SUSY in HERWIG

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Outline

- Implementation of SUSY in HERWIG
- Colour Flows in MSSM processes
- Colour Flows in RPV processes
- MSSM Higgs processes
- Examples of SUSY studies
- Conclusions

Implementation of SUSY in HERWIG

- HERWIG does not include a in-built spectrum generator
- Reads the sparticle masses and mixings from a data file
- We have written an interface to ISAJET
- This allows ISASUSY to be used to generate the spectrum
- This interface can also add RPV couplings and decays
- HERWIG includes MSSM SUSY and Higgs production processes
- RPV resonance production processes are also included

ISAWIG

- ISAWIG is our interface to ISAJET
- This allows all the SUSY models implemented in ISAJET to be used with HERWIG
- It also allows the user to have non-zero RPV trilinear (λ, λ', λ'') couplings
- In principle all the RPV couplings can be non-zero
- All 3-body neutralino, chargino and gluino modes are included
- 2-body squark and slepton modes are also included
- Also includes the option of using HDECAY for NLO Higgs widths and branching ratios
- Available from

  http://www-thphys.physics.ox.ac.uk/users/PeterRichardson/HERWIG/isawig.html

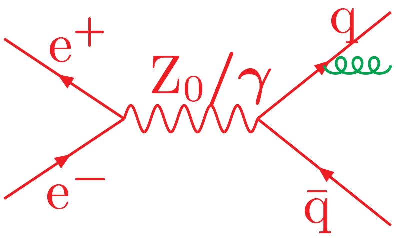
MSSM and RPV processes

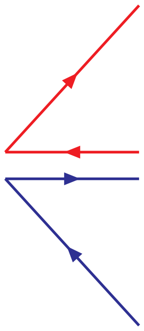
- All 2-to-2 MSSM processes are included
  - Sparton production
  - gaugino pair and gaugino-sparton production
  - Slepton pair production
- RPV resonant slepton production via λ' couplings
  - decay to neutralino/chargino lepton
  - decay to gauge boson slepton
  - decay to Higgs boson slepton
  - decay to leptons/quarks
- RPV resonant squark production via λ'' couplings
  - decay to neutralino/chargino quark
  - decay to gluino quark
  - decay to gauge boson squark
  - decay to Higgs boson squark
  - decay to quarks
- Sparticle pair production and resonant sneutrino production in $\mathrm{e}^+\mathrm{e}^-$ collisions are also included

Angular Ordering

- HERWIG uses the angular ordered parton shower to resum both the collinear and soft logarithms.

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

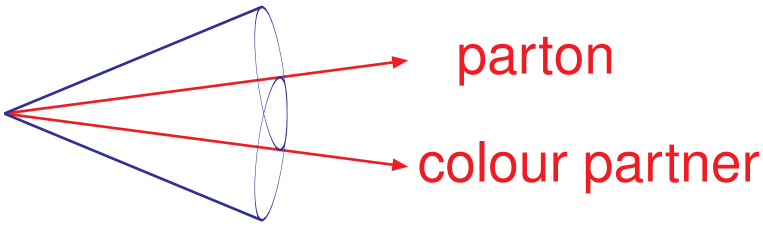




Colour Flow

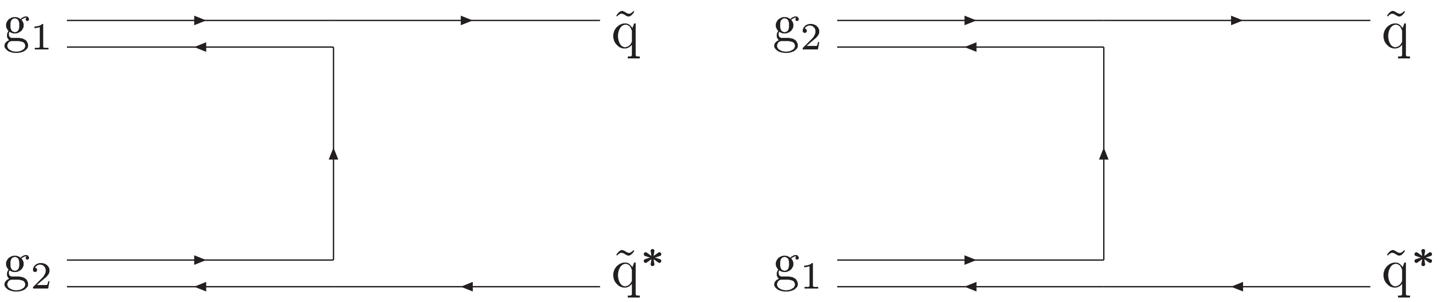
- We then get that
  - q and the g are colour connected
  - $\bar{q}$ and the g are anticolour connected

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



MSSM Colour Flows

- Work by K. Odagiri, JHEP 10:006, (1998).
- In MSSM processes the colour flows are not unique,
  e.g. $\mathrm{gg} \to \tilde{\mathrm{q}}\tilde{\mathrm{q}}^*$, (neglect squark masses and other diagrams for simplicity)



- The 'Non-planar' interferences terms between the different colour structures are in general suppressed by powers of $1/N_c$.

$$|\overline{\mathcal{M}}|^2 \left(\mathrm{gg} \to \tilde{\mathrm{q}}\tilde{\mathrm{q}}^*\right) = \frac{g_S^4 N_C}{N_C^2-1}\frac{\left(u^2\right)_u+\left(t^2\right)_t-\left(s^2/N_C^2\right)_{n.p.}}{s^2}$$

MSSM Colour Flows

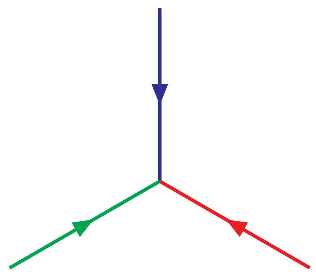
- Split the cross section by the ratio of the planar terms to obtain positive definite weights for different colour flows.

$$\frac{\left(u^2\right)_u+\left(t^2\right)_t-\left(s^2/N_C^2\right)_{n.p.}}{s^2}=\left[1-\frac{s^2/N_C}{u^2+t^2}\right]\frac{\left(u^2\right)_u+\left(t^2\right)_t}{s^2}$$

- There is currently no sparton showering
- The colour flow information is passed down the cascade and used in the showering of the partons, and the hadronization model.

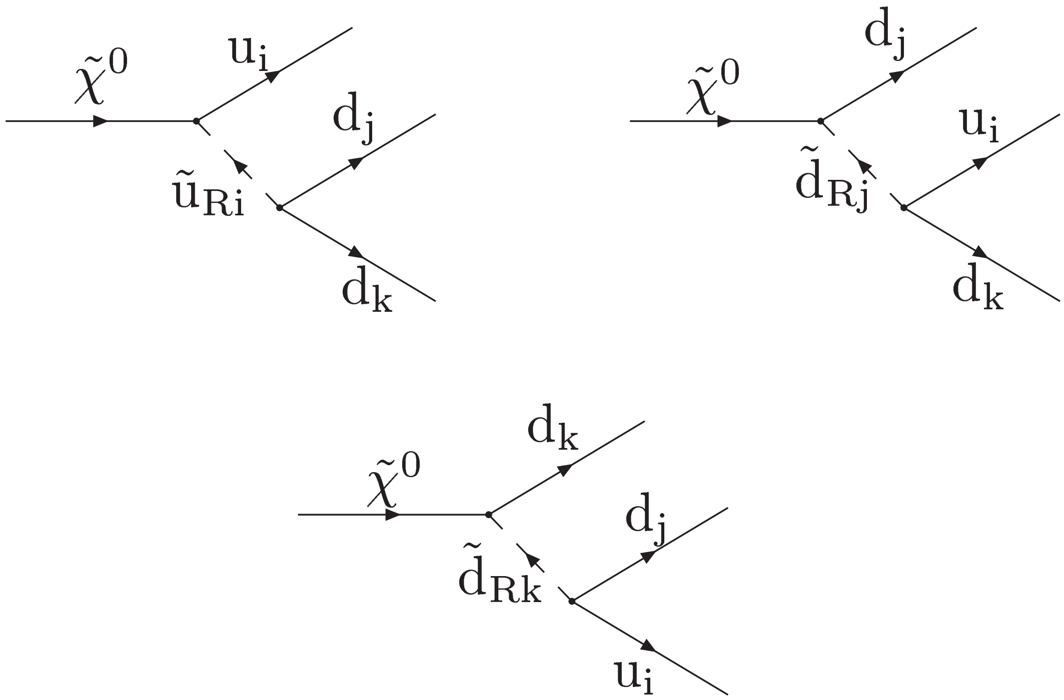
Angular Ordering in $\not{R}_p$

- H. Dreiner, P. Richardson and M. Seymour, JHEP 0004:008, (2000)
- 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.



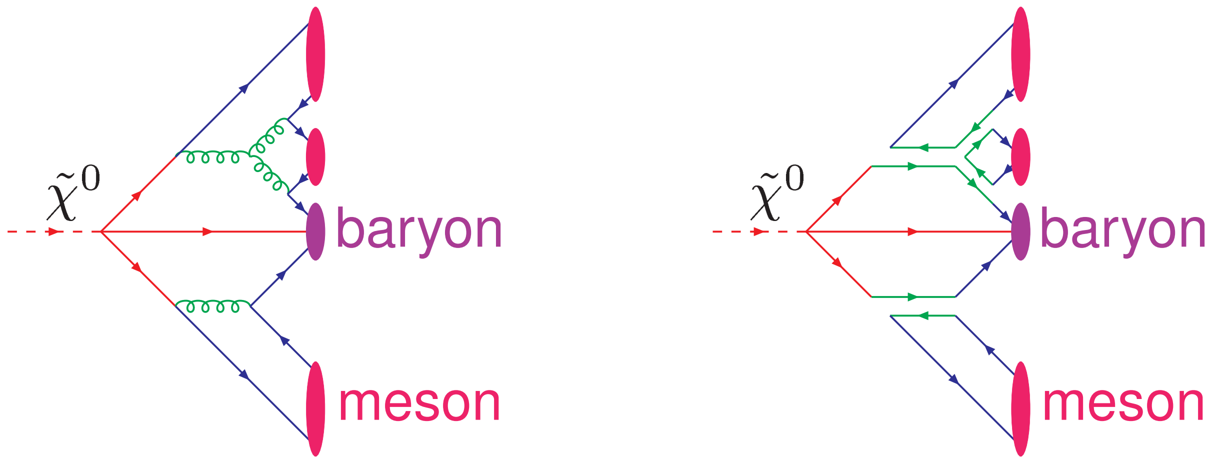
- There are no obvious pairs.

Neutralino Decay



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

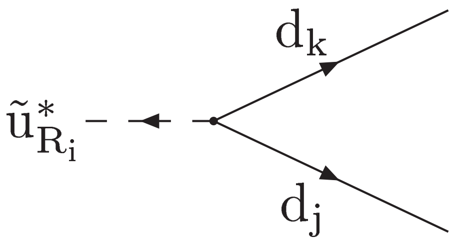
Hadronization



Hadronization of a $\not{B}$ Neutralino Decay

- 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 $\not{B}$

Squark Decays



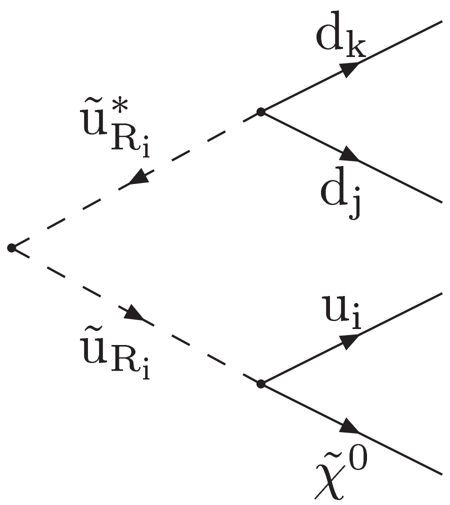
UDD decay of $\tilde{u}^*_R$.

- 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

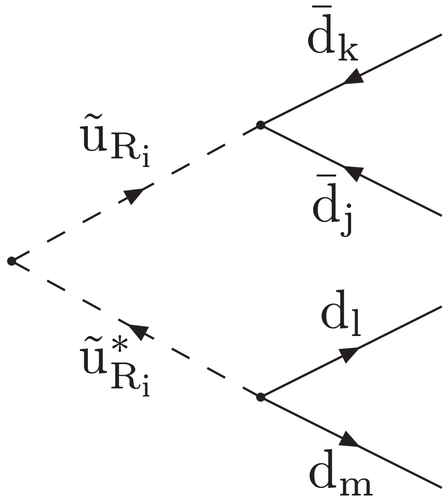
- There are two possibilities
- The squark is connected to a standard model particle or a SUSY particle which decays via a baryon number conserving mode



- The three quarks are formed into a baryonic cluster as before

Hadronization of $\not{B}$ squark decays

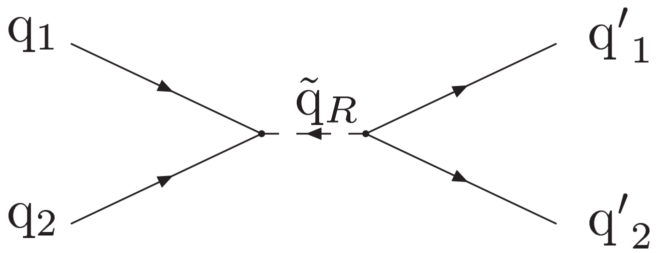
- The squark is connected to a second $\not{B}$ decay



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

Resonant Squark Production

- Can have resonant production followed by $R\!\!\!/_p$ decay



- Angular Ordering Procedure
  - Randomly connect incoming quark to either the other quark or to the final state
  - If connected to the final state randomly pick one of the quarks

- Hadronization
  - Randomly connect the colour partner of the initial state particle and one of the final state quarks to form a cluster.

MSSM Higgs Production Processes

- HERWIG currently includes SM Higgs production via
  - gluon gluon fusion
  - W/Z fusion
  - in association with top quark pairs
  - in association with W/Z
- neutral SUSY Higgs production via
  - gluon fusion via heavy (s) quark loops
  - W^*W^* & Z^*Z^* fusion
  - associated production with W/Z
  - associated production with heavy quark pairs

MSSM Higgs Production Processes

- charged SUSY Higgs production via
  - Drell Yan Production ($\mathrm{q\bar{q} \to H^+H^-}$)
  - bg fusion ($\mathrm{bg \to tH^-}$ & $\mathrm{gg \to t\bar{b}H^-}$)
  - $\mathrm{bW^*}$ fusion ($\mathrm{bg \to bq'H^\pm}$)
  - associated production with W
- production of $\mathrm{H^\pm h,\ H^\pm H,\ H^\pm A}$ are also included
- The next version (6.3) will also included
  - Associated Higgs (charged or neutral) production in association with a heavy squark pair

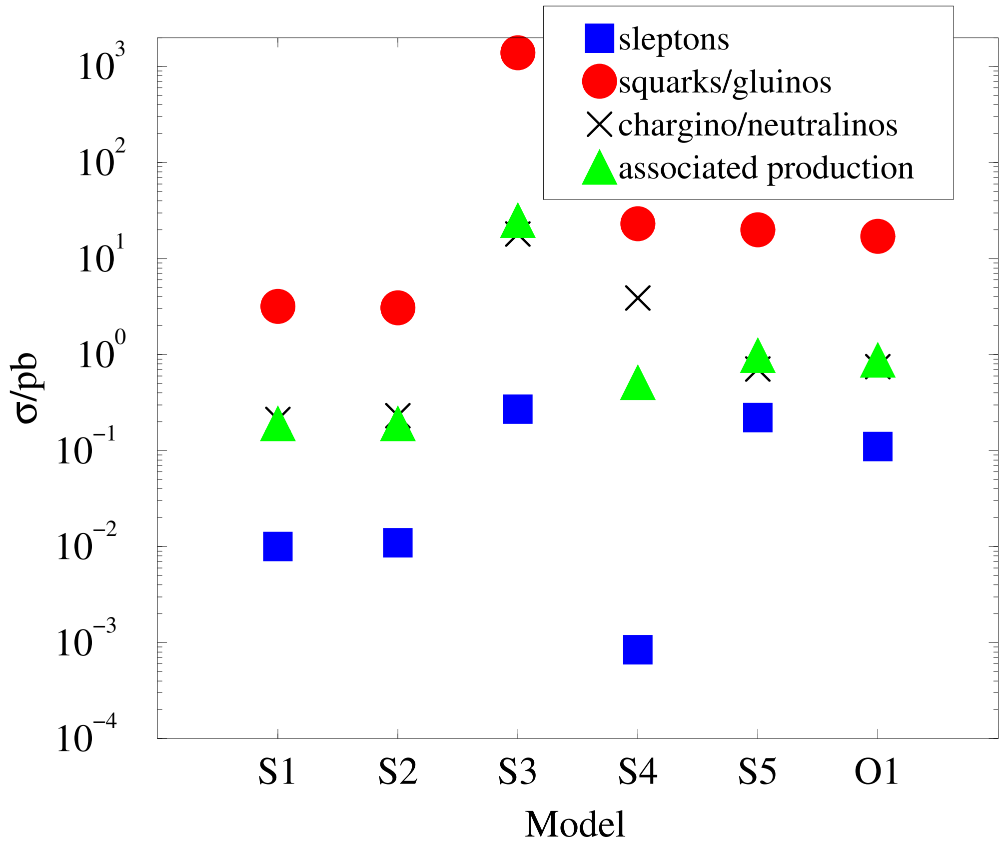
Distinguishing between SUSY models

Work by Cambridge ATLAS-HERWIG SUSY Group

B. Allanach, C. Lester, A. Parker and B. Webber, JHEP 0009:004,2000

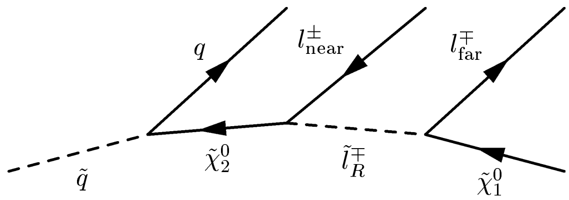
- String-motivated models suggest non-universal SUSY breaking masses.

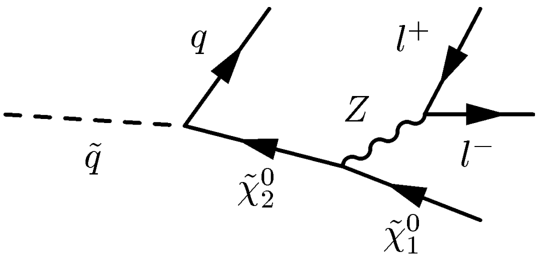
- the "Optimized" model of Casas, et. al. (O1 Model, hep-ph/9810266) is similar to mSUGRA model S5 but with heavier sleptons.



Distinguishing between SUSY models

- SUSY masses are obtained from kinematic edges due to decay chains





- Also used a new variable M_{T2} for finding processes like

$$pp \to \tilde{\ell}^+_R \tilde{\ell}^-_R, \qquad \tilde{\ell}^+_R \tilde{\ell}^-_R \to \ell^+ \tilde{\chi}^0_1 \ell^- \tilde{\chi}^0_1$$

C.G. Lester and D.J. Summers hep-ph/9906349

$$M^2_{T2}(\chi) = \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[\max \left\{ m^2_T(p^{l^+}_T, \not{p}_1, \chi), m^2_T(p^{l^-}_T, \not{p}_2, \chi) \right\} \right]$$

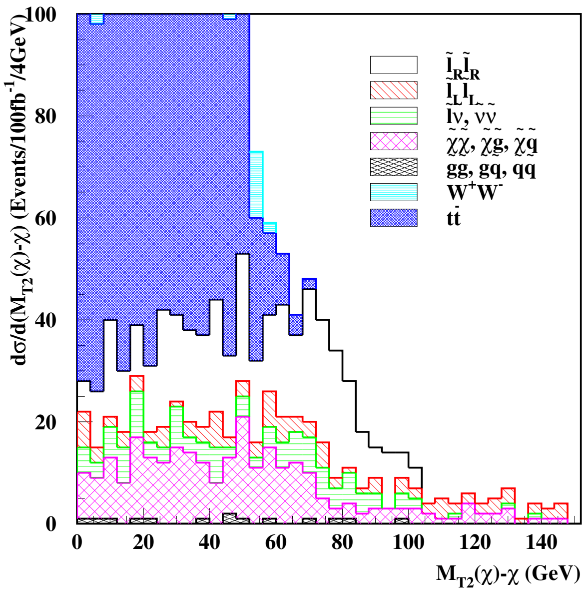
where

$$m^2_T(p^l_T, \not{p}, \chi) \equiv m^2_l + \chi^2 + 2\left(E^l_T E^\chi_T - p^l_T \cdot \not{p} \right)$$

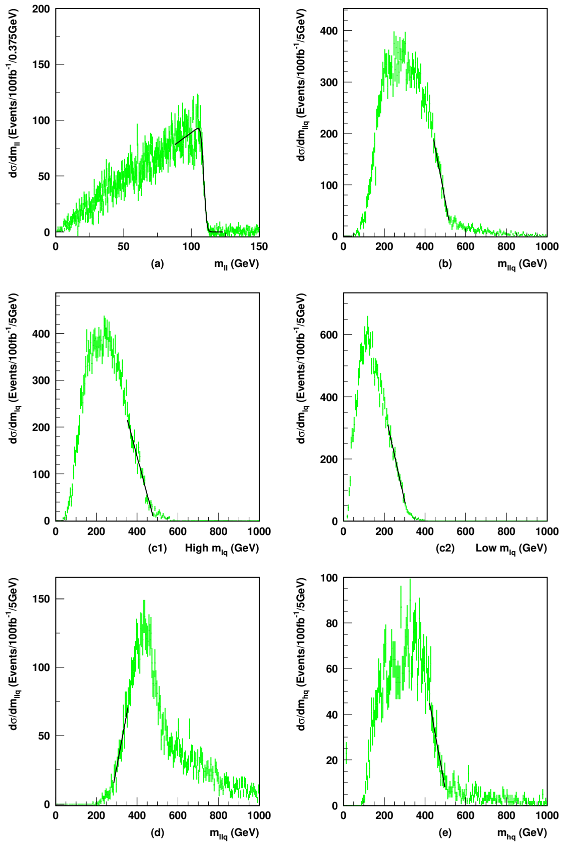
$$E^l_T = \sqrt{{p^l_T}^2 + m^2_l} \quad \text{and} \quad E^\chi_T = \sqrt{\not{p}^2 + \chi^2}$$

Distinguishing between SUSY models

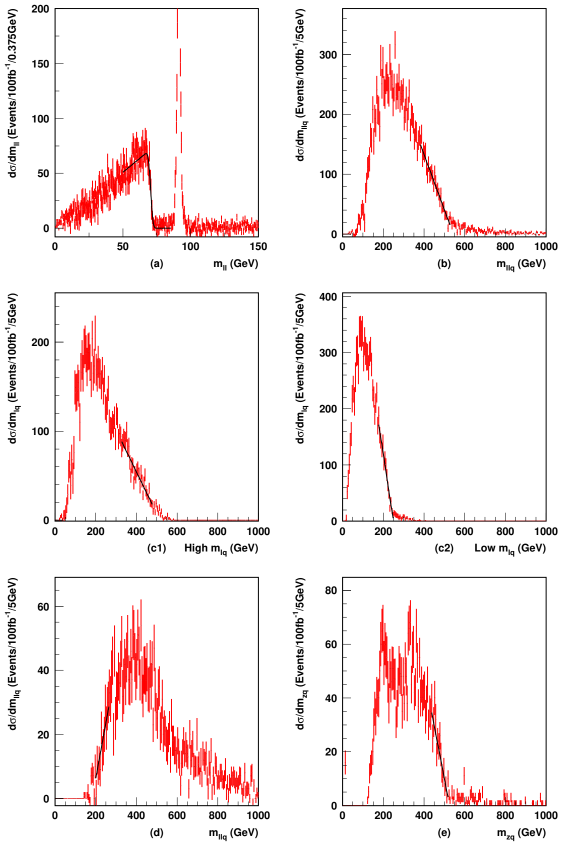
O1 Model



S5 Model



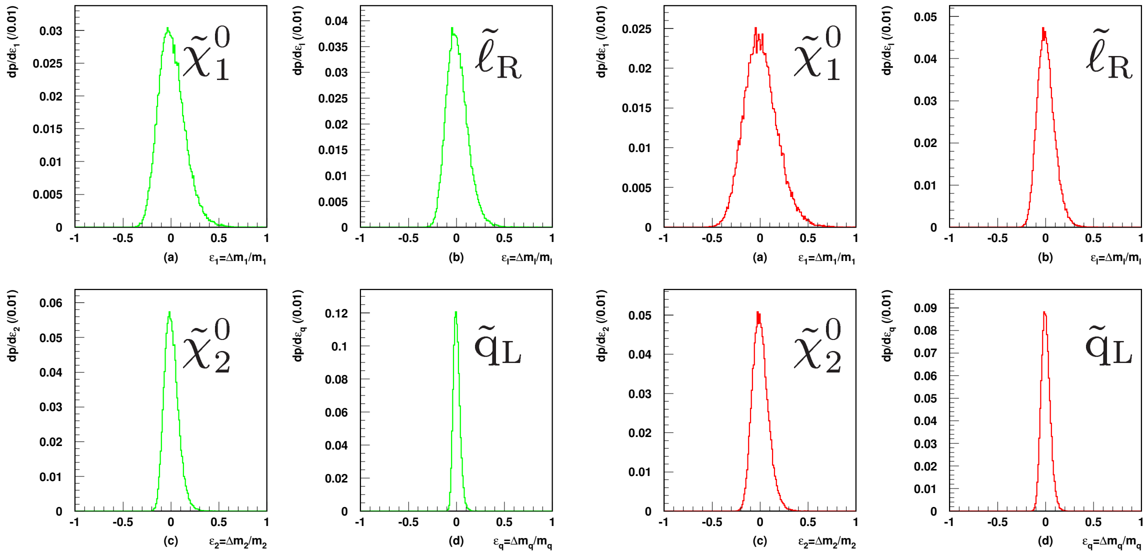
O1 Model



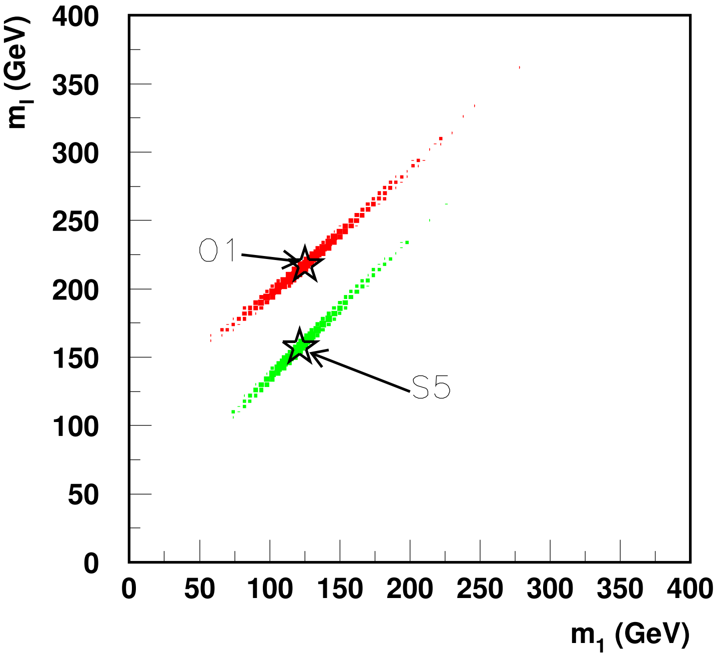
Distinguishing between SUSY models

- Masses are reconstructed by fitted edge positions

S5 Model O1 Model



- N.B. distributions 1 years running $\int \mathcal{L} = 100\text{fb}^{-1}$ at high luminosity



- Models are distinguished even though mass distributions are broad

Baryon Number Violating Neutralino Decays at LHC

Work by Cambridge ATLAS-HERWIG SUSY Group

B. Allanach, A. Barr, L. Drage, C. Lester, D. Morgan, A. Parker, P. Richardson and

B. Webber, JHEP 0103:048,2001

- This is the most experimentally challenging channel for the discovery of SUSY

- This analysis was performed at the SUGRA Point

$$M_0 = 100\ \text{GeV},\ M_{1/2} = 300\ \text{GeV},$$
$$A_0 = 300\ \text{GeV},\ \tan\beta = 10,\ \text{sgn}\,\mu\ +$$
$$\lambda''_{212} = 0.005$$

- 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

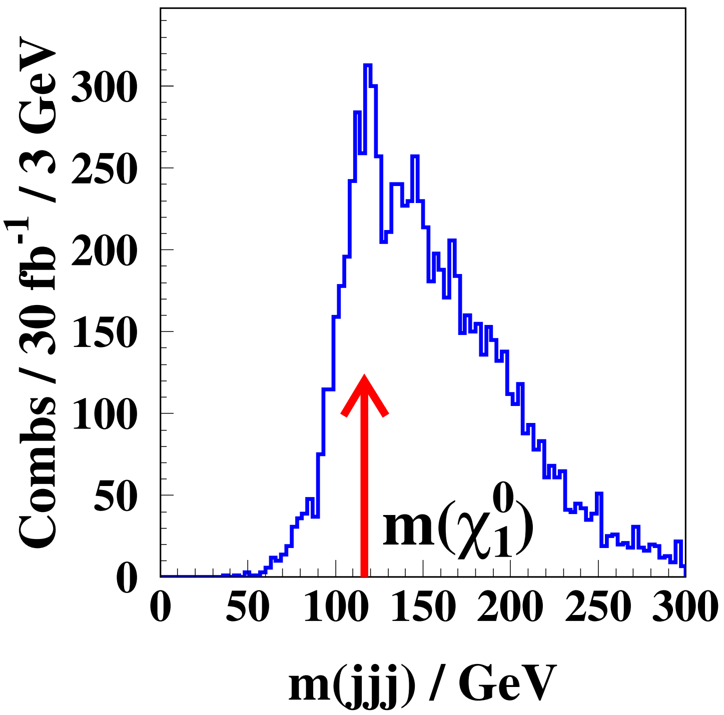
- As the coloured sparticles are predominantly produced the jet multiplicities are large

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

- When λ''_{212} is small two $\tilde{\chi}^0_1$s are produced.
- So search for two combinations of three jets with
- $\delta m_{jjj} = |m^a_{jjj} - m^b_{jjj}| < 20$ GeV where a and b are the neutralino candidates.
- Only consider $8 \leq N_{\rm jet} \leq 10$.
- 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
  - $E_T^{h1} > 200$ **GeV and** $E_T^{h2} > 100$ **GeV**
  - and only consider the other jets to reduce combinatorics

Results

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

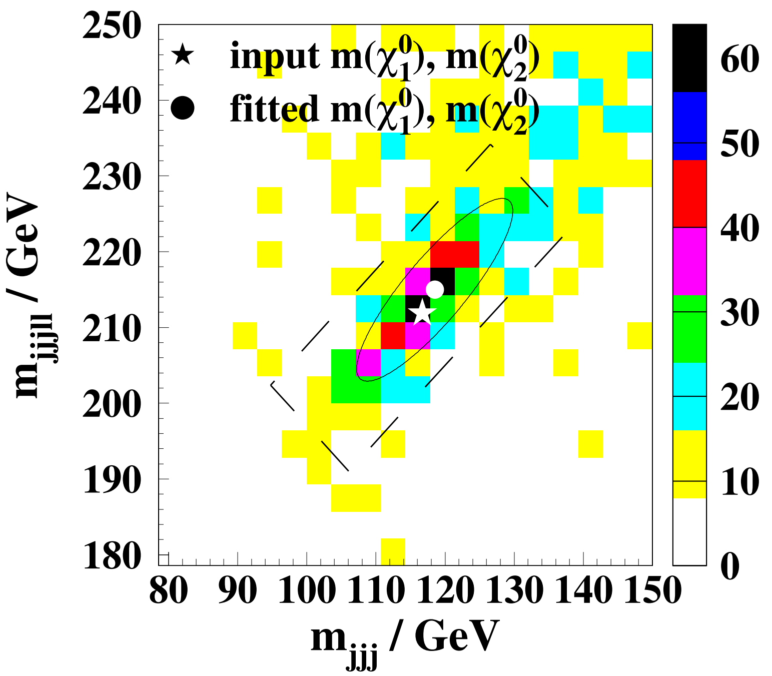


- There is a combinatoric background below the peak

- The shape of this background is defined by the cuts

Results

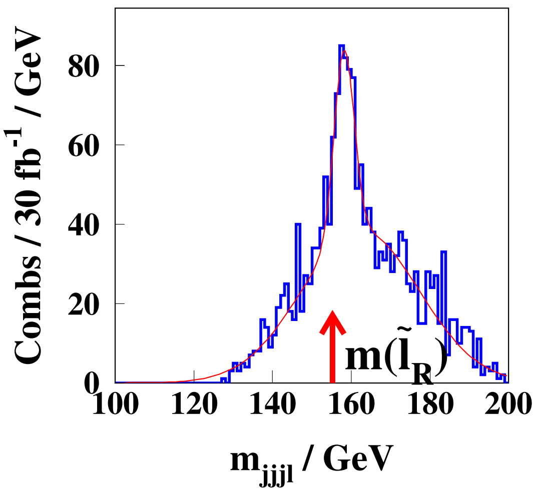
- The requirement that the events contain two leptons preferentially selects the decay chain $\tilde{q}_L \to \tilde{\chi}^0_2 q \to \tilde{l}_R l q \to \tilde{\chi}^0_1 l l q \to q q q l l q$
- Use these leptons to reconstruct the $\tilde{\chi}^0_2$ mass.



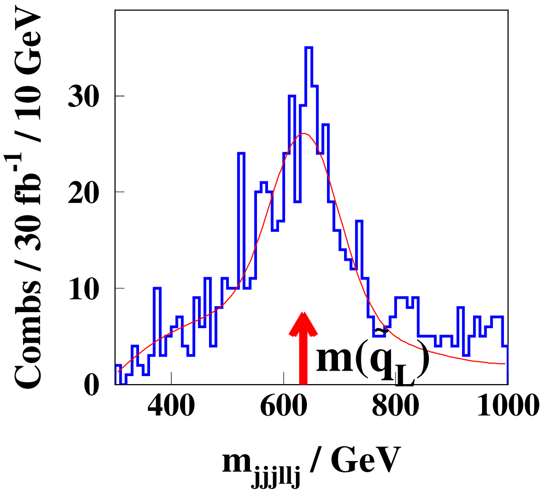
- We can then cut around the peak peak at the $\tilde{\chi}^0_1$,$\tilde{\chi}^0_2$ masses in the mass plane.

Results

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



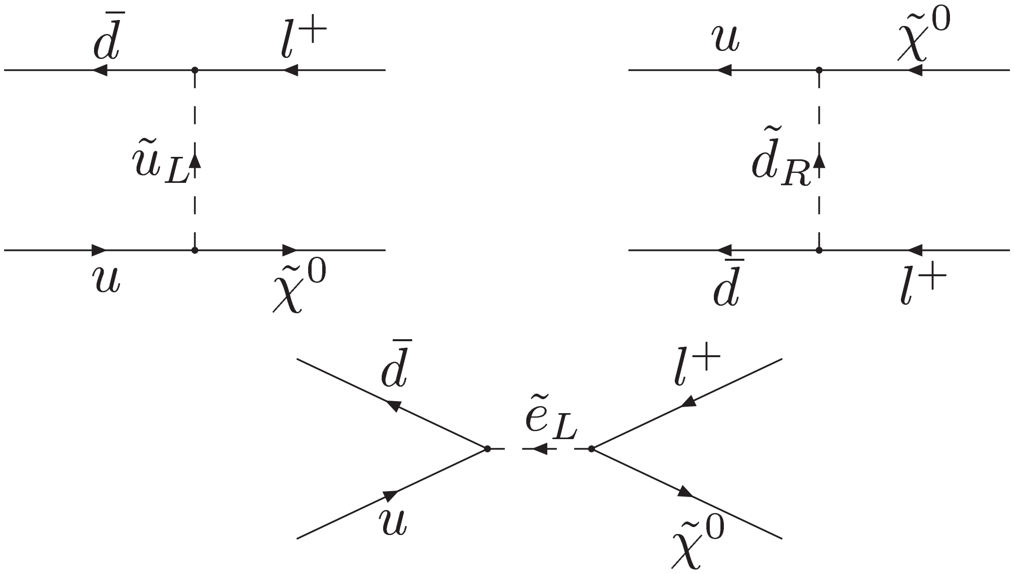
- and $\tilde{q}_L$ masses



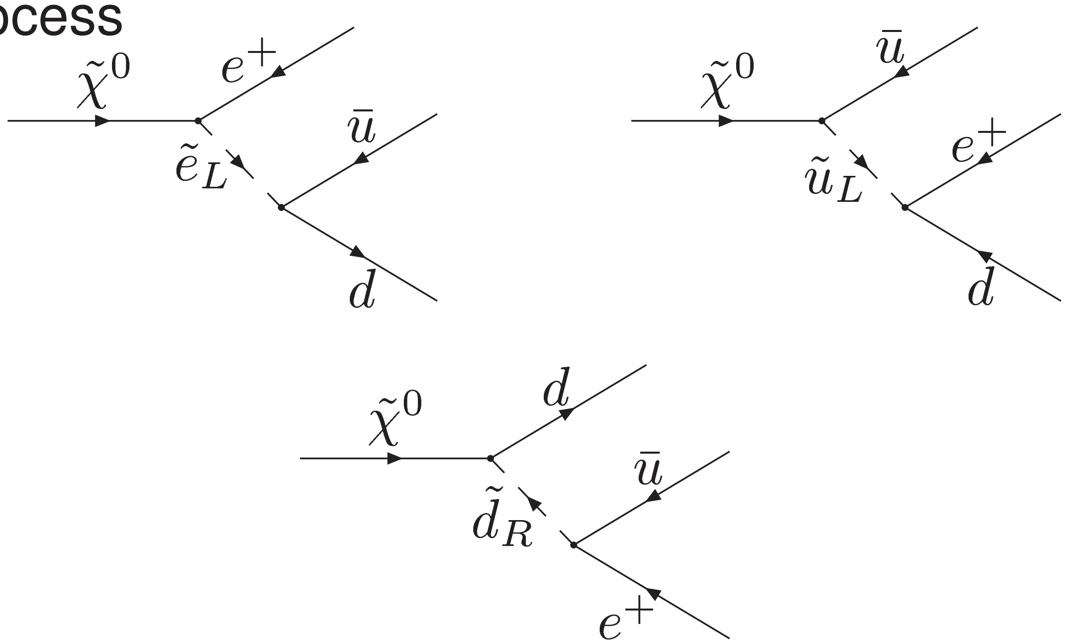
Resonant Slepton Production

H. Dreiner, P. Richardson and M. Seymour, Phys.Rev.D63:055008,2001

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



- The neutralino can then decay by the crossed process



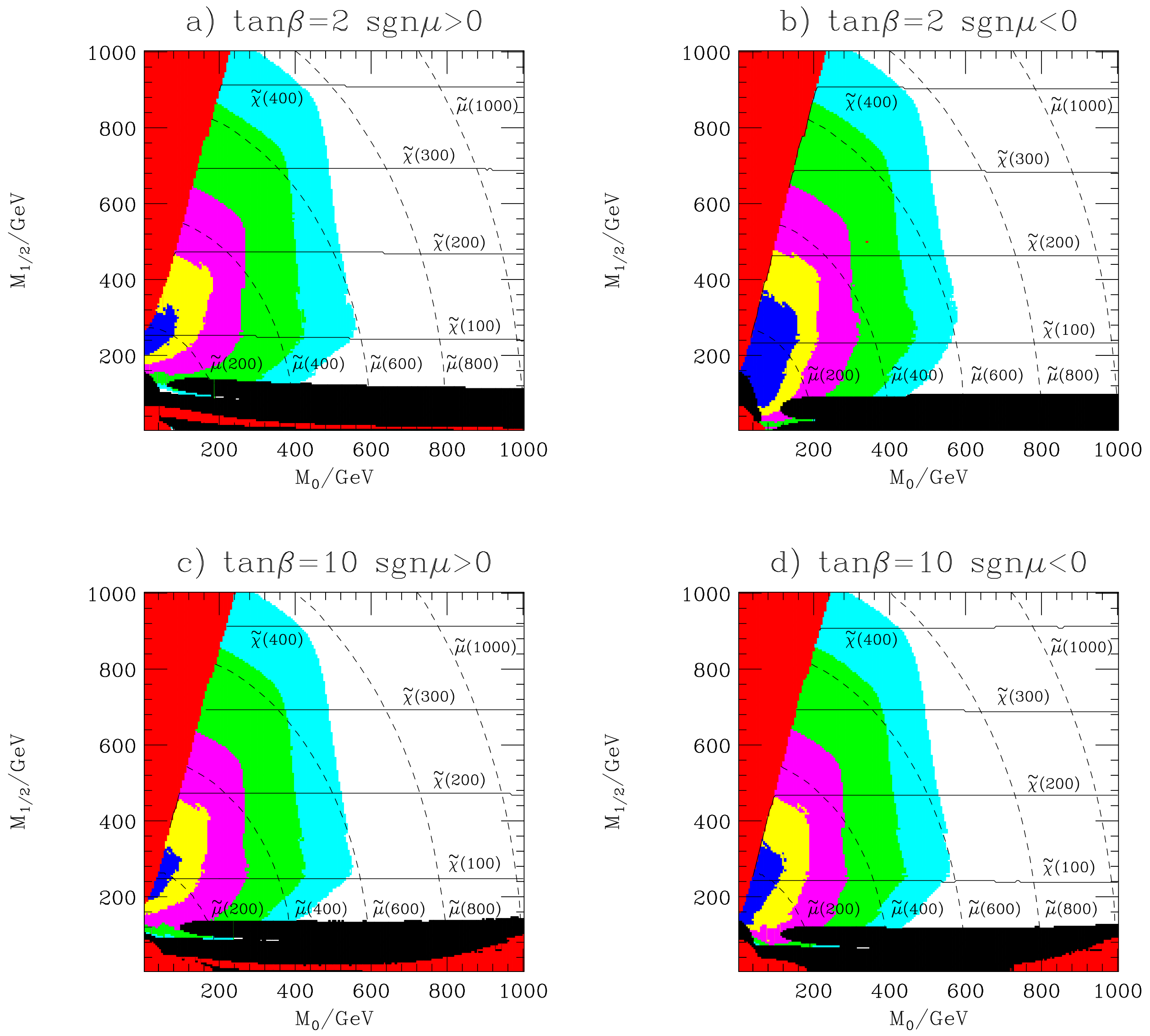
- This gives a signature of two **like-sign** leptons

- Other processes also contribute

Backgrounds

- Gauge Boson pair production
- $\mathrm{b\bar{b}}$ production
- $\mathrm{t\bar{t}}$ 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
- Impose the following cuts
  - $p_T^{\mathrm{lepton}} > 20$ GeV
  - An isolation cut on the $E_{\mathrm{cone}} < 5$ GeV
  - We cut the region $60\,\mathrm{GeV} < M_T < 85\,\mathrm{GeV}$
  - A veto on the presence of OSSF leptons with $p_T > 10$ GeV and pass the same isolation cut as the like-sign leptons.
  - $E^T_{miss} < 20$ GeV

Results for $\mathbf{2}\ \mathrm{fb}^{-1}$



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

Conclusions

- HERWIG includes a wide range of SUSY models (via an interface to ISAJET)
- All MSSM 2-to-2 production processes are included
- A wide range of MSSM Higgs processes are included
- All RPV resonance production processes are included
- RPV 2 and 3 body decays are included
- A number of SUSY studies have now been performed using HERWIG