SUSY in HERWIG

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HERWIG authors: G. Corcella, I. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P.Richardson, M. Seymour & B.R. Webber.

ATLAS-HERWIG: B. Allanach, A. Barr, L. Drage, J. Heatherington, C. Lester, D. Morgan & A. Parker.

Outline

- HERWIG 6.1
- Implementation of SUSY in HERWIG
- Hard Matrix Element Corrections
- Future Plans

HERWIG 6.1

- This is available from

  http://hepwww.rl.ac.uk/theory/seymour/herwig/

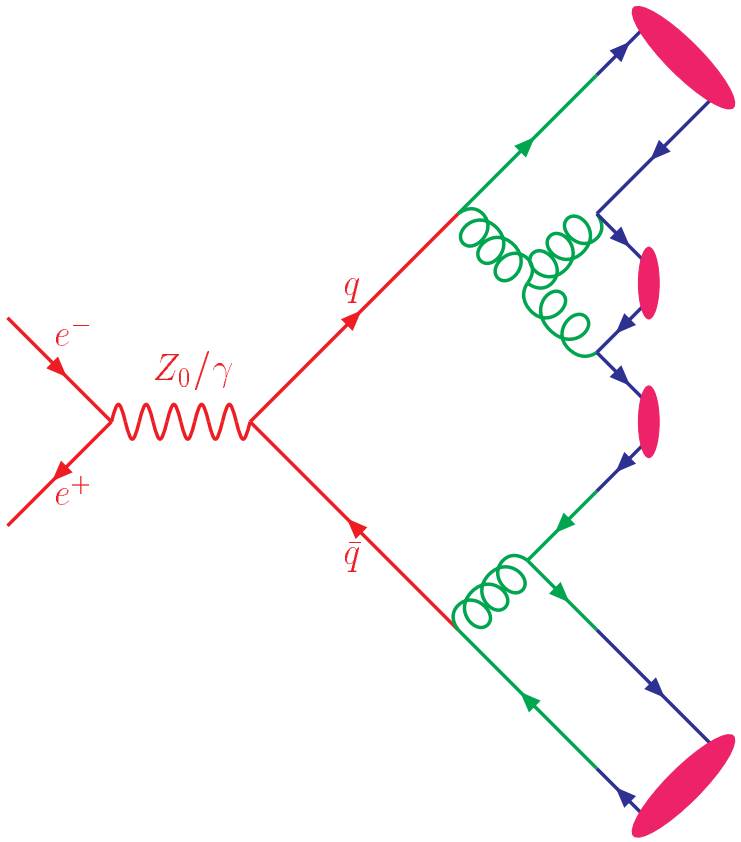
- It includes a number of new features
- SUSY

  - Interface to ISAJET for spectrum calculations, and MSSM decays.
  - Option of violating $\mathrm{R_p}$ and $\not{\mathrm{R}}_\mathrm{p}$ decays
  - All SUSY pair production processes in hadron collisions
  - Resonant $\not{\mathrm{R}}_\mathrm{p}$ processes in hadron collisions
  - A full treatment of colour coherence effects in all processes

- Also improvements to Standard Model Processes

  - Hard Matrix Element corrections in top decays and Drell-Yan

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)

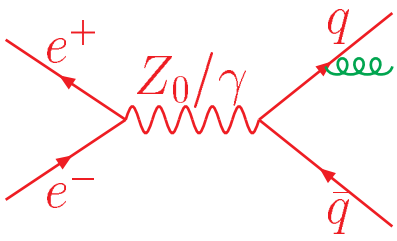
Angular Ordering

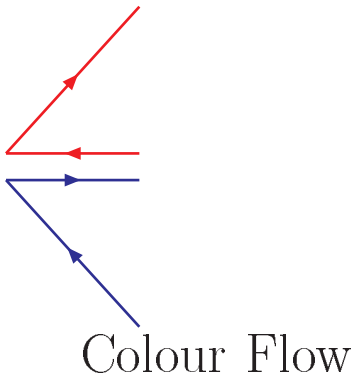
- **Two regions where the emission of QCD radiation is enhanced**

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

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

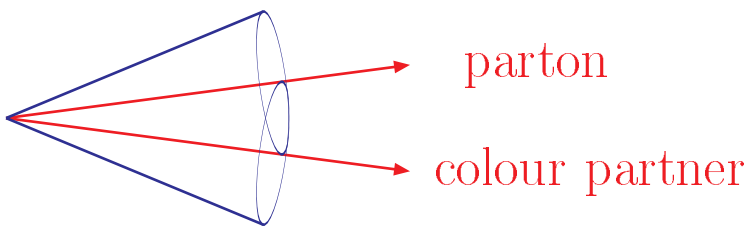
  e.g. $e^-e^+ \longrightarrow q\bar{q}g$ **with radiation of an extra gluon**



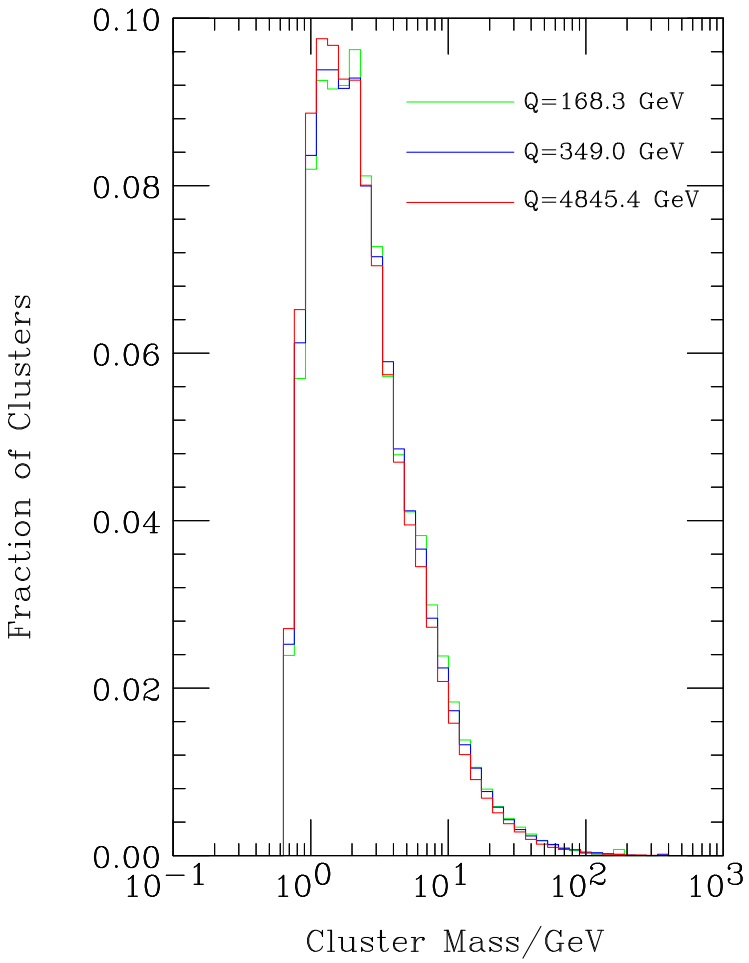


$$\mathcal{M}^{e^+e^-\to q\bar{q}gg}(p_q, p_{\bar{q}}, p_g, k) = g_s m^{e^+e^-\to q\bar{q}g}(p_q, p_{\bar{q}}, p_g)\mathbf{J}(k)$$

- **We then get that**
  - **q and the g are colour connected**
  - **$\bar{q}$ and the g are anticolour connected**
- **QCD radiation only occurs in a cone up to the direction of the colour partner (Marchesini & Webber)**



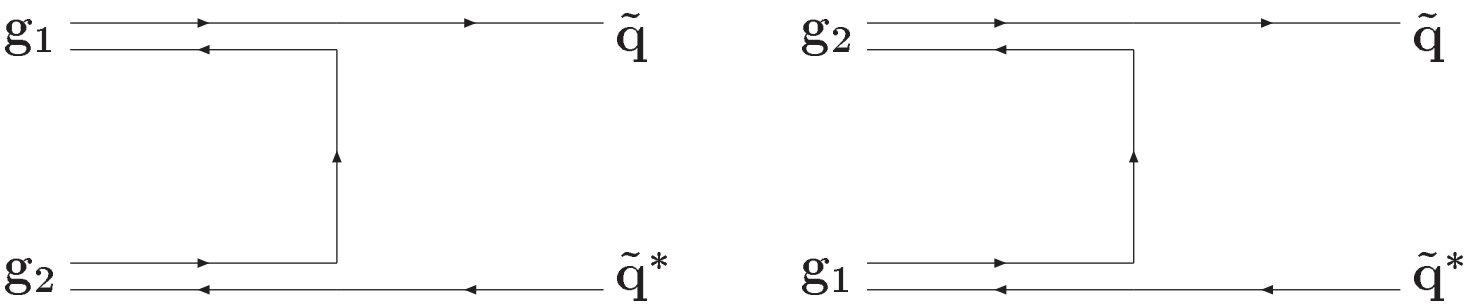
Cluster Hadronization Model



- 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.

MSSM Colour Flows

- Work by K. Odagiri, JHEP 9810:006, (1998).
- In MSSM processes the colour flows are not unique,
  e.g. $gg \to \tilde{q}\tilde{q}^*$, (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 $1/N_c$.

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

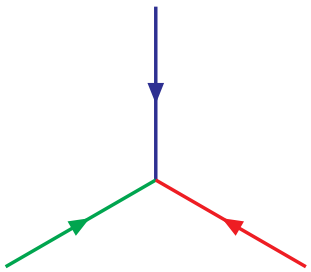
- Split the cross section by the ratio of the planar terms to obtain positive definite weights for different colour flows

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

- 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.

1. Neutralino Decay

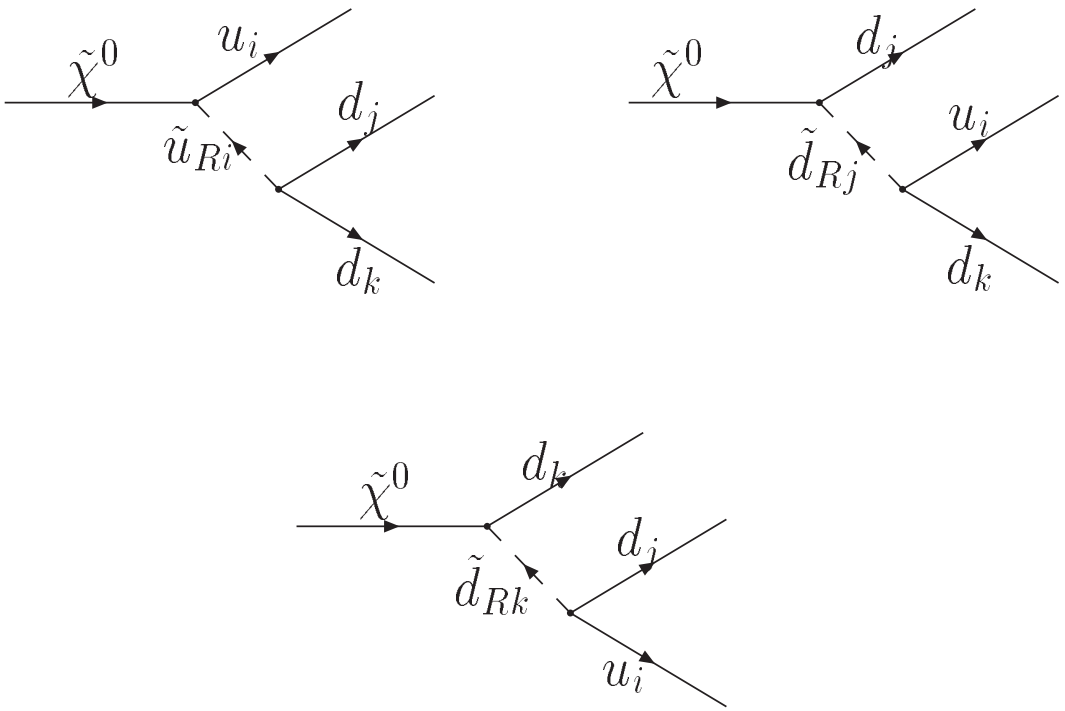


Figure 1: UDD decay of $\tilde{\chi}^0$.

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

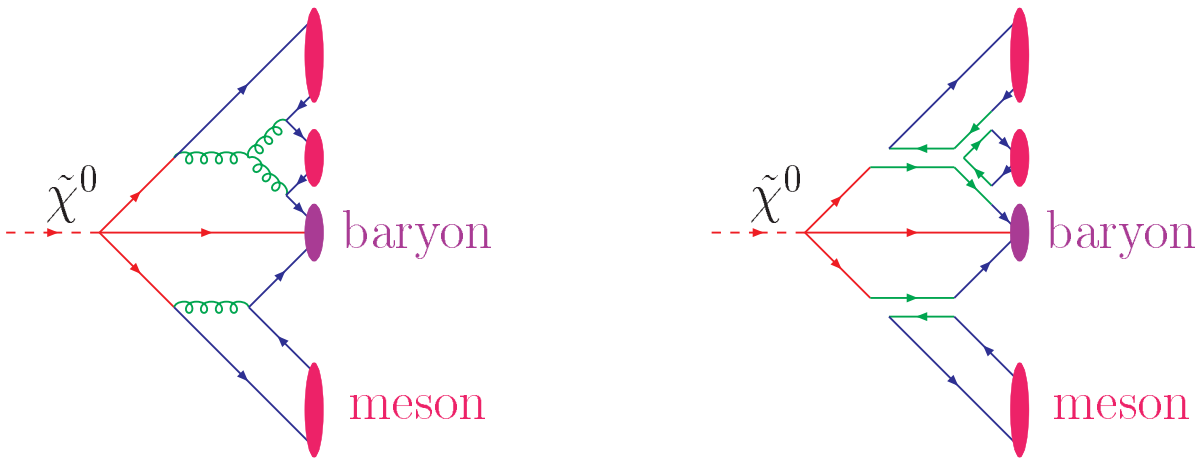


Figure 2: Hadronisation of a $\not{B}$Neutralino Decay

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

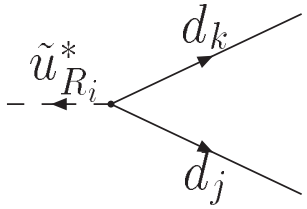


Figure 3: UDD decay of $\tilde{u}^*_R$.

- **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

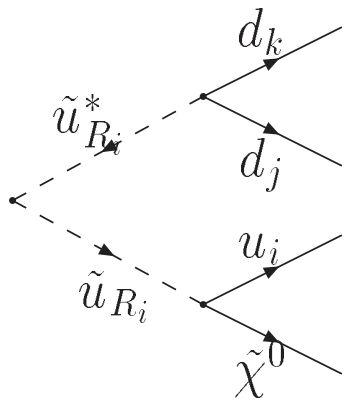


Figure 4: Hadronization with one $\not{B}$ decay.

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

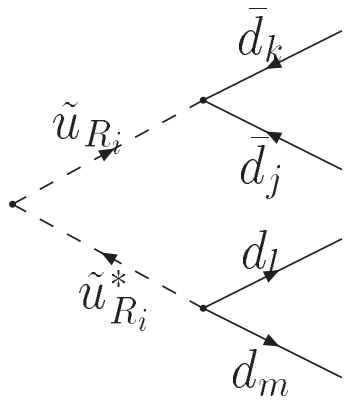
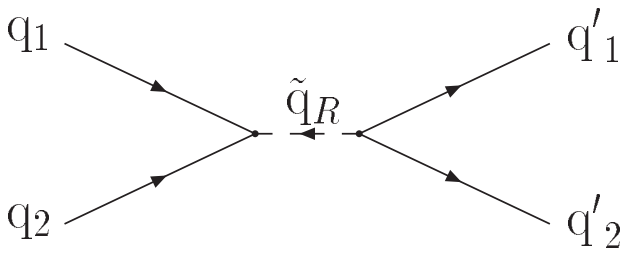


Figure 5: Hadronization with two $\not{B}$ decays.

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

Resonant Squark production

- Can have resonant production followed by $\not{R}_p$ 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.

Baryon Number Violating Neutralino Decays

Work by Cambridge ATLAS-HERWIG SUSY Working Group

in particular 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.

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

- λ''_{212} was chosen as it is only limited by perturbativity and is one of the harder signatures, *i.e.* no b tagging
- Each $\tilde{\chi}_1^0$ 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 10.5 jets after gluon radiation

  $\tilde{q}_L\tilde{q}_L$ gives 12.8 jets after gluon radiation

  $\tilde{g}\tilde{g}$ gives 13.6 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**

  $\delta m_{jjj} = |m^a_{jjj} - m^b_{jjj}| < 20$ **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 &** $|\eta| < 2$.
- **the following cuts on the jet momenta(all in GeV) were also used**

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

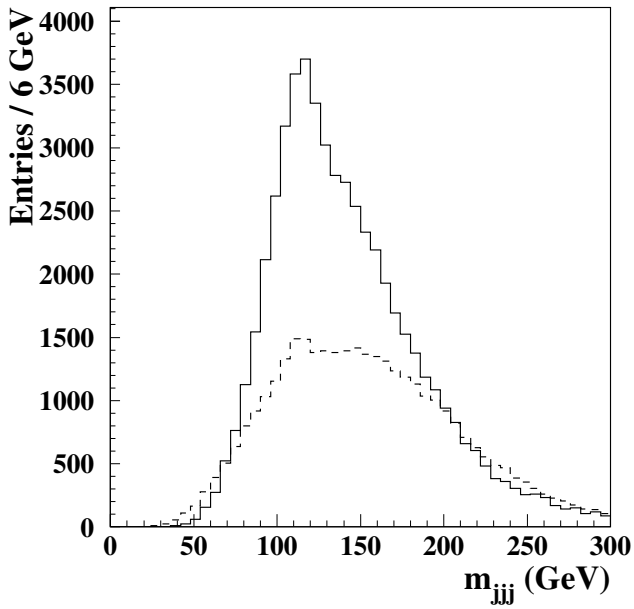
  2. $17.5 < p_T^{b1} < 300$; $17.5 < p_T^{a2} < 150$; $15.0 < p_T^{a3} < 75$
- **Since the cross section is dominated by squark and gluino production** $\approx 75\%$ **of the events contain hard jets from squark decays. Require**

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

  and only consider the other jets to reduce combinatorics

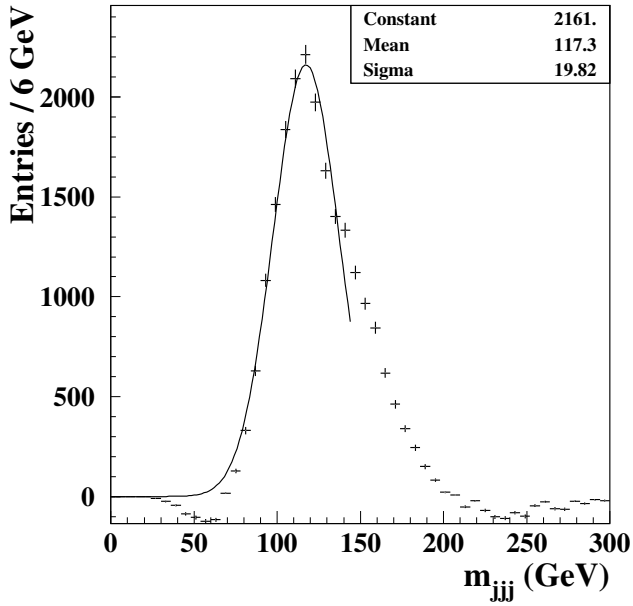
Results

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



(a)

- The combinatorial background can be subtracted

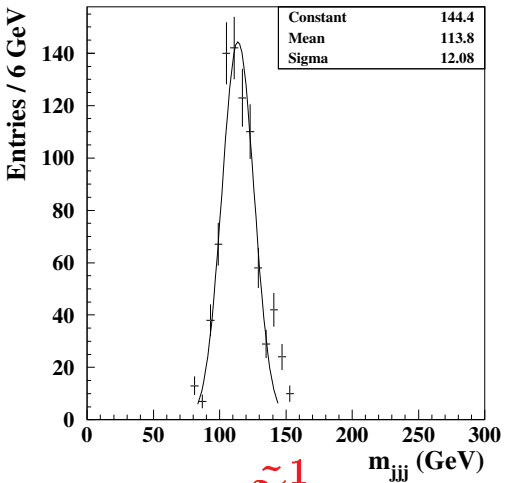


(b)

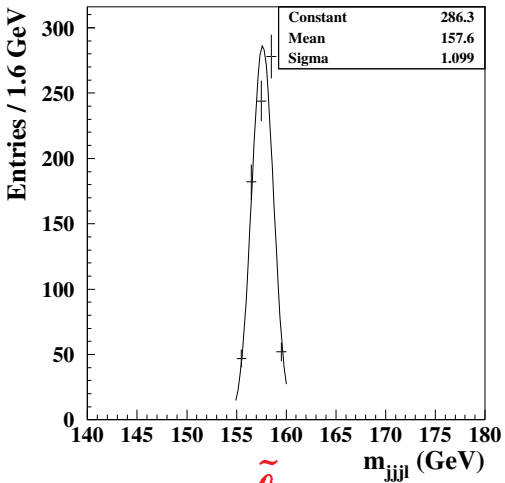
- The distribution had mean 119.2 GeV and width 19.7 GeV
- This is slightly lower than the generated mass of 121.5 GeV

Results

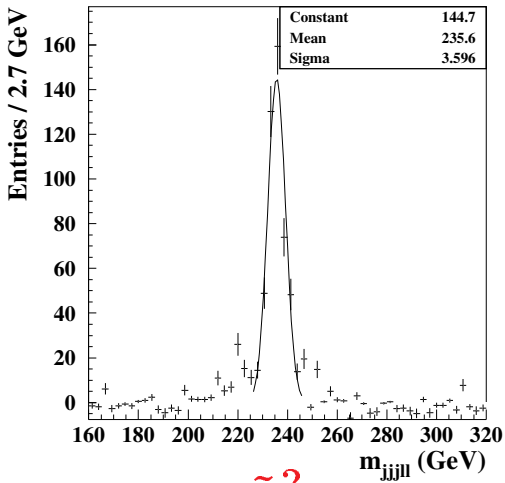
- Can also reconstruct the $\tilde{\ell}_R$ and $\tilde{\chi}_2^0$ masses using the leptons



$\tilde{\chi}_0^1$



$\tilde{\ell}_R$



$\tilde{\chi}_0^2$

- Gives the following results

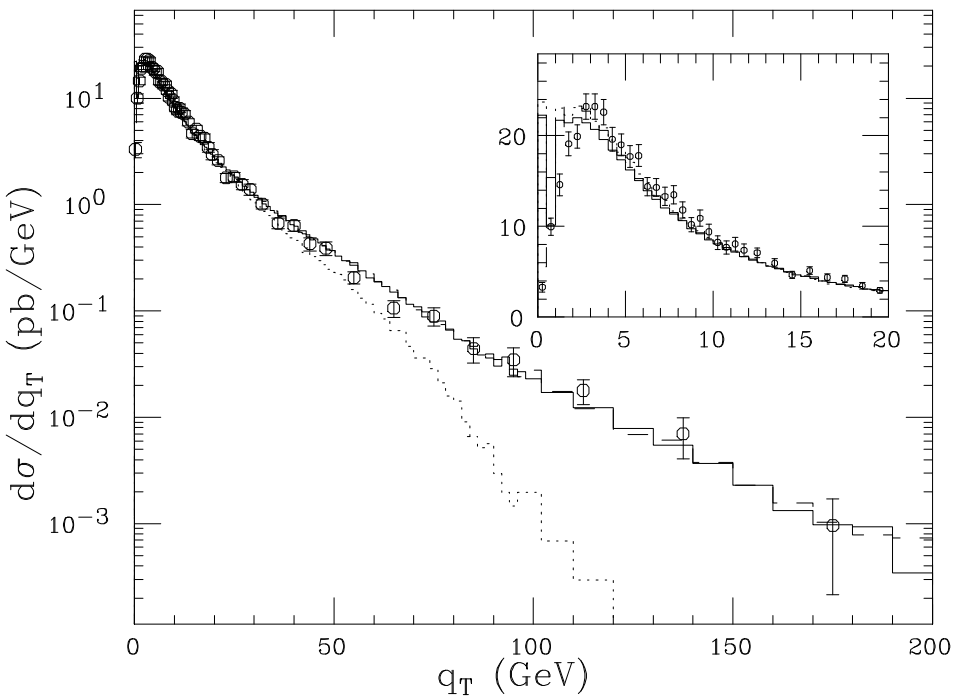
Sparticle	True Mass/GeV	Measured Mass/GeV
$\tilde{\chi}_1^0$	**121.5**	$124.8 \pm 0.6(\text{stat}) \pm 5.0(\text{had})$
$\tilde{\ell}_R$	**157.2**	$157.6 \pm 0.02(\text{stat}) \pm 5.0(\text{had}) \pm 0.1(\text{EM})$
$\tilde{\chi}_2^0$	**233.0**	$235.6 \pm 0.2(\text{stat}) \pm 5.0(\text{had}) \pm 0.1(\text{EM})$

Matrix Element corrections

- Work by G. Corcella and M. Seymour
- The parton shower algorithm correctly describes soft and collinear emission
- But can have hard emissions which are not described
- Add a matrix element correction
- This correction is process dependent
- $e^+e^- \to q\bar{q}$ and DIS already included
- Now also includes

  Top Decay Phys. Lett. B442:417, (1998)

  Drell-Yan Nucl. Phys. B565:227, (2000)



Comparison of Z p_T distribution from CDF with HERWIG without (dotted) and with (dashed and solid) M.E. corrections

Future Plans

- In the long term HERWIG will be replaced by a new improved generator written in C++
  - We have funding for 2 postdocs for 3 years to do this.
  - We plan to include a lot of improvements to the physics at the same time and make full use of object-oriented programming
  - *i.e.* not a straight rewrite of the code
  - If you have anything you want included the sooner you let us know the more likely it is.

- In the short term we will continue to maintain and improve the current FORTRAN version
  - The next version 6.2 will include SUSY Higgs production in hadron collisions, as well as additional SM Higgs production processes
- We also hope to include the following (eventually)
  - e^+e^- and ep SUSY production processes
  - Extra Dimensions
  - An independent mass spectrum and decay generator (in C++ ?)

Higgs Production Processes

- HERWIG currently only includes SM Higgs production via gluon/W/Z fusion
- A wide range of additional Higgs processes will be available in 6.2
- SM Higgs processes
  1. SM Higgs + heavy quark pairs
  2. SM Higgs + W/Z
- Neutral SUSY Higgs processes
  1. gluon fusion via heavy (s) quark loops
  2. W^*W^* & Z^*Z^* fusion
  3. associated production with W/Z
  4. associated production with squark pairs
- Charged SUSY Higgs processes
  1. Drell Yan Production ($q\bar{q} \to H^+H^-$)
  2. bg fusion ($bg \to tH^-$ & $gg \to t\bar{b}H^-$)
  3. bW^* fusion ($bg \to bq'H^\pm$)
  4. associated production with W
  5. associated production with heavy quark or squark pairs
- Also production of $H^\pm h$, $H^\pm H$, $H^\pm A$

Conclusions

- The implementation of SUSY processes is complete and this is now available.
- This includes both R_p conserving and violating production processes and decays
- This includes a full treatment of the colour structure of the SUSY processes
- HERWIG has now been used in number of phenomenological studies