The Descent to Supersymmetry

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In this audience, there is little doubt about the truth of supersymmetry as the description of the next energy scale in physics.

For example, as it says in Gordy's book **Supersymmetry**:

"The main goals of collider experiments now are finding superpartners and Higgs bosons, or (if somehow we are on the wrong track in spite of the indirect evidence and strong theoretical arguments) showing that the superpartners and Higgs bosons do not exist."

The LHC will give us an energy reach well beyond the mass scale of electroweak symmetry breaking, and a design luminosity corresponding to $10^4 - 10^5$ events/yr.

So the discovery of supersymmetry is not just the hope for this machine; it is the expectation.

But of course, not everyone sees it this way. And, if we want to claim that supersymmetry - or any other new fundamental framework - is realized at the LHC, we have to overcome a substantial burden of proof.

I see this as the most important problem in high energy physics.

If, as a community, we make a mistake, either by failing to discover what is there or by announcing a discovery that is not there, it could be the end of high energy collider physics.

An enormous effort has been devoted to this question. Many of the important contributors are here.

But I feel that this is a question that is too important to be left to the experts.

In this talk, I would like to explain how I like to think about this problem, and why I am optimistic that it can be solved.

In this lecture, I will concentrate on the most standard realization of the MSSM: squarks and gluinos below 1 TeV, gauginos or Higgsino at 100-200 GeV, R-parity conservation.

In this regime, SUSY events are complex, with long decay cascades.

More models than SUSY have this general set of signatures. Many models with WIMP dark matter fit into this general scheme.

Really proving that supersymmetry is there is an enormous challenge. Supersymmetry gives at best a tiny fraction of the total event sample at the LHC, fractions of a part per billion of the total rate.

Bob Cousins put the challenge in the following way:

For a discovery, we require a 5σ deviation from the Standard Model. This means that we must understand the tails of distributions to down to fluctuations of probability 10^{-4}. But tails of distributions at the LHC are generated by very complicated processes. Can we really understand them to the level of these small probabilities ?

To identify the events characteristic of supersymmetry, we must make the descent into the Standard Model background. Here are some of the levels that must be crossed:
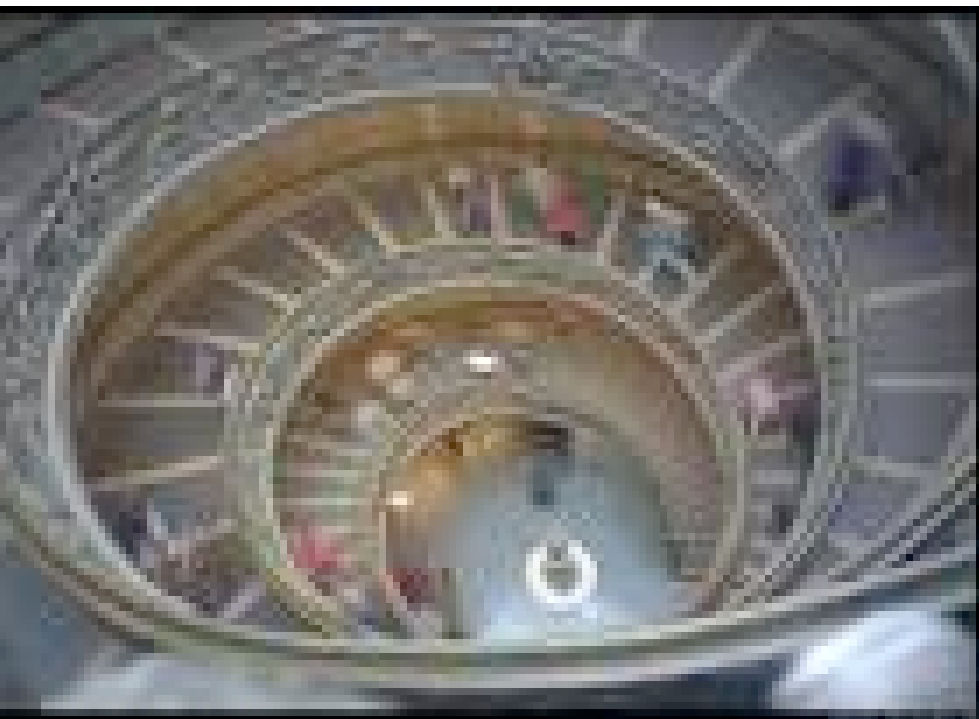
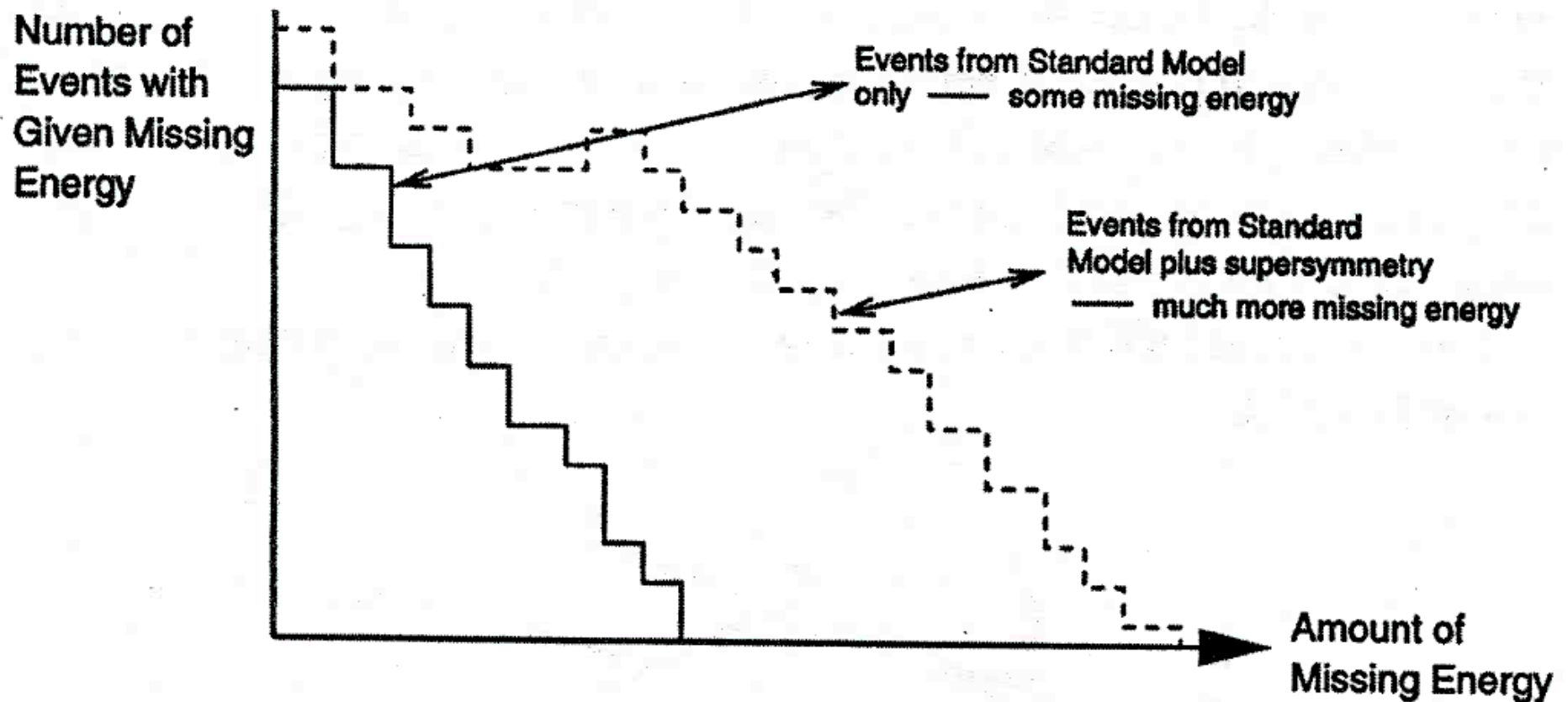$$\sigma_{tot} \qquad 100 \text{ mb}$$

$$\text{jets w. } p_T > 100 \qquad 1 \ \mu\text{b}$$

$$\text{Drell-Yan} \qquad 100 \text{ nb}$$

$$t\bar{t} \qquad 800 \text{ pb}$$

$$\text{SUSY } (M < 1 \text{ TeV}) \qquad 1\text{-}10 \text{ pb}$$

The generic signature of SUSY event is missing transverse energy.

This is expected to be a robust discriminator, especially against multi-jet QCD events.

Here is the figure from Gordy's book:

Here is a recent quantitative evaluation by Sanjay Padhi, using ALPGEN and the ATLAS full simulation code
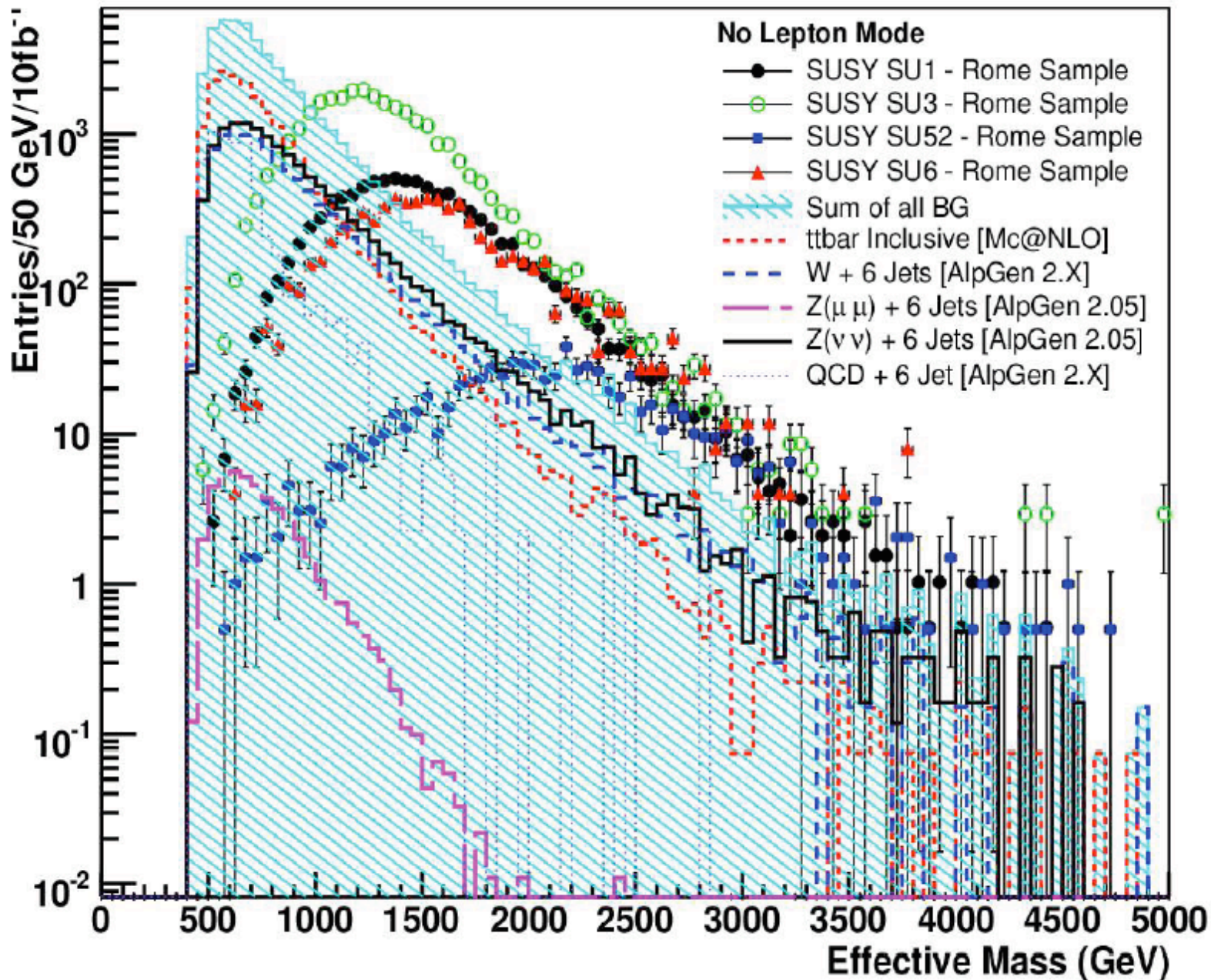
Meff distribution subject to

$$\not{E}_T > 100$$
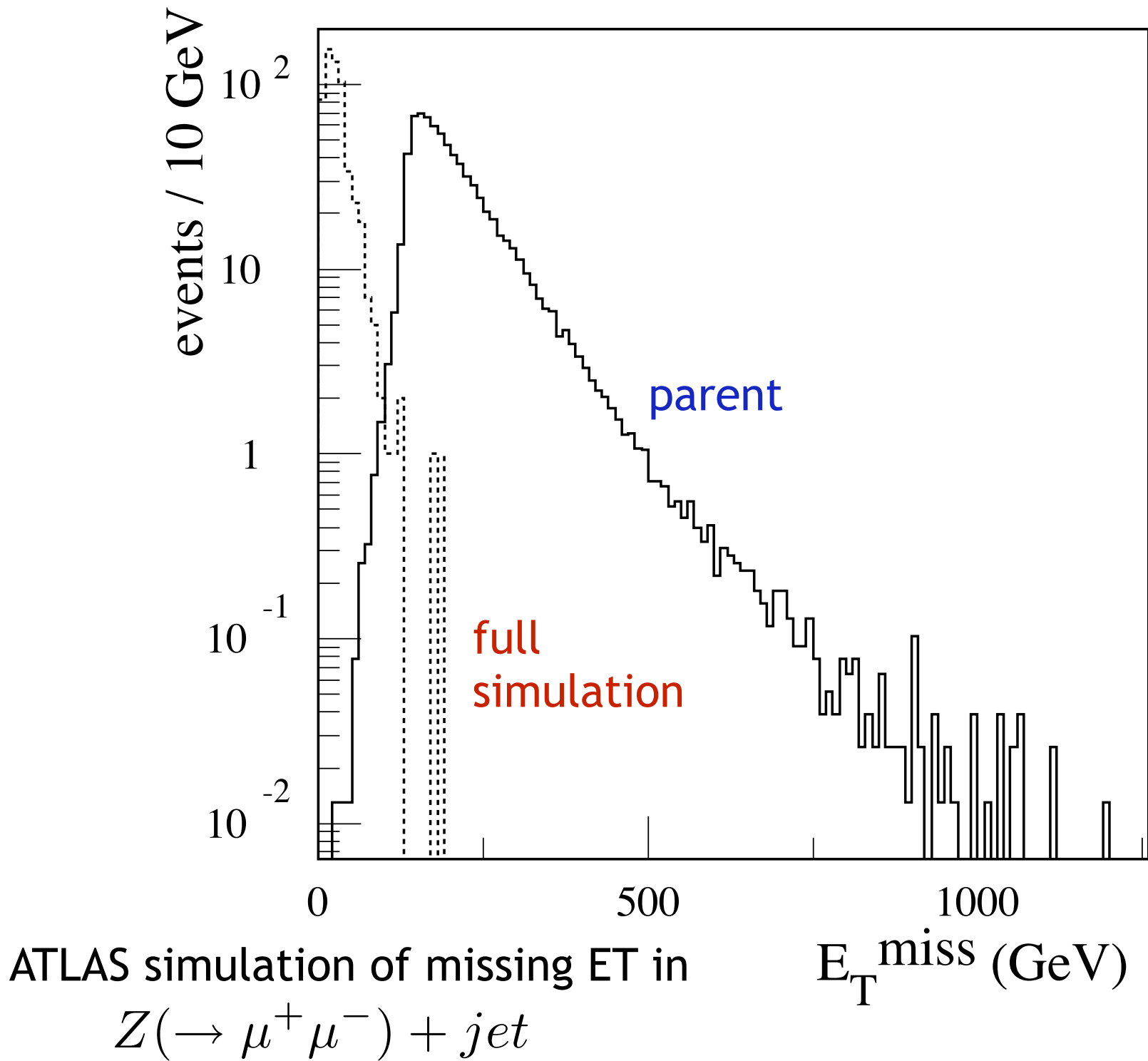4 jets, 2 w.
$$E_T > 100$$

Padhi's figure gives reason for optimism. This is not because of the position of the SUSY curves; those are chosen to give relatively large cross sections.

Rather, they motivate that the background is dominated by the production of high-mass standard model particles: W, Z, and t. This makes it practical to formulate an explicit model of the background to SUSY searches that can be validated by data.

We need a rather complete understanding of the detector to get to this point, but the experimenters expect to have this.

events / 10 GeV

10^2

10

1

10^{-1}

10^{-2}

parent

full simulation

0 500 1000

E_T^{miss} (GeV)

ATLAS simulation of missing ET in

$Z(\rightarrow \mu^+\mu^-) + jet$

Part of the strategy for cleanup up this distribution is to exclude missing ET events likely to be associated with cracks and mismeasurement.

ATLAS

η of the jet w. the highest ET in events w. ET > 50
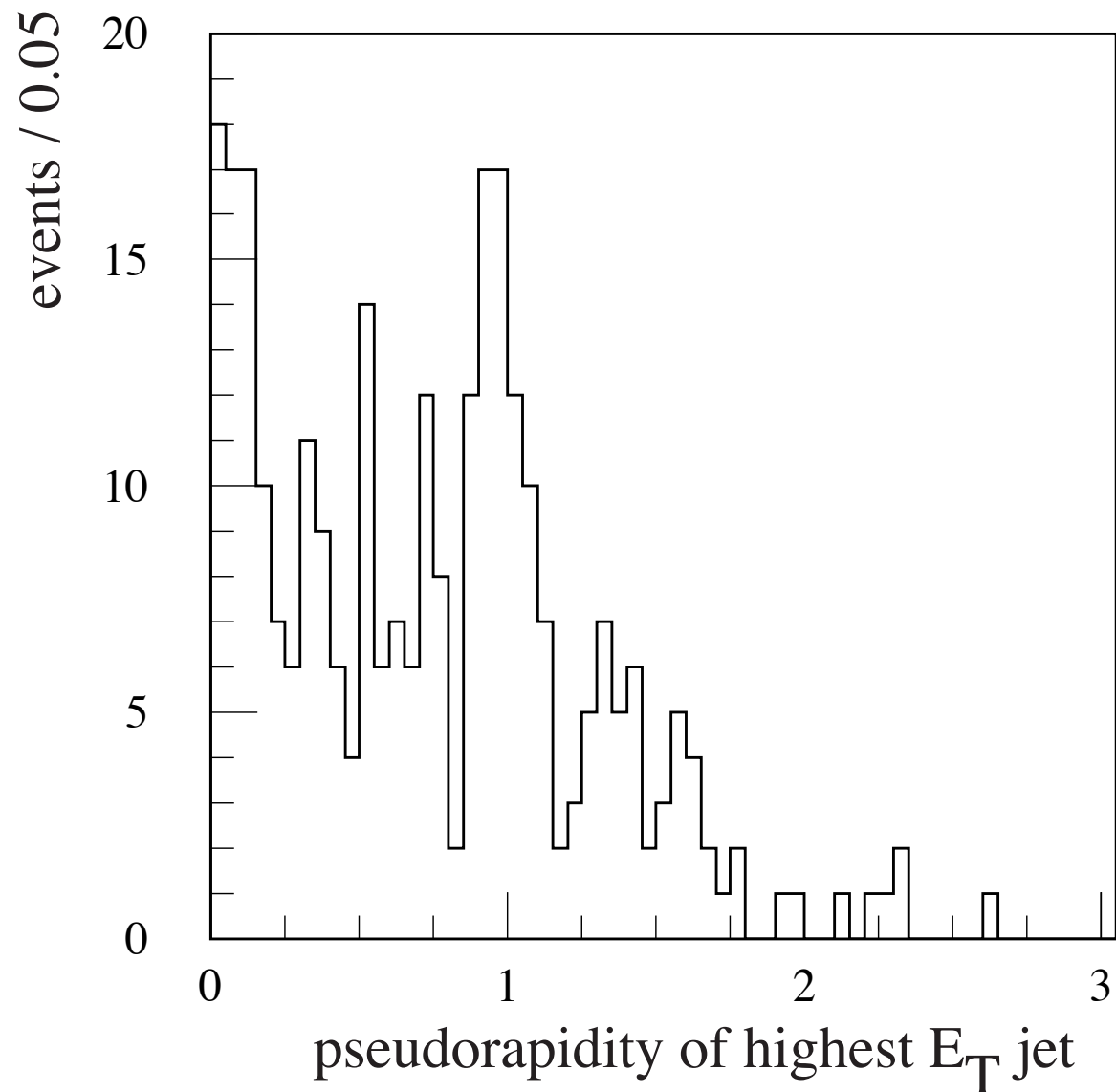
Given this situation, we can concentrate in formulating models of (W, Z, $t\bar{t}$)+ jets production.

A first level of this analysis is straightforward. Identify events of
$$pp \to Z + \text{jets} , \quad Z \to \ell^+ \ell^-$$
with no missing energy. These events are unlikely to be contaminated by SUSY production. Remove the leptons; this is a model for
$$pp \to Z + \text{jets} , \quad Z \to \nu\bar{\nu}$$
the single most important background shown above.

However, this simple analysis is rate-limited, since
$$\frac{\Gamma(Z \to e^+e^-, \mu^+\mu^-)}{\Gamma(Z \to \nu\bar{\nu})} = \frac{1}{6}$$
It would be better to build a complete model of
$$pp \to (W, Z) + \text{jets}$$
that uses data from both Z and W production.

There is a methodology for this that has been used successfully in the CDF and DO top quark analyses.

Use the fact that new particles appear in events with large numbers of jets and large

$$H_T = \sum_i E_{Ti}$$

Compute systematically the SM rates for n jet production. The results for fewer jets can be validated against data, both in a general setting and also with the experimental cuts that define the new physics search. Now extrapolate to large numbers of jets and large H_T.

This method is well-known, but it needs a name. Call it the Berends-Giele staircase.

UA1
1988

357 W → l ν EVENTS

$E_T^{jet} > 7$ GeV

QCD

FRACTION OF EVENTS

10^{-1}

10^{-2}

a)

UA1

number of jets
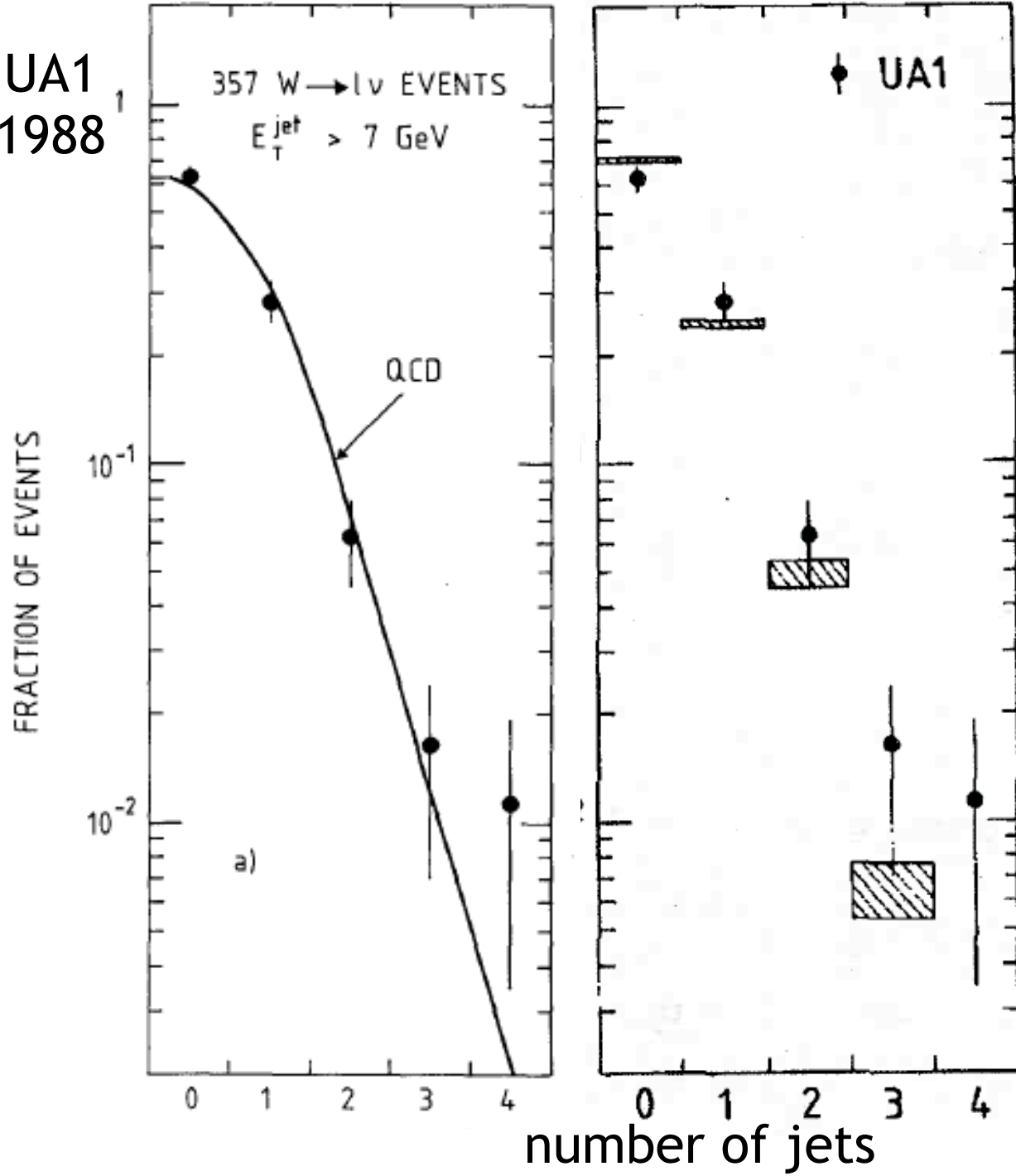
Berends,
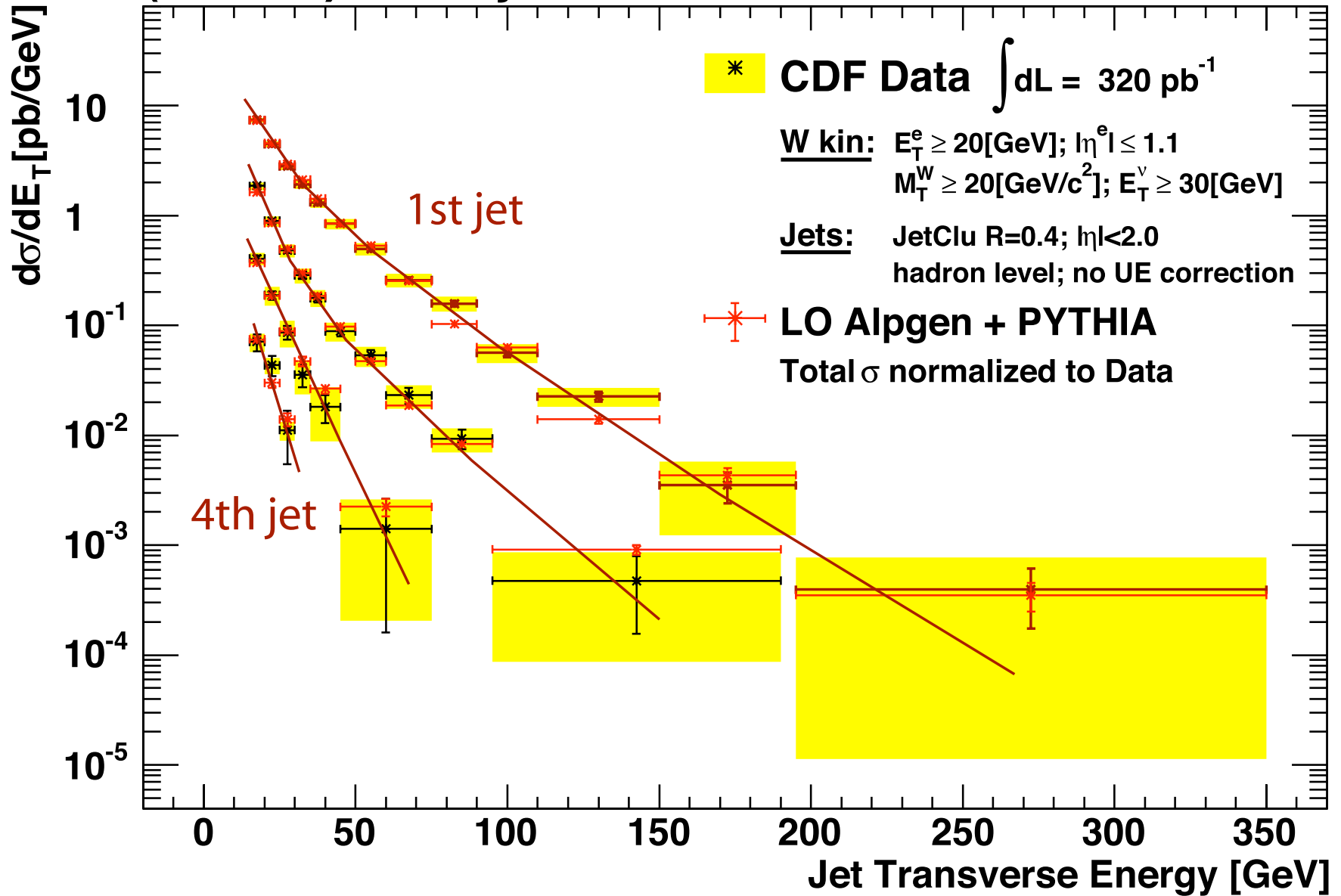Giele, Kuijf,
Kleiss, Stirling
1989

In 1989, the tool for this analysis was the Berends-Giele recursion formula. Now we have ALPGEN, and Britto-Cachazo-Feng recursion, and - soon - multijet NLO results.

Correct matrix element - parton shower matching (Mangano, Krauss, Mrenna ..) is also an important ingredient.

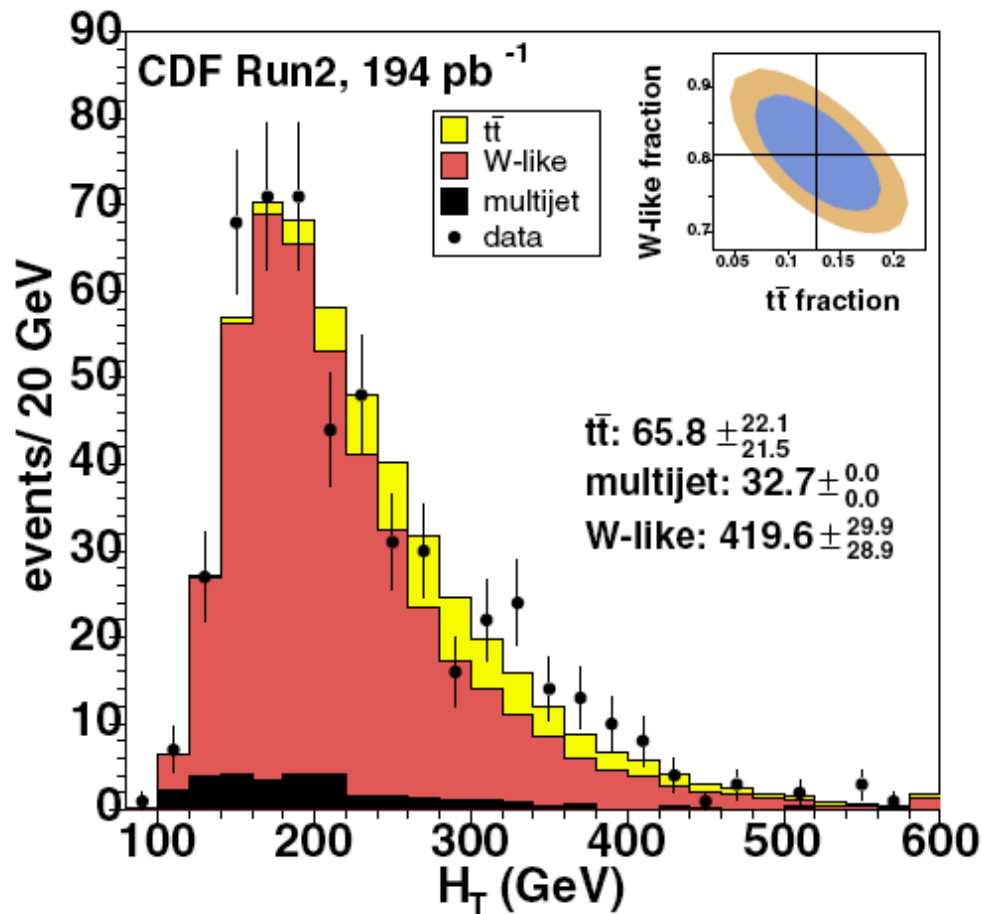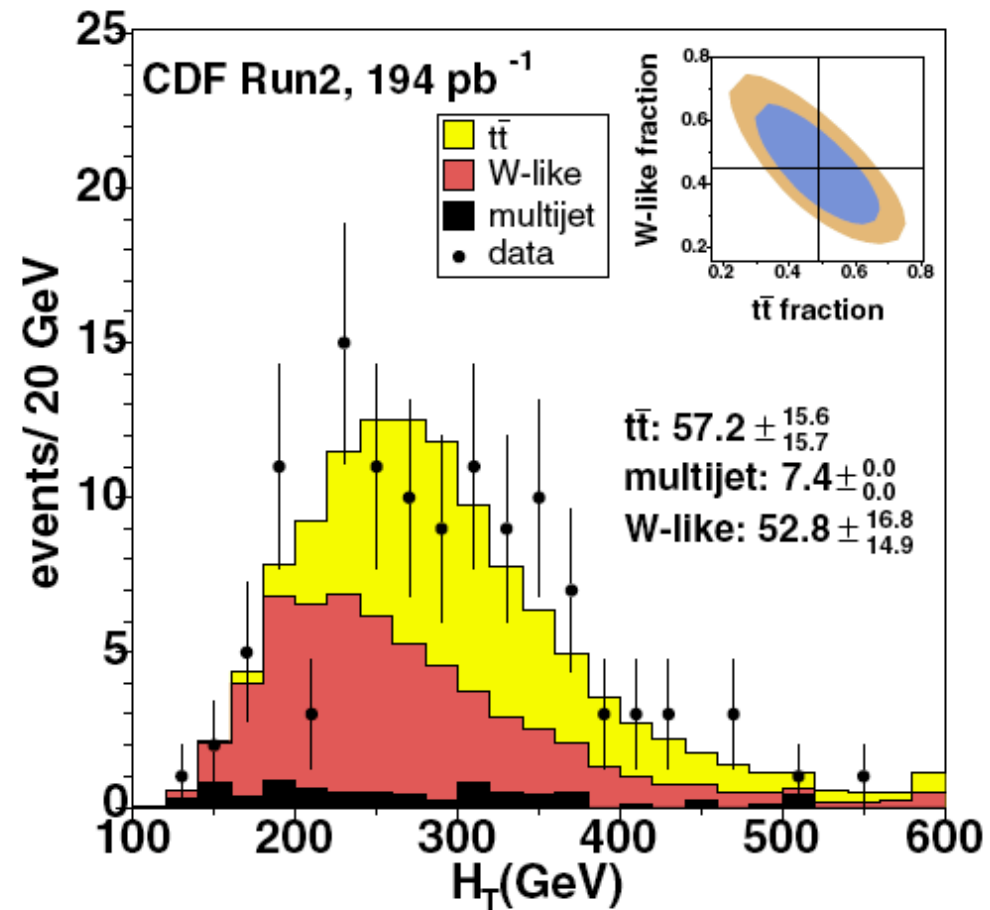Apply the model to events with single lepton and 1 b tag:

The analysis can run in more than one dimension.
Add a second b tag or a constraint on H_T .

It is very encouraging that CDF has demonstrated the ability to observe $t\bar{t}$ events without b-tagging. Here are the last two steps in the staircase in that analysis.

W+3 jets

W + 4 jets

$$H_T = \not{E}_T + E_{T\ell} + \sum_i E_{Ti}$$

A challenge for LHC analyses is to find a similar way to calibrate the Berends-Giele staircase for $t\bar{t} + \mathrm{jets}$.
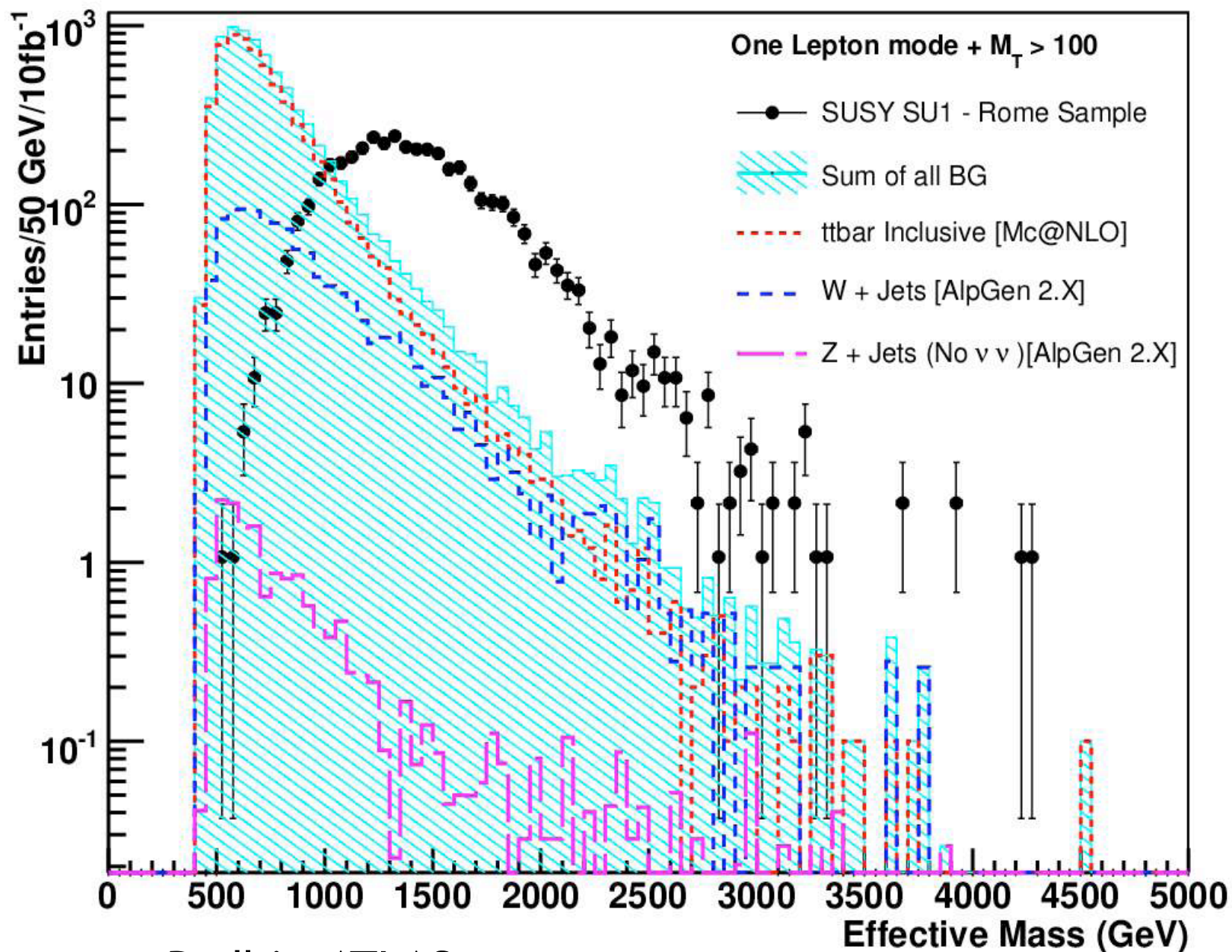
To do this, we need to select a sample of events enriched in top and uncontaminated by SUSY, without applying cuts on njets and H_T . This is an open problem.

Start with single-lepton events with missing energy but with $m_{tr} < m_W$. Impose b tag, $m_{jj} \approx m_W$, $m_{jjj} \approx m_t$?

A first step would be to measure $p\bar{p} \rightarrow t\bar{t}g$ at the Tevatron.
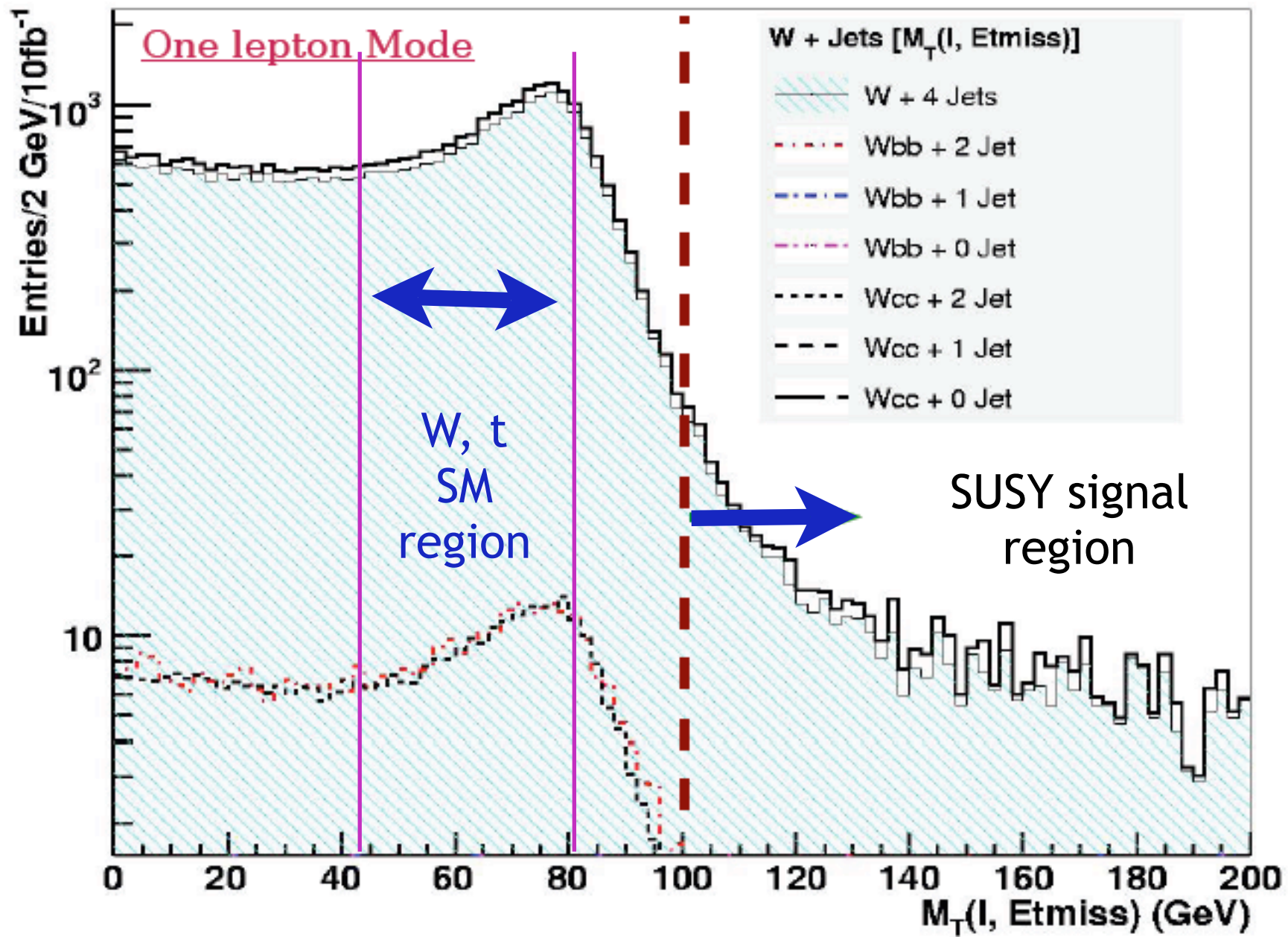
Here is the signal region in Pahdi's single-lepton analysis.

Padhi - ATLAS

We can also move in the direction of multilepton signatures.
Here there is another staircase, the Baer-Tata staircase.

It is well appreciated that SUSY models predict 2, 3, 4 - lepton
events in a steadily decreasing progression.

The Standard Model also
produces such events, from
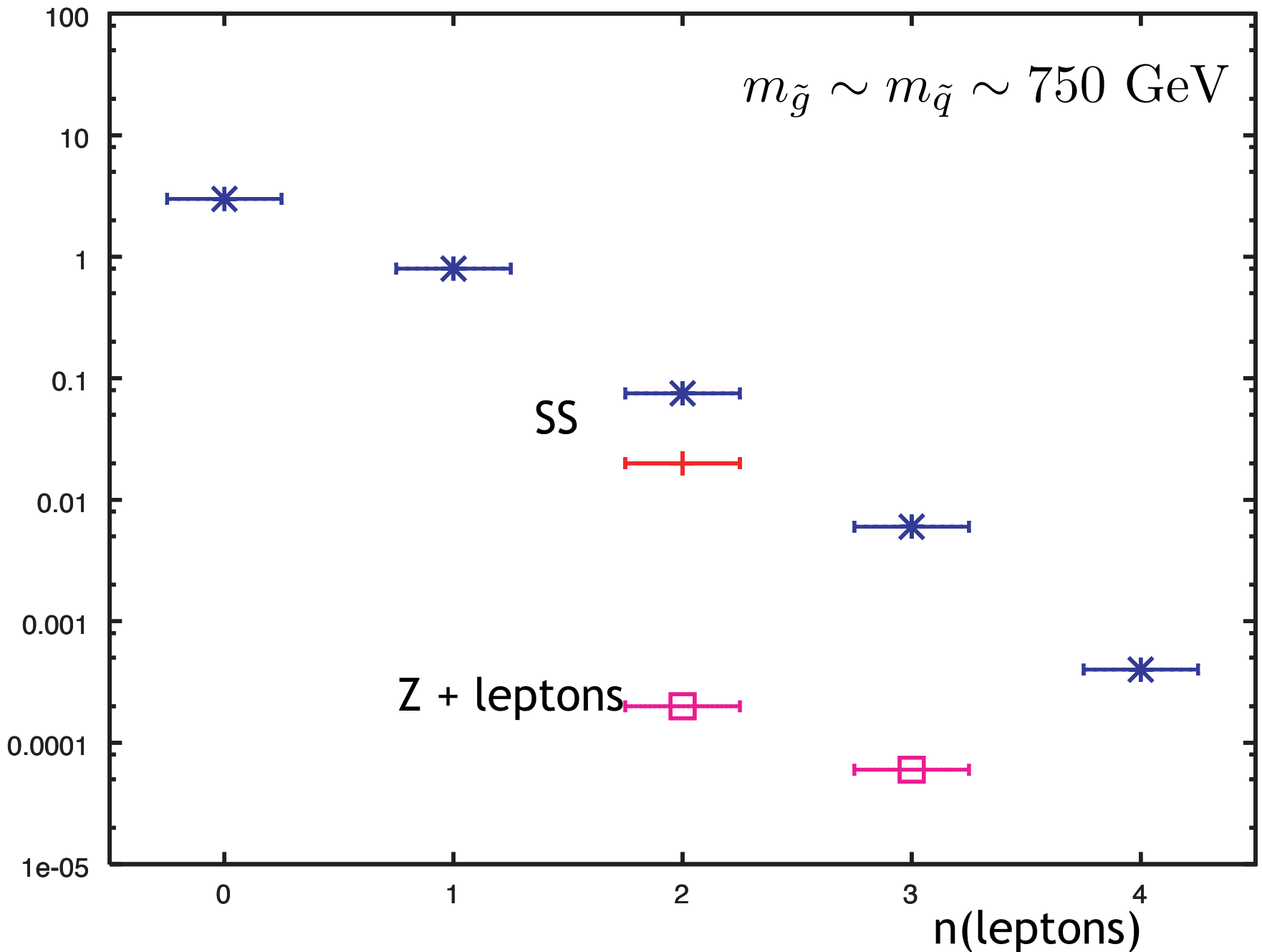multiple heavy-quark decays
and jets faking leptons.

Fortunately, these come from
the same W, Z, $t\bar{t}$ + jets
processes that we have
already been discussing.

Electroweak backgrounds,
e.g. $pp \rightarrow W^+W^+ \rightarrow \ell^+\ell^- + \mathrm{jets}$
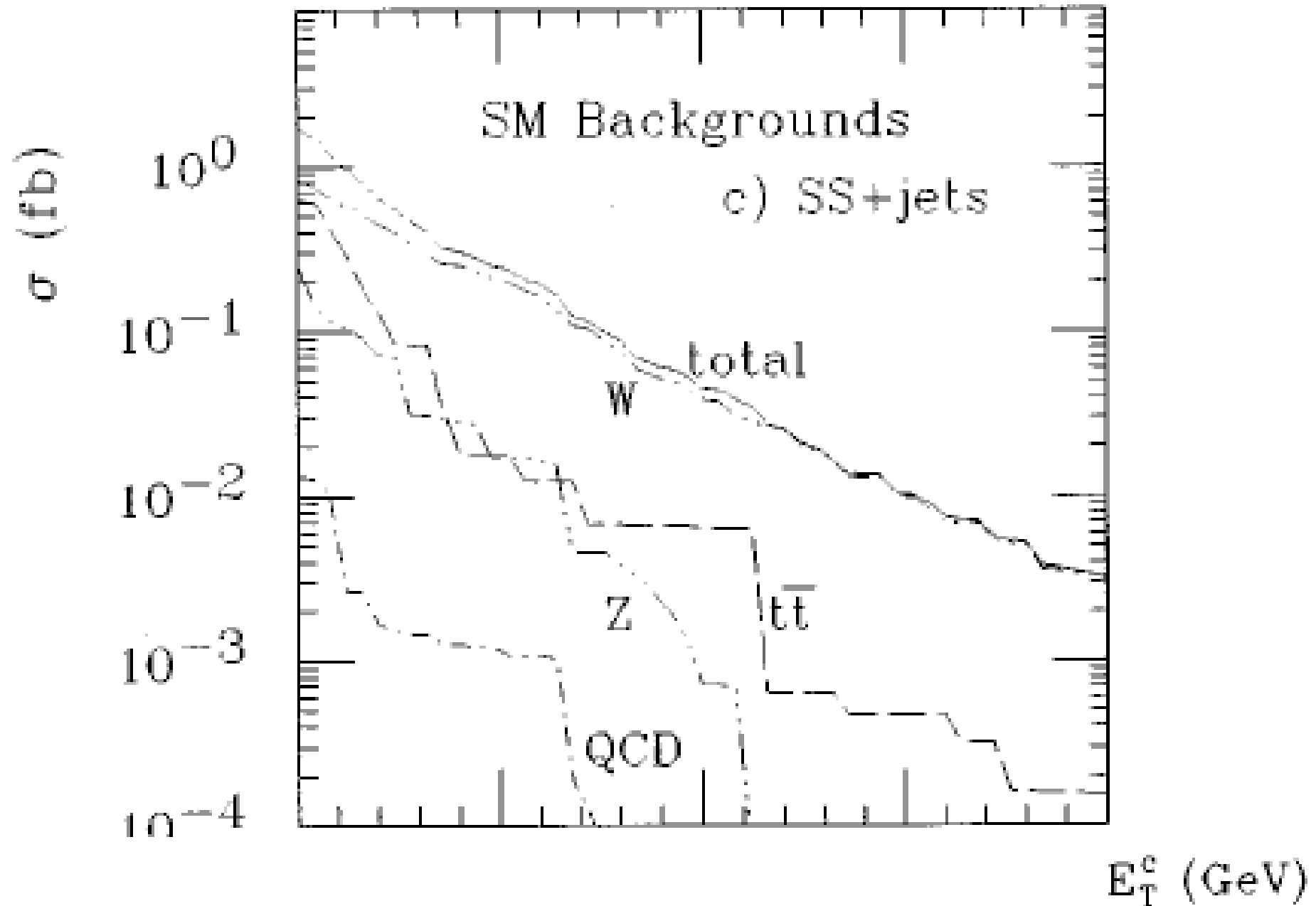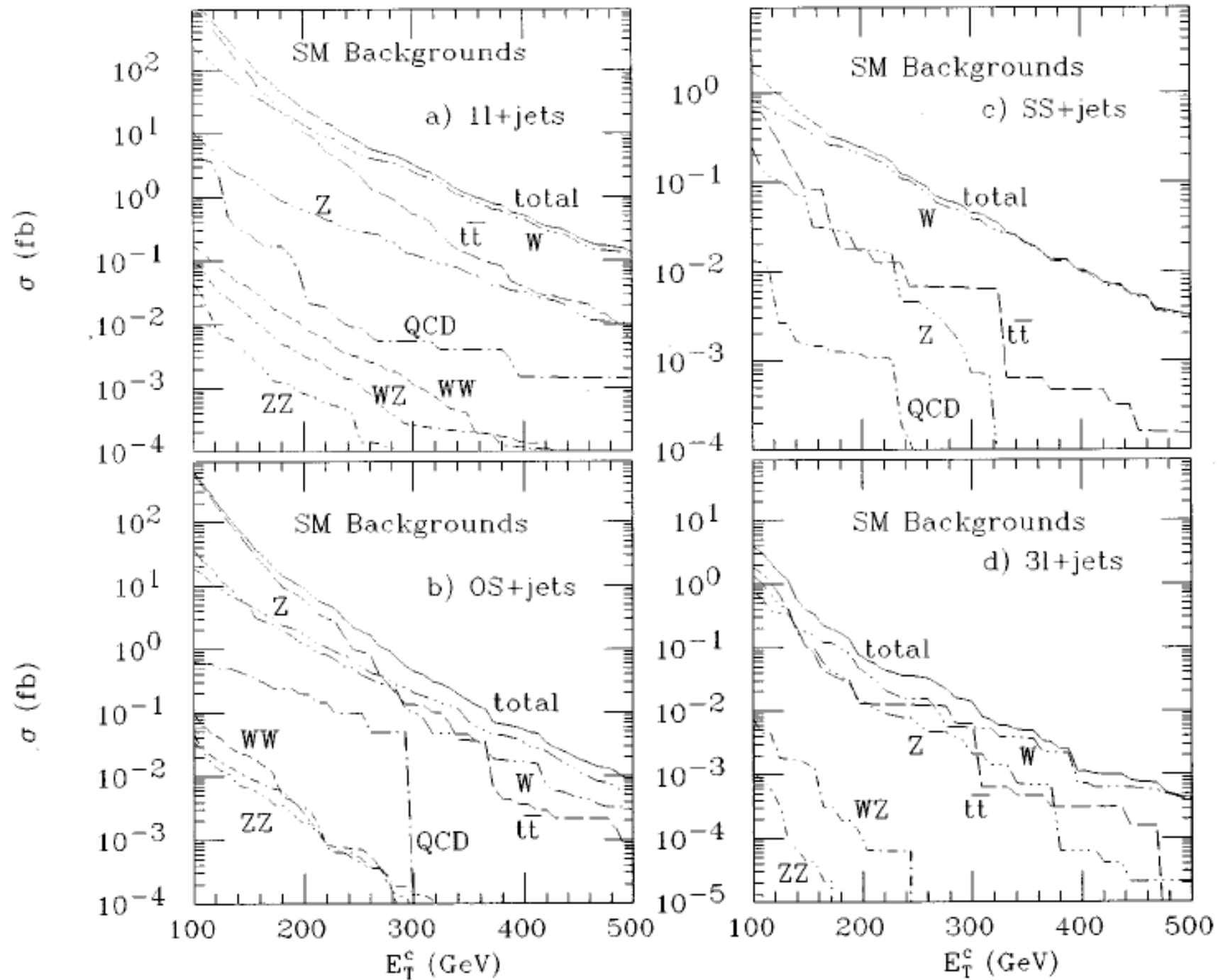are at the fb level.

signal cross sections from one of the models
of Baer, Chen, Paige, Tata

sigma (pb)

$m_{\tilde{g}} \sim m_{\tilde{q}} \sim 750 \text{ GeV}$

SS

Z + leptons

n(leptons)

dissection of the Same Sign dilepton background from this paper

Baer, Chen, Paige, Tata

It will not be easy to prove the presence of SUSY events in the LHC data sample, but I am optimistic about the prospect.   We have the theoretical tools to produce accurate models of the most important backgrounds. These models can be validated from experiment in the regions dominated by W, Z, $t\bar{t}$ production.

Then we can walk down the staircases, in several different directions in the signal space. In the world with SUSY, we should find unexplainable excesses in every direction that we move.

In this way, we will find a family of violations of the Standard Model. One violation might not be credible. But a consistent pattern will convince the skeptics.

Finally, a little about Gordy.

I met Gordy at the 1980 Moriond meeting. We were all working on Technicolor then.   At this meeting and over the next few years, I was strongly influenced by his notion that the search for new particles and interactions beyond the Standard Model was THE important direction.

At Snowmass 1982, he played a major role in the wholesale conversion of the HEP community to this idea.

We have been discussing the phenomenology of SUSY for more than 25 years. During this period, SUSY has continually failed to be discovered. As SUSY has moved to higher energies, the search for SUSY has required more sophisticated tools, which have called for great effort in their development.

Under these circumstances it is easy to lose faith.

But science is advanced by believers, not by skeptics.

Gordy lives in a world where SUSY is correctly a part of Nature. He has shown us how to live there also.

This is the absolute prerequisite to make the experimental discoveries that will leads us into a new picture of physics and of reality.