Hadron Emission Reactions With Interfering Gluons

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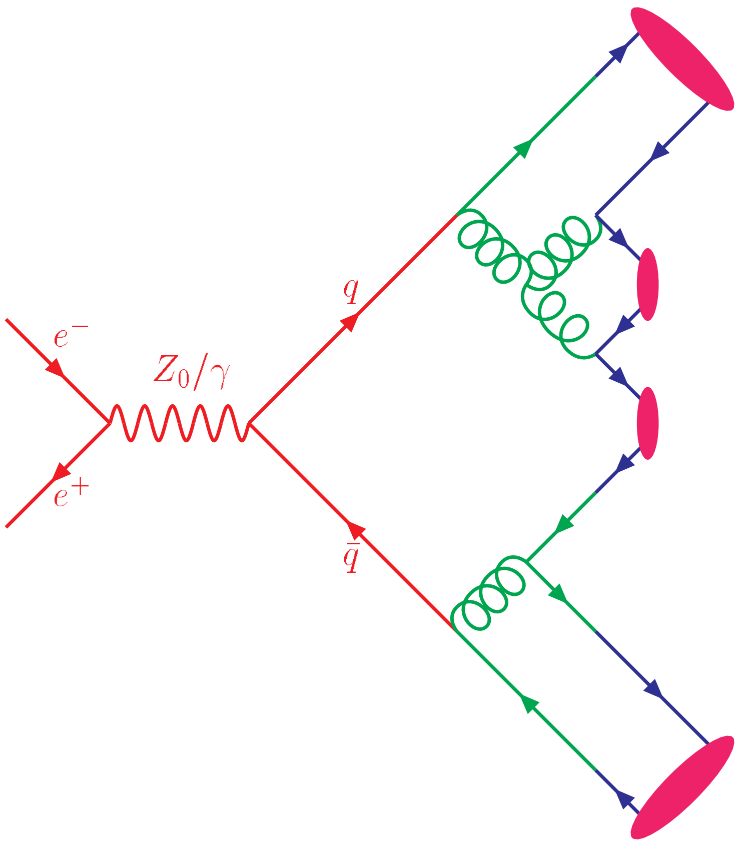
HERWIG authors: G. Corcella, I. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P.Richardson, M. Seymour & B.R. Webber.

Outline

- Basics of Monte Carlo event generation
- Collinear Parton Showers
- Angular Ordering
- Hadronization
- HERWIG
- Future Plans

Basic Idea of an event generator

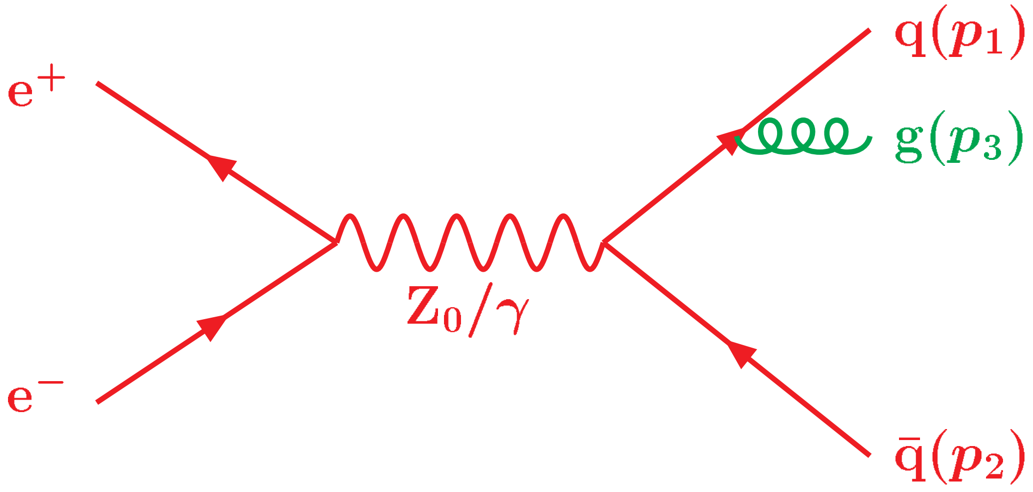


- There are three phases

 1. Hard Process
 2. Parton Shower
 3. Hadronization Model

QCD radiation

- It is impossible to calculate the matrix elements for processes involving large numbers of partons
- Instead we treat the regions where the emission of QCD radiation is enhanced
- Consider $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q}\bar{\mathrm{q}}\mathrm{g}$

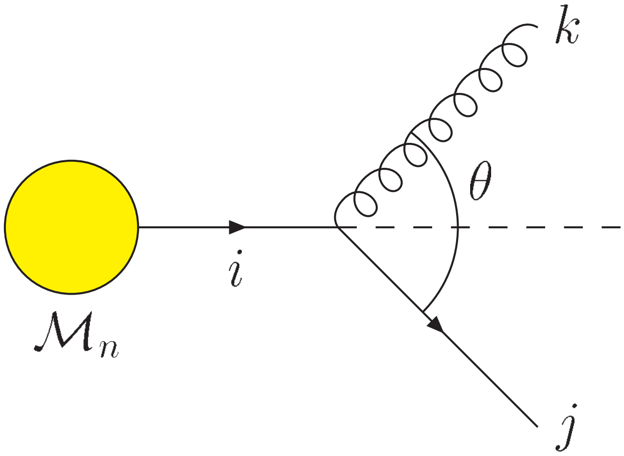


- The cross section is given by

$$\frac{d\sigma_{q\bar{q}g}}{dx_1 dx_2} = N_c \sigma_0 Q_q^2 C_F \frac{\alpha_s}{2\pi} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

- This diverges as $x_{1,2} \to 1$ where $x_i = 2E_i/\sqrt{s}$
- Physically this happens when
  1. The gluon and one of the quarks are collinear
     $(1-x_1) = \frac{E_2 E_3}{Q^2}(1-\cos\theta_{2g})$
     Collinear singularity
  2. The energy of the gluon goes to zero
     $x_1 + x_2 + x_3 = 2,\ x_1, x_2 \to 1 \Rightarrow x_3 \to 0$
     Soft Singularity

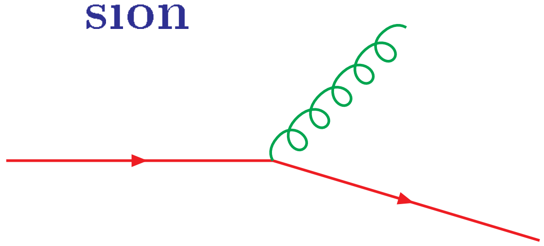
Collinear Singularities



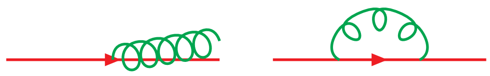
- In the collinear limit the cross section for a process factorizes

$$d\sigma_{n+1} = d\sigma_n \frac{d\theta^2}{\theta^2} dz \frac{\alpha_s}{2\pi} P_{ji}(z)$$

- P_{ji} is the DGLAP splitting function
- This is singular as $\theta \to 0$
- What is a parton? (difference between collinear pair and a parton)
- Introduce resolution criterion *e.g.* $k_T > Q_0$
- Combine virtual corrections & unresolvable emission



Resolvable Emmission
Finite



Unresolvable Emmission
Finite

- Unitary: Unresolved + Resolved = 1

Monte Carlo procedure

- Probability of Emission between q^2+dq^2 and q^2

$$d\mathcal{P} = \frac{\alpha_s}{2\pi}\frac{dq^2}{q^2}\int_{Q_0^2/q^2}^{1-Q_0^2/q^2} dz P(z) \equiv \frac{dq^2}{q^2}\bar{P}(q^2)$$

- Define probability of no emission between Q^2 and q^2 $\Delta(Q^2, q^2)$

$$\frac{d\Delta(Q^2, q^2)}{dq^2} = \Delta(Q^2, q^2)\frac{d\mathcal{P}}{dq^2}$$

$$\Rightarrow \Delta(Q^2, q^2) = \exp\left[-\int_{q^2}^{Q^2}\frac{dk^2}{k^2}\bar{P}(k^2)\right]$$

- $\Delta(Q^2, Q_0^2) \equiv \Delta(Q^2)$ The Sudakov Form Factor probability of emitting no resolvable radiation
- We can implement this in the following way

  Generate a random number $0 < \rho < 1$

  If $\rho < \Delta(Q^2)$ no resolvable emission

  Otherwise solve

$$\rho = \Delta(Q^2, q^2)$$

  to give the emission scale q^2

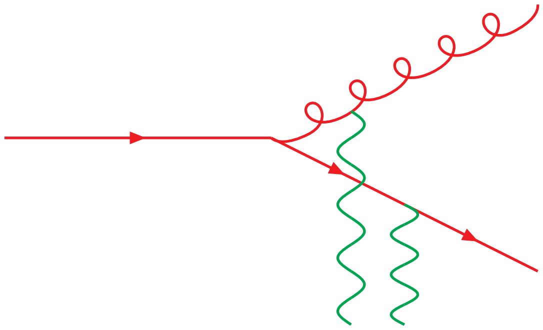
- A number of formally free choices

  Evolution scale: $q^2/k_\perp/\theta$

  z: Energy, light-cone momentum

Soft Emission

- Two regions where the emission of QCD radiation is enhanced
- The soft limit also factorizes but at the amplitude Level

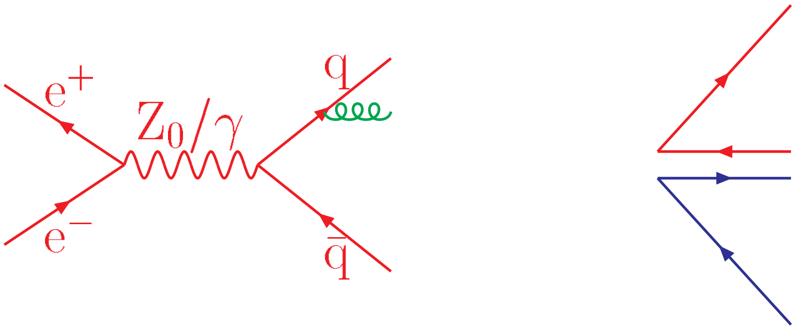


- Soft gluon come from everywhere in the event
- There is quantum interference between these gluons
- Does this spoil the parton shower picture?

Angular Ordering

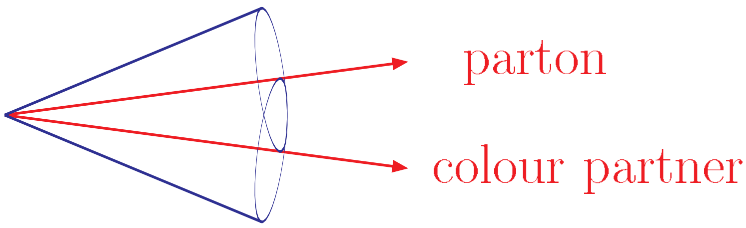
- Consider the soft emission using the eikonal current

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



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

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



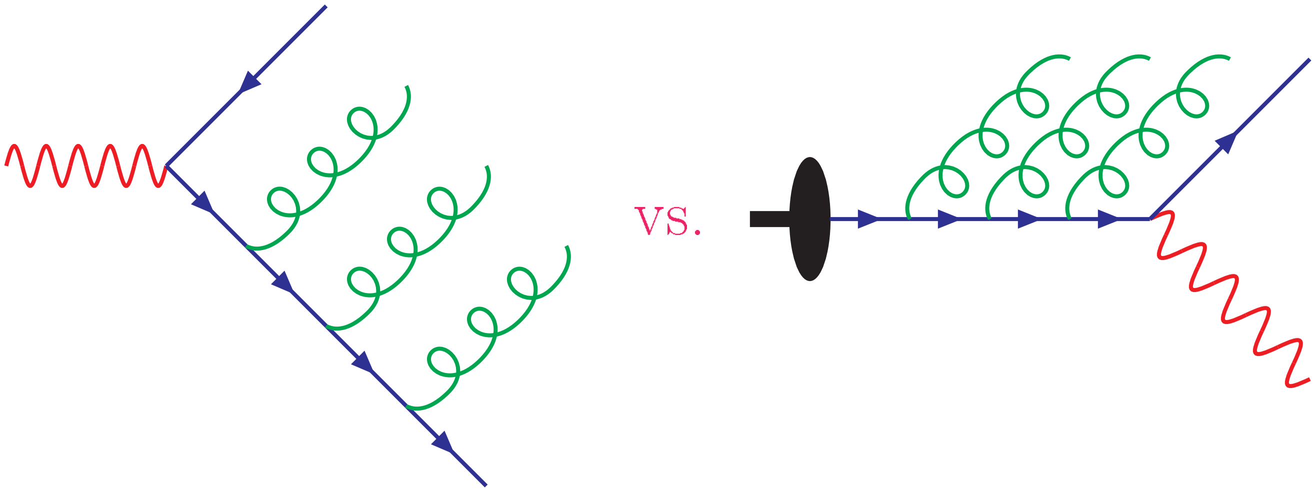
- Soft gluon effects fully incorporated by using θ as evolution variable: Angular Ordering
- Choice of evolution variable constrained

Initial-State Radiation

- So far only considered final-state radiation in *e.g.* $e^+e^- \to q\bar{q}$
- In hadron collision must also include initial-state radiation from the incoming partons
- Problem is both ends of the evolution are fixed

  At a high scale by the parton-parton collision

  and a low scale by the PDFs



- Use a modification of the final-state algorithm: Backward Evolution
- Start with the hard collision and evolve down in q^2 and up in x towards the incoming hadron
- replace $\Delta(Q^2, q^2)$ with $\Delta(Q^2, q^2)/f(x, q)$

Parton Showers

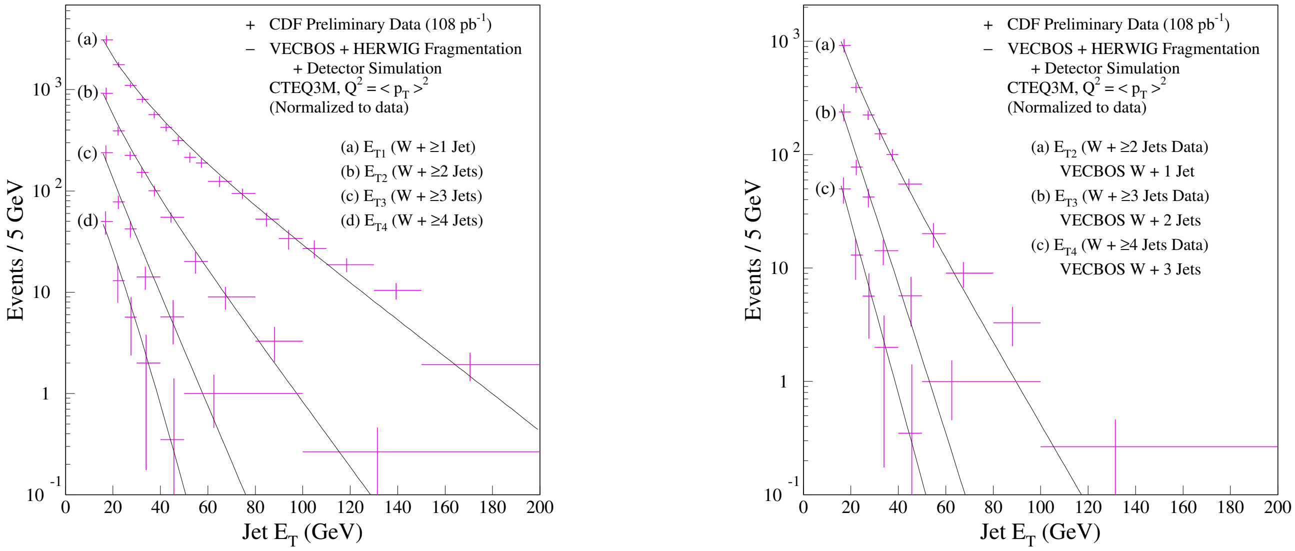
- Emission of QCD radiation is enhanced for soft & collinear emission
- Both can be included by using angles as the evolution variable
- Only HERWIG fully includes these effects
- ISAJET only treats the collinear limit
- PYTHIA includes the soft effects using a veto on non-angular ordered final states
- In these limits the parton shower gives an accurate simulation of the QCD radiation
- Has proved to give a reasonable results outside this regime, but must be careful
- NO event generator will reliably predict distributions for large numbers of hard, wide angle jets
- The effects of Angular Ordering have been observed in Tevatron data

Comparisons of Matrix Elements and the Parton Shower

- **For some processes the calculation of many parton final states has been performed**

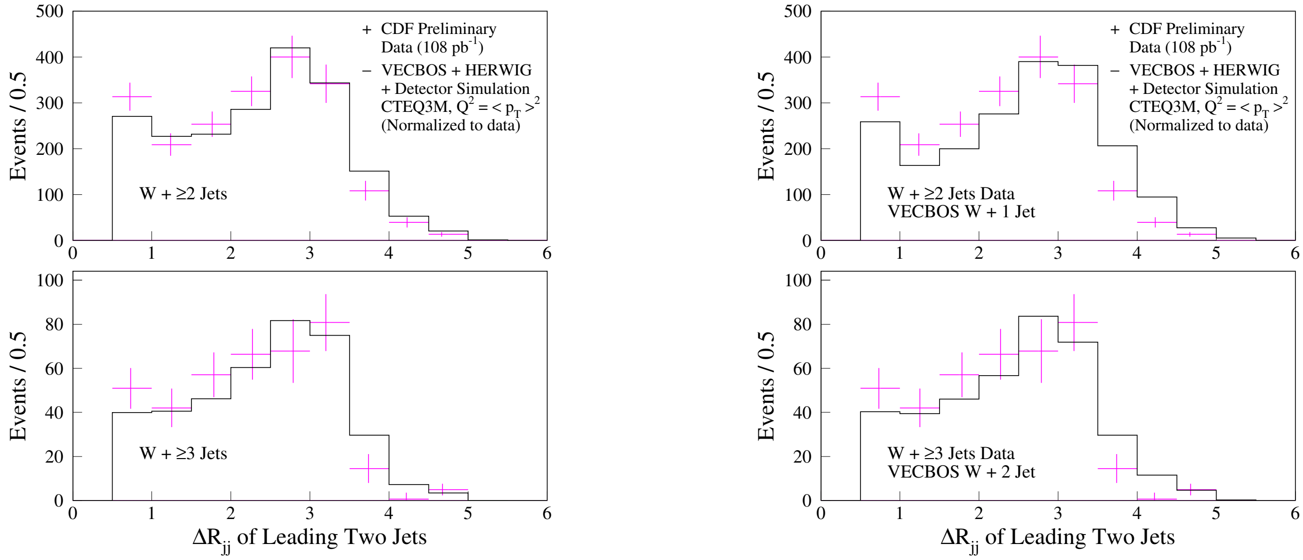
  e.g. **W+n jets**

- **Can compare the results of the matrix element and the parton shower**
- **CDF Phys.Rev.Lett.79:4760-4765,1997**
- **Simulated W+n jet events with VECBOS**
- **Then used HERWIG to either**
  1. **Generate the internal jet structure + hadronization**
  2. **Generate an extra jet as well**
- **HERWIG gives surprisingly good agreement with the matrix element calculation and the data**



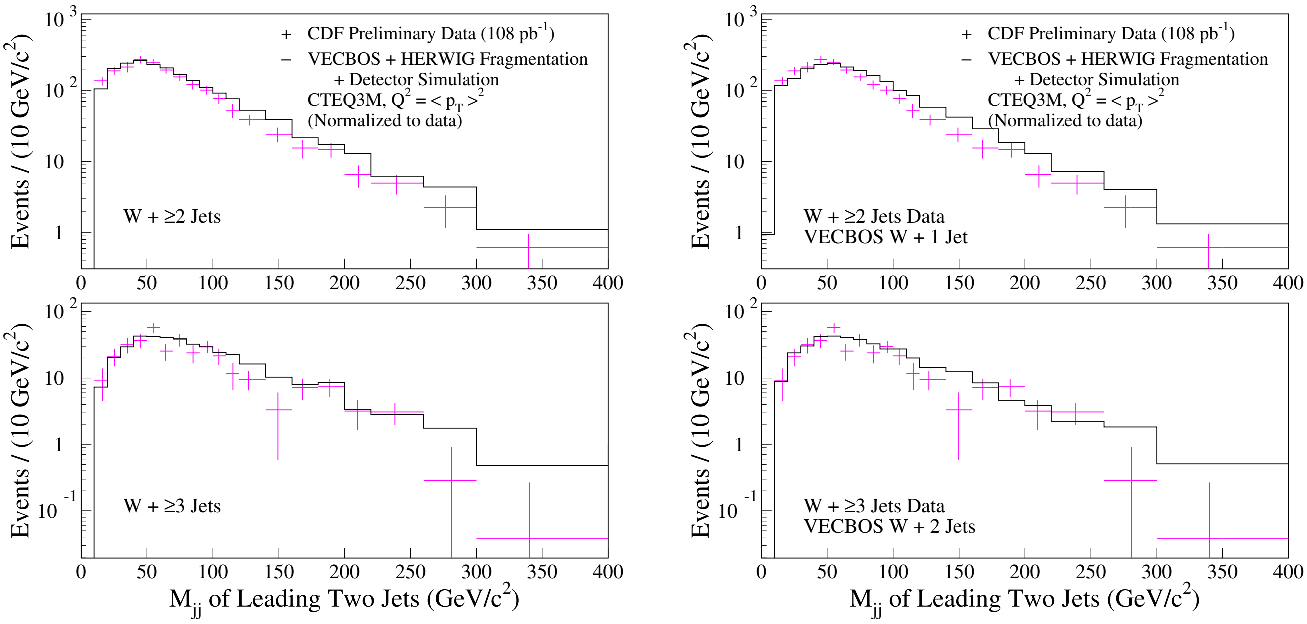
(a) **VECBOS** (b) **HERWIG**

Figure 1: ***E_t* of the lowest *E_t* jet**



(a) **VECBOS** (b) **HERWIG**

Figure 2: **Distance in (η, ϕ) between leading jets**



(a) **VECBOS** (b) **HERWIG**

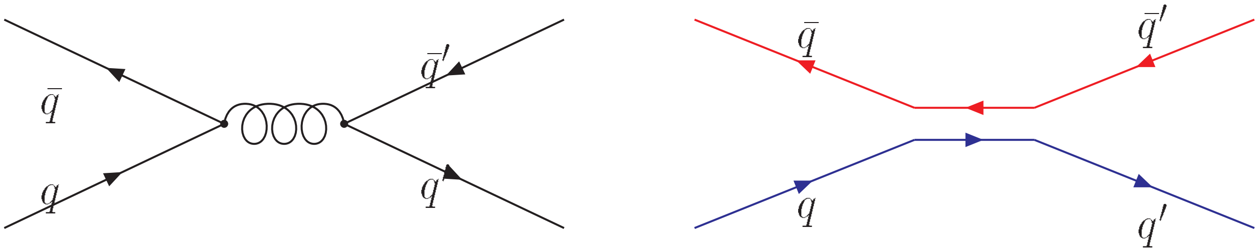
Figure 3: **Invariant Mass of leading jets**

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

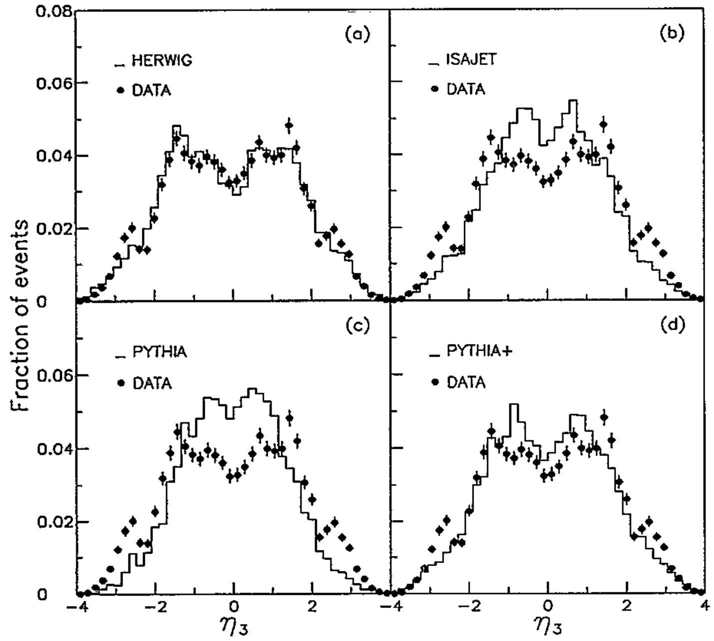


FIG. 13. Observed η_3 distribution compared to the predic-ions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

• α Distributions

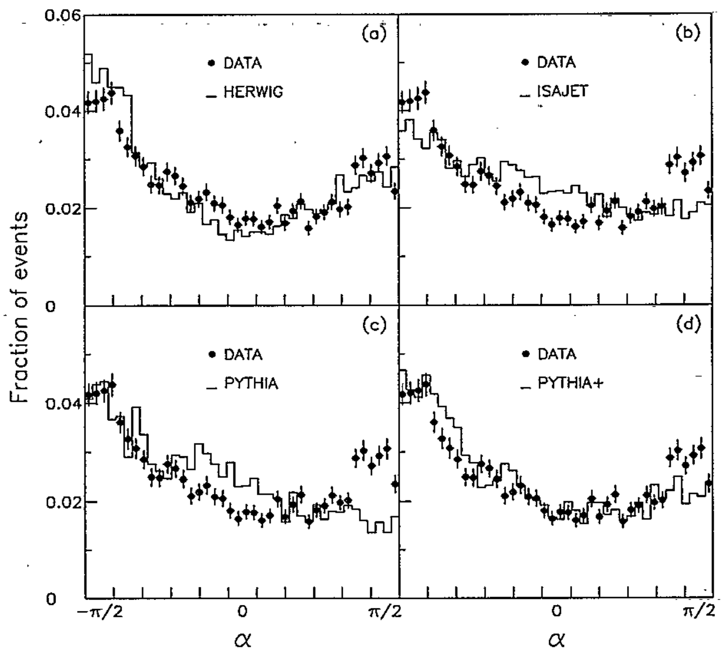


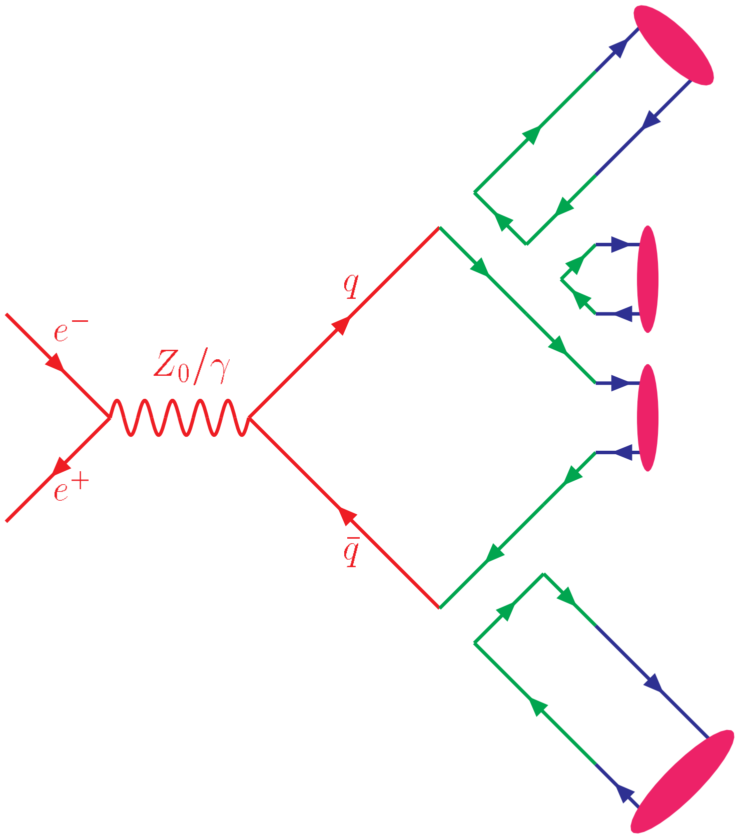
FIG. 15. Observed α distribution compared to the predic-ions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

Hadronization

- Experiments detect hadrons not quarks and gluons
- How do we go from the quarks and gluons to the hadrons?
- Can't calculate must use a model with free parameters which are fitted to the data
- The different event generators use different models
- ISAJET uses independent fragmentation, this poorly describes the LEP data
- PYTHIA/JETSET uses the string model, gives a good fit to the LEP data
- HERWIG uses the cluster model
- HERWIG fits the LEP data less well than PYTHIA
- The main problems are in heavy quark, *i.e.* b, hadronization and in identified particle spectra
- Gives a good fit to jet observables

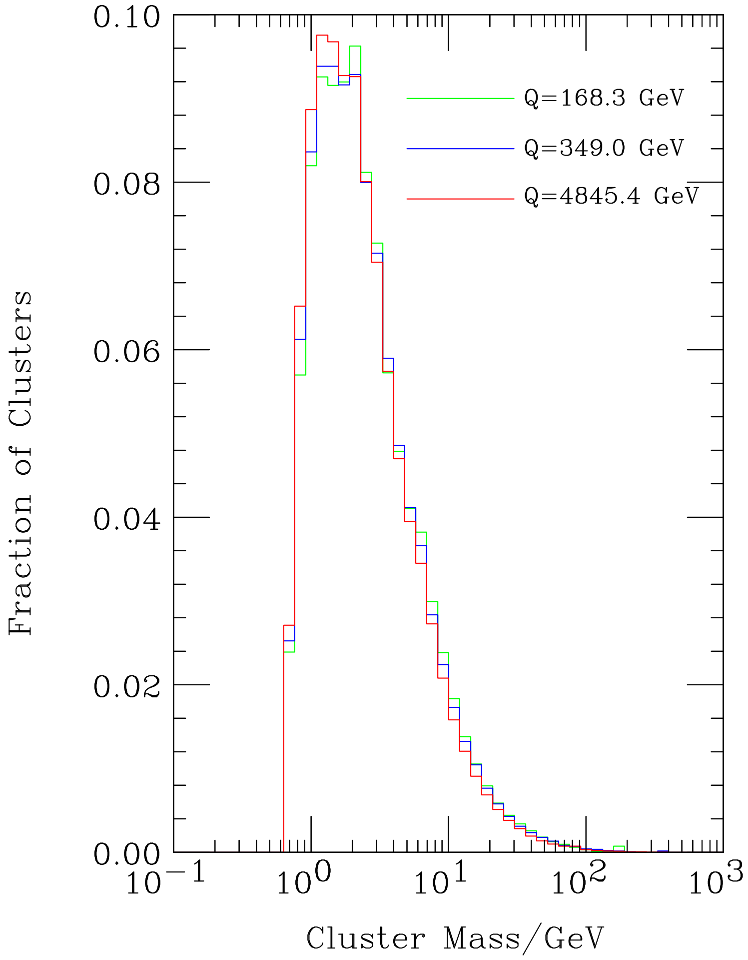
Cluster Hadronization Model

- 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.**

HERWIG 6.1

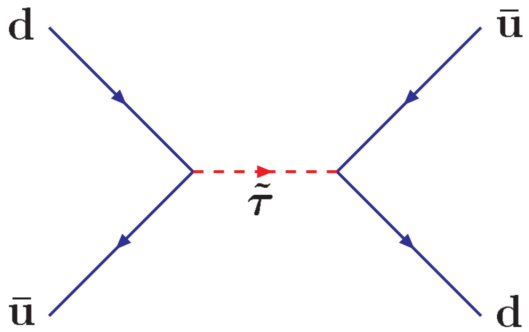
- This is available from
  http://hepwww.rl.ac.uk/theory/seymour/herwig/
- HERWIG contains a large number of processes in lepton-lepton, lepton-hadron and hadron-hadron collisions
- A wide range of Standard Model, including Higgs, processes are implemented
- I will briefly look at those things which have been added recently which are of relevance for the Tevatron
  - SUSY
  - Hard Matrix Element corrections
- I will then talk about our future plans

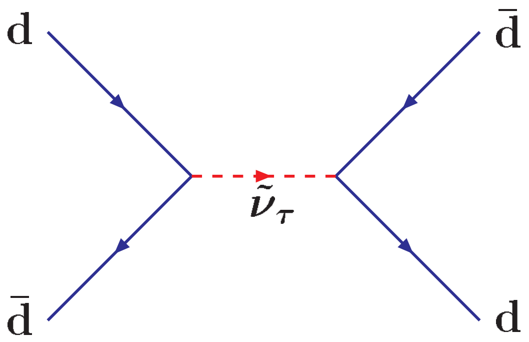
SUSY

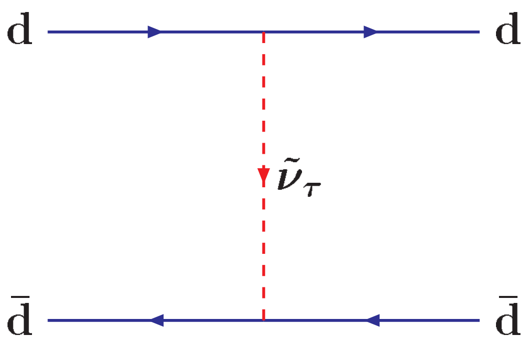
- HERWIG6.1 is the first version to include SUSY
  - Interface to ISAJET for spectrum calculations, and MSSM decays.
  - Option of violating R_p and $\not{R}_p$ decays
  - All SUSY pair production processes in hadron collisions
  - Resonant $\not{R}_p$ processes in hadron collisions
  - A full treatment of colour coherence effects in all processes
  - Most analyses so far have been for the LHC. I will briefly show some Tevatron results

Resonant Slepton Production

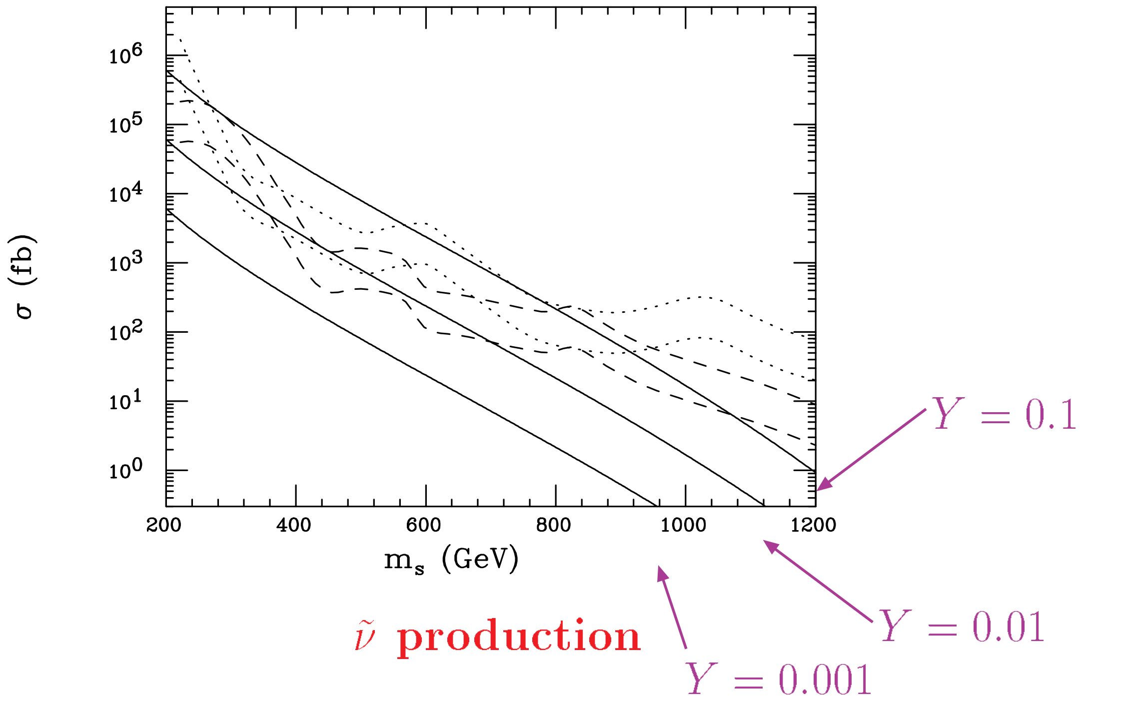
- In $\not{R}_p$ models resonant slepton is possible
- Studies based on the parton-level cross section (narrow width approximation) suggest that di-jet production can be used to search for resonance production to fairly small couplings.
- This does not include the effect of QCD radiation.
- These processes are now included in HERWIG.



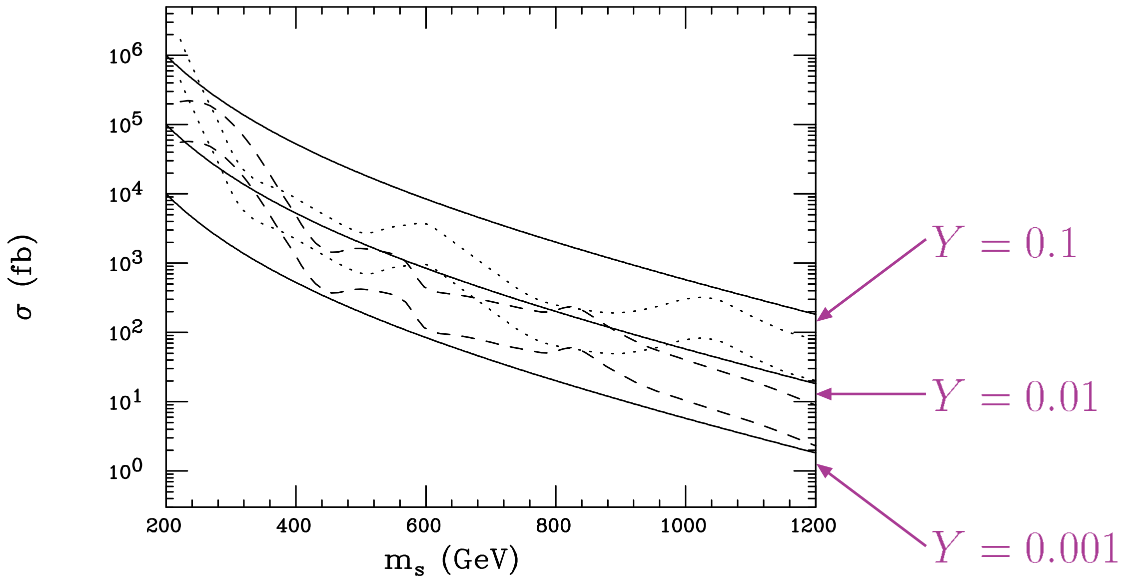




- **Taken from hep-ph/9809525, J. Hewett and T. Rizzo.**



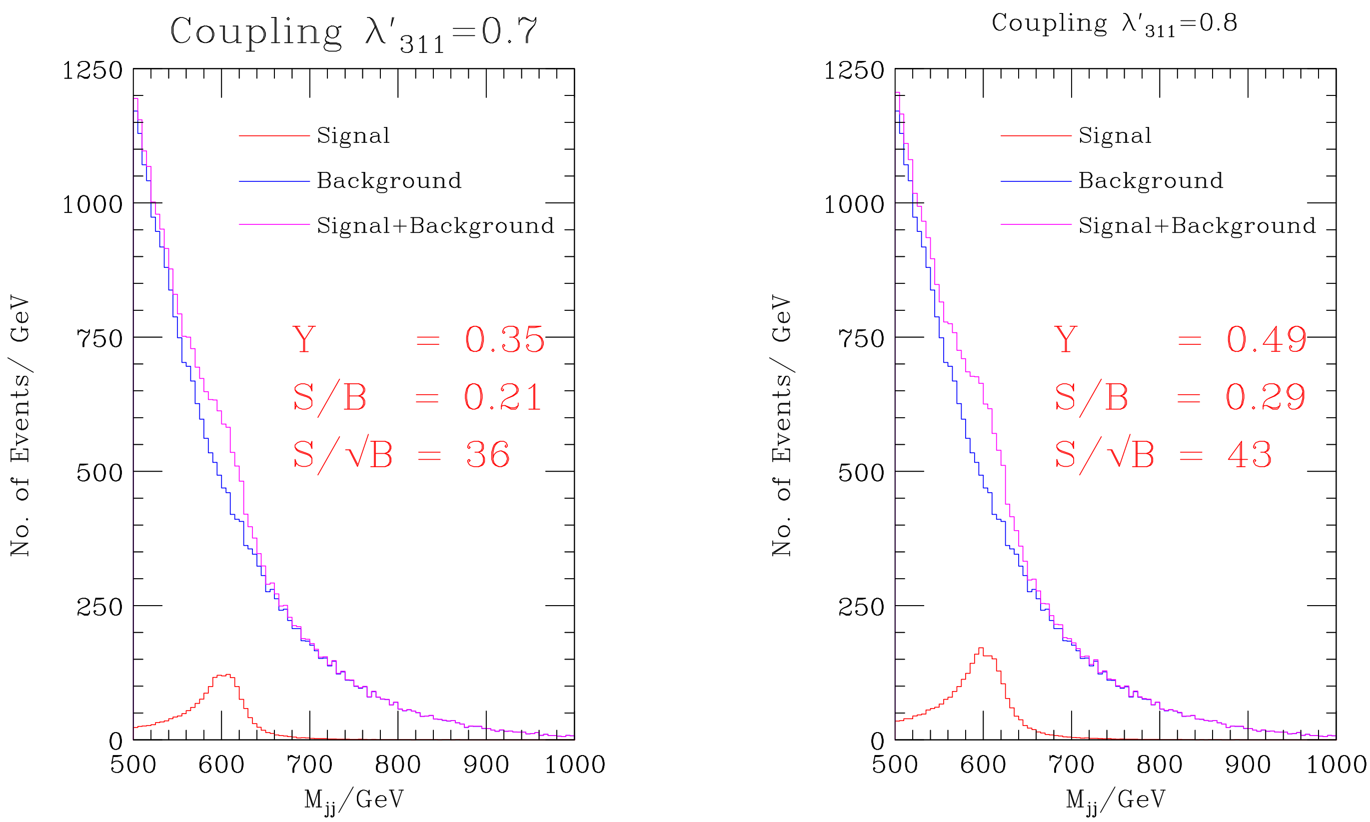
$\tilde{\nu}$ production



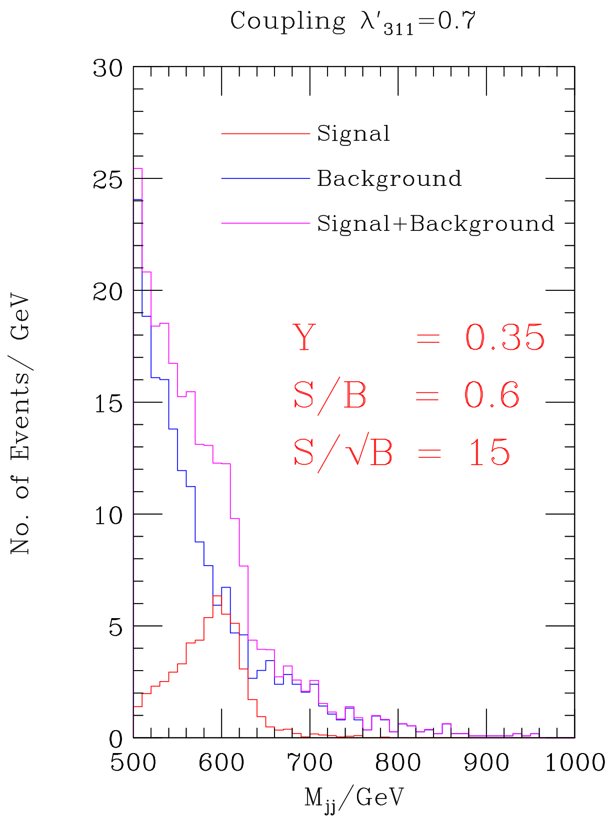
$\tilde{\tau}$ production

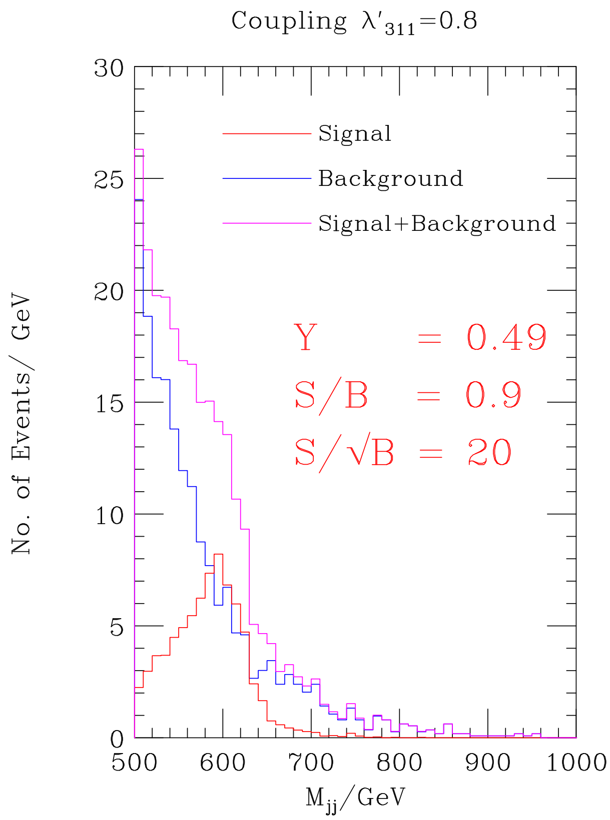
- $Y = \lambda'^2 \times \mathrm{BR}(\tilde{\ell} \to \mathrm{jets})$
- **dots CDF discovery potential at 2 fb^{-1} and 30 fb^{-1}**
- **dashes D0 discovery potential at 2 fb^{-1} and 30 fb^{-1}**

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.**





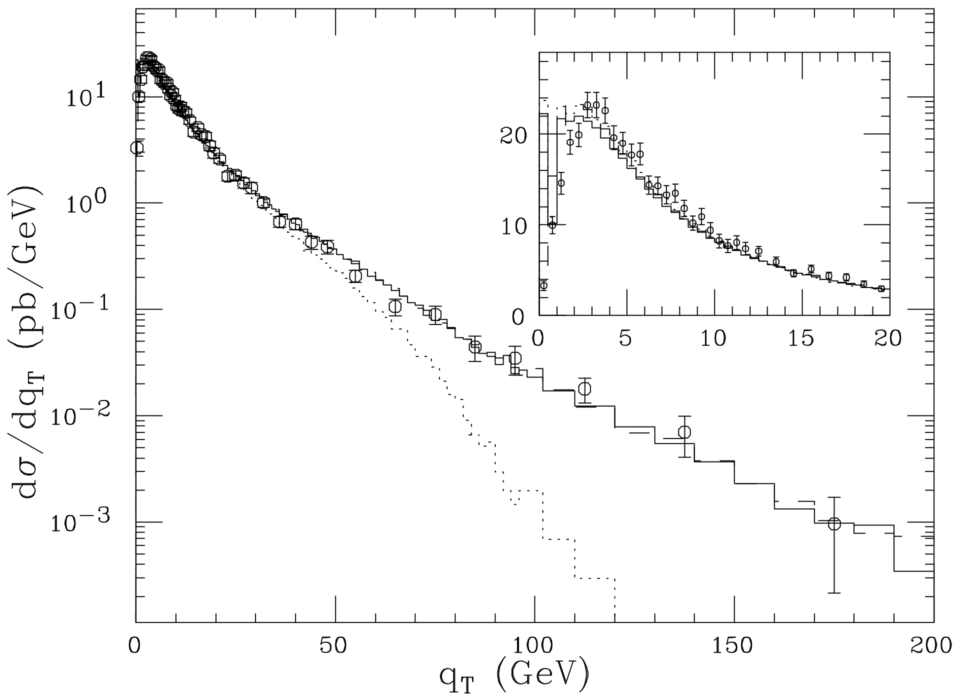
- **Require the presence of a third jet with** $E_T > 10\ GeV$.
- **Require** $|\alpha| < 0.4$
- S/B **is improved at the expense of a reduced** $S/\sqrt{B}$

Matrix Element corrections

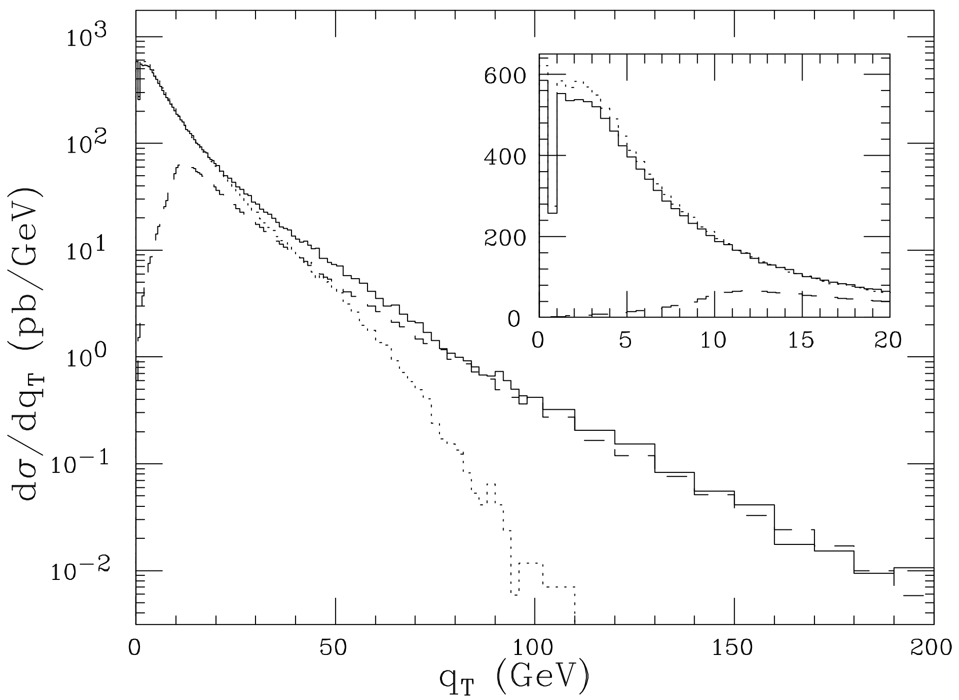
- Work by G. Corcella and M. Seymour
- The parton shower algorithm correctly describes soft and collinear emission
- But can have hard emissions which are not described, *e.g.* large angle hard gluons
- Add a matrix element correction
- This correction is process dependent
- $e^+e^- \to q\bar{q}$ and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

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

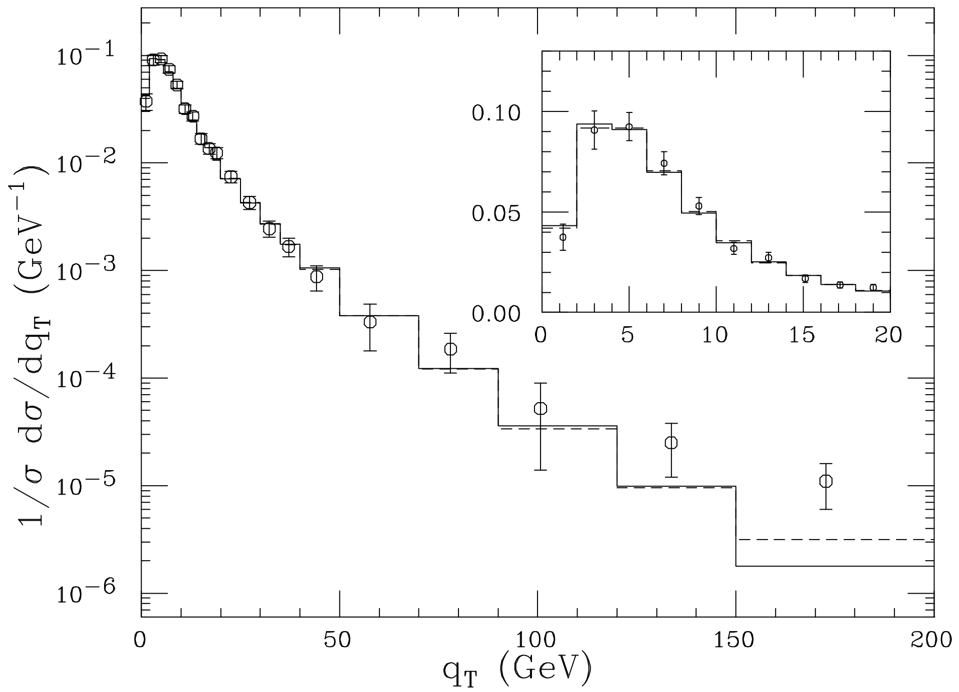
  Drell-Yan Nucl. Phys. B565:227, (2000)
- Main effects in the W and Z transverse momentum spectrum



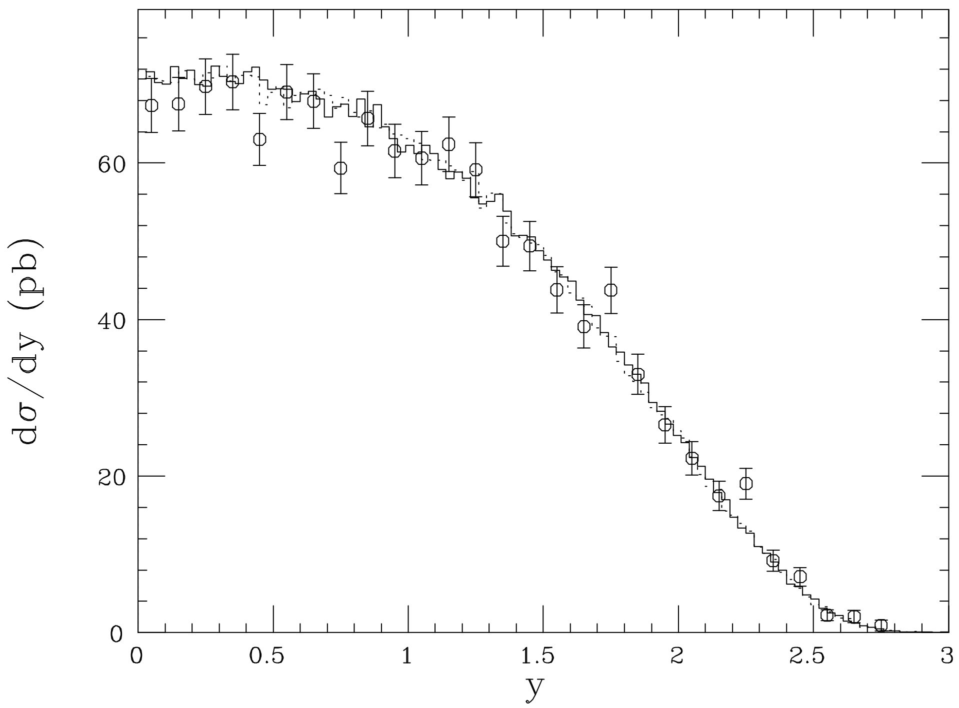
Comparison of Z p_T distribution from CDF with HERWIG without (dotted) and with (dashed and solid) M.E. corrections



W p_T distribution at with HERWIG without (dotted) and with (solid) M.E. corrections. The W+1 jet matrix element in shown dashed.



Comparison of W p_T distribution from D0 with HERWIG with M.E. corrections



Z rapidity distribution at CDF with HERWIG without (dotted) and with (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 parton-shower phase, using angles as the evolution variable describes soft & collinear emission

- This gives good agreement with the data

- The Cluster hadronization model gives good agreement with the data on jet distributions

- HERWIG 6.1 includes a number of new features to improve the description of hadron-hadron data