Tools for New Physics at the LHC

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Tools 2008
MPI Munich

I am glad to be invited to the last meeting on software tools for new physics in preparation for the LHC data.

In the future meetings of this series, we will have data from the LHC -- and, I believe, we will have new physics.

This gives a sense of urgency to the work that we will discuss this week.

In this talk, I will review the various levels at which we expect to use our tools to understand aspects of the data from the LHC. My intent is to provide a broad picture into which the codes presented at this meeting will fit.

Hopefully, this discussion will be provocative...

The epigraph of

Numerical Methods for Scientists and Engineers
by Richard Hamming (1962):

"The purpose of computing is insight, not numbers."

But,also, remember: Very clever codes provide new, unexpected, types of insight.

One more word of introduction:

Many people now ask:

Will the LHC discover the Higgs boson ?

My answer is ...

By the time the LHC discovers the Higgs boson, that discovery will not longer be considered interesting.

At the LHC energies, we are confronting much bigger mysteries:

First, we need an explanation for the spontaneous breaking of the weak interaction symmetry SU(2)xU(1).

Models that do not just parametrize that breaking but actually explain it are complex. They require a new spectroscopy at hundred-GeV energies.

The most attractive of these models -- supersymmetry, Randall-Sundrum -- require a new new way to look at space-time structure.

Second, we need an explanation for the cosmic dark matter. Generic models of dark matter, with the assumption that the dark matter was once in thermal equilibrium, suggest that the dark matter particle is a part of this new spectroscopy.

These statements have been discussed for almost 30 years.

Now it is time for them to be confirmed by the data.

We ought to be impatient.

We ought to be set to extract as much knowledge as possible from the first nuggets of data. Of course, we must also get the correct knowledge.

For this, we need effective tools.

I will review tools in four stages:

Tools for the Standard Model,
viewed as a background to new physics

Tools for the first analysis of new physics

Tools for the detailed analysis of new physics

Tools for the analysis of dark matter

First, there is a question of the observability of new physics over backgrounds from the Standard Model.

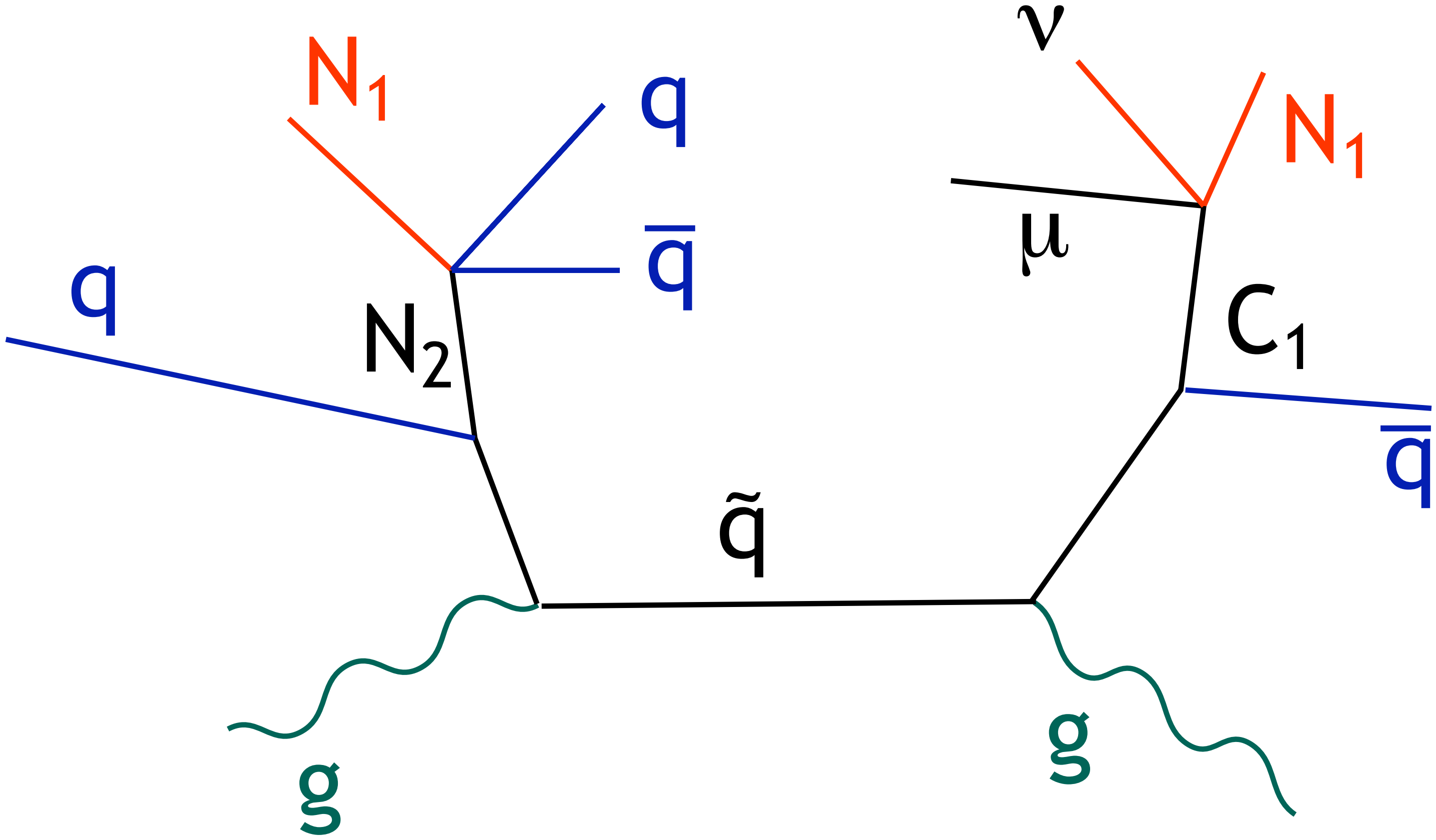
For this discussion, I will focus on the following problem of 'generic new physics models':

The dominant cross sections are those for pair-production of colored states of the new physics sector.

Each member of the pair then decays by a cascade, emitting quarks, leptons, or bosons.

The final state of the decay is the invisible dark matter particle.

This problem models typical scenarios for SUSY, Randall-Sundrum and UED extra dimensions, Little Higgs, etc.


N1
q
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g

To uncover events of this type, we need to work down through the hierarchy

$\sigma_{\rm tot}$	100 mb
jets w. $p_T > 100$	1 μb
Drell-Yan	100 nb
$t\bar{t}$	800 pb
SUSY ($M < 1$ TeV)	10 pb

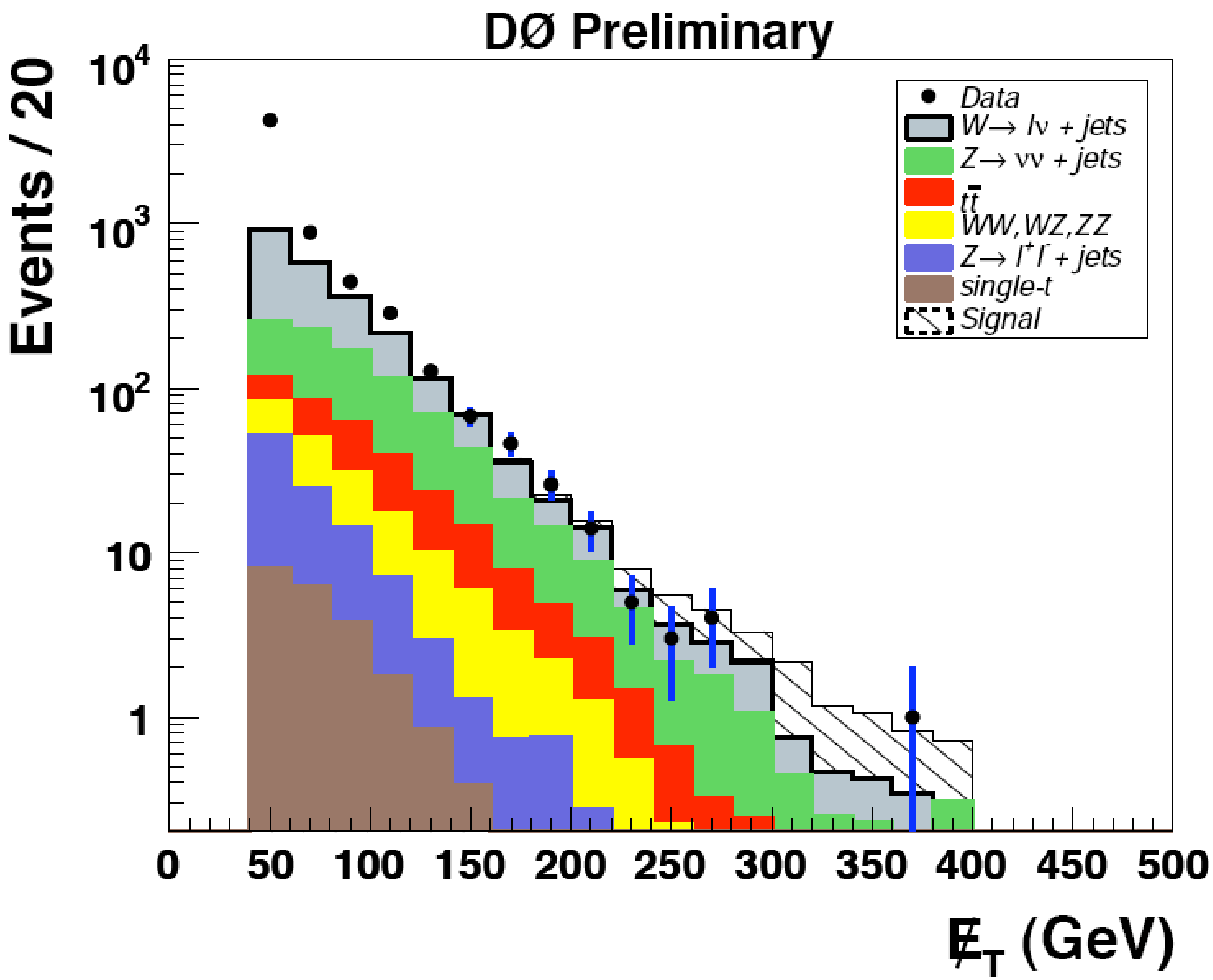
It should be easy to remove processes high on this hierarchy by insisting on large jet activity.

However, each additional hard jet costs only $\alpha_s/\pi \sim 0.1$, so we need to understand the basic SM processes decorated with addition hard gluon or quark emissions.

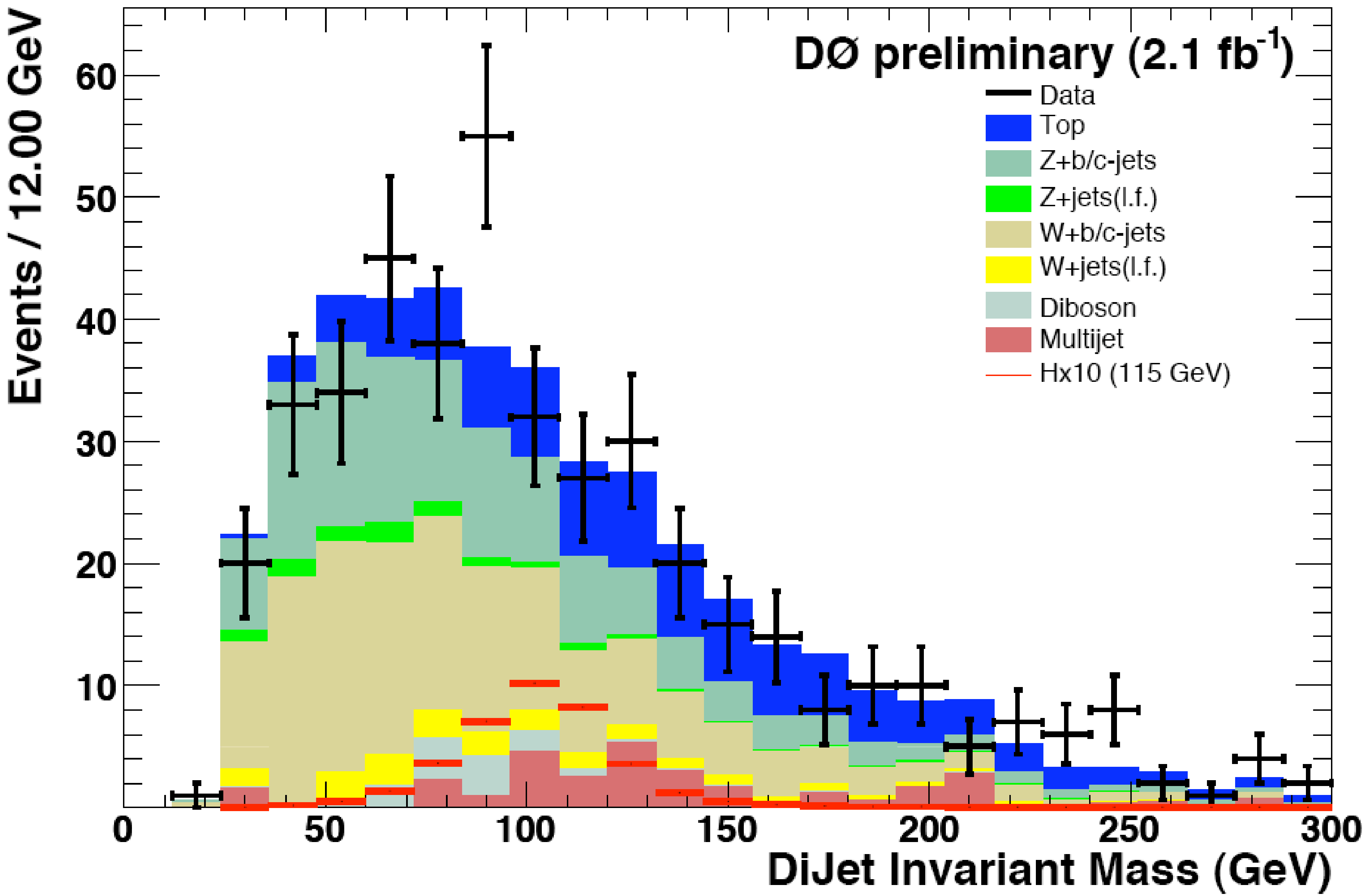
At the Tevatron, events with SM heavy particle production (W, Z, t) provide the dominant backgrounds to new physics searches.

DO SUSY search in acolinear dijets

(2007)



DO Higgs search in $p\bar{p} \rightarrow b\bar{b} + \text{invisible}$ (2008)



It is a very important problem to model these background processes accurately.

Some methods at our disposal are:

Parton shower: evolve in Q (or p_T or angle) from the hard scale

$$d\,\mathrm{Prob} = d\log Q\ dz\ \frac{\alpha_s(Q)}{\pi} P(z)$$

As multi-parton final states appear, fewer-parton final states are suppressed by the Sudakov factor:

$$\exp[-S(Q_1, Q_2)] = \exp[-\int_{Q_2}^{Q_1} d\log Q dz\, \frac{\alpha_s}{\pi} P(z)]$$

Exact tree level calculation: using n-parton matrix-element generators and integration over phase space

Parton shower calculations are accurate for collinear emissions and easily generate as many partons as you wish.

Matrix element calculations have a shape closer to the correct one for wide-angle emissions. This is just the region in which SM processes mimic new particle production. However, these calculations are divergent in the collinear limit and are limited in the number of partons that can be generated.

So it is necessary to match matrix element calculations in the hard region to parton shower treatment of the collinear region.

Catani-Krauss-Kuhn-Webber (CKKW) prescription: SHERPA

For $Q^2 > Q^2_{ini}$ apply exact matrix elements modified by Sudakov factors.

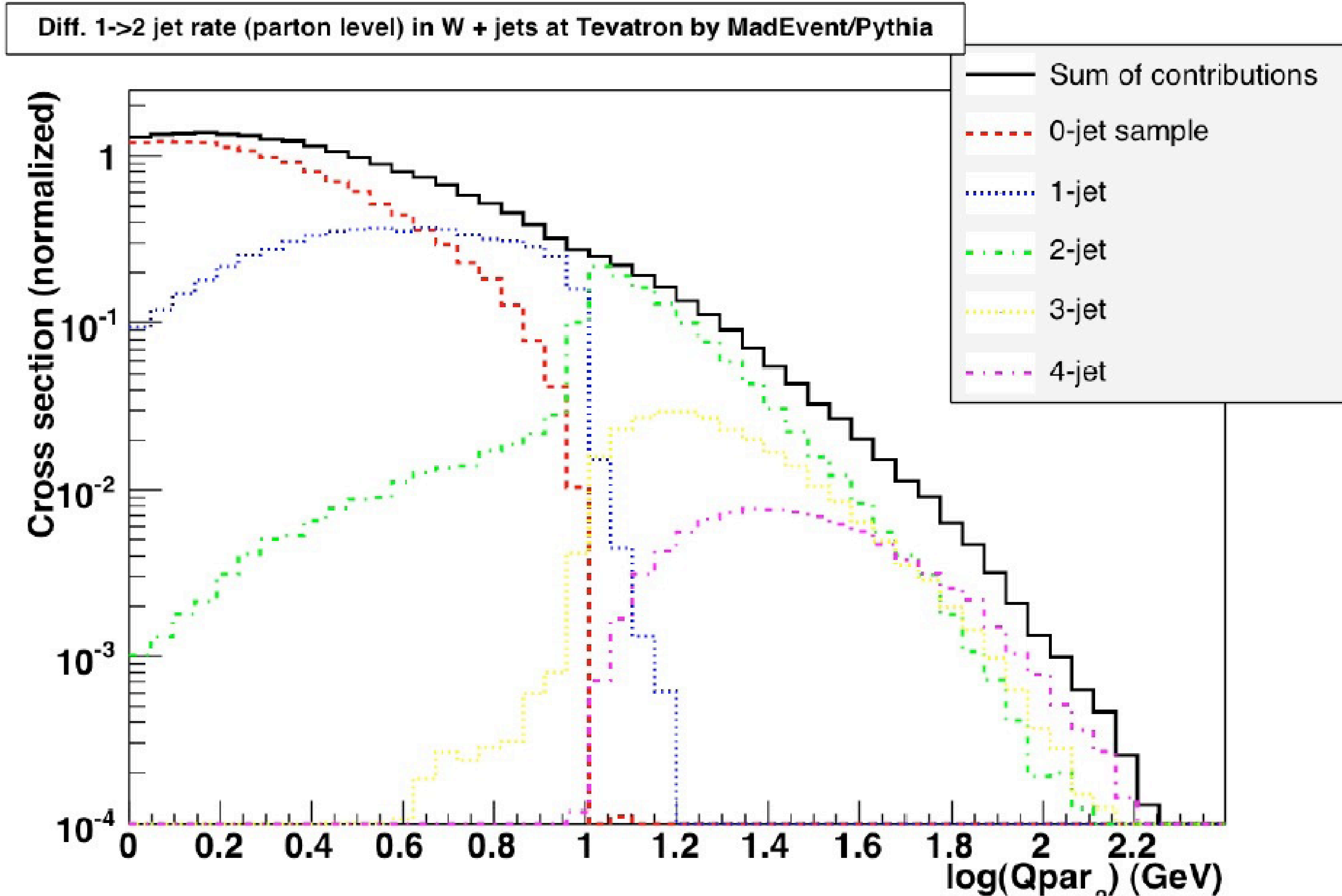
$$\text{exact tree} \cdot \prod e^{-S(Q_1,Q_2)}$$

For $Q^2 < Q^2_{ini}$ use a parton shower (PYTHIA, HERWIG, SHERPA)

If the parton shower is not Q^2-ordered, remove emissions that should have been generated by the matrix element.

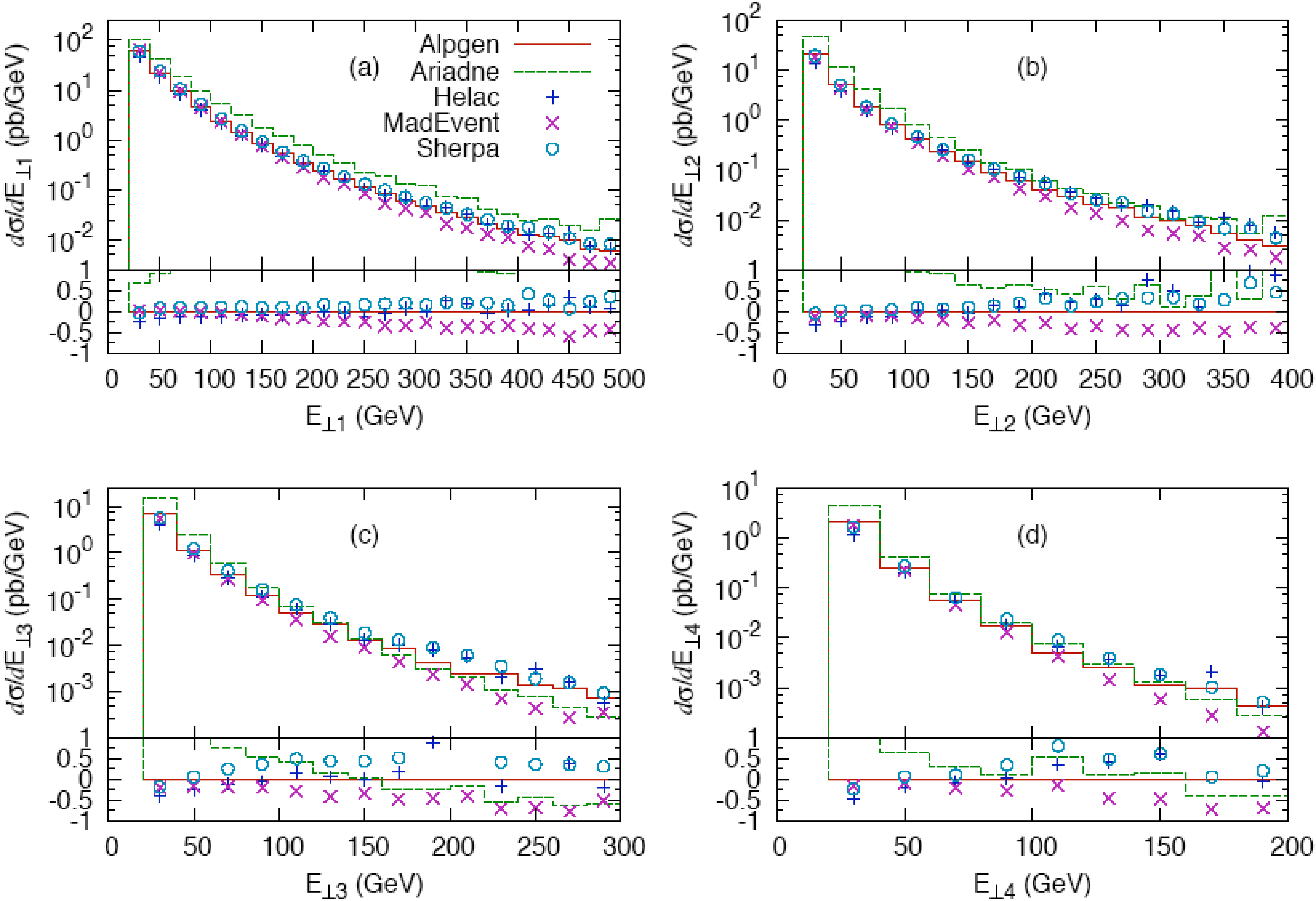
ALPGEN, MadGraph, and HELAC use different but related prescriptions (versions of the MLM prescription).

In general, it is necessary to study in detail exactly what the parton shower is doing in order to make this matching.



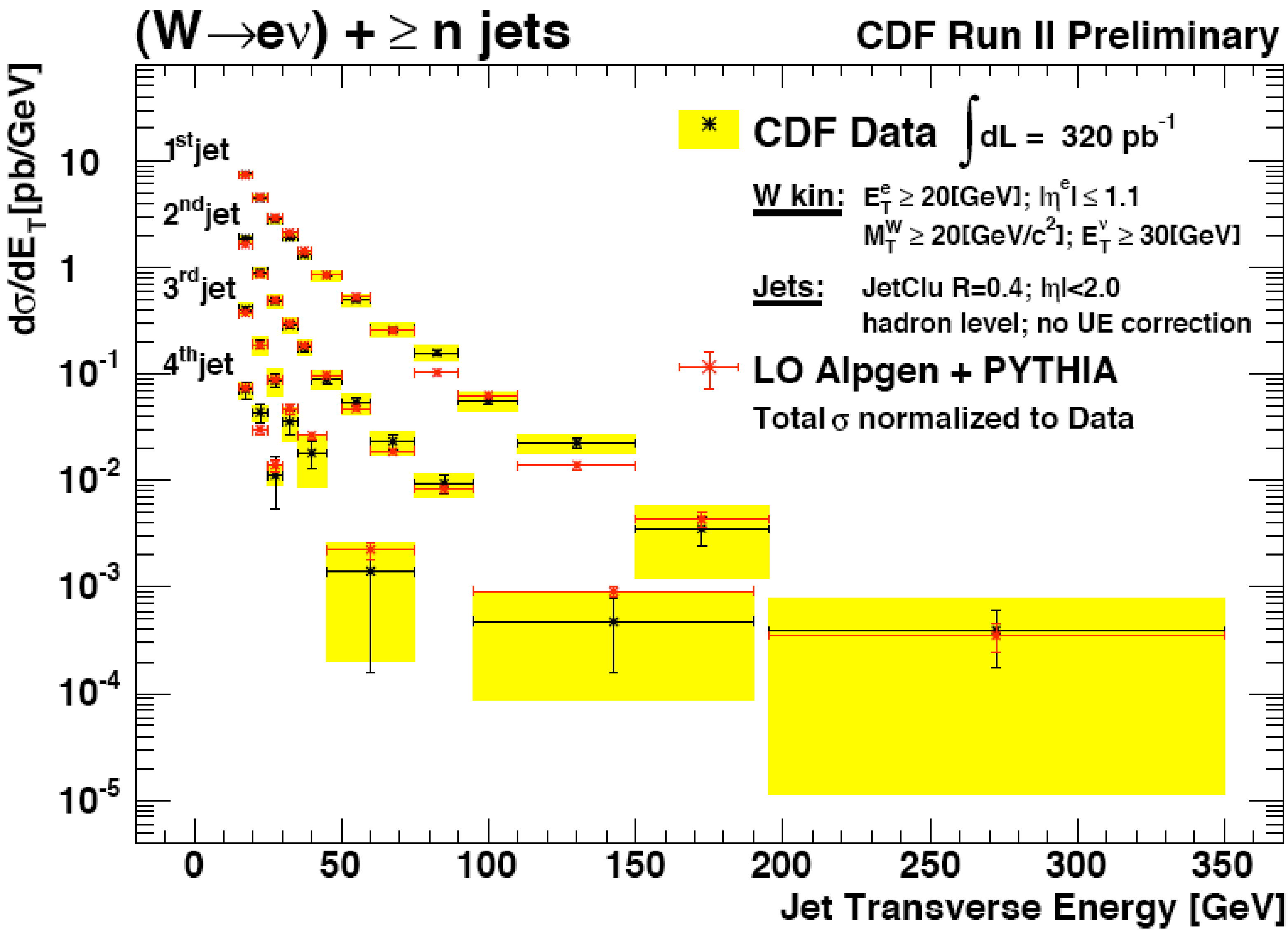
J. Alwall: W + 2 jet rates from MadGraph

A summer 2007 comparison of these codes gave reasonable agreement for the E_T spectra in W + jets.

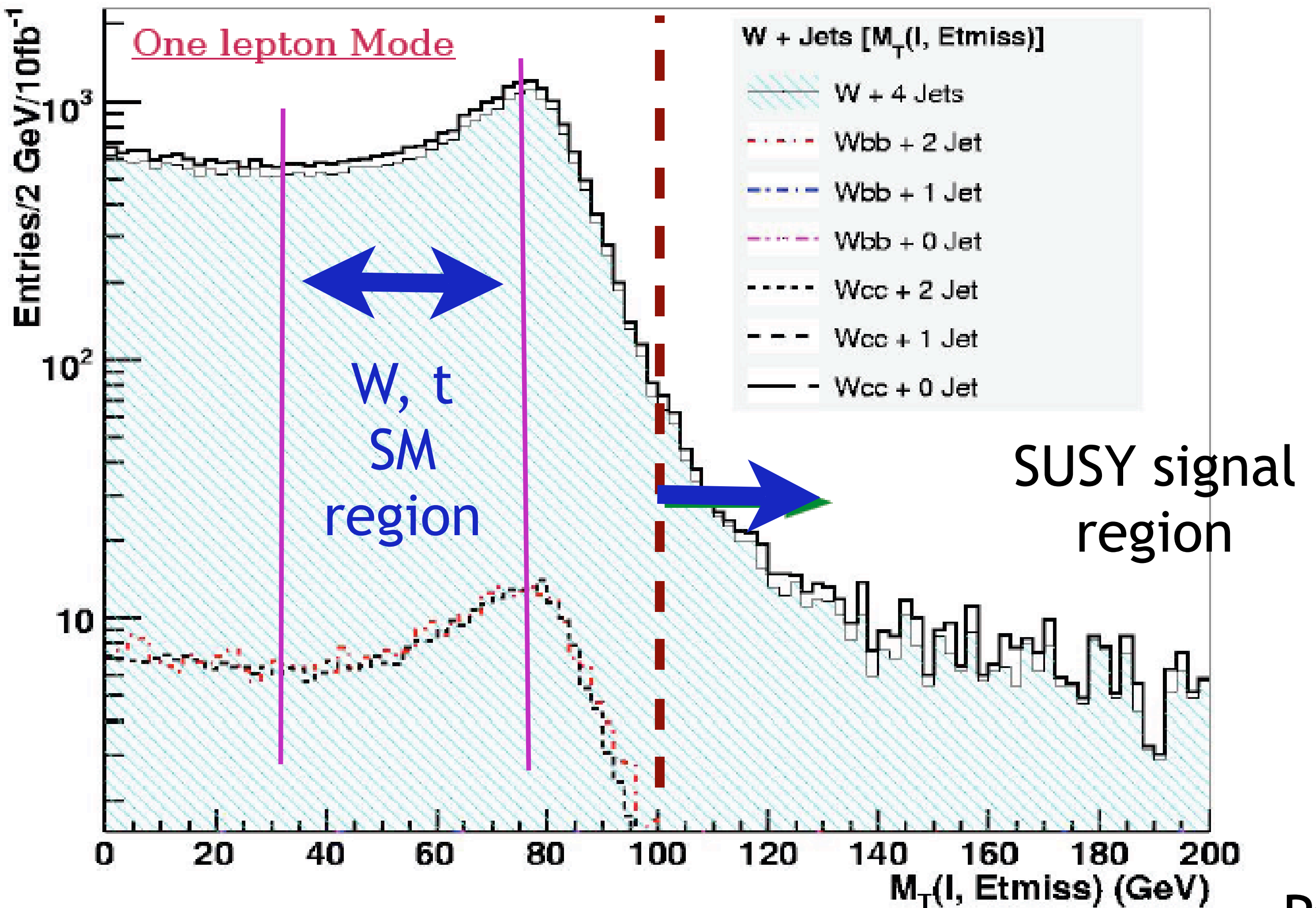


Before being applied to data in the signal regions, these codes need to be validated by comparison to data on W+jets and Z+jets.

Matrix elements to leading-order accurary will not have the correct normalization. This also will need to be fixed by comparison to data.



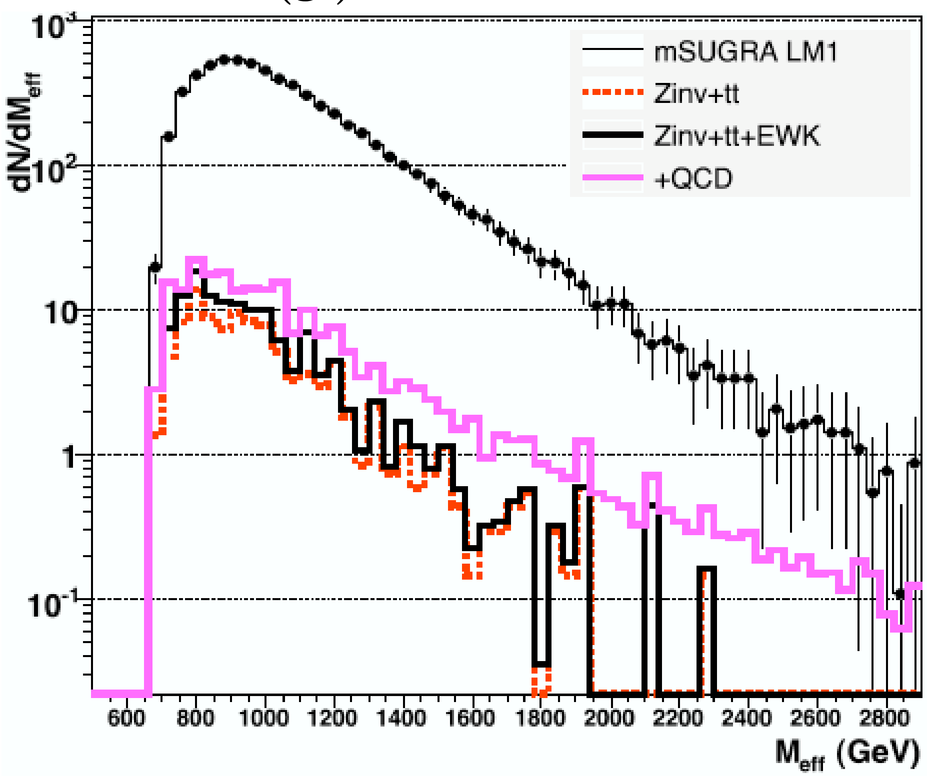
I do not know of comparable work on the $t\bar{t}$ + jets background. It is important to compare generators for this process also, and to devise a strategy for validating them against data.



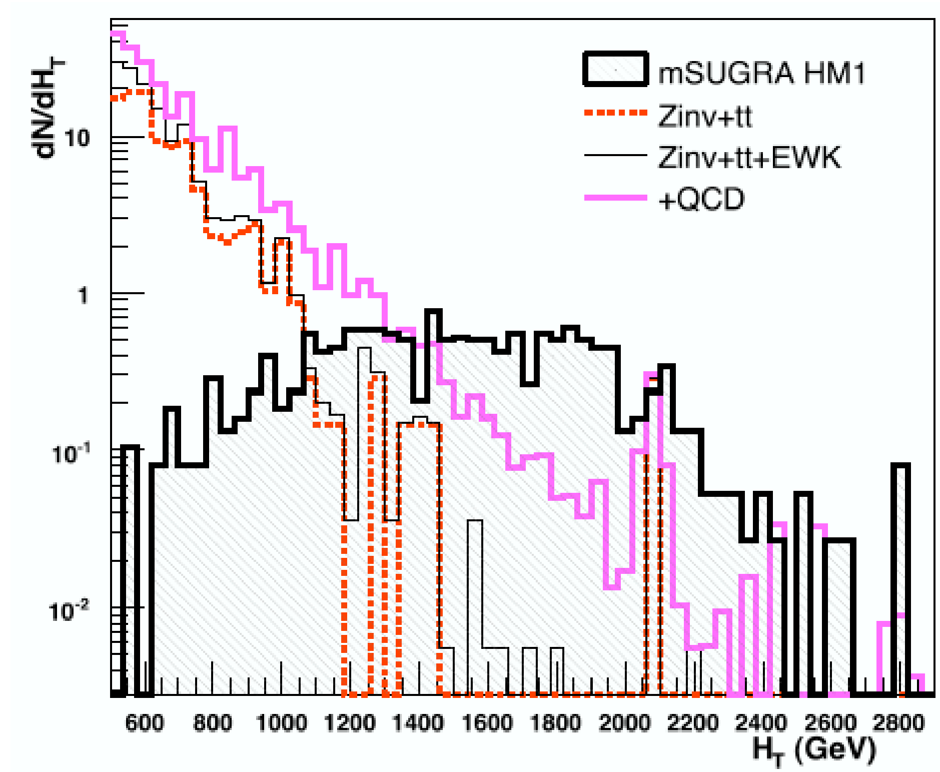
Padhi

Because of the strong dependence of LHC pair-production cross sections on mass, the search for anomalies can be trivial or very difficult. We should be prepared for the latter case.

$m(\widetilde{g}) = 600\ \mathrm{GeV}$



$m(\widetilde{g}) = 1890\ \mathrm{GeV}$



Yetkin and Spiropulu; CMS

Some pieces of the story are still missing:

Improvement with NLO QCD calculations ?   Calculation of K-factors and shape corrections to the above results ?

NLO QCD Monte Carlos exist for many 2→3 processes:

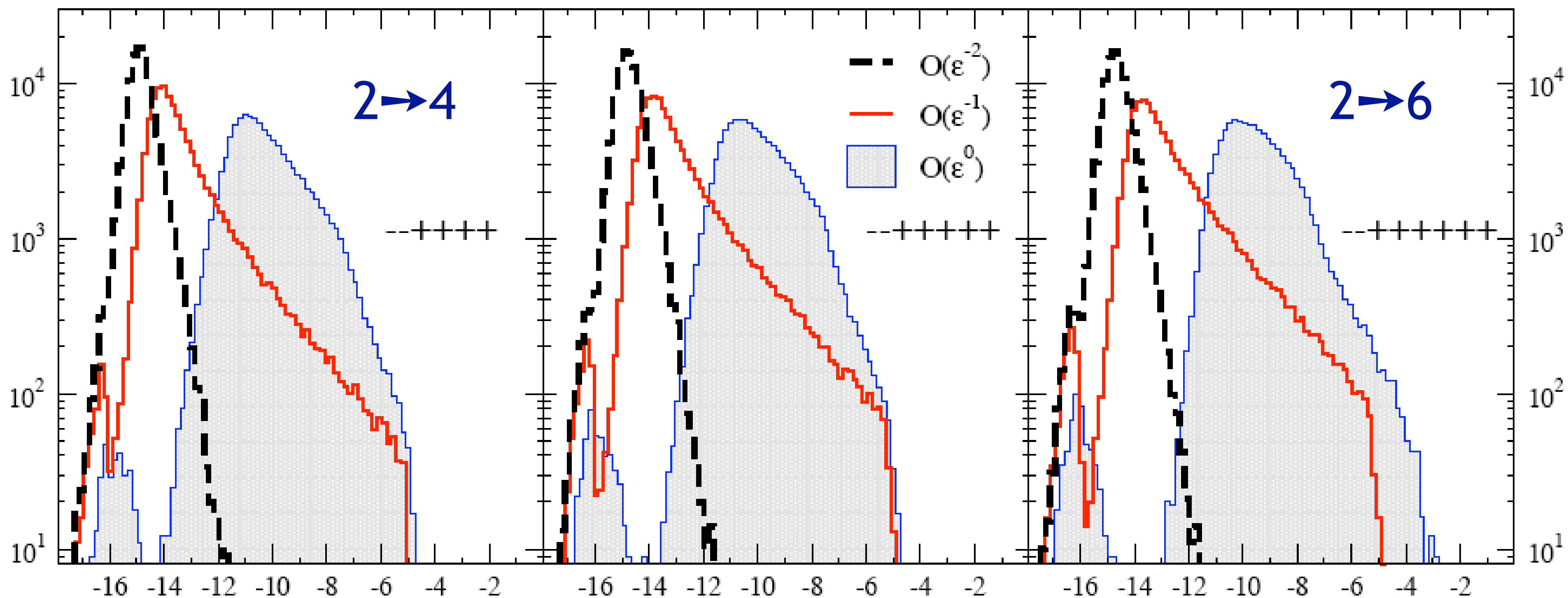
NLOJET   Z. Nagy   MCFM   J. Campbell and K. Ellis

MC@NLO   S. Frixione and B. Webber

Until recently there have been no NLO results for 2→4 processes. However, there has has been much progress in the past two years. The new results are based on the "unitarity method": Possible one-loop structures are enumerated in a well defined basis, and their coefficients are evaluated from tree amplitudes by (multiple) unitarity cuts. Papadopoulos will discuss this method at the workshop.

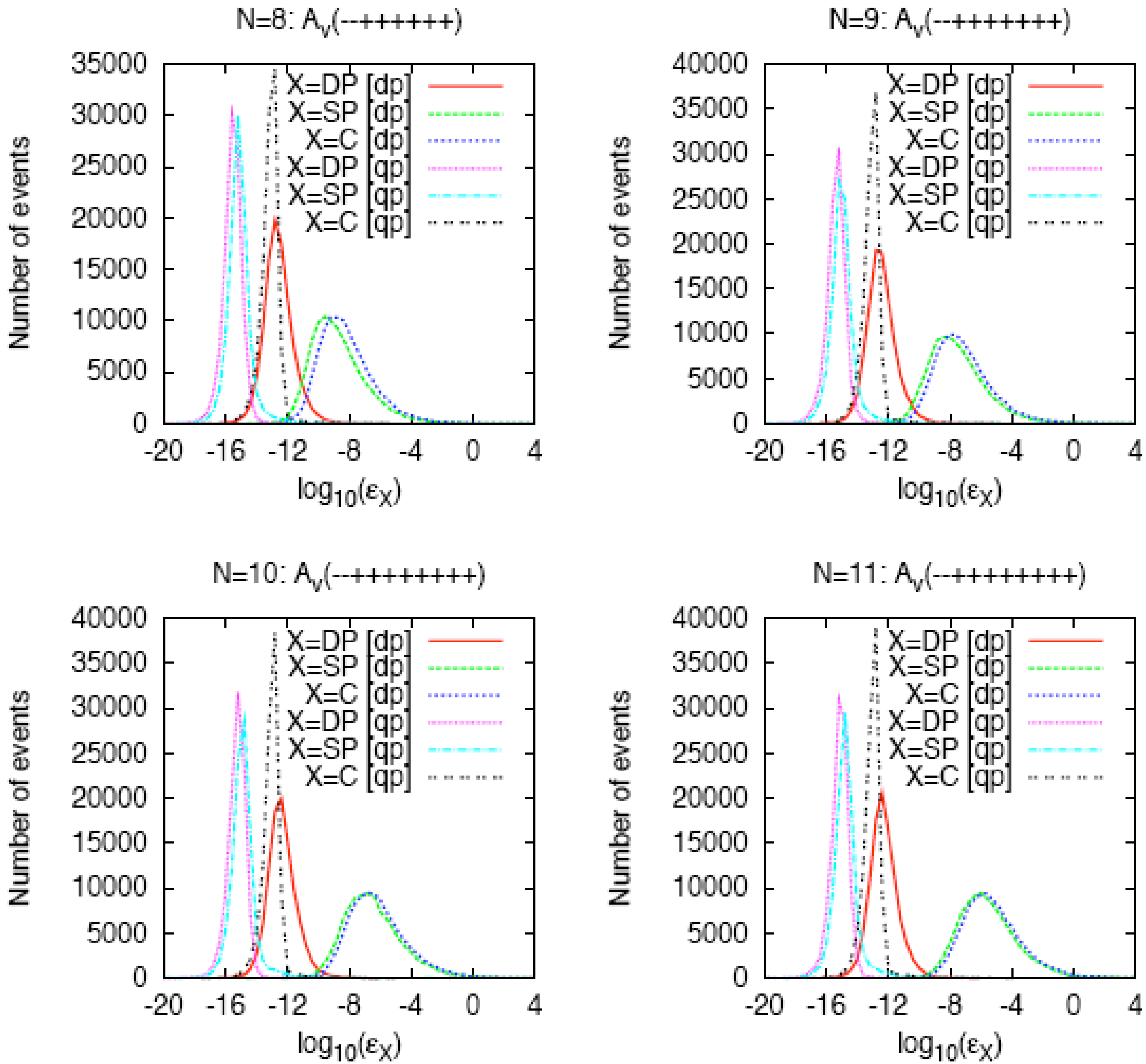
Two groups have gone far into the evaluation of 1-loop amplitudes for n-gluon matrix elements. The hope is that their methods generalize to automate more general multi-parton NLO calculations.

BlackHat: Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre



recursion formulae for 1-loop amplitudes

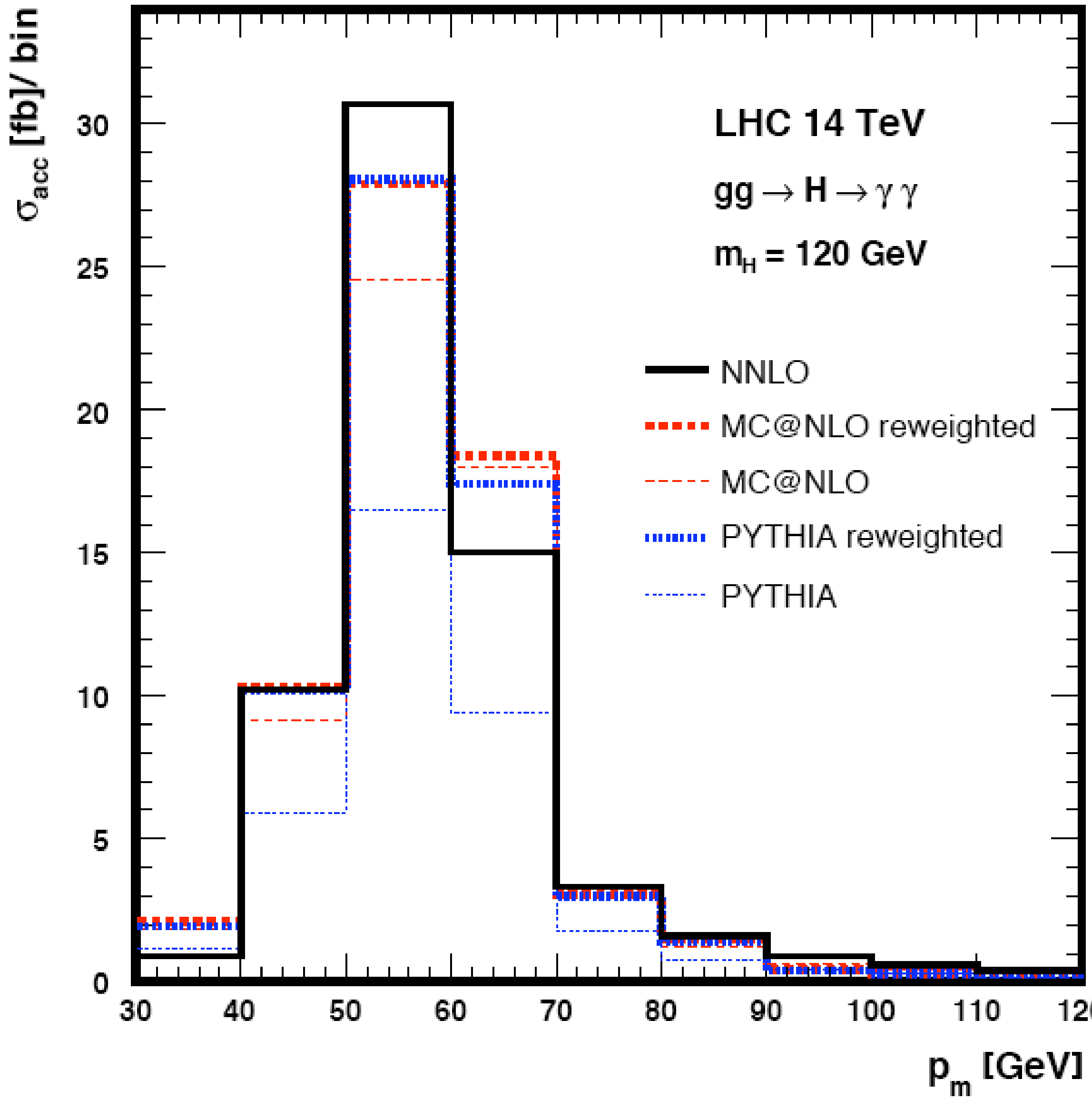
Rocket (Rucula): Giele and Zanderighi



direct evaluation of basis coefficients; results up to 20 g

At NNLO, results are only available for 2→1 processes. But there are important examples here, Drell-Yan and Higgs production.

Davatz et al. have used the exclusive NNLO calculations of Higgs production by Anastasiou Melnikov, and Petriello to reweight events from more standard Monte Carlo treatments.



$p_T(\gamma\gamma)$ spectrum in

$$gg \to h^0 \to \gamma\gamma$$

Next, assume that we have convinced ourselves that the Standard Model is violated, with signals in multijets + $\not{E}_T$, jets + leptons, etc.

How can we make a first analysis of the mass spectrum of new particles ?

I presume that the answer is not to fit the data to some constrained version of the MSSM. What if the correct answer is not supersymmetry ? What if an imperfect fit were obtained ?

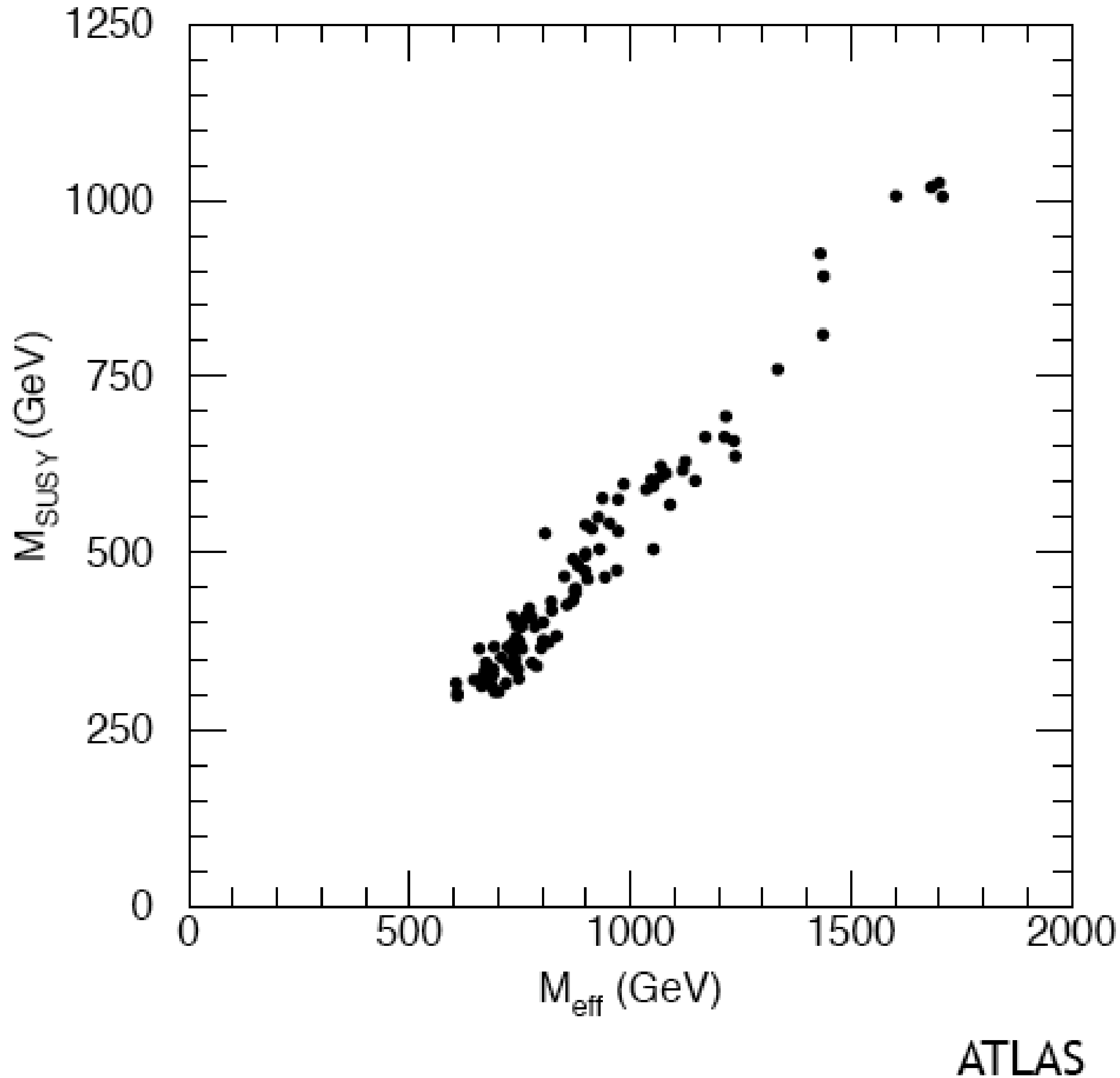
Could an LHC collaboration deal with this level of uncertainty ?
Could 2,000 collaborators keep the discovery secret ?

As a start, consider the overall transverse energy deposition in the detector. To remove noise from the underlying event, we might alternatively sum the ET of the hardest jets.

Hinchliffe, Paige, Shapiro, Soderqvist and Yao proposed the observable

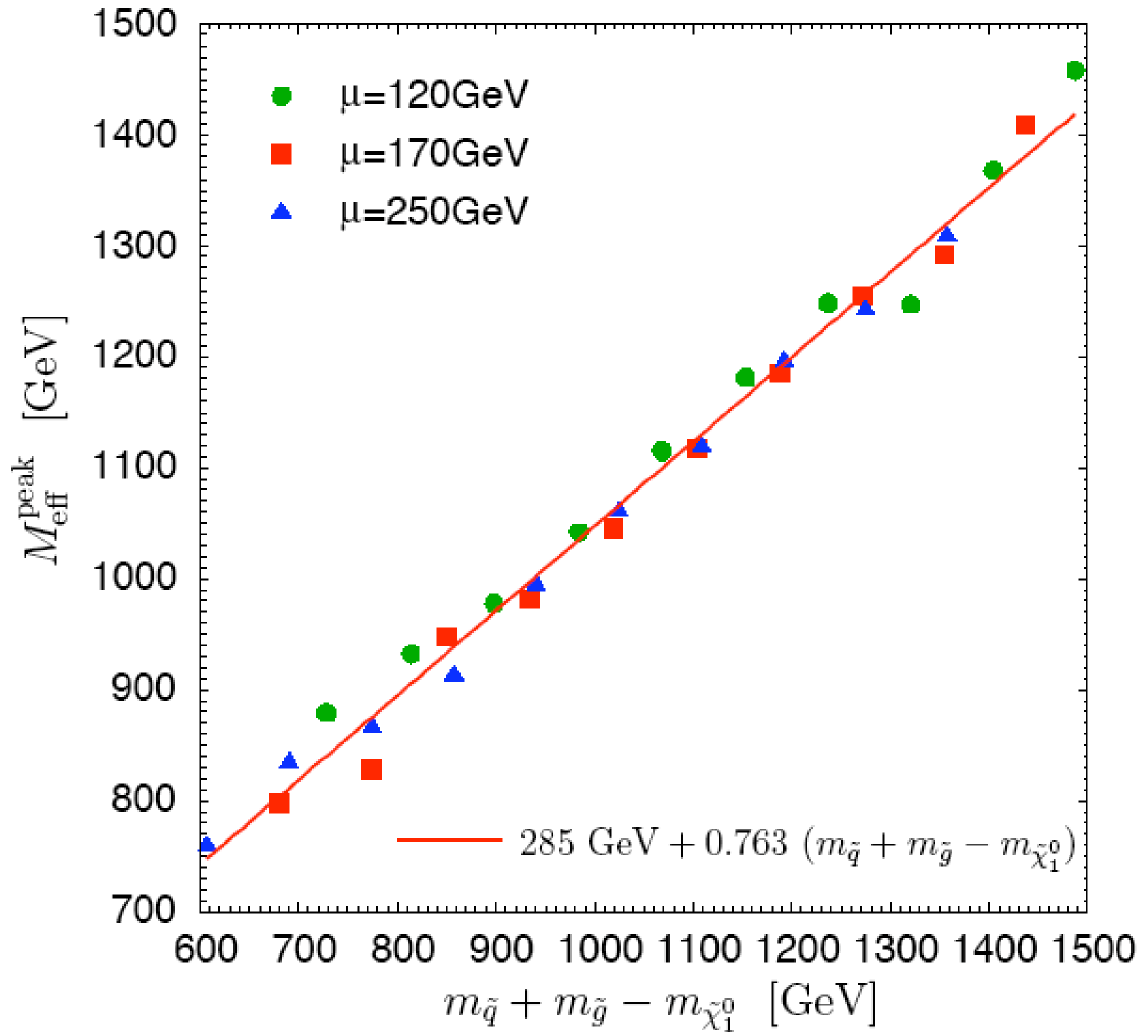
$$M_{eff} = \not{E}_T + \sum_{jets=1}^{4} E_{Ti}$$

and showed that, in a variety of 'mSUGRA' models, it correlates well with the smallest of the squark and gluino masses.



That analysis worked because it was applied to models with gaugino universality.

In models with small mass differences between the gluinos and the charginos and neutralinos, much of the transverse energy in the reaction is carried off by neutalinos and is invisible. But still, the quantity M_{eff} is a reasonable indicator of the mass difference between the directly produced and the final SUSY states.



Kitano-Nomura

These relations rely on the fact that most new particle production occurs close to threshold. The production cross sections turn on at threshold and then rise only slowly when $\hat{s} \gg 4m^2$, while parton luminosities fall off very rapidly.

Arkani-Hamed and the members of his group suggested that we take this idea and turn it into a tool.

Choose an appropriate set of candidate new particles

Approximate all production cross sections by constants

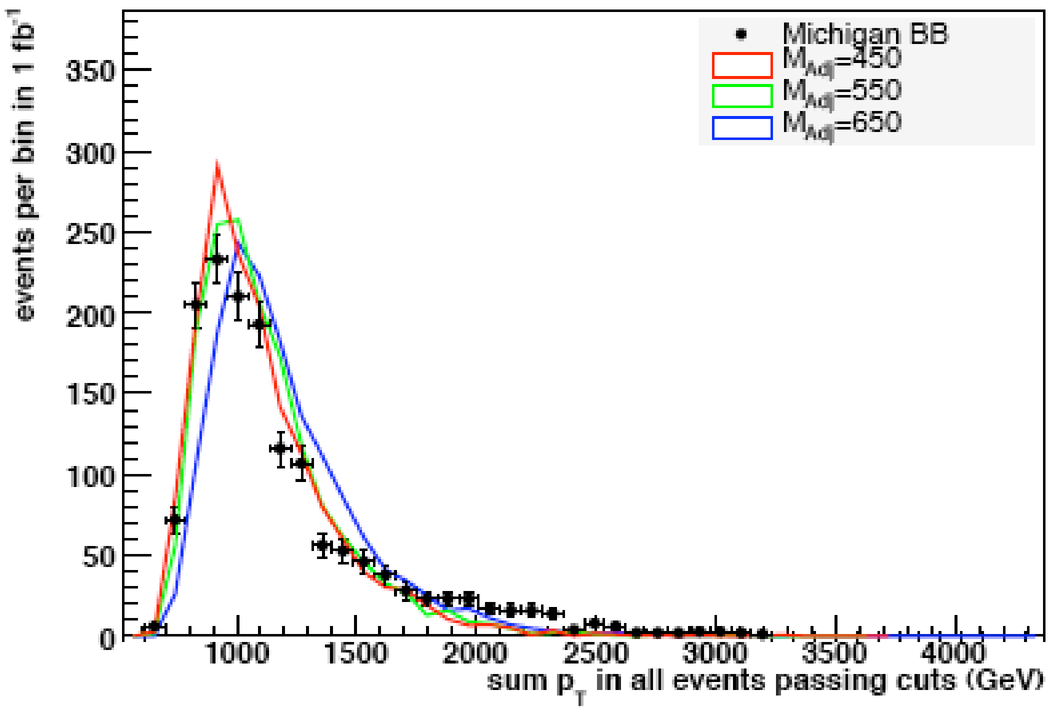
Choose appropriate decay modes for each particle. These might be 2-body decays or multi-body decays through effective operators. Approximate all decay matrix elements by constants.

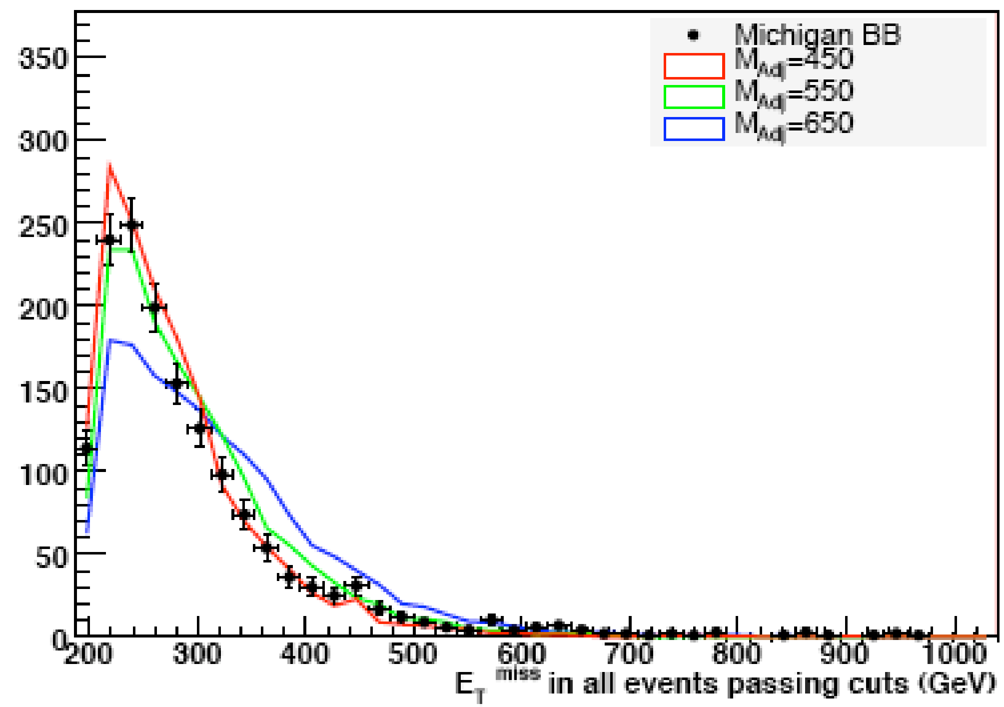
Fit the data to obtain the masses, cross sections, and branching fractions.

They refer to this description as an on-shell effective theory (OSET). The program is encoded in a software package called MARMOSET.

Two of the authors, Schuster and Toro, will present this program at the workshop.

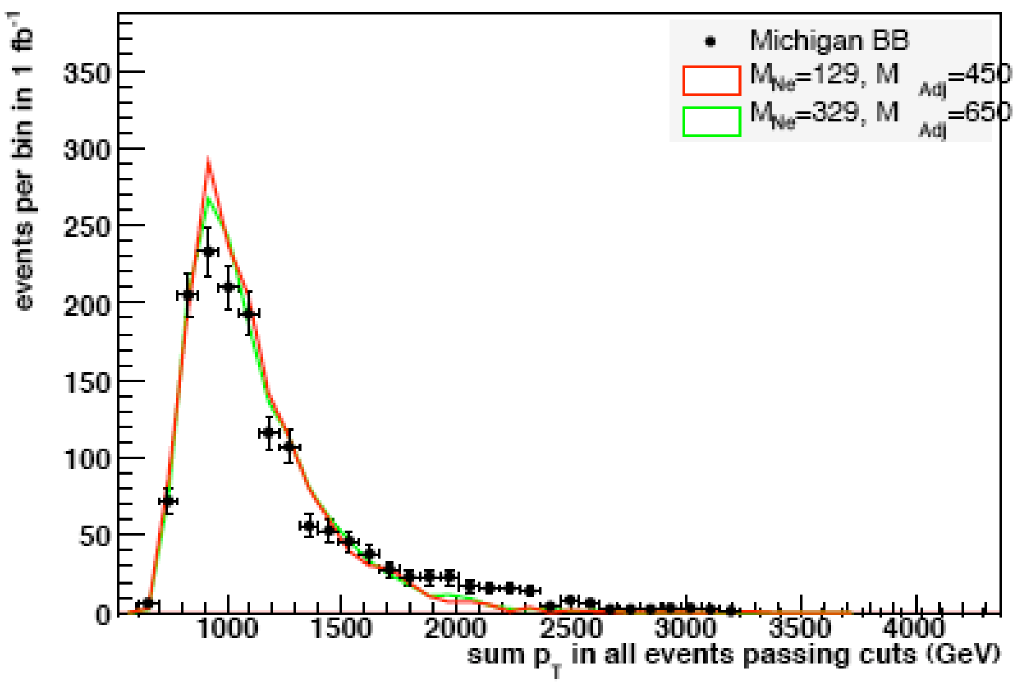
Here is a fit to the H_T and $\not{E}_T$ distributions for a specific SUSY model (red) and the corresponding curves (green, blue) when the gluino mass is shifted by 20%, 40%.

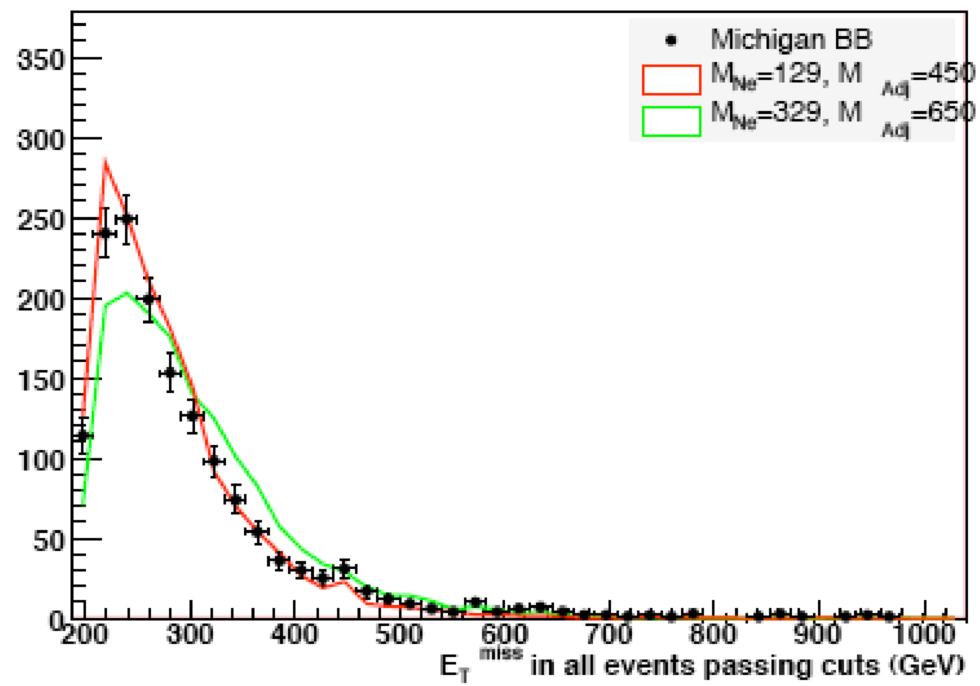




Here is the effect of shifting the gluino mass by 40%, keeping the gluino-neutralino mass difference fixed.

The H_T distribution is unaffected, but the $\not{E}_T$ distribution gives a poor fit.





The MARMOSET program can also be used to identify the most important decay chains and find the masses and quantum numbers of the intermediate states in these decays.

I would like to see ATLAS and CMS characterize anomalies observed in early data by fits to simple OSET models. These fits could be published and would provide significant information for the whole HEP community.

For any such fit, there are many complete BSM models that give results close to these OSET models in the published channels. These models have would have very different predictions for more exclusive cross sections and the rates of subdominant processes.

This is gives a path for winnowing the models and eventually finding the right physics explanation from the data.

I will talk later about complete BSM generators that implement all processes following from a Lagrangian. These are necessary for a full understanding of the sector of new particles.

In the present context, an interesting question is, can we get there from here ?

That is, we would like to have a code that implements OSETs, but then allows the replacement of

constant cross sections with correct QCD cross sections
dominant decay modes with all decay modes
isotropic decays with polarized decays

and, hopefully, replacement in a way that allows exploration rather than all-or-nothing.

This should be straightforward to achieve if the more complete generators will implement OSETs. MadGraph, e.g., has this as a project.

In the same context, we ought to talk about the assignment of tasks to modules.

Most authors of codes for physics beyond the Standard Model would prefer not to be concerned with low-energy QCD and hadronization.

And, we would like them not to be concerned. If codes give different results, we would like the differences to come from treatments of the new physics, not from a hadronization model that differs from a standard one.

There is now a simple technology that implements this program, called the Les Houches Accord.

The basic Les Houches Accord allows insertion of events from a parton level event generator into a parton shower generator such as PYTHIA, HERWIG, or SHERPA. Originally, the Accord was a common block transferring information between FORTRAN subroutines. But now, a stand-alone generator can write a text file that can then be read by one of these programs.

The file type is 'lhe' (actually an XML file), documented in

J. Alwall et al., hep-ph/0609017

One generates the initial and final 4-vectors and writes them, (with essential metadata) in an lhe file. The hadronization program will read it and carry out the rest of the process.

For example, here is the specification of a Drell-Yan event.

global event information -- no of particles   factorization scale

alpha and alphas

```
<LesHouchesEvents version="1.0">
              ...
<event>
 5 661  0.2119363E-01  0.7758777E+02  0.7818608E-02  0.1203148E+00
#
 1   -1    0    0  501    0   0.0000E+00  0.0000E+00  0.35806E+01  0.3580E+01  0.0E+00 0.    -1.
-2   -1    0    0    0  501  0.000E+00   0.00000E+00 -0.42030E+03  0.4203E+03  0.0E+00 0.     1.
-24   2    1    2    0    0   0.000E+00   0.00000E+00 -0.41672E+03  0.4238E+03  0.775E+02 0.  0.
 11   1    3    3    0    0   0.3765E+02  0.45351E+01 -0.16391E+03  0.1682E+03  0.000E+00 0. -1.
-12   1    3    3    0    0 -0.3765E+02 -0.45351E+01 -0.25283E+03  0.2556E+03  0.000E+00 0.  1.
</event>
```

PDG codes   status   parents   color flow   4-vector   mass   spin

The author of a BSM program should make a definite choice for where his or her responsibility should end and where that of PYTHIA or another hadronizer should begin. For example,

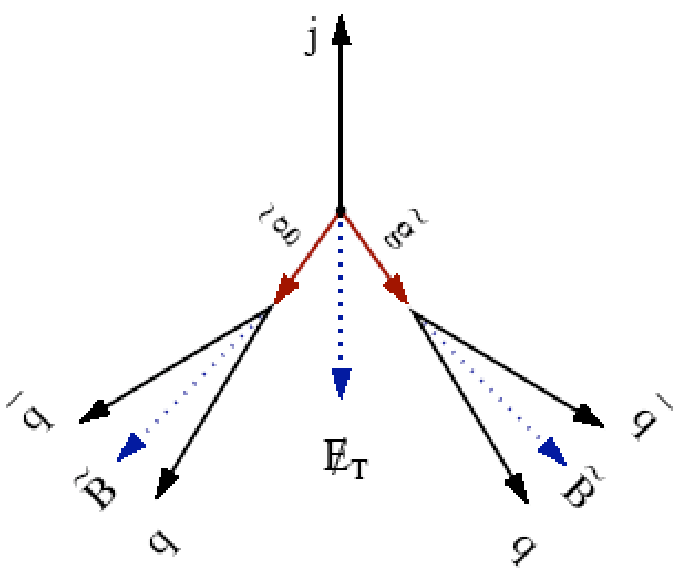
The BSM generator could create particles known to PYTHIA (top quarks, Ws, MSSM states), and hand them to PYTHIA to be decayed isotropically.

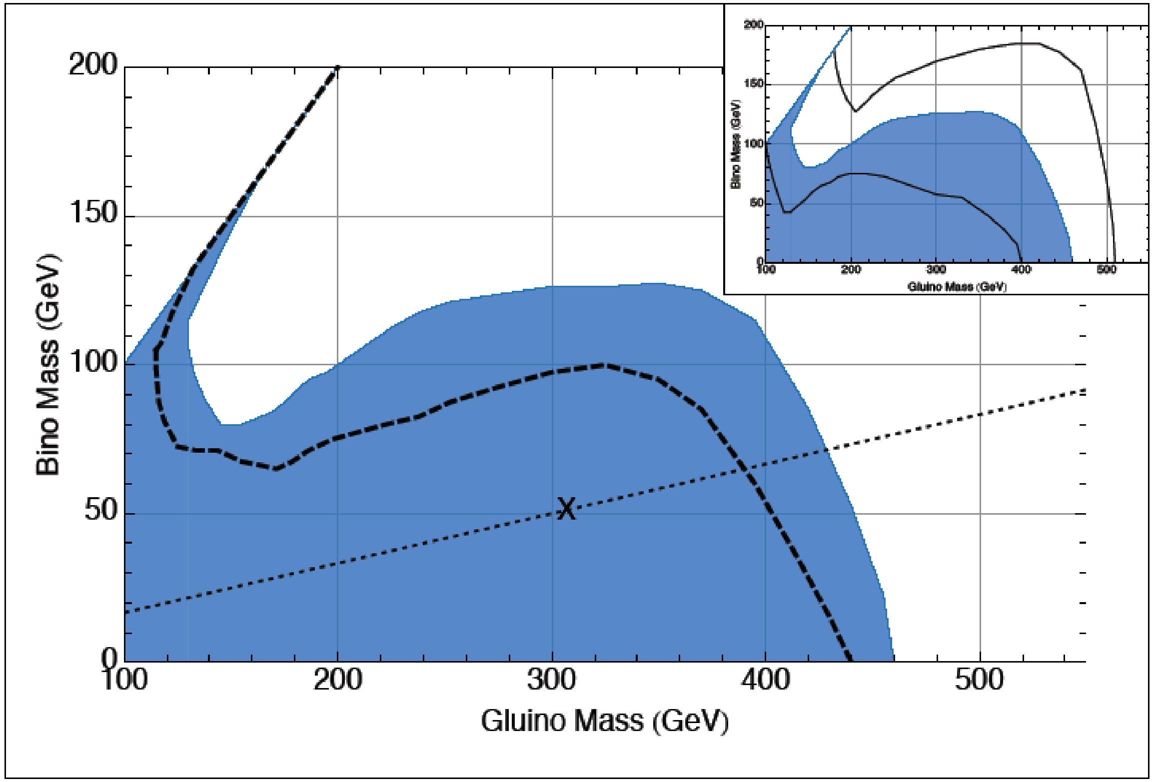
The BSM generator could create BSM particles and decay them with correct spin correlations. The products of these decays could be handed to PYTHIA.

The BSM generator could add QCD effects, such as initial- and final-state radiation. This could be done with methods that go beyond the parton shower, using matrix-element matching. The final-state BSM particles and gluons are then handed to PYTHIA at a low value of the factorization scale for the treatment of low-energy QCD and hadronization.

The implementation of matching in Madgraph is done technically in this way. The implementation is sufficiently flexible that one can turn on matching in signal process.

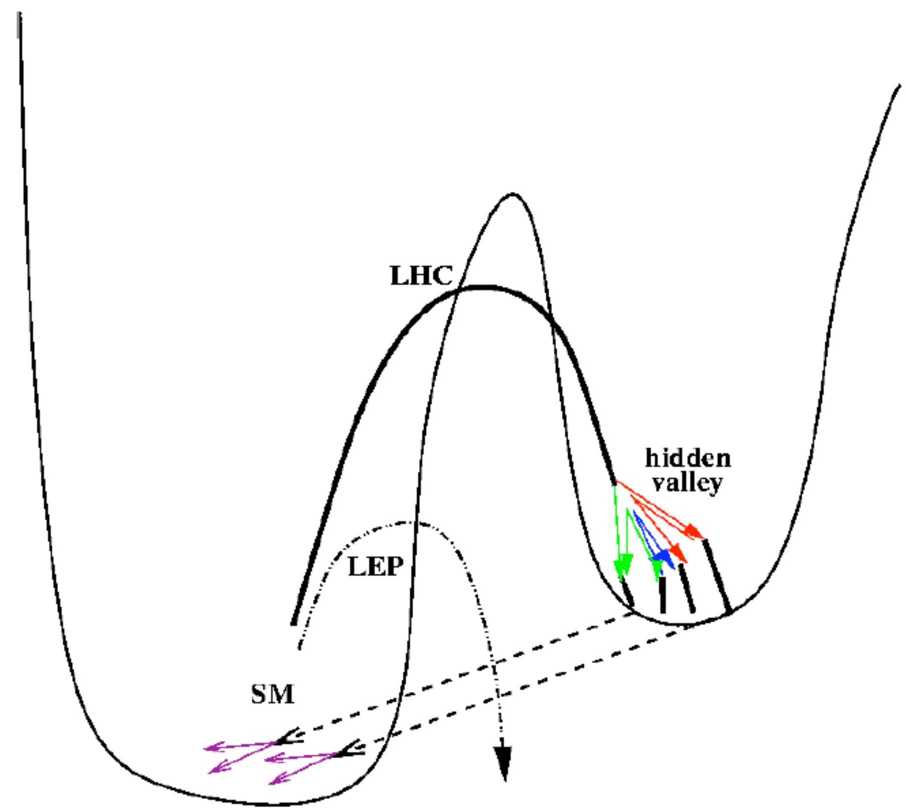
Alwall, Le, Lisanti, and Wacker have recently used this technique with Madgraph to study SUSY searches at the Tevatron for arbitrary ratios of $m(\widetilde{b})/m(\widetilde{g})$, even to a ratio of 1. At the limit, initial state radiation creates a significant signal, but this must be computed exactly, not simply in the parton shower approximation.





Eventually, we reach models so far away from the generic case that special simulation algorithms are required.

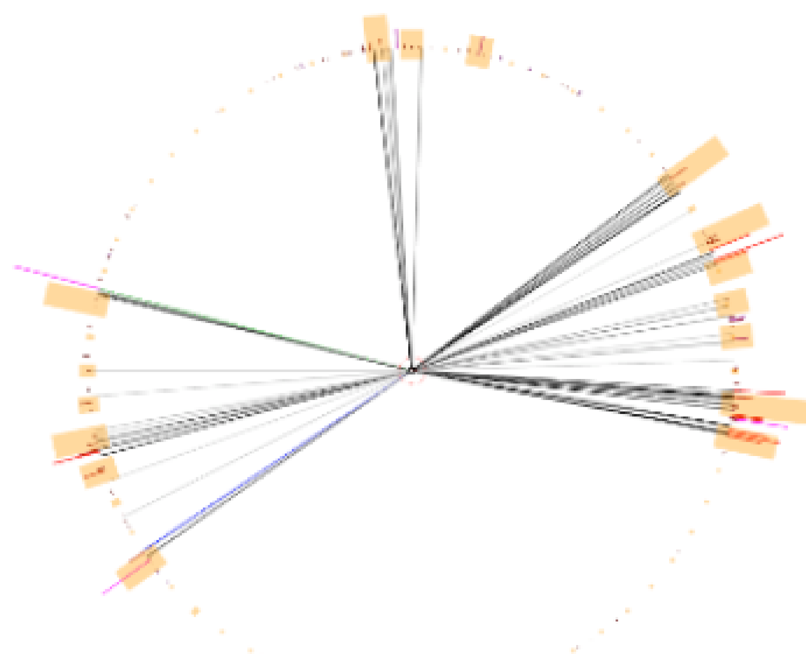
As an example, consider the 'hidden valley' models of Strassler and Zurek. The idea of these models is that there exists a new strong interaction sector that is hidden in the sense that it has no direct full-strength SM interactions. The new sector may be reached by a quark-antiquark annihilation to a Z' or by mixing of the familiar electroweak bosons with new ones.



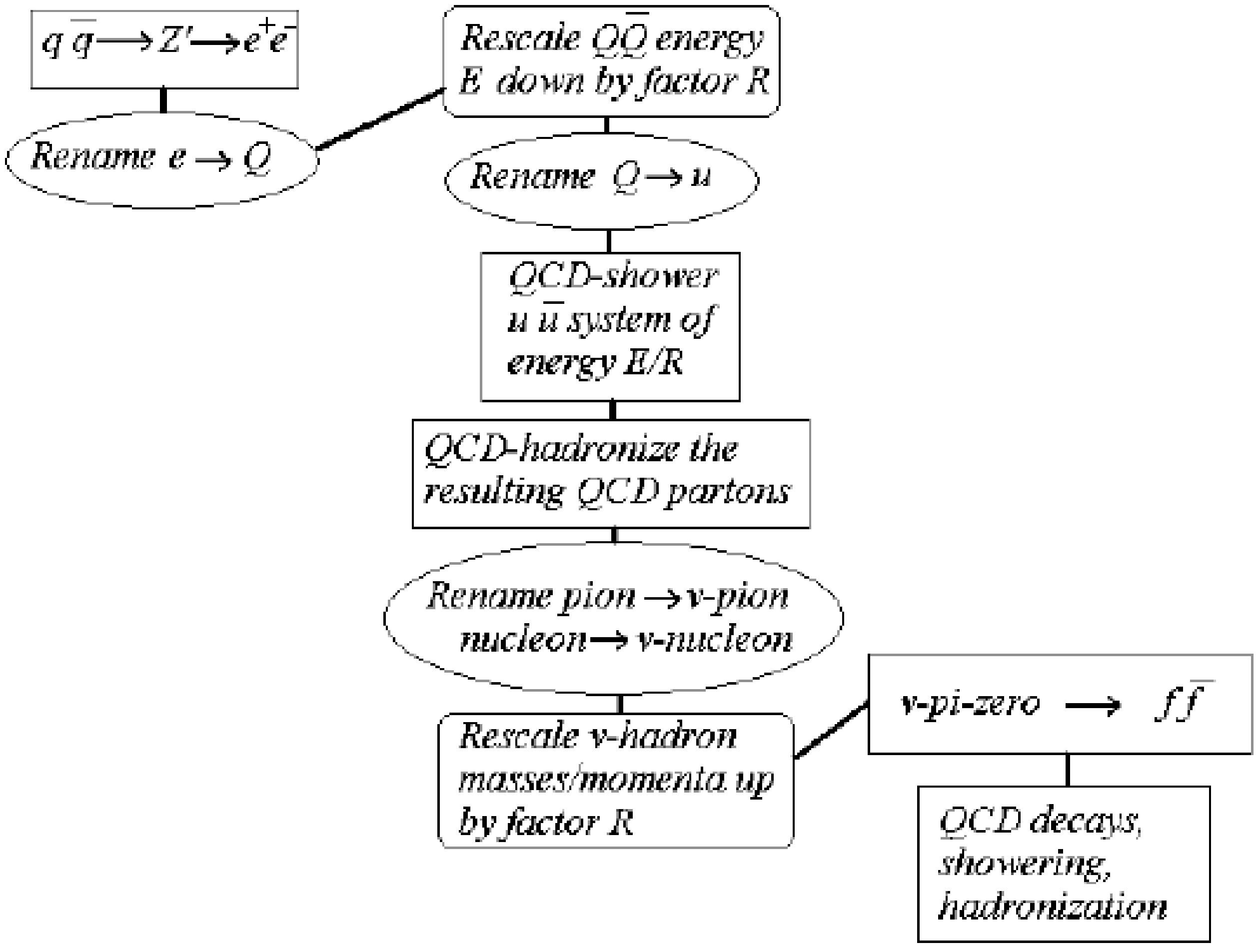
The model becomes especially interesting when the new strong interactions have a QCD scale at tens or hundreds of GeV. Then the new sector undergoes hadronization, creating a large multiplicity of hidden hadrons. These may decay back to the SM sector through such modes as

$$\pi^0 \to A^0 \to b\bar{b} \, , \rho^0 \to Z' \to \mu^+\mu^-$$

This yields a large multiplicity of heavy flavor jets originating from vertices with long lifetimes. Many of the hidden hadrons decay invisibly, so the events also have unbalanced mometum.



How do you model this ? Strassler has hacked PYTHIA to implement the following algorithm:



This Monte Carlo has been used by ATLAS to understand whether these events will be triggered on, stored, and analyzed.
You might think about other scenarios that require a comparably nonstandard Monte Carlo treatment.

Now let's return to the main road.

Once we have an idea of what the complet BSM theory might be, we would like to simulate it as realistically as possible.

This will be a major theme of this workshop.

For well-defined models such as the MSSM or the two-Higgs-doublet model, there exist detailed codes with one-loop electroweak accuracy.

For more general BSM models, ideally, we should be able to achieve tree-level accuracy automatically. We should the Lagrangian, push a button, and have a machine compute all Feynman diagrams for a specified process. Durr, Christensen, Pukhov, and others will present schemes that implement this idea.

For the well-defined models, it is important to analyze the data in terms of the full parameter set of this model.

This idea has been abused most in SUSY analyses. The general MSSM (even flavor- and CP-conserving) has 24 parameters, but most analyses restrict themselves to the 4-parameter subspace of mSUGRA or the CMSSM.

Over the past ten years it has become clear that

1. There are many interesting SUSY models with very different physics from mSUGRA (e.g. models with soft terms that induced by non-GUT-singlet F terms, general gauge-medidated models, 'mirage mediation' of Choi, Jeong, and Okumura)

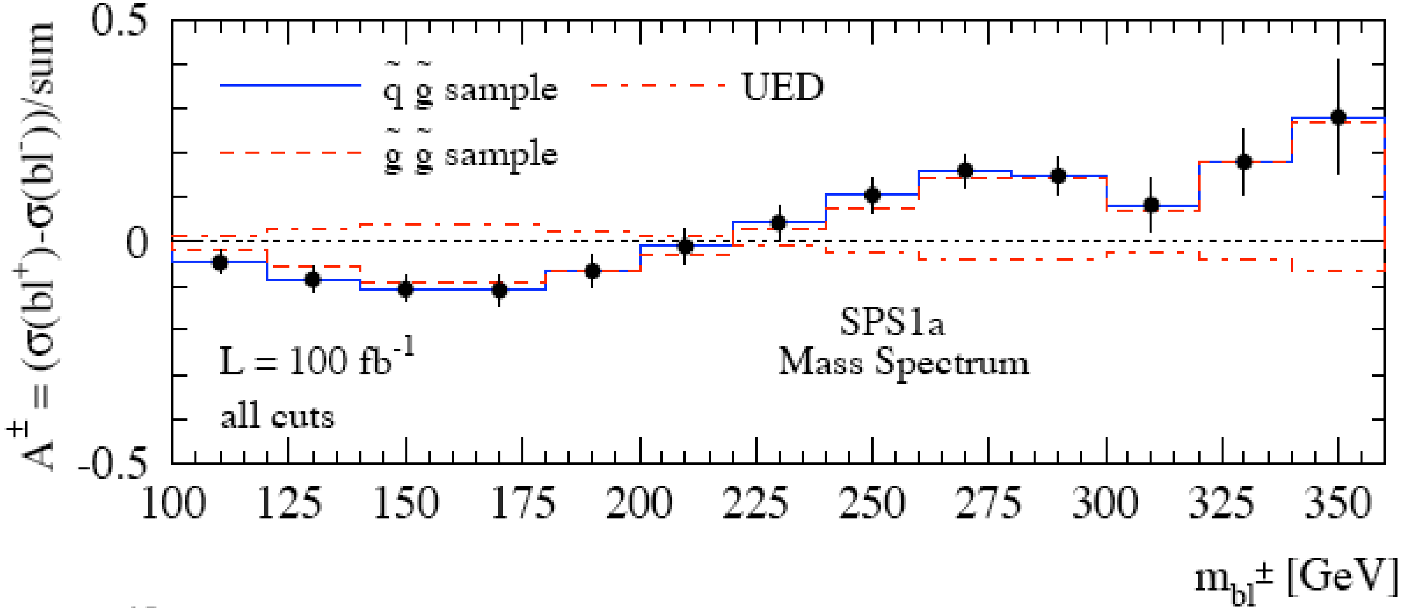
2. The mSUGRA subspace is so constrained by

$$m_h \ , \ b \to s\gamma \ , \ \Omega_{DM}; \ m(\widetilde{C}^+), m(\widetilde{\tau}) \text{ from LEP}$$

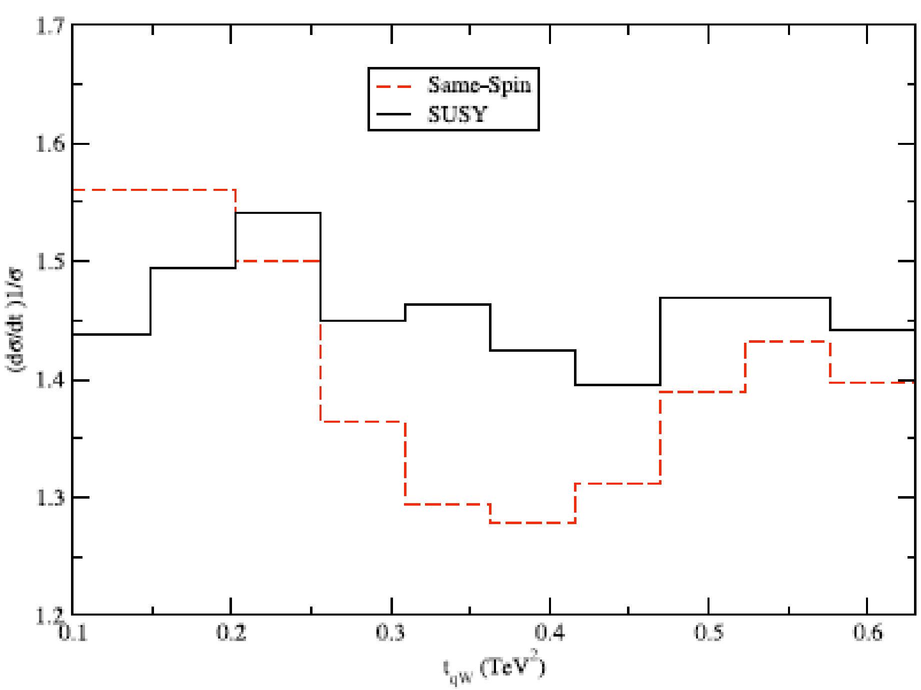
as to be almost excluded, while simple variations of the soft parameters open large allowed regions.

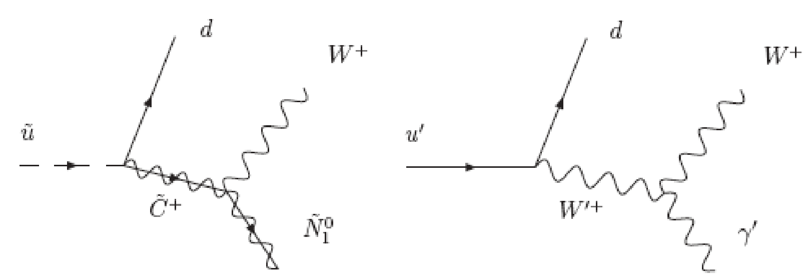
Talks at the workshop on SFitter (by Turlay) and on the technique of Markov Chain Monte Carlo (by Hamann) will provide methods for controlling such large parameter spaces.

There are examples of spin correlations that test the spin or chirality assignments of BSM particles:



Alves-Eboli-Plehn





Wang-Yavin

But much more work is needed on this issue, particularly in dealing with combinatoric ambiguity of reconstructing a decay within a complete BSM event.

This requires simulation codes that allow a very large number of partons, with spin correlations among them correctly described, before handing the simulation over to PYTHIA or HERWIG.

In this context, there are issues for generators that seek to maintain full spin coherence:

HERWIG approach:

use helicity decay amplitudes normalized, at each stage, to $\sum |\mathcal{M}(h_A \to h_B h_C)|^2 = 1$

COMPHEP, MadGraph approach:

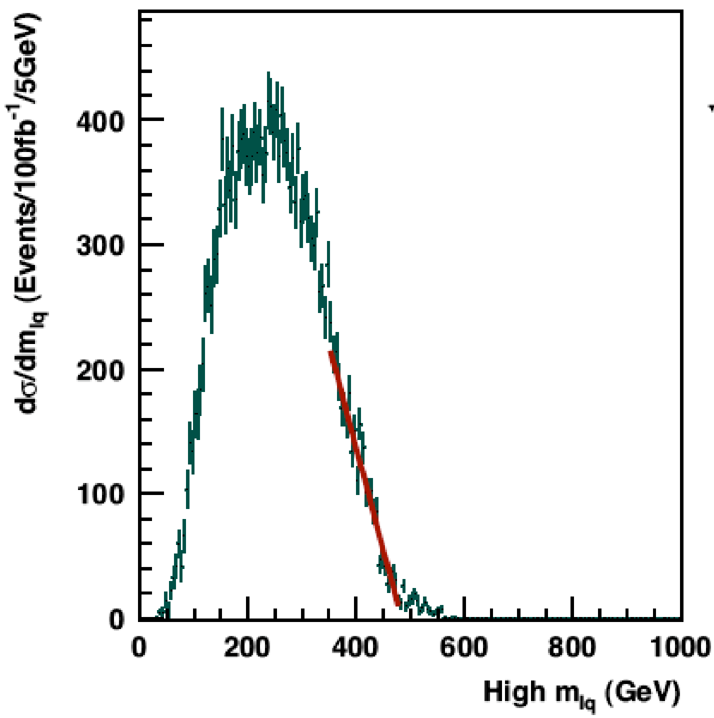
compute complete Feynman diagrams, using the zero-width approximation for propagators

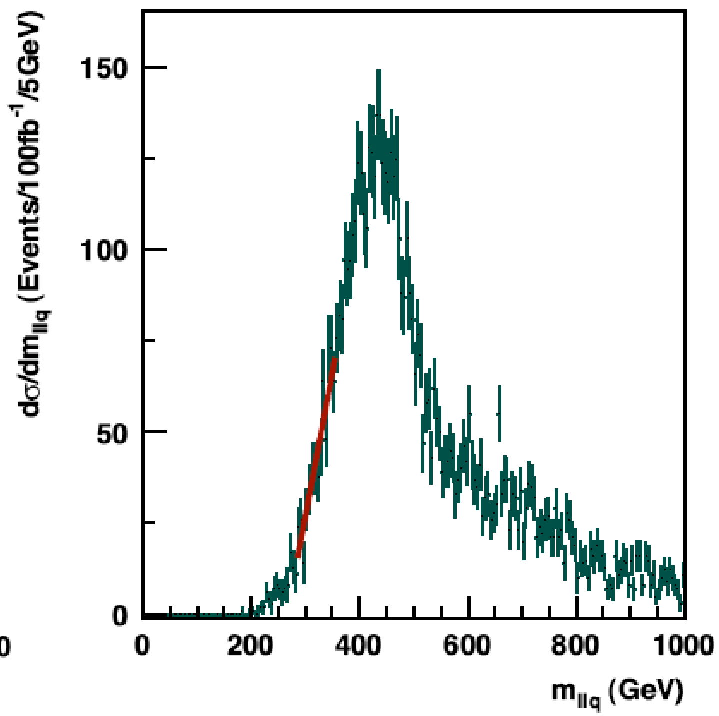
BRIDGE approach: (Meade and Reece)

use helicity cross sections (e.g. from MadGraph), use MadGraph or another calculator separately for decays

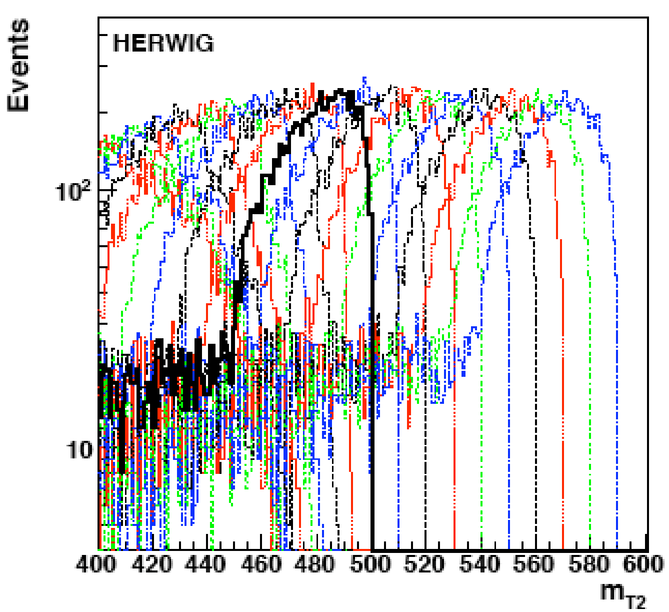
The BRIDGE approach is very convenient, but it is an approximation in treating the BSM particle helicity states incoherently. For example, $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta}(t \to \ell^+) \neq \frac{1}{2}(1+\cos\theta)$

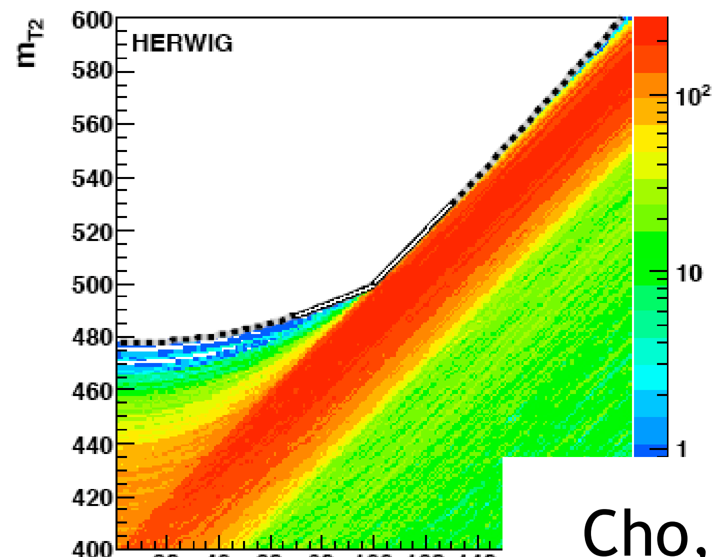
Again at this finer level of detail, it is necessary to ask whether QCD needs to be included at a high level of accuracy than that parton shower.   At this level, we are discussing precision determinination of particle masses. There are now beautiful methods to extra masses from kinematic endpoints or other features. For accuracies below 10%, we would like simulations to correctly include the rounding of these features by QCD.





Allanach, Lester, Parker, Webber





Cho, Choi, Kim, Park; Barr, Gripaios, Lester

Finally, I would like to briefly comment on dark matter.

At this workshop, we will hear from Edsjo and Pukhov about the current status of the codes DarkSUSY and MicrOmegas that compute the cosmic density of a dark matter neutralino. MicrOmegas can in principle do this computation for the dark matter particle of any Langrangian.

Their two groups and others have taught us that the physics that establishes the dark matter density can be very complex. For example, in SUSY, the following reactions, and many more, can compete:

$$
\begin{aligned}
N + N &\rightarrow \ell^+ \ell^- \\
N + N &\rightarrow W^+ W^-, Z^0 Z^0 \\
N + N &\rightarrow A^0 \rightarrow b\bar{b} \\
\widetilde{\tau} + N &\rightarrow \gamma + \tau \\
\widetilde{\tau} + \widetilde{\tau} &\rightarrow \tau + \tau \\
C^+ + C^- &\rightarrow W^+ W^-, Z^0 Z^0
\end{aligned}
$$

It will be a long time before we can predict Ω_{DM} from collider data.

But in next few years, there are very exciting prospects for the understanding of dark matter.

If dark matter is composed of a weakly interacting massive particle (WIMP) with mass of the order of 100 GeV:

This particle should be seen as the missing-energy particle at the LHC.

This particle should be observed in the next-generation direct detection experiments (e.g. super-CDMS, LUX) sensitive to 10 zeptobarn Np cross sections.

This particle might be observed in indirect detection, from its annihilation products of gammas (GLAST) or positrons (PAMELA).

It is important to ask, how can we put together the data from these experiments to test and apply the WIMP model ?

An obvious goal is to measure the WIMP mass with all three techniques and see if the results are the same. A comparision to 20% accuracy might be possible.

Here is a second question: Can we learn from LHC data whether the annihilation of dark matter particles is dominantly

S-wave, as in $N + N \to W^+W^-$ or $N + N \to A^0 \to b\bar{b}$

P-wave, as in $N + N \to \ell^+\ell^-$

or unimportant, as in coannihilation scenarios ?

In the first case, we have $\sigma_{NN} v \approx \ 1 \text{ pb}$ to a good enough accuracy that this result is useful in mapping dark matter in the galaxy. In this other cases, we expect no indirect detection signals, and astrophysicists can make use of that information.

For the answer, we only need a qualitative, not a quantitative, result.

Is it possible to answer this from gross features of the LHC data, before we have worked out the complete particle spectrum ?
This is an interesting question to think about.

I have now reviewed many aspects of the physics and simulation of new particles from beyond the Standard Model.

We will learn much about these particles in the next few years.

The results to be described at this workshop will play an important role in that development. So, let's learn all we can !