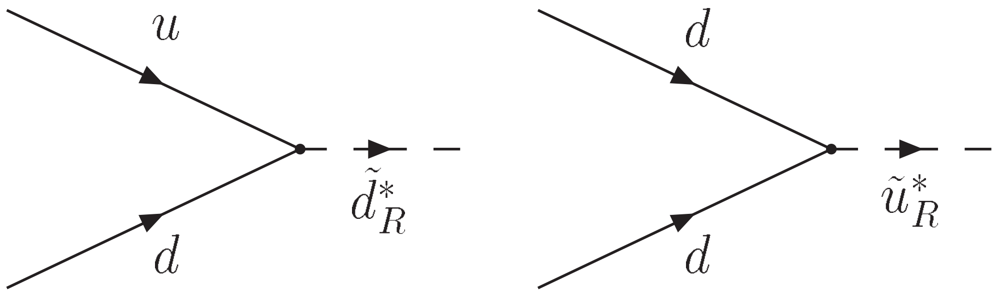
- In electron-proton collisions

LQD

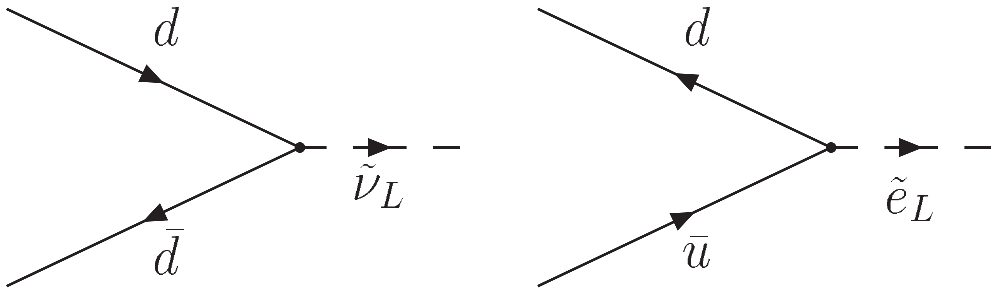


- In hadron-hadron collisions

UDD



LQD



Resonant Slepton Production

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

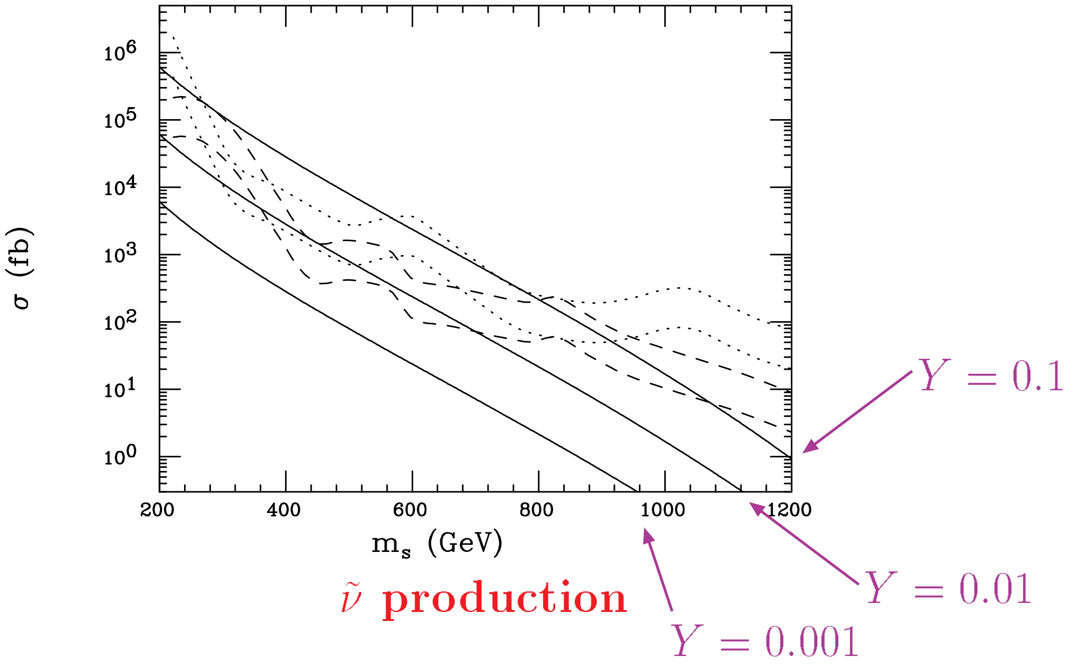
	Charged Sleptons	Sneutrinos
Gauge Decays	$\tilde{\ell}_{i\alpha} \to \ell_i^- \tilde{\chi}^0$	$\tilde{\nu}_i \to \nu_i \tilde{\chi}^0$
	$\tilde{\ell}_{i\alpha} \to \nu_i \tilde{\chi}^-$	$\tilde{\nu}_i \to \ell_i^- \tilde{\chi}^+$
$\not{R}_p$ Decays	$\tilde{\ell}_{i\alpha} \to \bar{u}_j d_k$	$\tilde{\nu}_i \to \bar{d}_j d_k$
	$\tilde{\ell}_{i\alpha} \to \bar{\nu}_j \ell_k^-$	$\tilde{\nu}_i \to \ell_j^+ \ell_k^-$
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

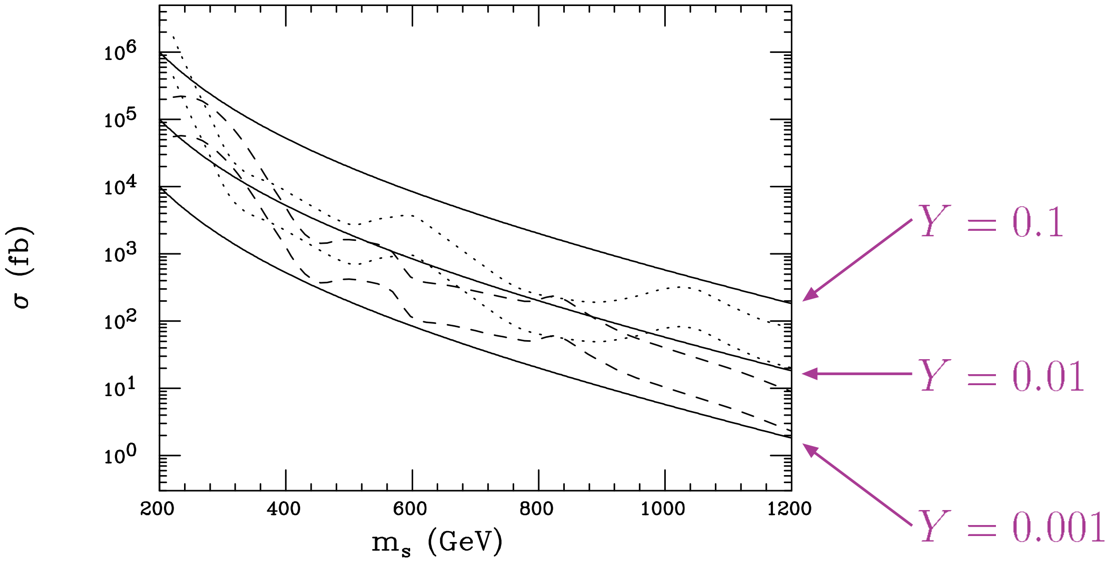
Resonant Slepton Production

- 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.**



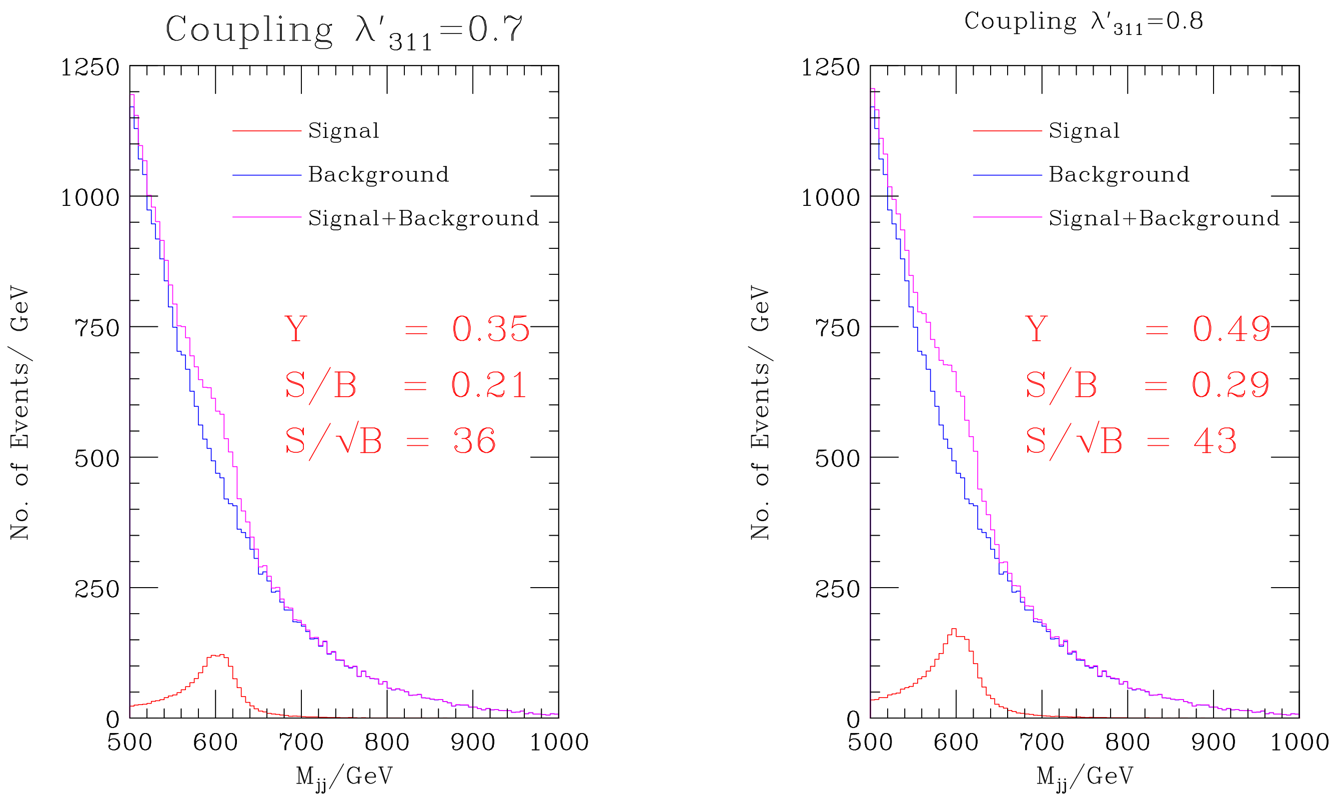
$\tilde{\nu}$ **production**



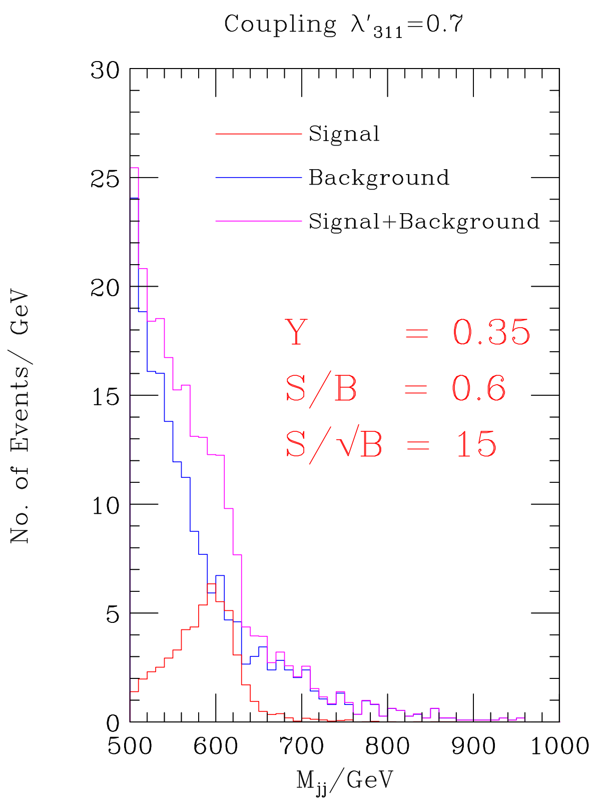
$\tilde{\tau}$ **production**

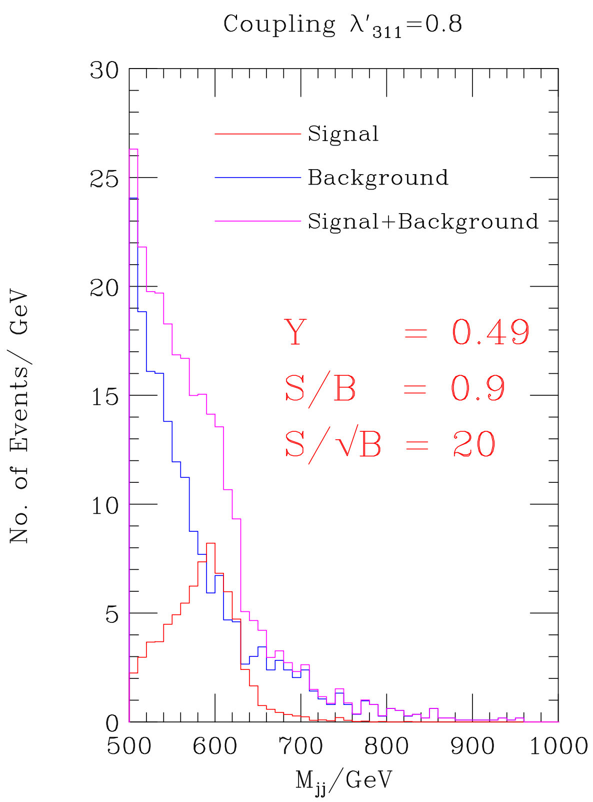
- $Y = \lambda'^2 \times \mathrm{BR}(\tilde{\ell} \to \mathrm{jets})$
- **dots CDF discovery potential at 2 fb^{-1} and 30 fb^{-1}**
- **dashes D0 discovery potential at 2 fb^{-1} and 30 fb^{-1}**

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%.**
- **This can be improved by applying cuts using the different QCD radiation patterns for the signal and the QCD background.**





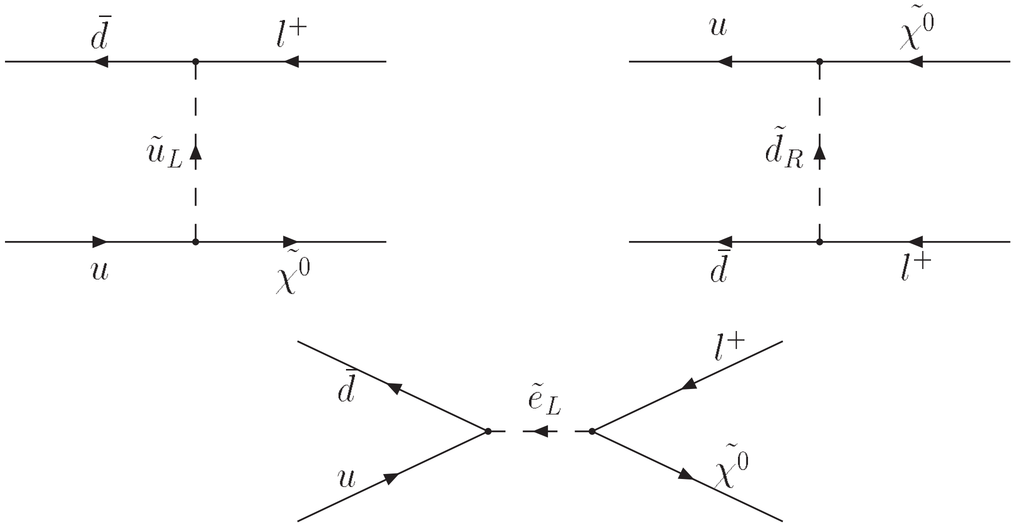
- **Defining**

  1. $\Delta\eta = \eta_3 - \eta_2$ **pseudo-rapidity between 2nd and 3rd jets.**
  2. $\Delta\phi = \phi_3 - \phi_2$ **azimuthal angle between 2nd and 3rd jets.**
  3. $R = \sqrt{\Delta\eta + \Delta\phi}$ **distance is** (η, ϕ) **space between second and third jets**
  4. $\Delta H = \mathrm{sgn}\,\eta_2\ \Delta\eta$, **signed pseudo-rapidity difference**
  5. $\alpha = \tan^{-1}\left(\frac{\Delta H}{\Delta\phi}\right)$, **azimuthal angle in the** $(\Delta H, \Delta\phi)$ **plane.**

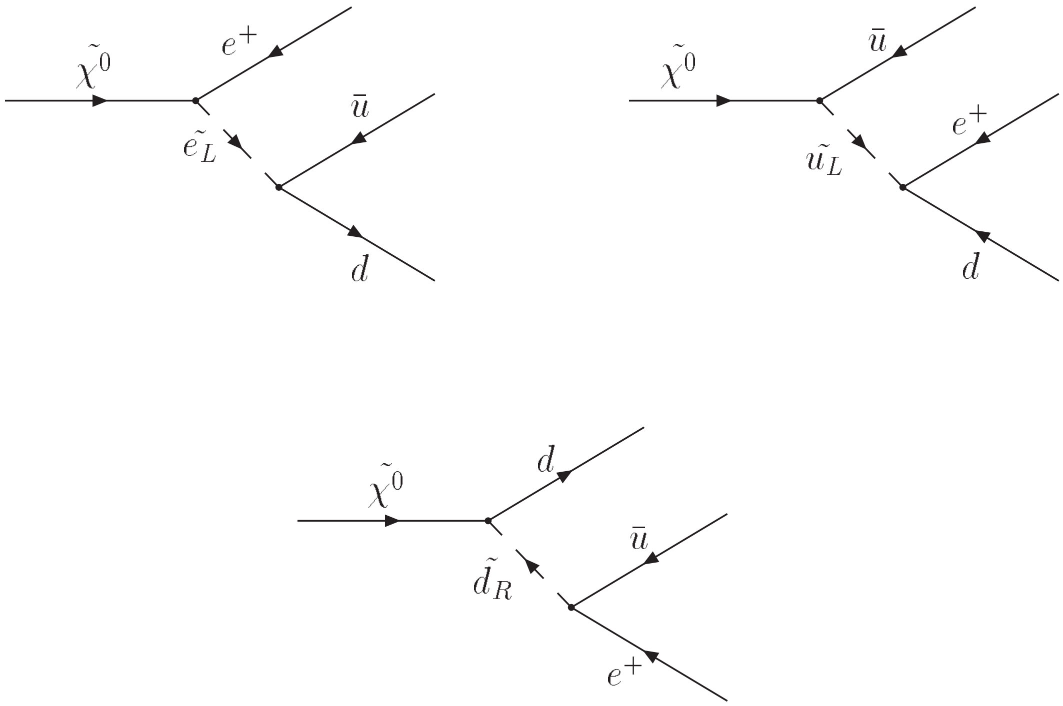
- **Require the presence of a third jet with** $E_T > 10\ GeV$.
- **Pseudo-Rapidity cut** $|\eta_1|,\ |\eta_2| < 0.7$.
- **Require the jets be back-to-back** $||\phi_1 - \phi_2| - \pi| < 20^0$.
- **Cut to avoid overlapping cones** $1.1 < R < \pi$.
- **Require** $|\alpha| < 0.4$
- S/B **is improved at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

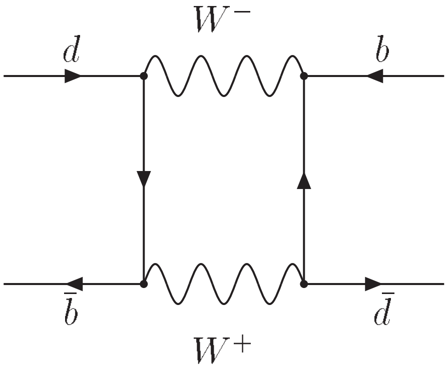
Standard Model Backgrounds

- <u>Gauge Boson pair production</u>

  particularly WZ and ZZ followed by leptonic decays of the gauge bosons with some of the leptons not being detected.

- <u>$b\bar{b}$ production</u>

  followed by the production of a B_d^0 or B_s^0 meson which can undergo mixing

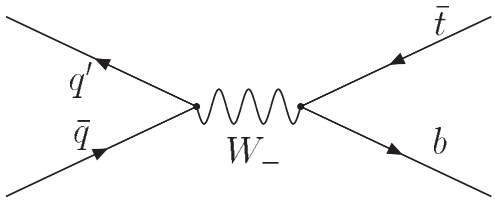


  If the two B mesons in the event decay semi-leptonically this gives two like-sign charged leptons

- <u>$t\bar{t}$ production</u> followed by

$$t \to W^+ b \to e^+ \bar{\nu}_e b$$
$$\bar{t} \to W^- \bar{b} \to q\bar{q}\bar{b} \to q\bar{q} W^+ \bar{c} \to q\bar{q} e^+ \bar{\nu}_e \bar{c}$$

- single top production (s and t channel)



followed by semi-leptonic decay of the $\bar{t}$ and B meson

- 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.

Background Analysis

- The following cuts can be used to reduce these backgrounds

- p_T and isolation cuts

  – The leptons from the signal will have

    high p_t

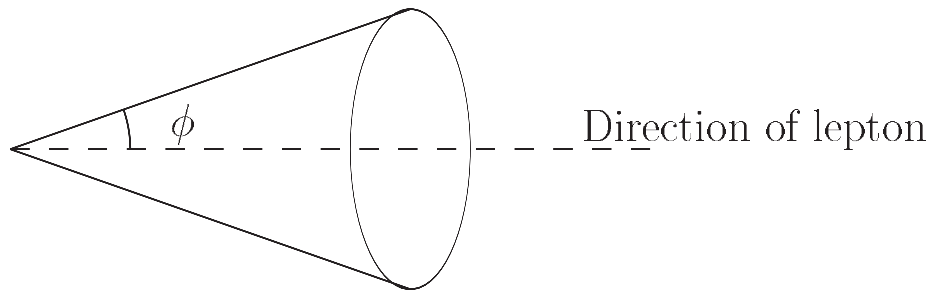
    be well isolated

  – The leptons from the backgrounds will have

    lower p_t

    be poorly isolated

  – therefore we hope an isolation and a p_t cut can reduce the background



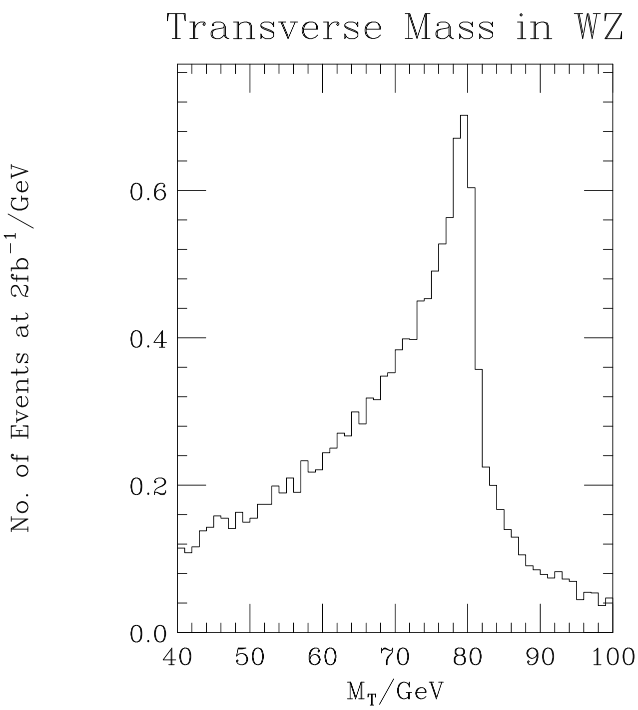
  – The isolation cut requires the transverse energy in a cone of angle 0.4 radians about the direction of the lepton to be below a certain value.

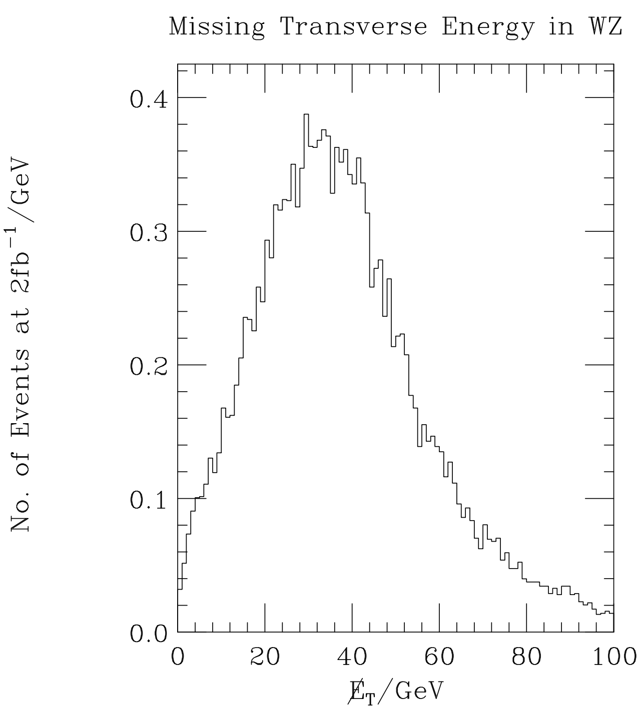
  – These cuts are mainly designed to reduce the $t\bar{t}$ and $b\bar{b}$ backgrounds

- Veto on presence of addition leptons
  - The signal will only contain additional leptons from semi-leptonic hadron decays, or the cascade decays of heavier neutralinos.
  - Therefore a veto on the presence of leptons with the opposite charge and the same flavour as one of the like-sign dileptons will reduce the background from WZ and ZZ production.
- Cut on the transverse mass
  - $M_T^2 = 2|p_{T_\ell}||p_{T_\nu}|(1 - \cos\Delta\phi_{\ell\nu})$.
    p_{T_ℓ} is the transverse momentum of the charged lepton,
    p_{T_ν} is the transverse momentum of the neutrino, assumed to be all the missing transverse momentum in the event, and
    $\Delta\phi_{\ell\nu}$ is the azimuthal angle between the lepton and the neutrino, *i.e.* the missing momentum in the event.
  - A removing those events with $60\ \mathrm{GeV} < M_T < 85\ \mathrm{GeV}$ suppresses the background from WW and WZ production.
- Cut of the missing transverse energy, $\not{E}_T$.
  - The signal will only have $\not{E}_T$ from semi-leptonic hadron decays
  - A cut on the $\not{E}_T$, $\not{E}_T < \not{E}_T^{\mathrm{cut}}$ will reduce the background from WW and WZ production.

Tevatron

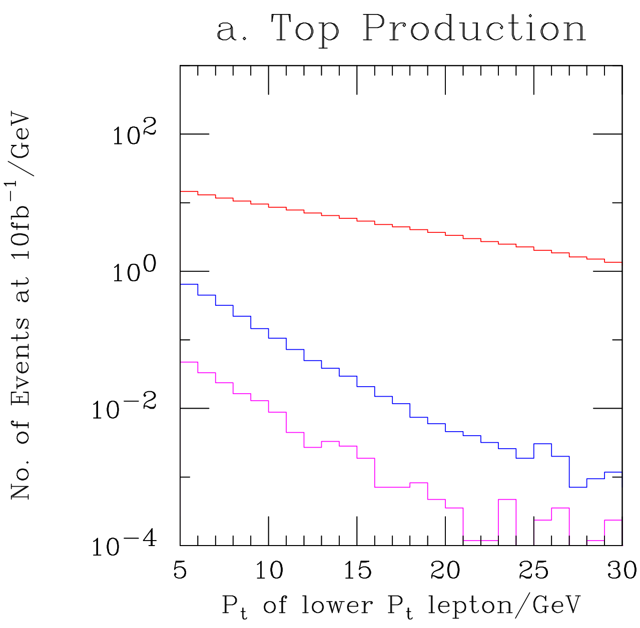
- **We impose the following cuts**
  1. $p_T^{\text{lepton}} > 20$ **GeV**
  2. **An isolation cut on the like-sign leptons so that the transverse energy in a cone about the direction of the lepton is less than** 5 **GeV.**
  3. **We cut the region** $60\,\mathrm{GeV} < M_T < 85\,\mathrm{GeV}$.
  4. **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.**
- **All distributions have been normalized to** $2\ fb^{-1}$ **integrated luminosity of Run II of the Tevatron.**

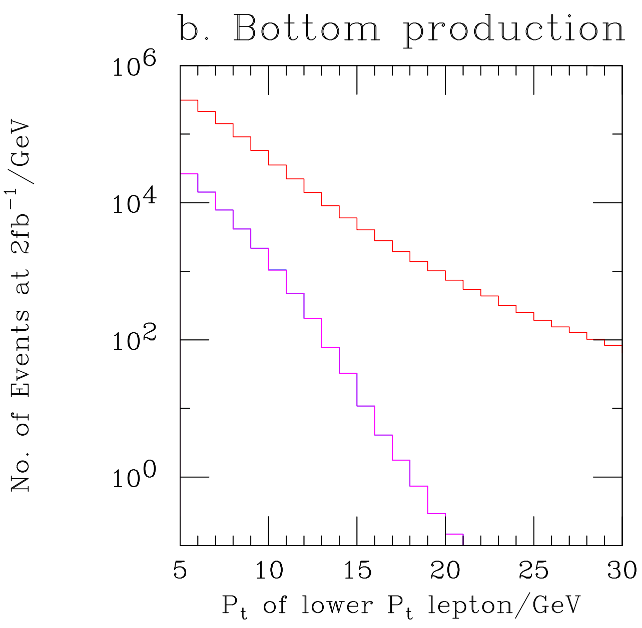




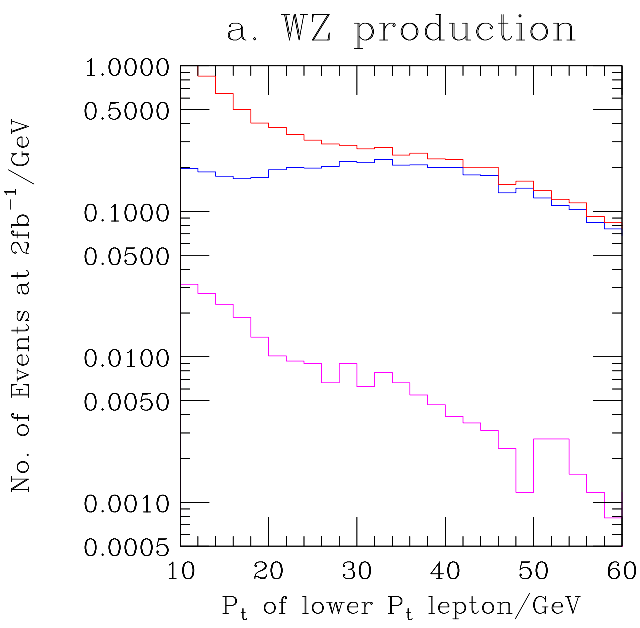
Effect of the Cuts

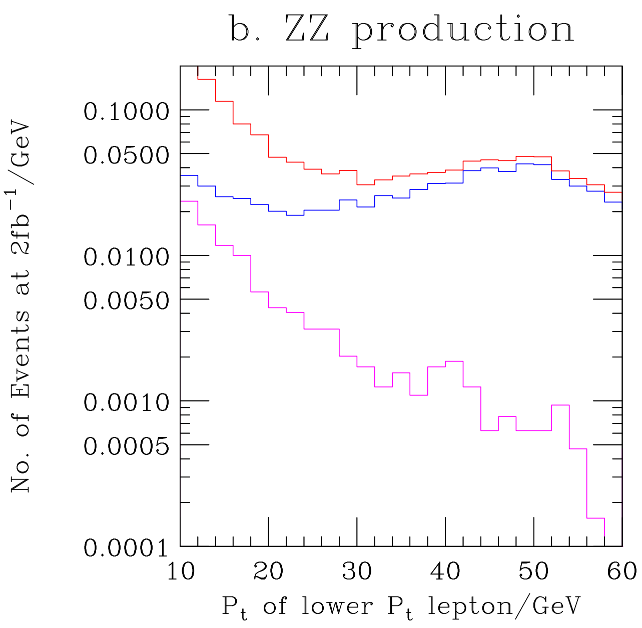
• $b\bar{b}$ and $t\bar{t}$ production.





• Gauge Boson pair production.





No cuts

Isolation cut

All cuts

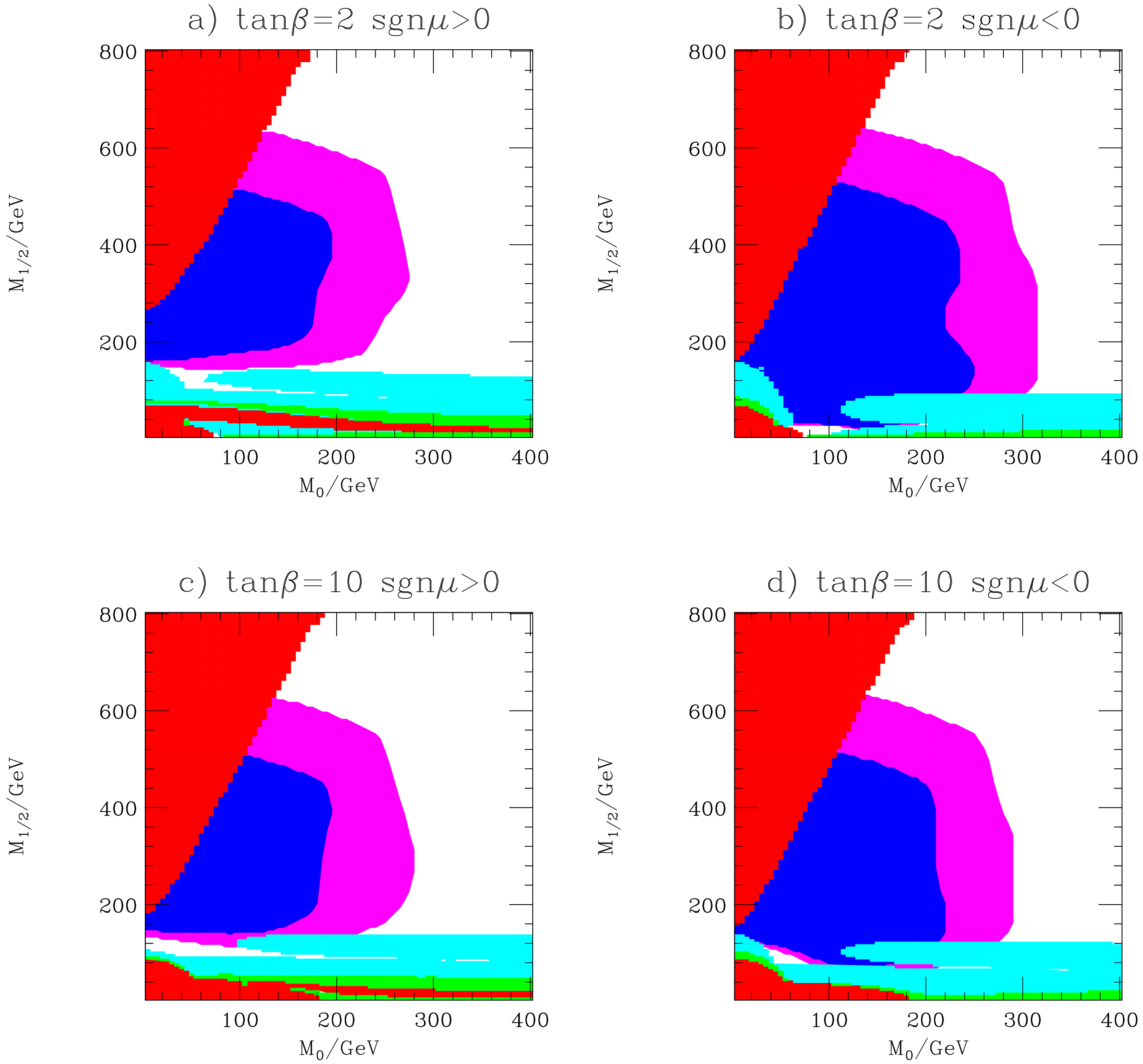
Summary of Tevatron Backgrounds

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
$\mathrm{t\bar{t}}$	34.1 ± 1.6	0.028 ± 0.002	0.0032 ± 0.0006
$\mathrm{b\bar{b}}$	$(3.4 \pm 1.3) \times 10^3$	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

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

Results

- **We have taken** $\lambda'_{211} = 0.01$



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

Neutralino decays outside detector

Excluded by LEP

Discoverable with 2 fb^{-1} integrated luminosity

Discoverable with 10 fb^{-1} integrated luminosity

SUSY backgrounds

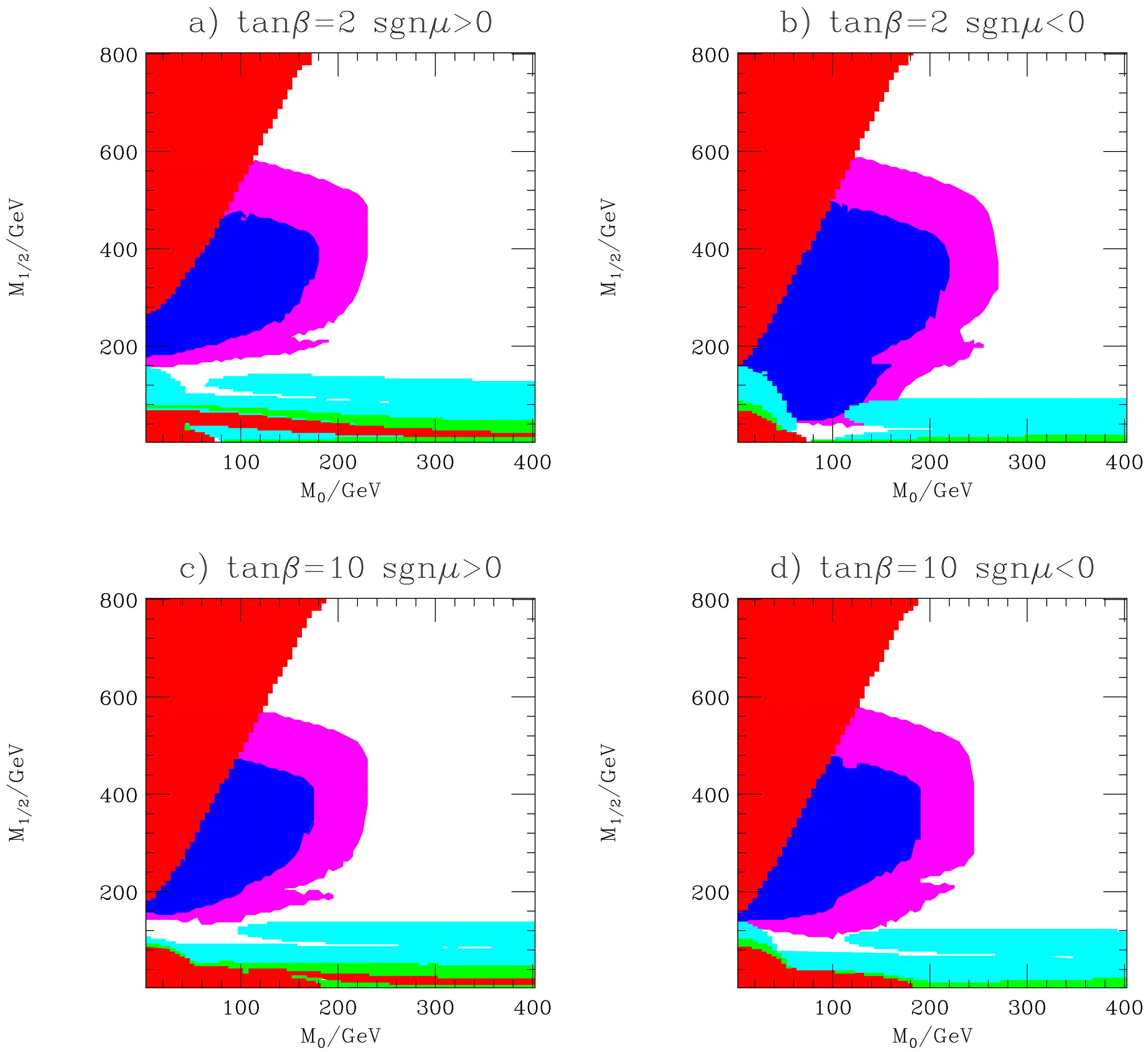
- **In addition on the Standard Model backgrounds SUSY particle pair production is a major source of background**
- **The dominant processes are sparton pair production**
- **the sparticles then cascade decay to the LSP, provided the $\not{R}_p$ couplings are small.**
- **the two LSPs produced can then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

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

  $\tilde{g} \rightarrow \tilde{q}_L\ \bar{q} \rightarrow \tilde{\chi}^0\ \bar{q}q \rightarrow \ell^+\ d\ \bar{u}\ \bar{q}q$
- **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 have taken** $\lambda'_{211} = 0.01$



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Conclusions

- We have studied resonant slepton production using the first Monte Carlo event generator for these processes
- The decay to jets can only be extracted for large values of $\not{R}_p$ couplings
- The gauge decays can be seen using like-sign dileptons for small values of the couplings for large ranges of SUSY parameter space.
- A study of the same signature for the LHC is underway.