Simulations of Beyond the Standard Model Physics

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- Background Simulation
- BSM Simulation
- Examples
- Future

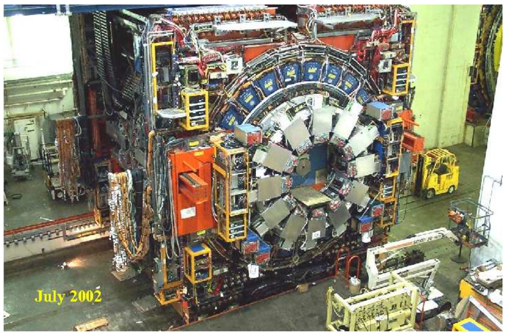
Introduction

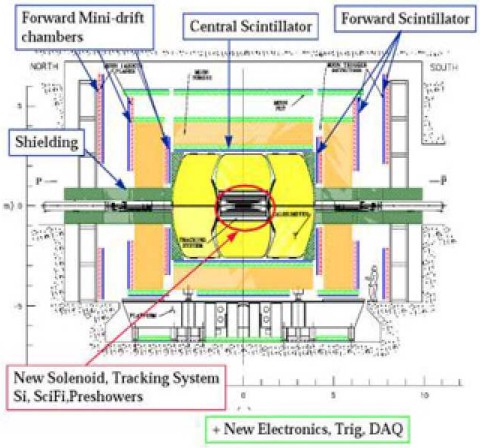
- The Standard Model of particle physics has been very successful in describing experimental data.
- However it is widely believed that there is physics Beyond the Standard Model.
- The major goal of the highest energy particle physics experiments is to:
  - Measure the properties of known heavy particles, *e.g.* top quark;
  - Discover the Higgs boson predicted by the Standard Model;
  - Discover physics beyond the Standard Model by observing new particles.
- In the next 5-10 years these experiments will be CDF and D0 at the Tevatron, and ATLAS and CMS at the LHC, (and possibly a linear collider.)

Tevatron Experiments

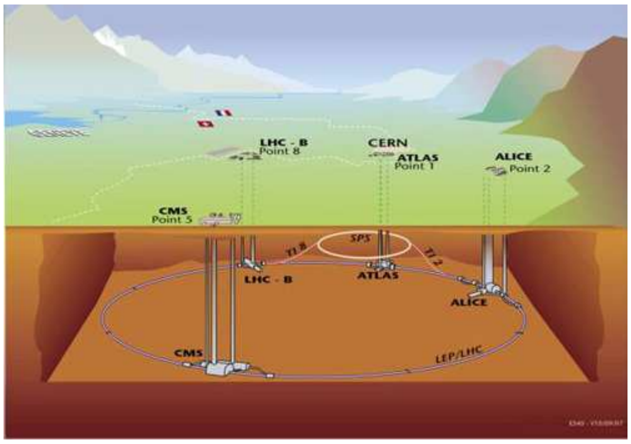
CDF

D0



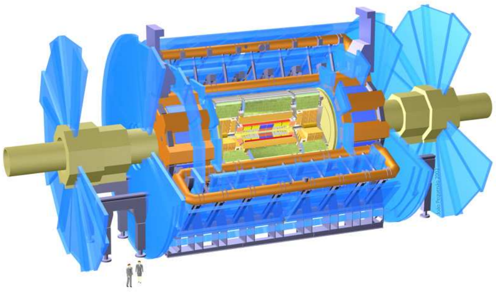


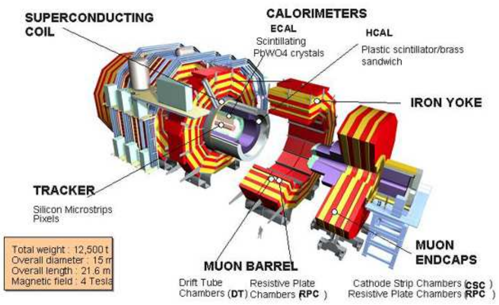
LHC Experiments



ATLAS

CMS

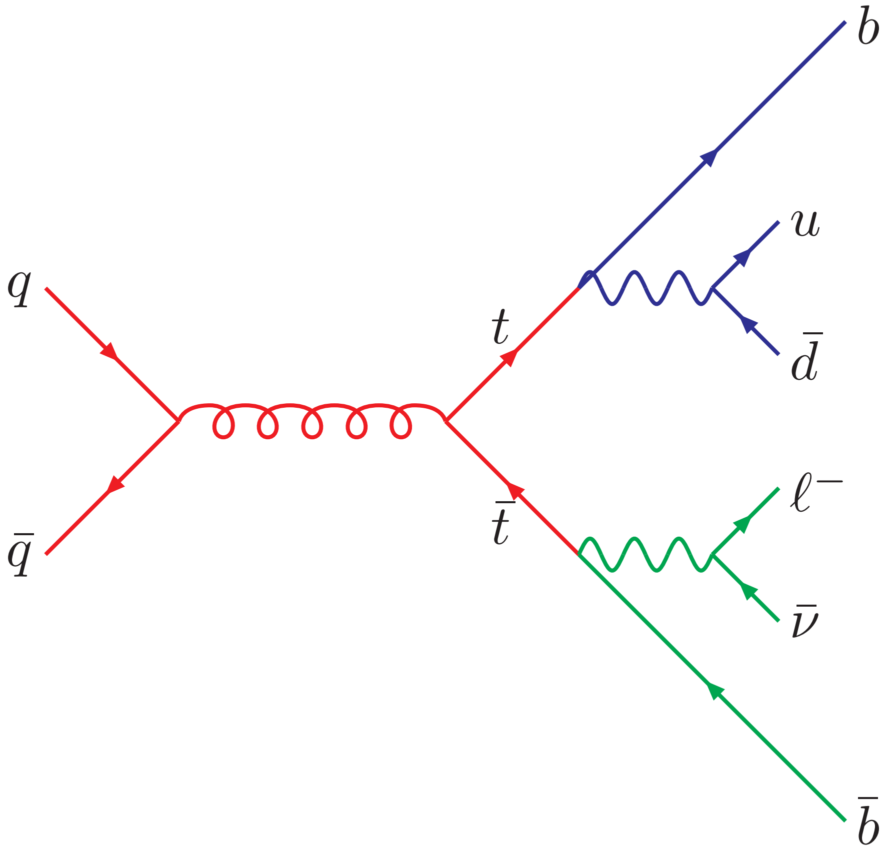




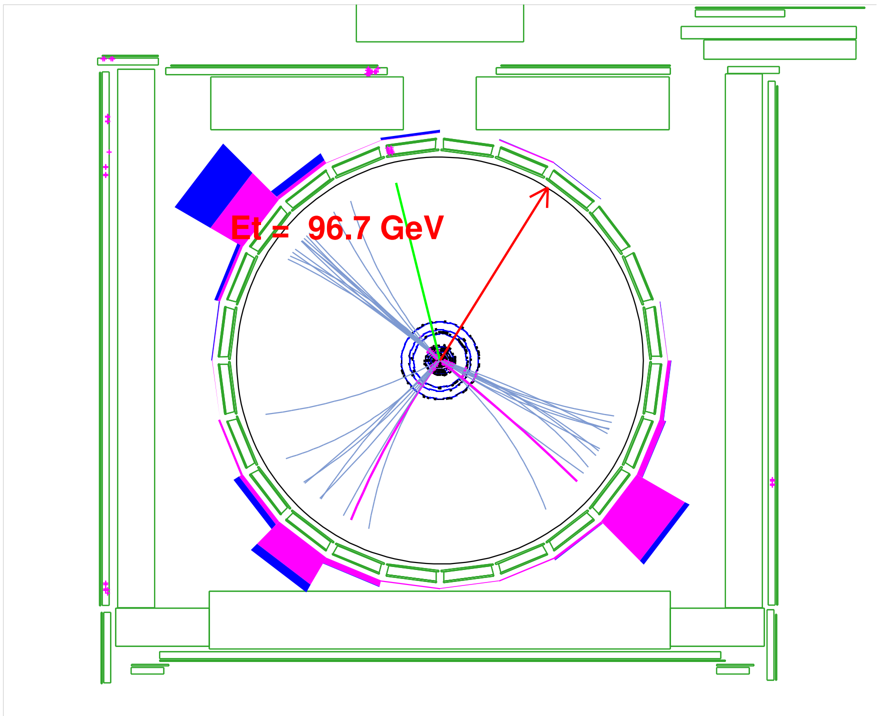
Simulations

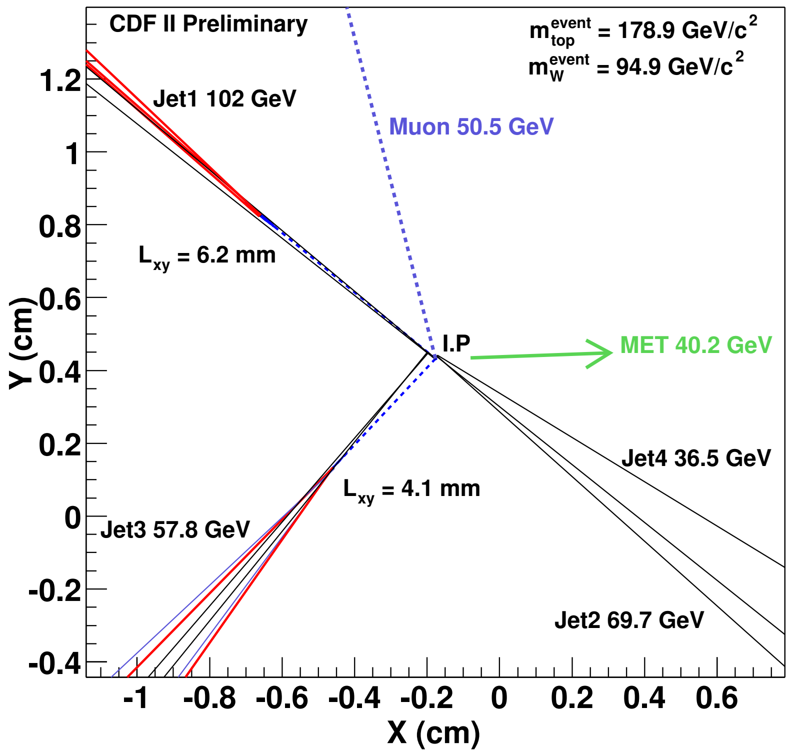
- The experimental signatures of all these processes are complicated.

- Consider Standard Model top quark production as an example.



Top Production





Monte Carlo Simulations

- In order to perform any experimental study we need a simulation of both the signal processes and the background.

- This is in two parts
  - The first piece, a Monte Carlo Event Generator includes the fundamental physics and gives the stable particles which interact with the detector.
  - The second part is a detector simulation which describes how these particles interact in the detector.

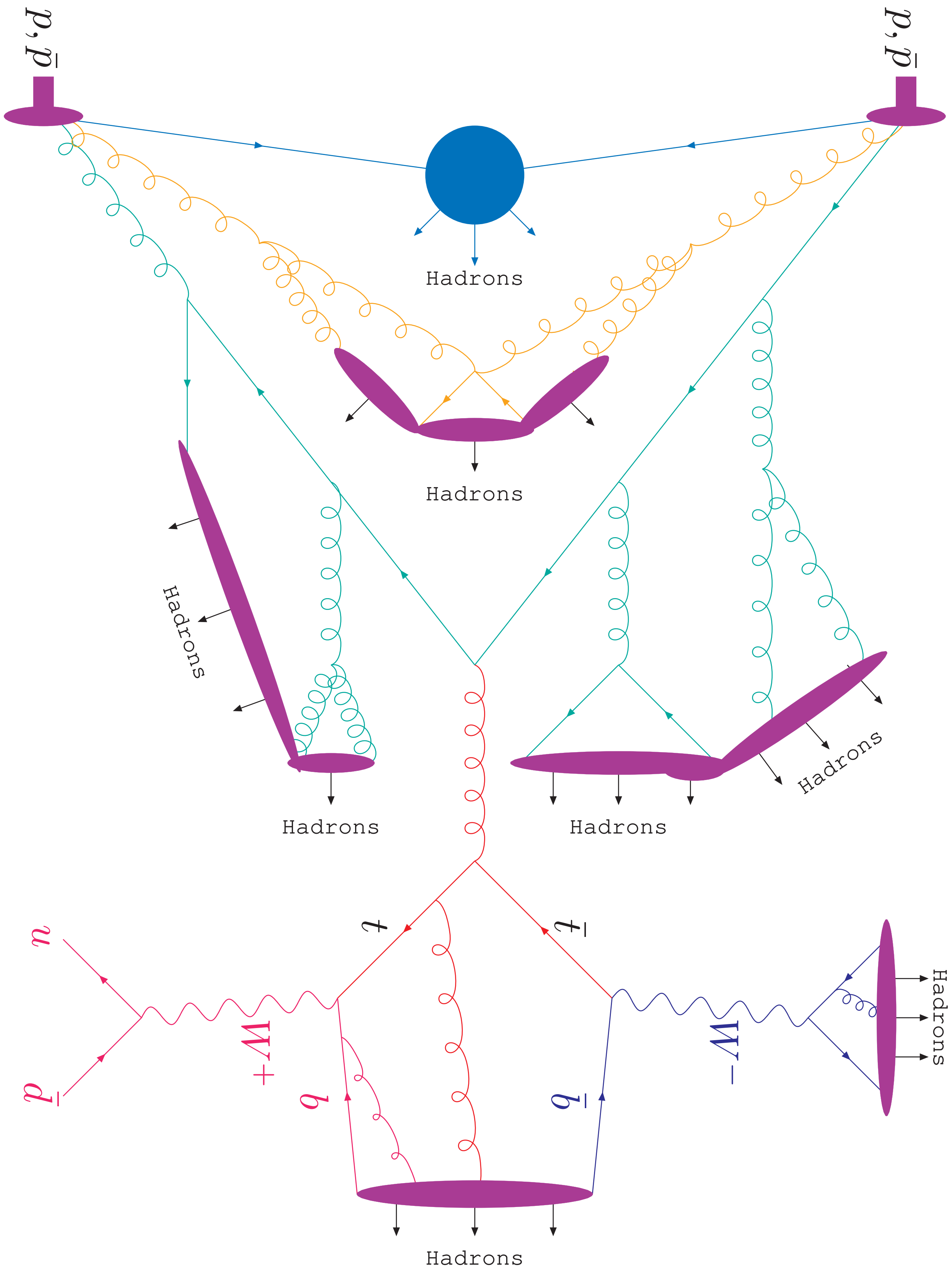
- Monte Carlo event generators have become an essential tool in all experimental analyzes.

- Much of my work is involve with one of these programs HERWIG which is used by all Tevatron and LHC experiments.

Monte Carlo Event Generators

- The aim of a Monte Carlo event generator is to provide a simulation of the events seen in experiments based on theoretical predictions.

- The simulation is split into a number of phases
  - Hard Process
  - Parton Shower
  - Secondary Decays
  - Multiple Scattering/Soft Underlying Event
  - Hadronization
  - Hadron Decays



$p, \bar{p}$
$p, \bar{p}$
Hadrons
Hadrons
Hadrons
Hadrons
Hadrons
Hadrons
Hadrons
Hadrons
t
$\bar{t}$
W^+
W^-
b
$\bar{b}$
u
$\bar{d}$

Hard Process

- The hard process is the fundamental interaction.
- Usually this is a $2 \to 2$ scattering process.
- This process is normally calculated at leading order, although some processes are now available at NLO.
- This is the piece where most theoretical calculations stop.

QCD Radiation

- It is impossible to calculate and integrate the matrix elements for processes involving large numbers of partons.

- Instead we treat the regions where the emission of QCD radiation is enhanced.

- There are two regions:
  - Collinear a quark or gluon radiates a gluon in the same direction.
  - Soft a quark or gluon radiates a very low energy gluon.

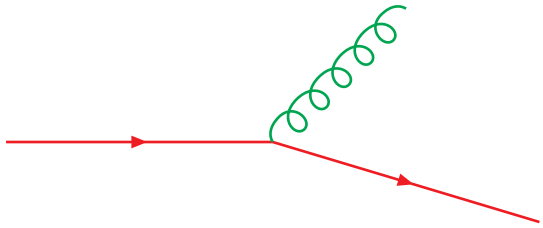
- In both these limits we can factorize the matrix element

Cross Section with emission of extra parton	=	Cross Section before the emission	×	Radiation function for extra parton

- The radiation piece is singular in both these limits.

QCD radiation

- Introduce resolution criterion *e.g.* $k_T > Q_0$.
- Combine virtual corrections & unresolvable emission.



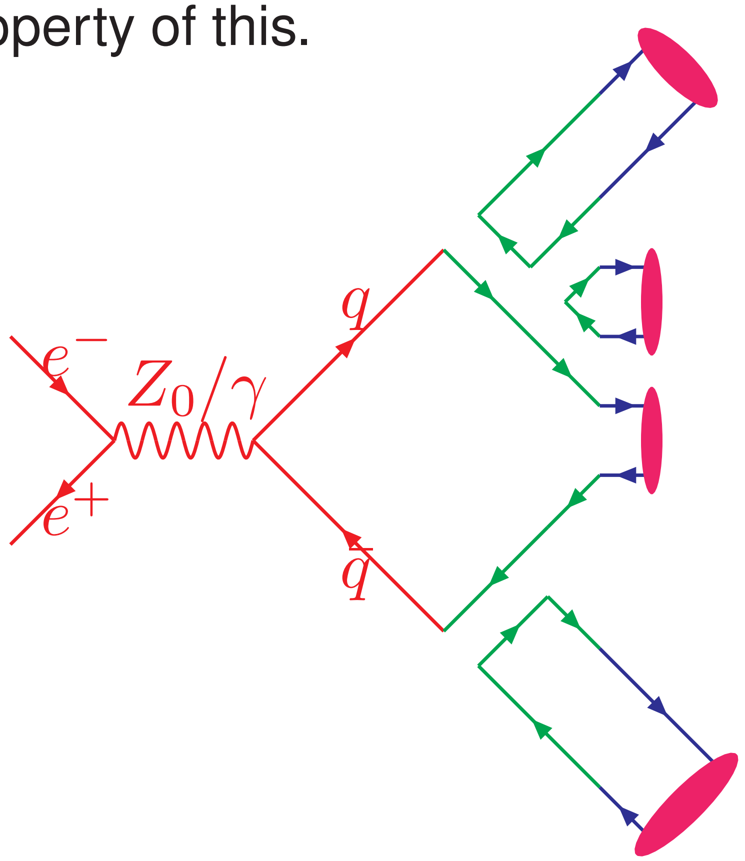
Resolvable Emission
Finite

Unresolvable Emission
Finite

- Unitary: Unresolved + Resolved = 1.
- Allows us to calculate the Sudakov form factor $\Delta(Q^2, q^2)$ the probability of no resolved emission between two scales.

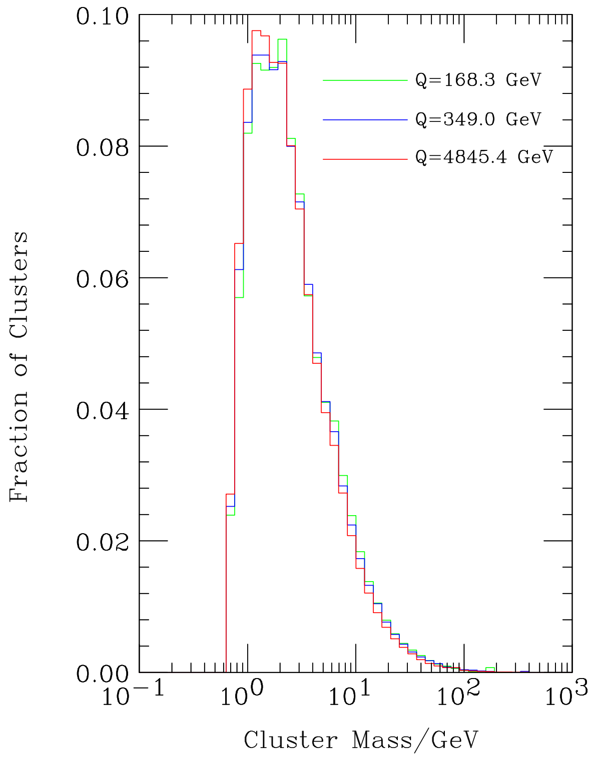
Hadronization

- We can't calculate the hadronization so we use a phenomenological model.
- HERWIG includes angular-ordered parton showers.
- The hadronization model is based on one property of this.



- First split the gluons into $\mathrm{q\bar{q}}$ 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.
- The hadrons decays are then performed using phase space and the measured branching ratios.

Study of BSM Physics

- In order to study BSM physics we must get both the signal and the background right.

- I will now discuss two pieces of work I've been doing recently in order to improve the simulation of each of these.
  - Better simulation of multi-jet production with gauge bosons.
  - Better simulation of spin correlations in particle decays.

Background Simulation

- Often the general purpose event generators are run to calculate backgrounds without much thought.
- The parton shower is based on the soft and collinear approximations.
- It does not describe large angle and high p_T jet emission.
- Despite this it is not uncommon to see studies where Monte Carlo simulations have been used to calculate the backgrounds for many hard jets.

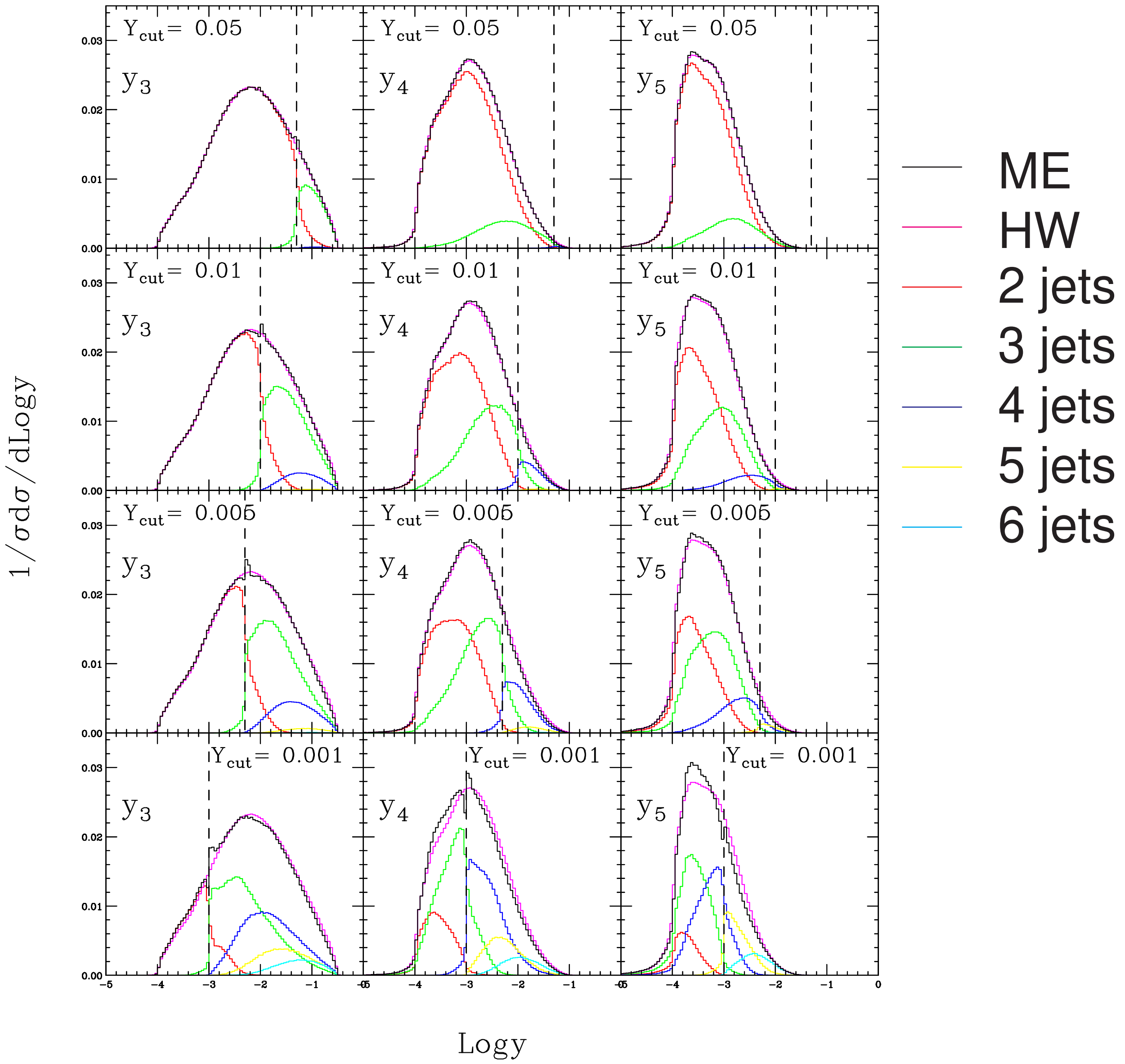
Background Simulation

- To improve this we want to do the following:
  - Separate the phase space such that we have two regions;
  - One contains the soft and collinear singularities and is filled by the parton shower;
  - One contains hard jet emission and is filled by fixed order matrix elements;
  - Smooth matching between the matrix element and parton shower;
  - No double counting of radiation.
- One such proposal is the CKKW algorithm which uses the Durham jet algorithm to separate the phase space.
- We are interested in making predictions for hadron collisions but an important first step is to check we don't mess up the good agreement between the simulations and data for $\mathrm{e^+e^-}$ collisions.
- The best thing to compare is the distribution in y_n which is the value of the Durham jet measure where the event changes from an n to an $n-1$ jet event.

Effect of Varying the cut-off at M_Z

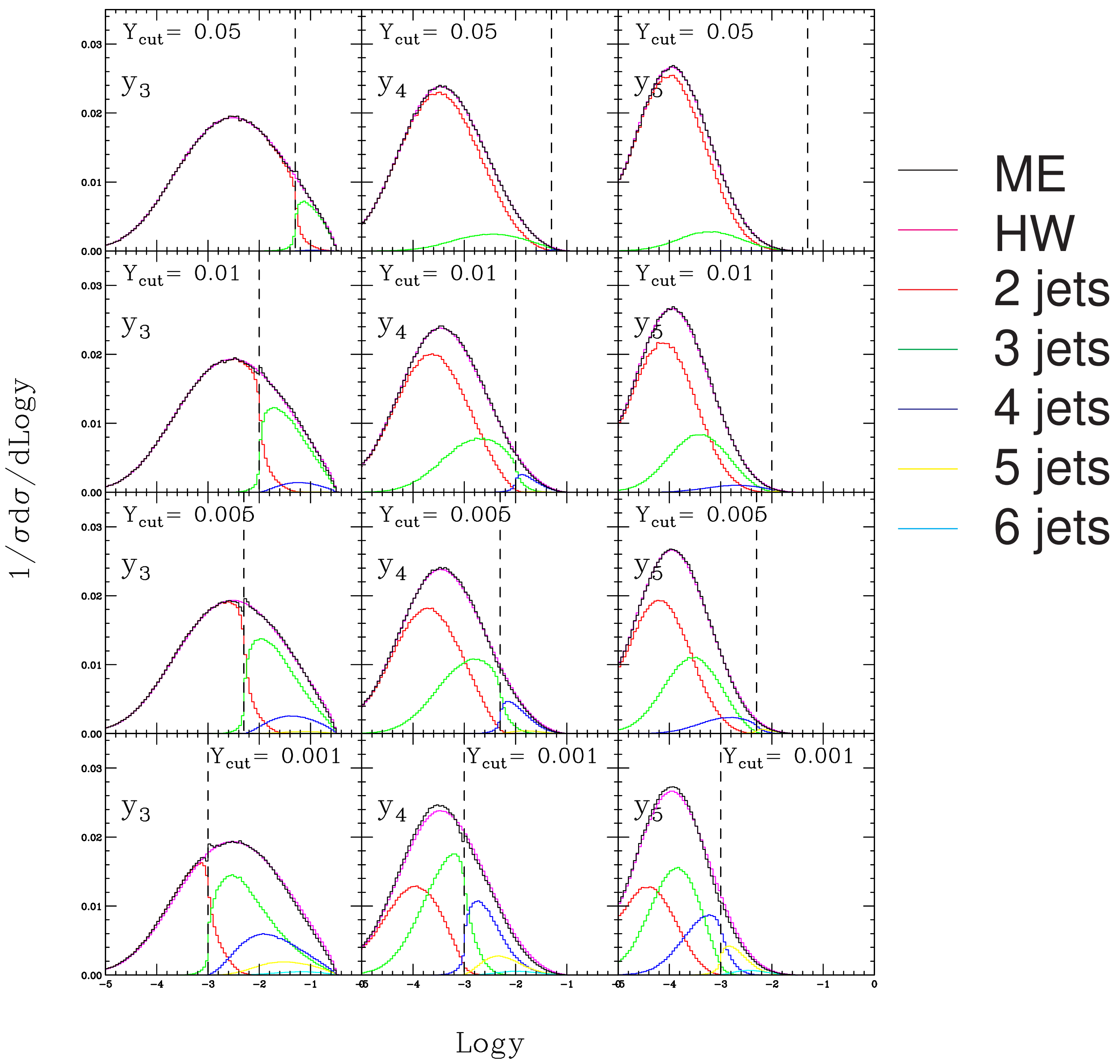
- There is a matching scale between the matrix element and parton shower.

- The results should be insensitive to the value.



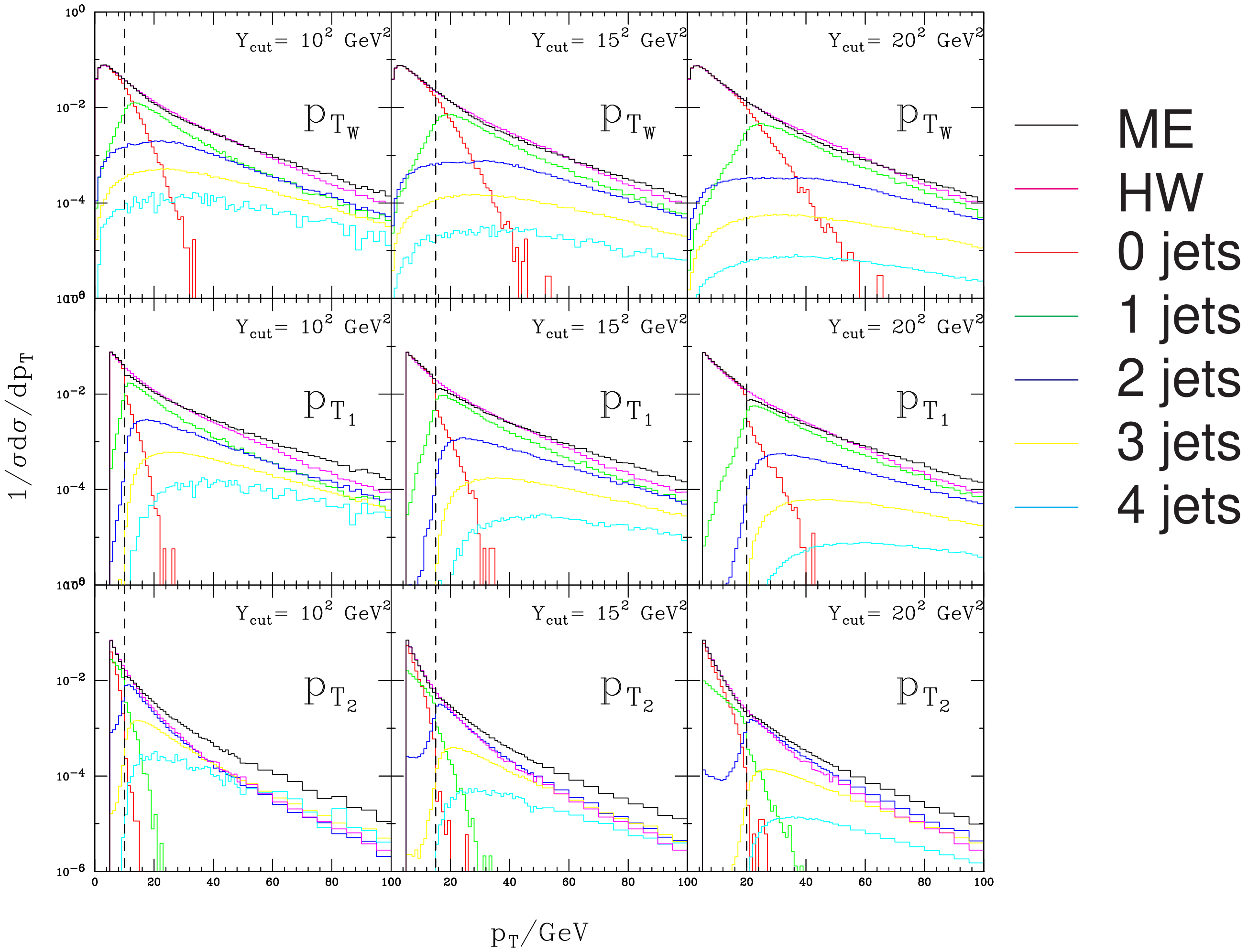
Effect of Varying the cut-off at 500 GeV

- If we have the right answer it should improve with energy.



W Production at the Tevatron

- Look at p_T distributions.
- Jets defined with a cone algorithm and $R = 0.7$.



Heavy Particle Decays

- Until recently we simulated processes involving heavy particle decays in the following way:
  - The production processes were implemented as $2 \to 2$ scattering processes;
  - The decay rates were calculated;
  - The decays of the particles were then performed according to phase-space, or in some cases a matrix element was used.

- However this neglects a number of effects which are important:
  - In some models where phase space was used the matrix elements give important effects;
  - Correlations between the production and decay are important, as are polarization effects in lepton collisions.

Spin Correlations

- There are two different approaches used in generators.

- The first calculates the matrix element as a $2 \rightarrow n$ body process, including any decays.
  - This is the traditional method.
  - Has problems if many final-state particles or decay modes.

- The second calculates helicity amplitudes for the production and decay.
  - Production and decay performed separately.
  - Reproduces the matrix element in a step by step algorithm.
  - Allows many final-state particles and decay modes to be simulated.

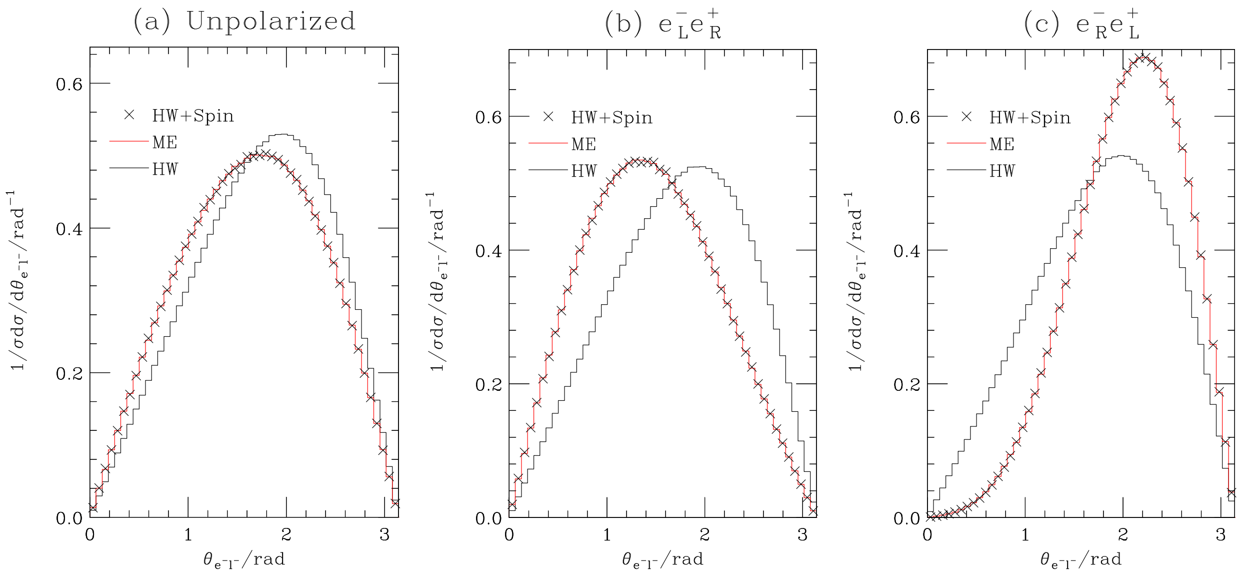
- This is the method I developed to simulate these processes.

- Implemented in HERWIG for a wide range of processes, gives the best simulation currently available of heavy particle production and decay.

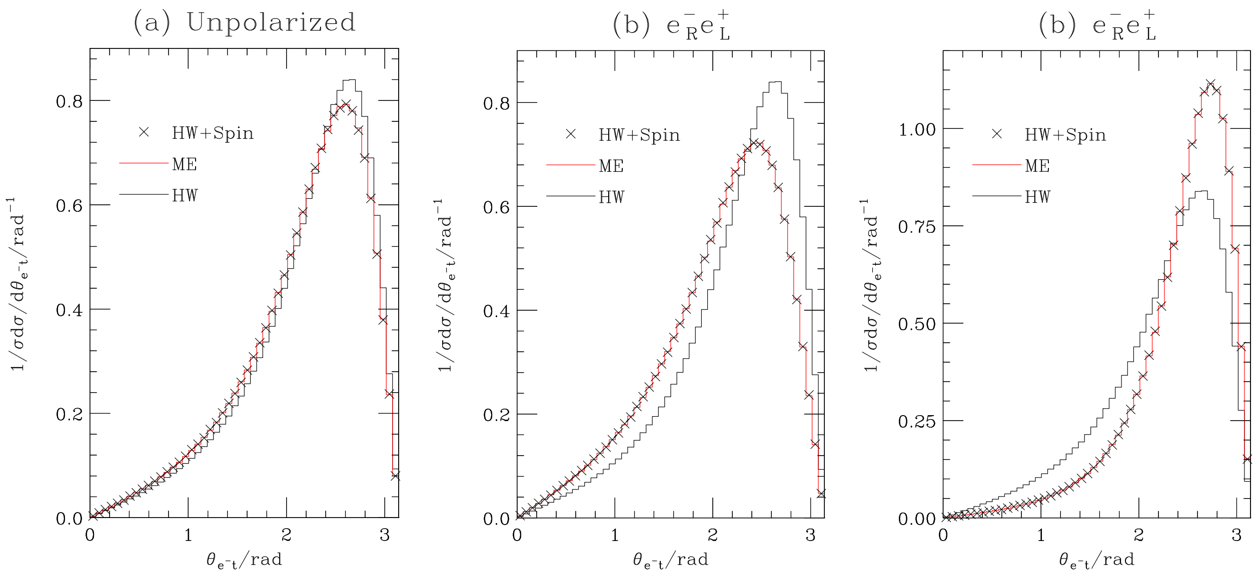
Top pair production in e^+e^- collisions

- Study the semi-leptonic decays of both top quarks and look at the correlations.

- Between the lepton produced in the antitop decay and the beam.



- Between the lepton and the top quark.



Phenomonology

- So far I've described work that I've been doing to produce better simulations.
- This is interesting, and particularly for the experimental community very important.
- However I'm also interested in using these simulations to study interesting physics models.
- I'll now present some examples of work I've been doing in this area.

Baryon Number Violation

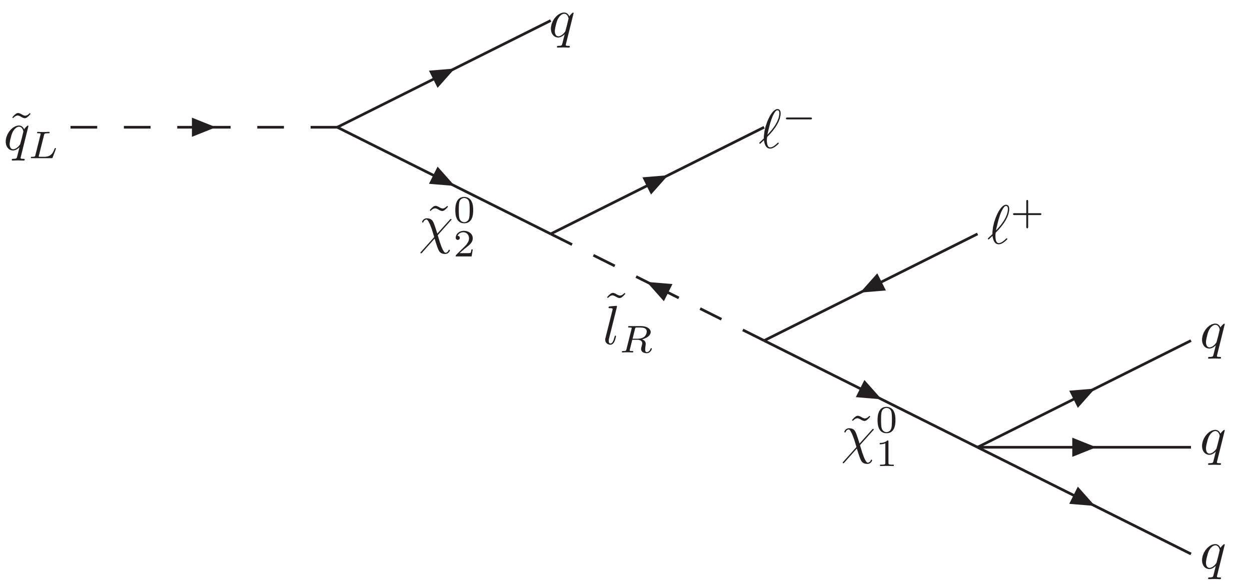
- In SUSY models there is a partner of different spin for every Standard Model particle.
- The lightest SUSY particles tend to be a mixture of fermionic partners of the photon, Z and Higgs bosons, called neutralinos.
- In most models the lightest of these $\tilde{\chi}^0_1$ is stable.
  - This makes it a dark matter candidate.
  - Missing energy is the collider signature.
- However in some models it can decay.
  - No longer a dark matter candidate.
  - Signature depends on the decay mode.
- One possibility is that it decays to give quarks so the signature is hadronic jets.
- This violates baryon number.
- This is a worst case for SUSY at the LHC.

Baryon Number Violation

- This is work done in collaboration with the Cambridge ATLAS group based on simulations I wrote.
  - This was the first simulation of these processes.
  - Required calculations of all the decay modes and cross sections.
  - Detailed study of QCD radiation from these processes which is complicated as baryon number is violated.

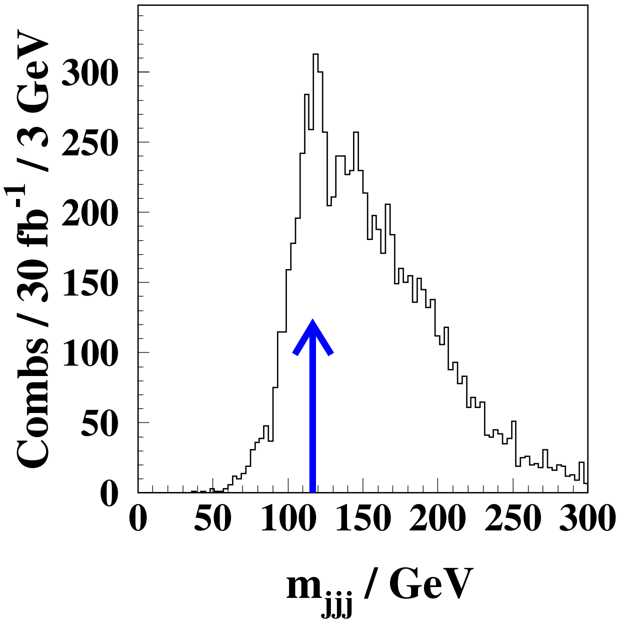
- It is very difficult to look at decays which are entirely hadronic.

- Instead require some leptons to reduce backgrounds.

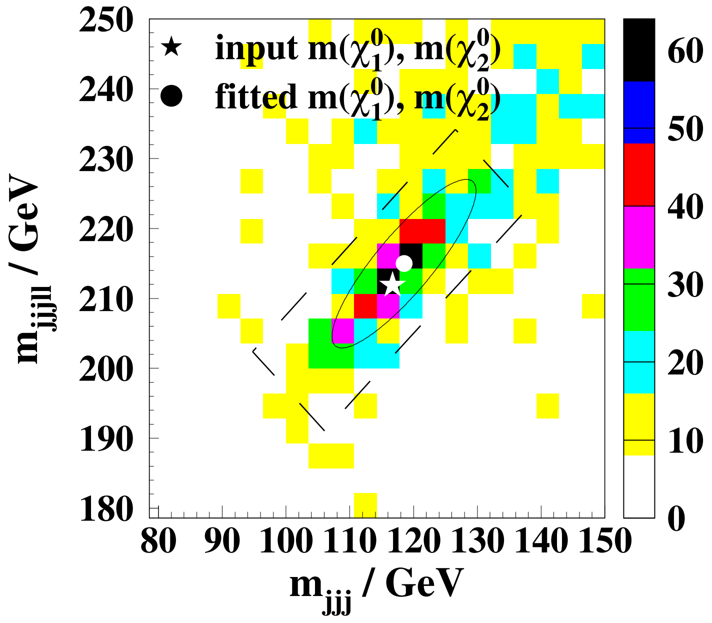


Baryon Number Violation

- Start by constructing the jjj mass, this should be the mass of the lightest neutralino.



- Shape dominated by backgrounds. Instead look at the correlation of jjj and $jjjll$ masses, there should be a peak at the mass of the lightest two neutralinos.



Black Holes

- Even more exotic things can be simulated.
- Recently there's been interest in models in which black holes can be produced in colliders.
- In these models the black holes are produced in the collision.
- They then decay via Hawking radiation.
- We can also simulate this.

Future

- HERWIG, and other event generators, are been rewritten in C++.
- This gives us a unique chance to improve the physics in these codes.
- In the next few years I will work be putting physics into these programs:
  - Better simulation of BSM physics so we can do accurate simulations of many more models, without as much effort;
  - Simulation of production and decay of particles including additional hard radiation at all stages and all the correlations.
- These build on some of the ideas I've discussed here but are impossible to do in the current codes due to technical problems.
- This program is essential for the LHC.
- At the same time as we produce these better simulations we can do better physics studies of the sort I've shown, and even studies that would have been impossible without these new tools.