Beyond the Standard Model: the next 20 years

1. (Orientation and) LHC

M. E. Peskin
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Many people interested in experimental elementary particle physics are interested in many different problems, including flavor, neutrinos, CP violation, proton decay, and grand unification, and aspects of inflationary cosmology.

With my apologies, I am only interested in one problem -- the study of new particles and forces in the energy range 100 GeV - 1 TeV.

I am convinced that these new particles exist. If this is so, we will begin to discover them in the next few years.

And, if this is so, this study will define elementary particle physics for the next 20 years.

In these lectures, I would like to discuss three chapters in this study:

1. LHC: How will we discover the existence of new particles in the hundred-GeV mass range ?
2. ILC: How will we study the interactions of these particles in detail, and what will we learn by doing this ?
3. Beyond ILC: How will we pursue the study of these particles to higher energies ?

The presence of new physics in the hundred-GeV mass range is motivated by two pressing problems:

electroweak symmetry breaking and cosmic dark matter

I will review the first of these today, the second tomorrow.

The problem of electroweak symmetry breaking is particularly compelling.

We know that the weak and electromagnetic interactions are based on an SU(2) x U(1) Yang-Mills gauge theory.

This theory prohibits masses for the quarks, leptons, W and Z bosons unless the symmetry is spontaneously broken.

There is a simple theory of this spontaneously symmetry breaking based on the minimal Higgs boson. But this theory is inadequate. It is not a physics explanation.

Let me review the pieces of this story.

First, the SU(2) x U(1) structure of the weak interactions is well established experimentally. This structure is built on three key observations:

1. **Universality:** all QED, W, Z couplings arise from the two constants g, g'
2. **Chirality:** left- and right-handed fermions have different weak couplings
3. **non-Abelian gauge struture:** The couplings of vector particles are of the form predicted by Yang and Mills.

All of these features received new confirmation by the LEP and SLC experiments.

Universality:

In the context of the precision Z experiments, this is the statement that the coupling of each species of quark and lepton is given by

$$\frac{g}{c_w}(I^3 - s_w^2 Q)$$

with only two parameters g, s_w^2 . These parameters can be extracted from $\alpha,\ G_F,\ m_Z$, e.g.,

$$\sin^2 2\theta_w = \frac{4\pi\alpha(m_Z^2)}{\sqrt{2}G_F m_Z^2}$$

These points are tested by the measurements of the Z partial widths.

The partial width of the Z into a fermion species f should be given by:

$$\Gamma(Z \to f\overline{f}) = \frac{\alpha m_Z}{6 s_w^2 c_w^2} \cdot S_f$$

times the factor $3(1+\alpha_s/\pi)$ = 3.11 for quarks.

This gives the following table of partial widths and branching ratios:

species	$\Gamma(Z \to f\overline{f})$	BR
ν_e, ν_μ, ν_τ	167 MeV	6.7%
e, μ, τ	84 MeV	3.4%
u, c	300 MeV	12.0%
d, s, b	383 MeV	15.3%

Including a small correction for the case of $\Gamma(Z \to b\overline{b})$, we find a total width

$$\Gamma_Z = 2.50 \text{ GeV}$$

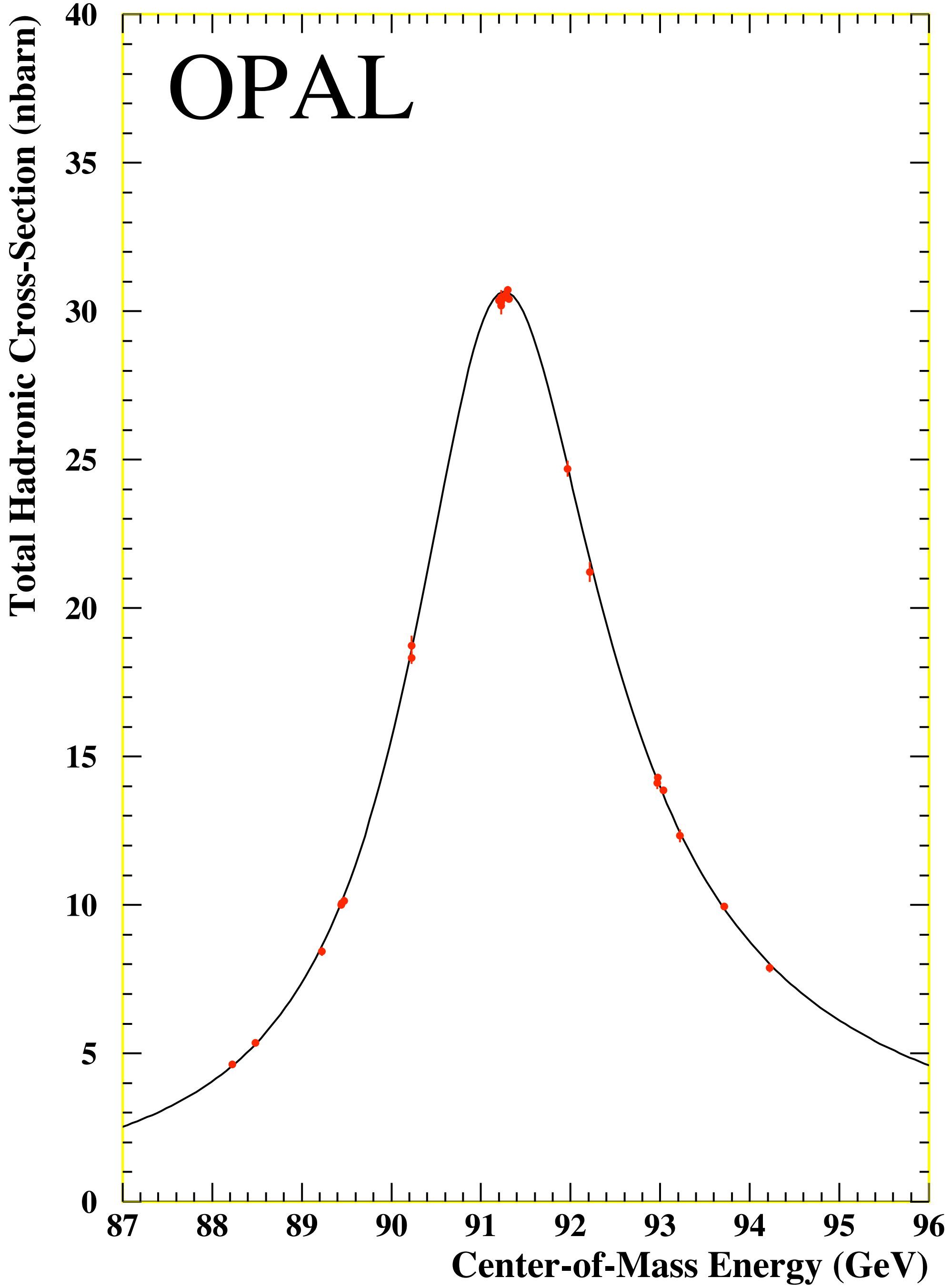
To test these predictions, we first measure e+e- annihilation at the Z resonance and measure the relative branching ratios to hadrons and to visible leptons.

Then we must determine the total width.

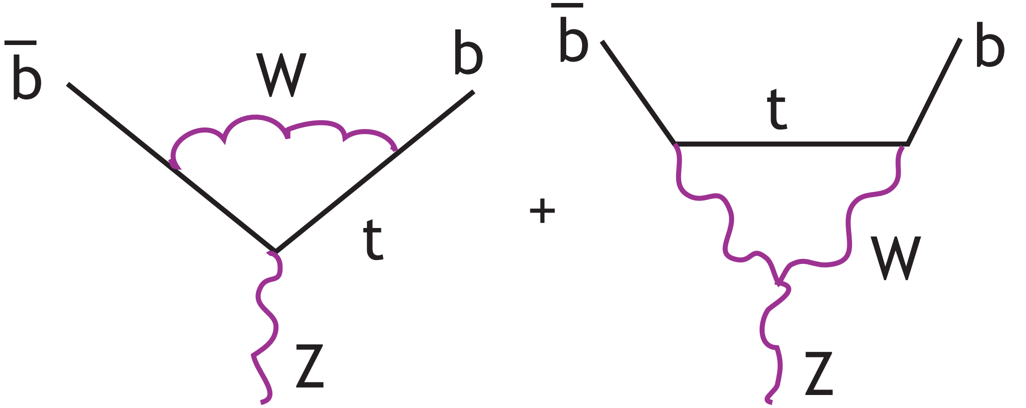
The shape of the resonance is distorted by initial-state photon radiation. Thus, it is necessary to measure the detailed shape of the resonance to extract Γ_Z.

It is amusing to note that all three of the Standard Model interactions - QED, QCD, and of course SU(2) x U(1) contribute to the Z line-shape.

The result is: $\Gamma_Z = 2.4952 \pm .0023 \text{ MeV}$


OPAL
Total Hadronic Cross-Section (nbarn)
0
5
10
15
20
25
30
35
40
87
88
89
90
91
92
93
94
95
96
Center-of-Mass Energy (GeV)

There is a special consideration for the b quark. The diagrams



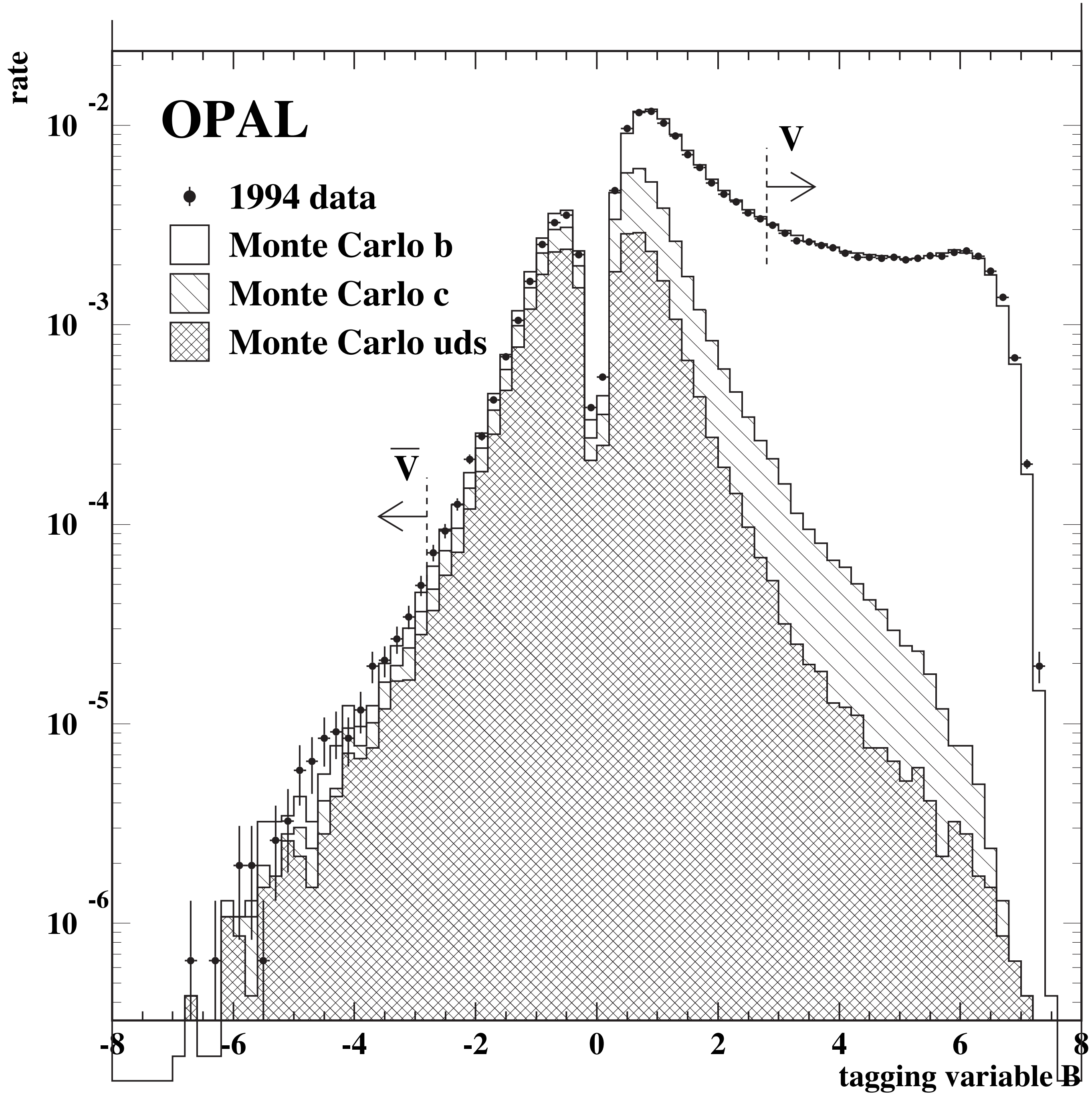
contribute a correction to the b_L Z charge,

$$Q_{ZbL} = -(\frac{1}{2} - \frac{1}{3}s_w^2 - \frac{\alpha}{16\pi s_w^2}\frac{m_t^2}{m_W^2})$$

This is a -2% correction to the partial width. It is easier to measure the quantity

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{ hadrons})}$$

which, if universality is correct, is almost independent of s_w^2.



OPAL
rate
10^-2
10^-3
10^-4
10^-5
10^-6
1994 data
Monte Carlo b
Monte Carlo c
Monte Carlo uds
V
V̄
-8
-6
-4
-2
0
2
4
6
8
tagging variable B

The final result is:

$$R_b = 0.21643 \pm 0.00073$$

in excellent agreement with the Standard Model and confirming the -2% shift due to the t-W diagrams.

Chirality:

It is clear from phenomenology of parity violation in beta decay that the weak interactions couple differently to left- and right-handed fermions.

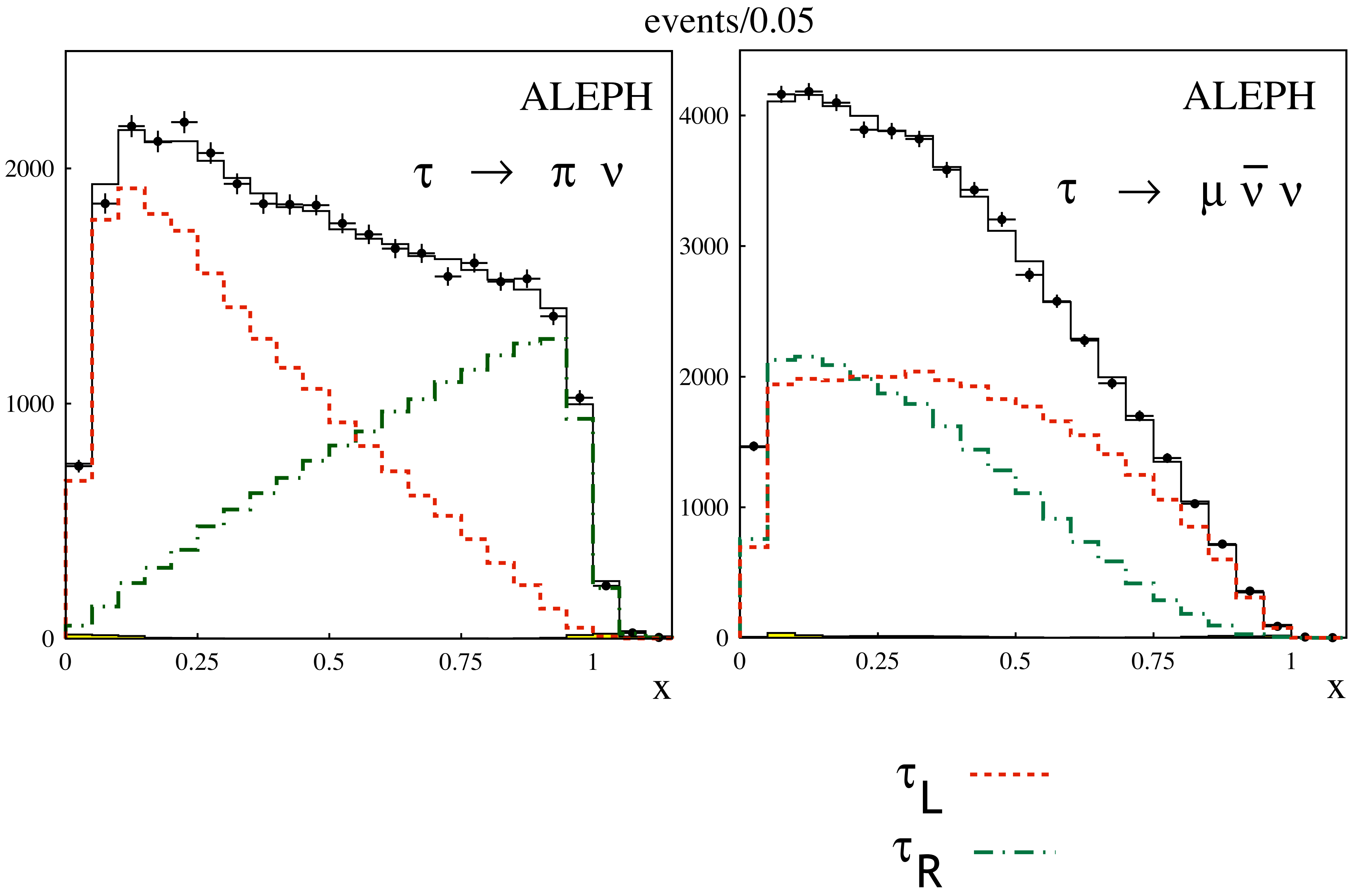
In the context of a gauge theory, this tells us directly that the left and right species have different gauge quantum numbers.

There is a new test of this in the Z decays, the measurement of final-state helicity in $Z^0 \to f\overline{f}$. This is given by

$$A_f = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}$$

A_f has quite different values for different species:

15% for leptons , 94% for down-type quarks

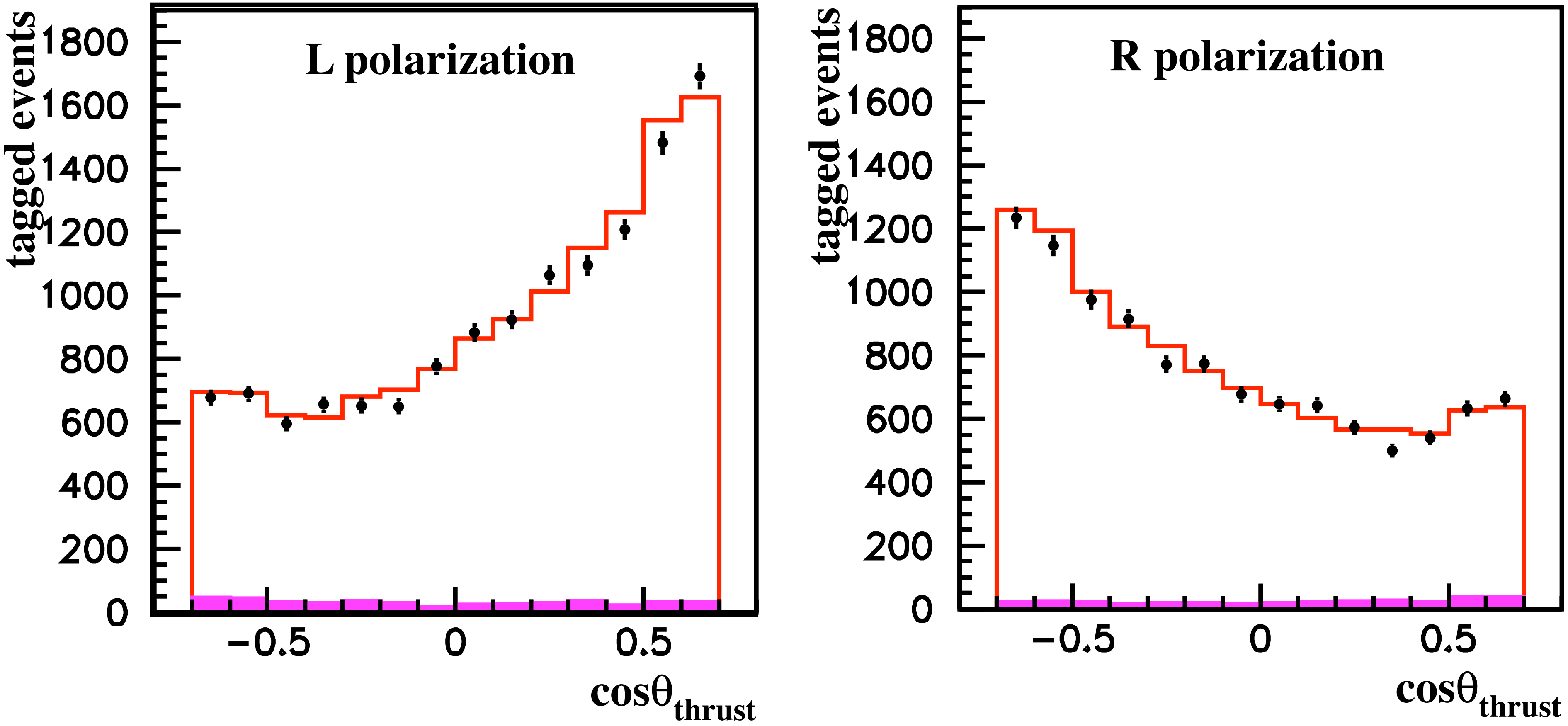

events/0.05
ALEPH
τ → π ν
2000
1000
0
0
0.25
0.5
0.75
1
x
ALEPH
τ → μ ν̄ ν
4000
3000
2000
1000
0
0
0.25
0.5
0.75
1
x
τ_L
τ_R

From this and other measurements of final-state lepton polarization, we obtained:

$$A_\ell = 0.1465 \pm 0.0033$$

It was also possible at SLAC to polarize the electrons and measure A_e directly as an asymmetry in the total cross section on the Z resonances. This gave:

$$A_e = 0.1513 \pm 0.0021$$

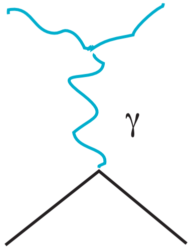


$A_b = 0.94$ at the Z^0

SLD

Yang-Mills structure:

This is tested by the LEP measurements of $\sigma(e^+e^- \to W^+W^-)$.
This reaction has a long-recognized danger of violation of unitarity.



$$\sim \bar{v}\gamma^\mu u \; \frac{1}{s} \; (k_+ - k_-)_\mu \epsilon_+^* \cdot \epsilon_-^*$$

W^+ has 3 polarization states. In the rest frame $\epsilon^\mu = (0, \hat{n})^\mu$

$$\epsilon_R = \frac{1}{\sqrt{2}}(0,1,i,0)$$

but for a W in motion

$$p^\mu = (E_W, 0, 0, k_W)$$

$$\epsilon_L = \frac{1}{\sqrt{2}}(0,1,-i,0)$$

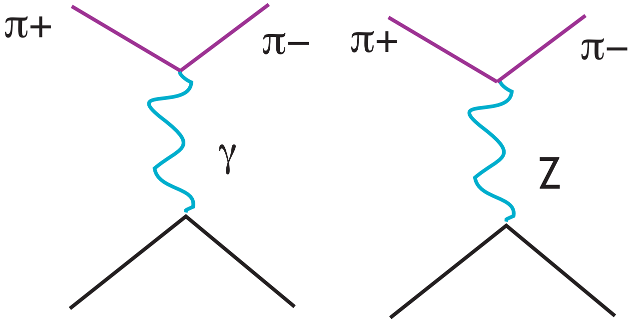
$$\epsilon_0 = \frac{1}{m_W}(k_W, 0, 0, E_W) \approx p^\mu / m_W$$

Notice that $\epsilon_{+0}^* \cdot \epsilon_{-0}^* = \dfrac{E_W^2 + k_W^2}{m_W^2} \approx \dfrac{s}{2m_W^2}$

This is trouble; unitarity requires $|i\mathcal{M}(e^+e^- \to W^+W^-)| \; < \; \mathrm{const}$
in each partial wave.

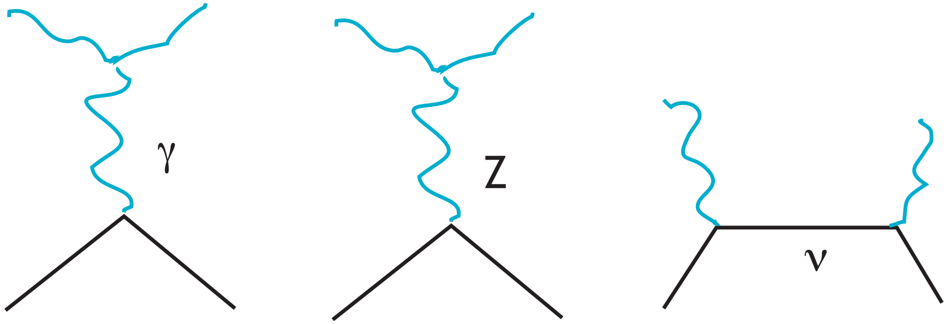
However, in a spontaneously broken gauge theory, the 0 polarization state of the W comes from eating a Goldstone boson. It turns out that the predicted cross section is just that for producing the Goldstone bosons.

$$i\mathcal{M}(e^-_L e^+_R \to W^+_0 W^-_0) =$$



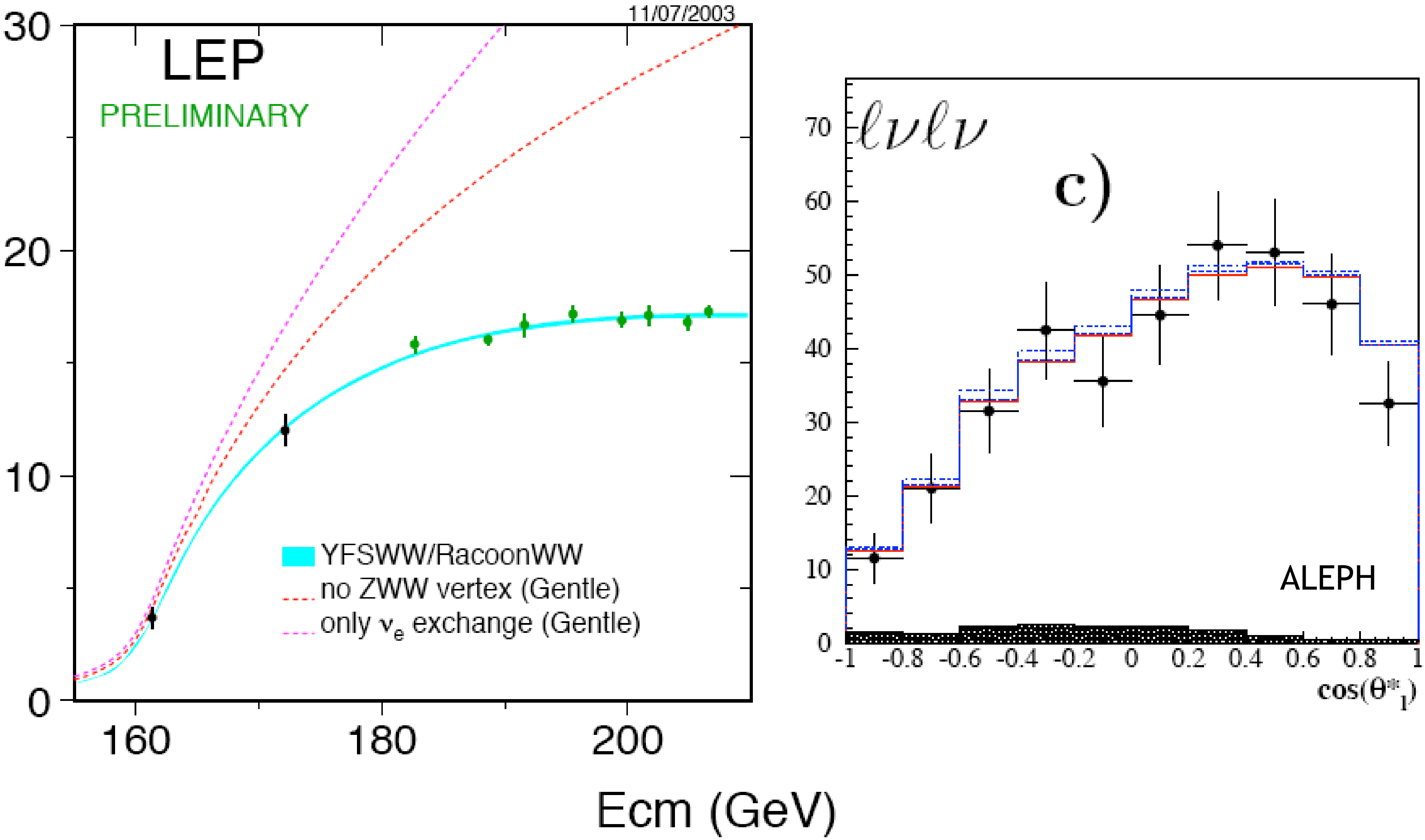
$$= ie^2\left[\frac{1}{4c_w^2}+\frac{1}{4s_w^2}\right]\bar{v}\gamma^\mu u\frac{1}{s}(k_+ - k_-)_\mu$$

The SU(2) x U(1) model gives this result by a delicate cancellation among the diagrams



This cancellation takes place only if the form of the 3-boson vertex is *exactly* that given by Yang-Mills theory.

$\sigma(e^+e^- \to W^+W^-)$



Thus, the evidence that the weak and electromagnetic interactions are a

spontaneously broken gauge theory of SU(2) x U(1)

is impressively strong.

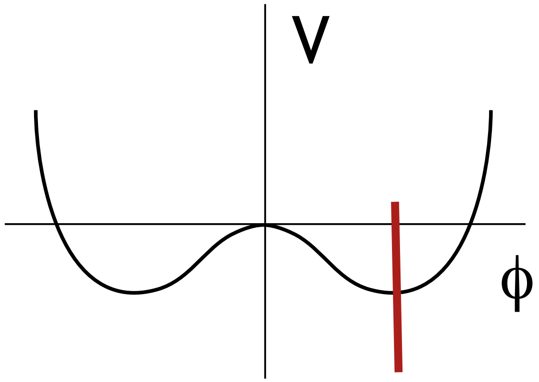
This brings up an obvious question:

What is the explanation for the breaking of SU(2) x U(1) ?

In the minimal form of the Standard Model, we explain this spontaneous symmetry breaking by postulating the existence of an SU(2)-doublet scalar field ϕ with the potential

$$V = \mu^2|\phi^2| + \lambda|\phi|^4$$

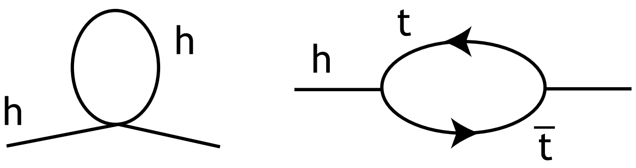
If $\mu^2 < 0$, the minimum of the potential does not respect SU(2) x U(1).



So, why is $\mu^2 < 0$? No answer !

μ^2 receives additive corrections from higher-order corrections

$$\mu^2 = \mu^2_{\text{bare}} + \frac{\lambda}{8\pi^2}\Lambda^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$



So $\mu^2 < 0$ is not a simple criterion in the underlying theory.

What does an explanatory theory of SU(2) x U(1) breaking look like ?

The theory must include an SU(2) doublet that obtains a vacuum expectation value. This field can be either composite or (effectively) elementary at the 100 GeV scale.

If the doublet of fields is composite, the theory should include their excited states. It is very difficult for these not to upset the precision electroweak results. So I will assume that there is an elementary Higgs field ϕ .

The theory should generate the potential for ϕ from physics. That is,

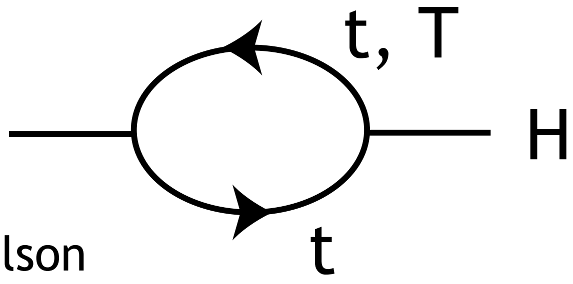
1. μ^2 should not receive additive, divergent corrections.
2. A calculation should give $\mu^2 < 0$.

It is very difficult to prohibit additive corrections to the mass term of a scalar field. However, there are three known ways to forbid this term by symmetry:

$\delta\phi = \epsilon$	ϕ is a Goldstone boson
$\delta\phi = \epsilon \cdot A$	ϕ is part of a higher-dimensional gauge field
$\delta\phi = \epsilon \cdot \psi$	ϕ is part of a supersymmetry multiplet

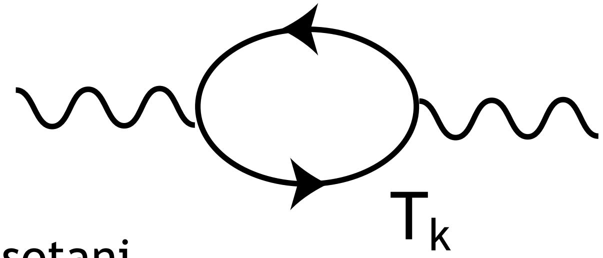
In each case, there is a natural mechanism to generate a potential with $\mu^2 < 0$, if the top quark Yukawa coupling is the largest relevant coupling in the model.

In Little Higgs models, the loop corrections due to the top quark and its partner cancel with a negative residue.



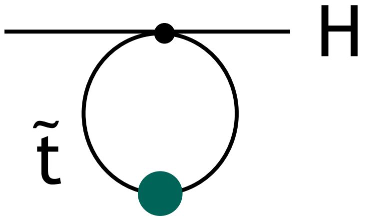
Katz-Nelson

In extra-dimensional models, the Kaluza-Klein excitations of the top quark give a symmetry-breaking potential for A^5



Hosotani

In supersymmetry, the renormalization by the top quark Yukawa coupling gives a negative correction.



Ibanez-Ross-Alvarez-Gaume-Polchinski-Wise

In all cases, we need a complex model, with new particles that are partners of the top quark.

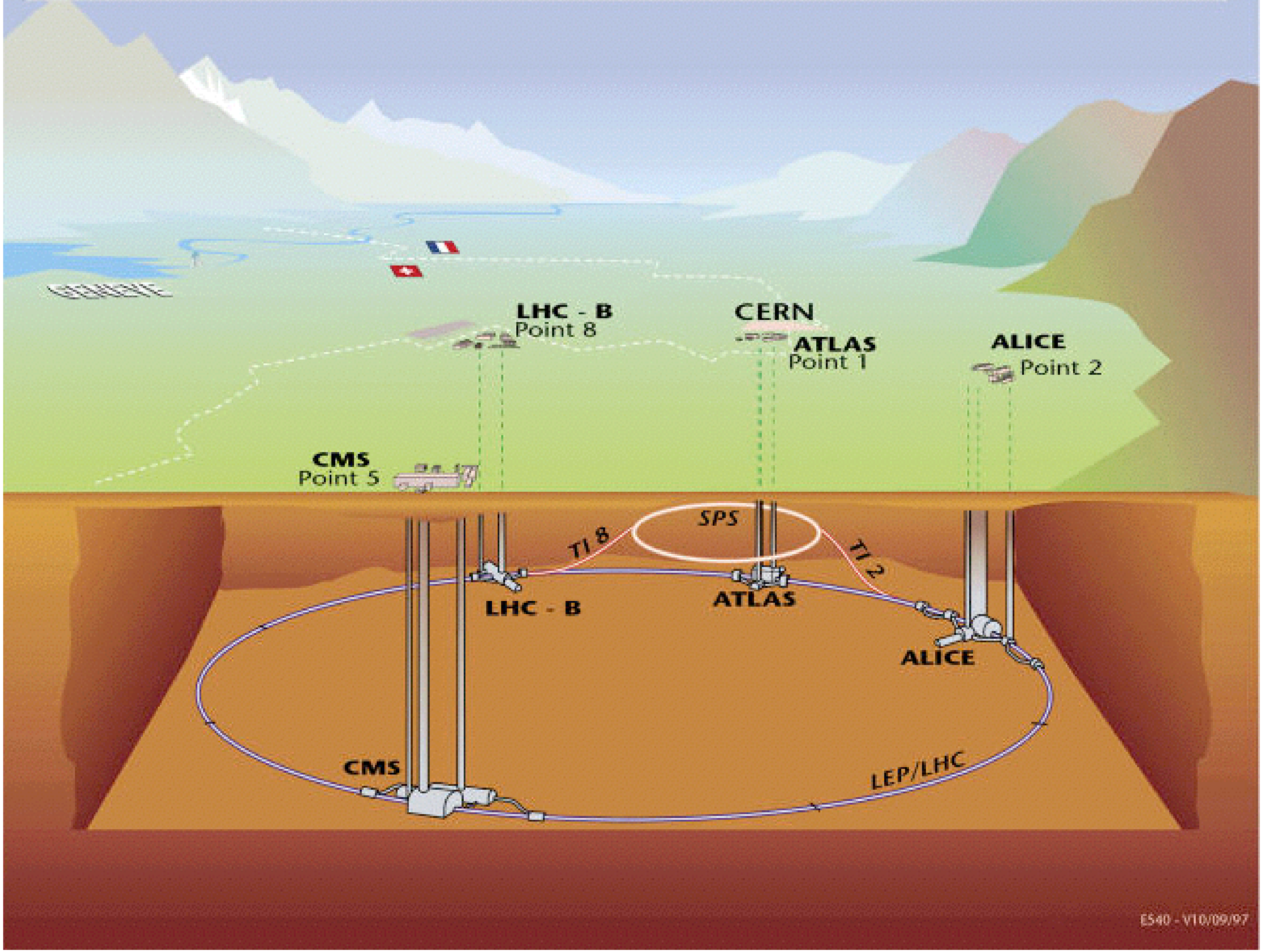
I do not ask you to literally accept these models, but I do ask you to accept the principle that a model of electroweak symmetry breaking must have multiple components and interacting parts.

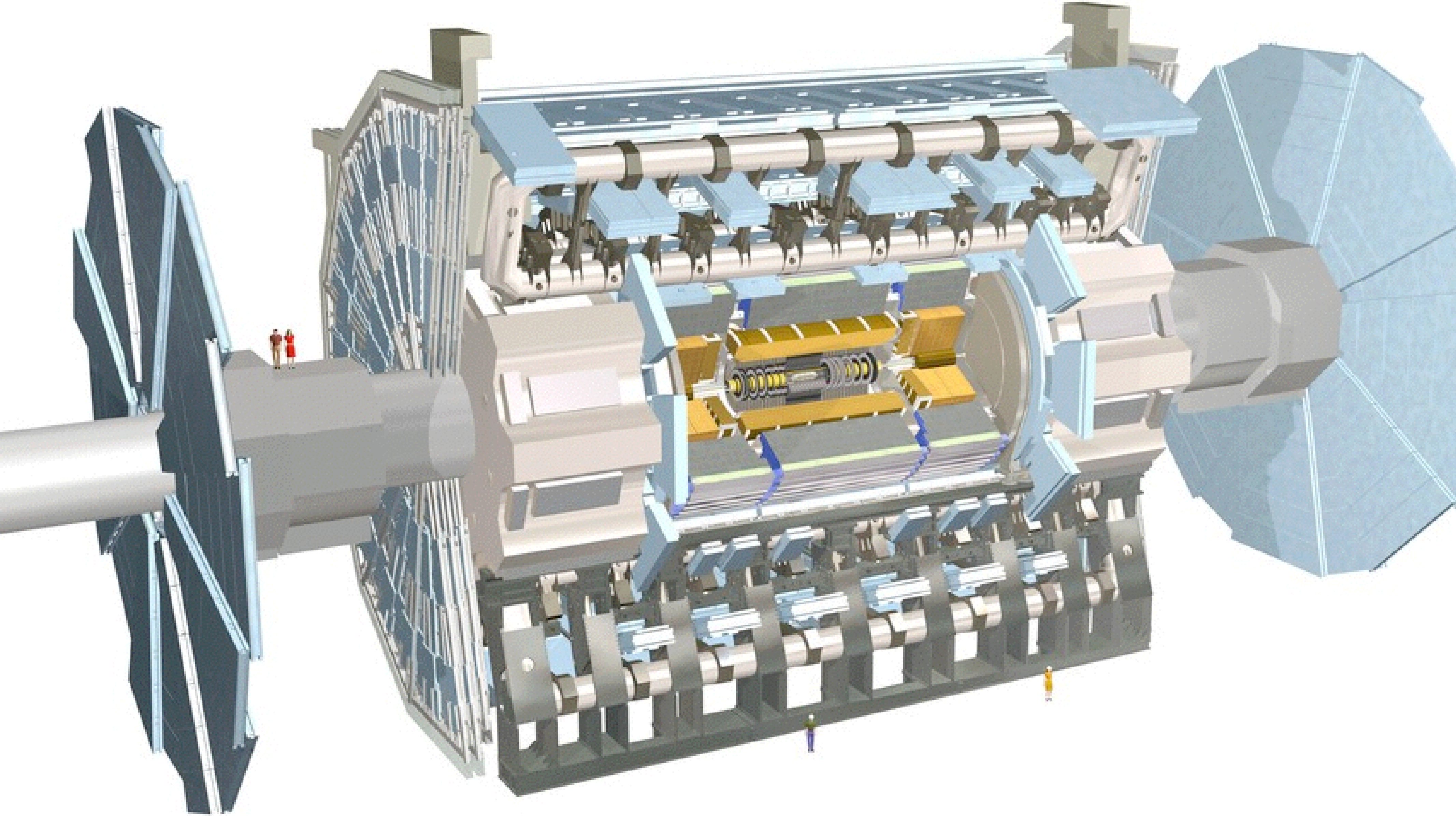
These cannot belong to the Standard Model. They are new particles associated with the hundred-GeV mass scale of the Higgs potential.

By this logic, the new particles must be there.

If some are partners of the top quark, they must have QCD interactions. Can we find them ?

Overall view of the LHC experiments.

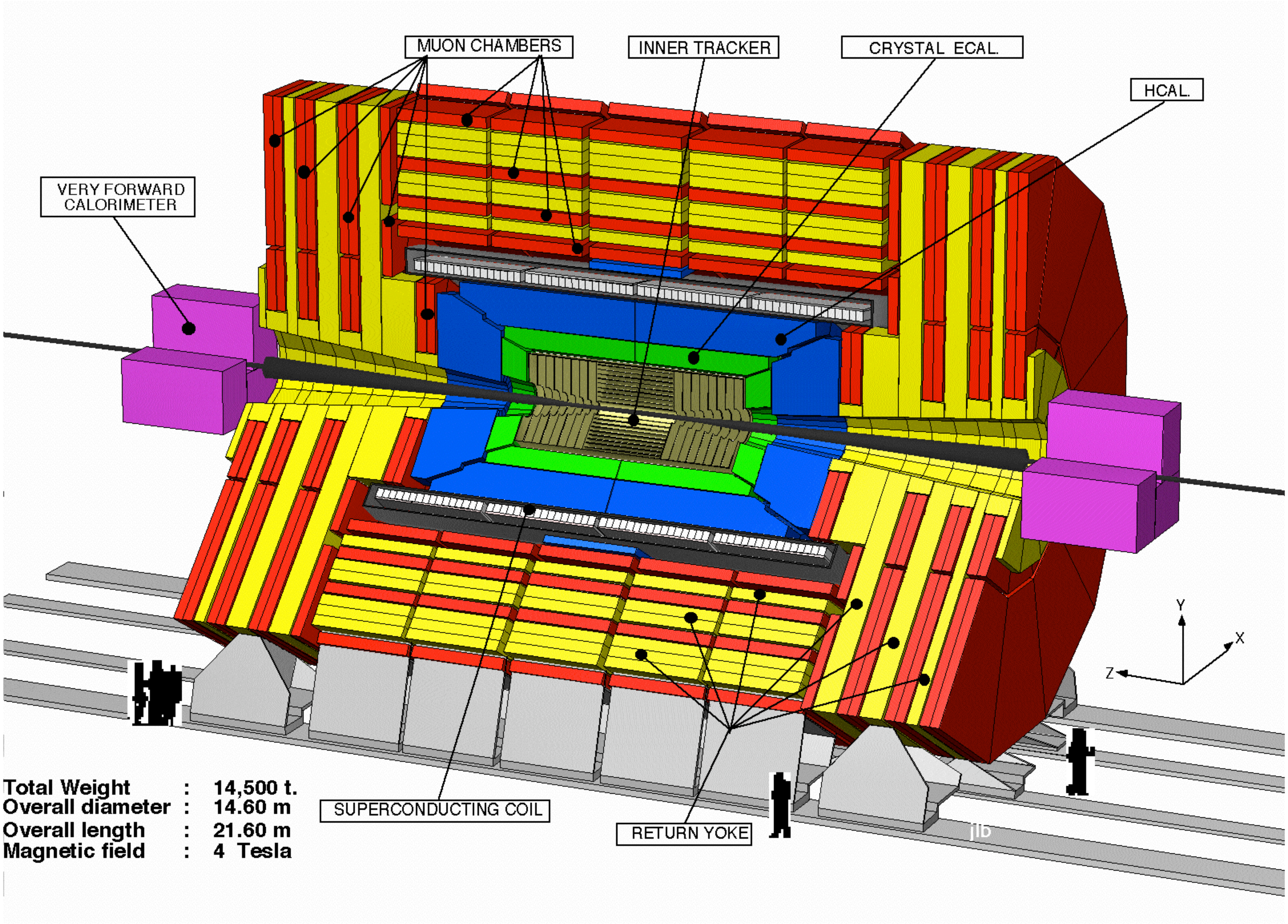




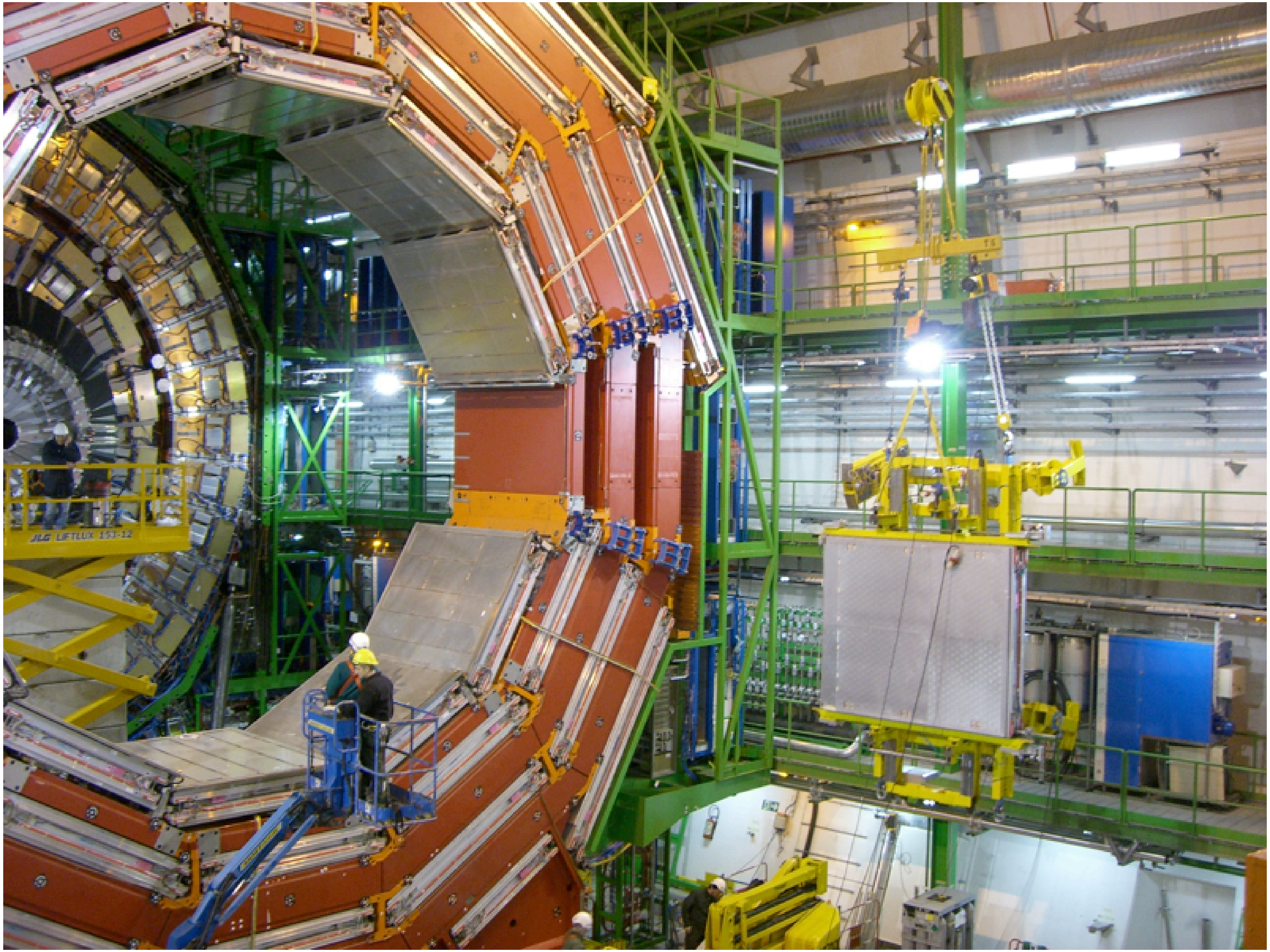
the ATLAS experiment

arrival of a superconducting muon toroid at CERN

A Compact Solenoidal Detector for LHC



Total Weight	:	**14,500 t.**
Overall diameter	:	**14.60 m**
Overall length	:	**21.60 m**
Magnetic field	:	**4 Tesla**



CMS iron toroid installation

As I will discuss in a moment, the LHC brings with it an exceptionally difficult environment in which to search for new physics. But this does not mean that new physics must be hard to find. There are two scenarios that are quite likely in which the discovery is straightforward.

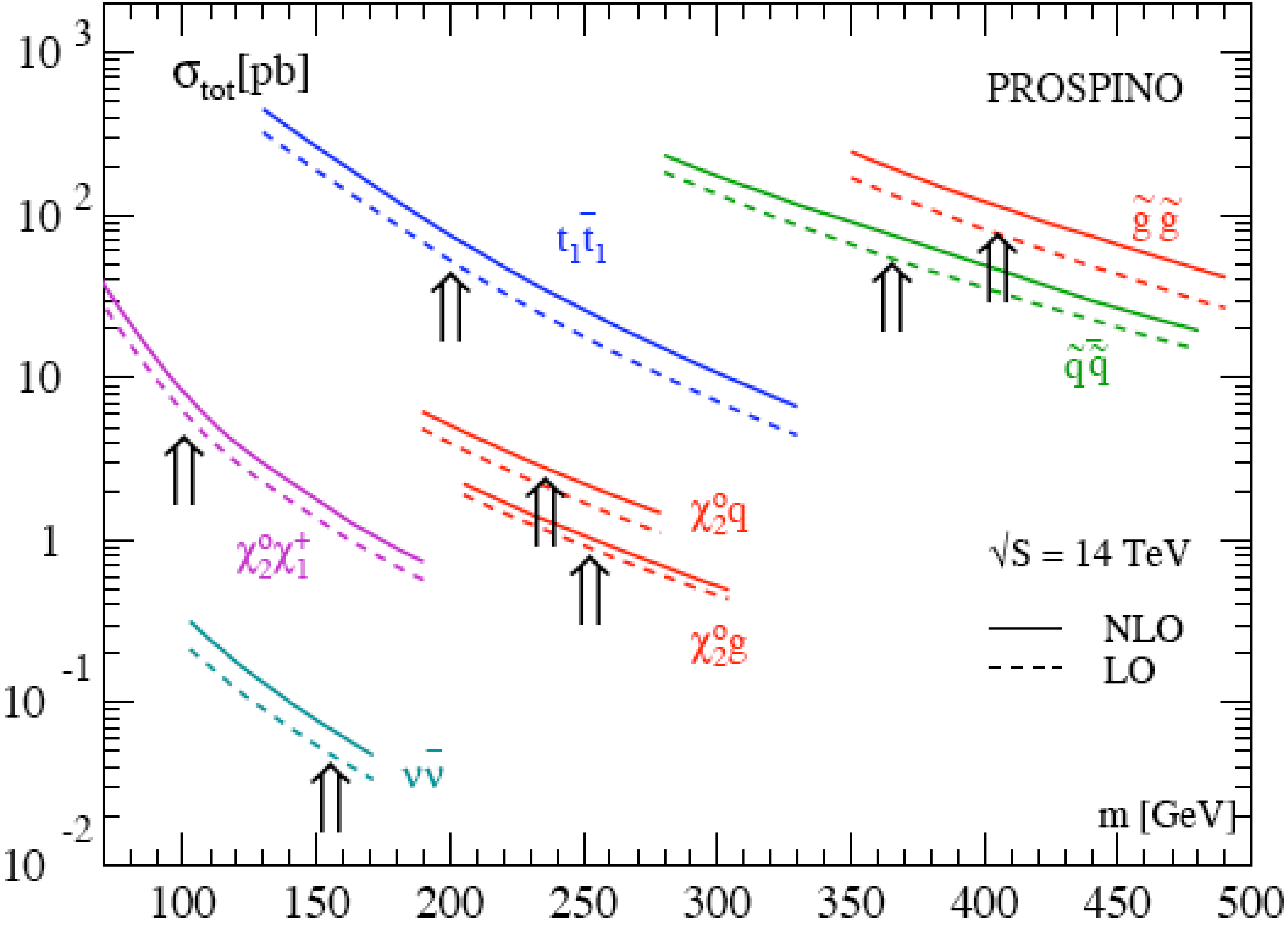
new vector bosons decaying to $\mu^+\mu^-$

new stable heavy leptons

However, if you will excuse me, I will concentrate in this lecture on the more generic hypothesis of new heavy particles with QCD color. I will return to these models in lecture 3.

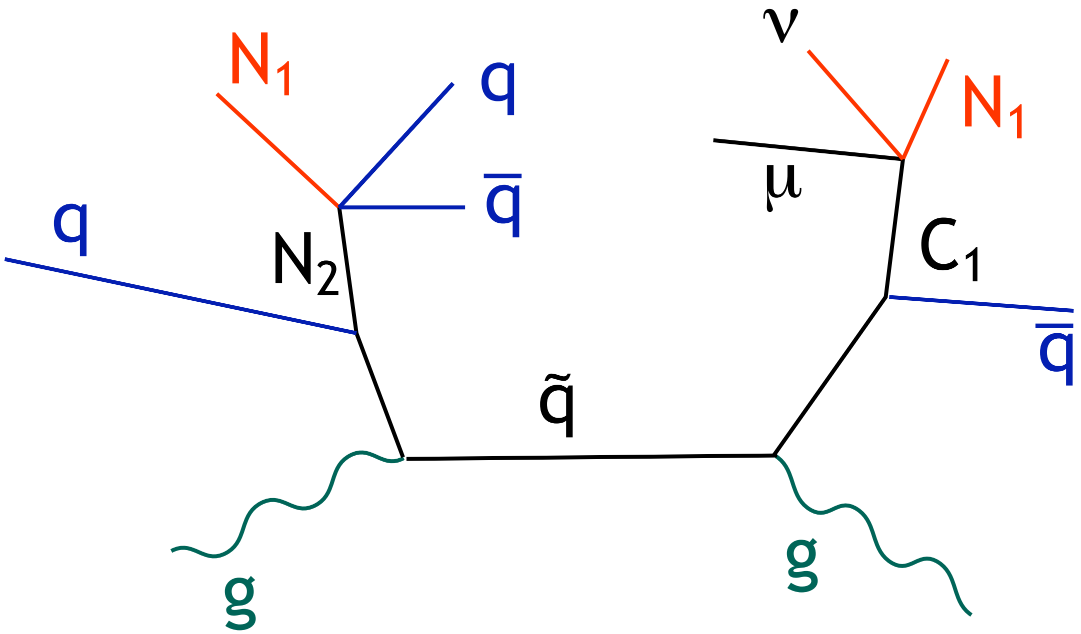
One feature that I would like to keep in this discussion is the possibility of producing invisible particles that carry away missing energy and momentum. I will argue tomorrow that the fundamental particle of cosmic dark matter is likely to be in the hundred-GeV mass range. This would be a final decay product of new particles produced at the LHC.

For new particles with QCD color, the expected cross sections are at the 10 pb level, corresponding to 10^5 events/yr at the luminosities expected for early LHC running.



Plehn, Spira, Zerwas

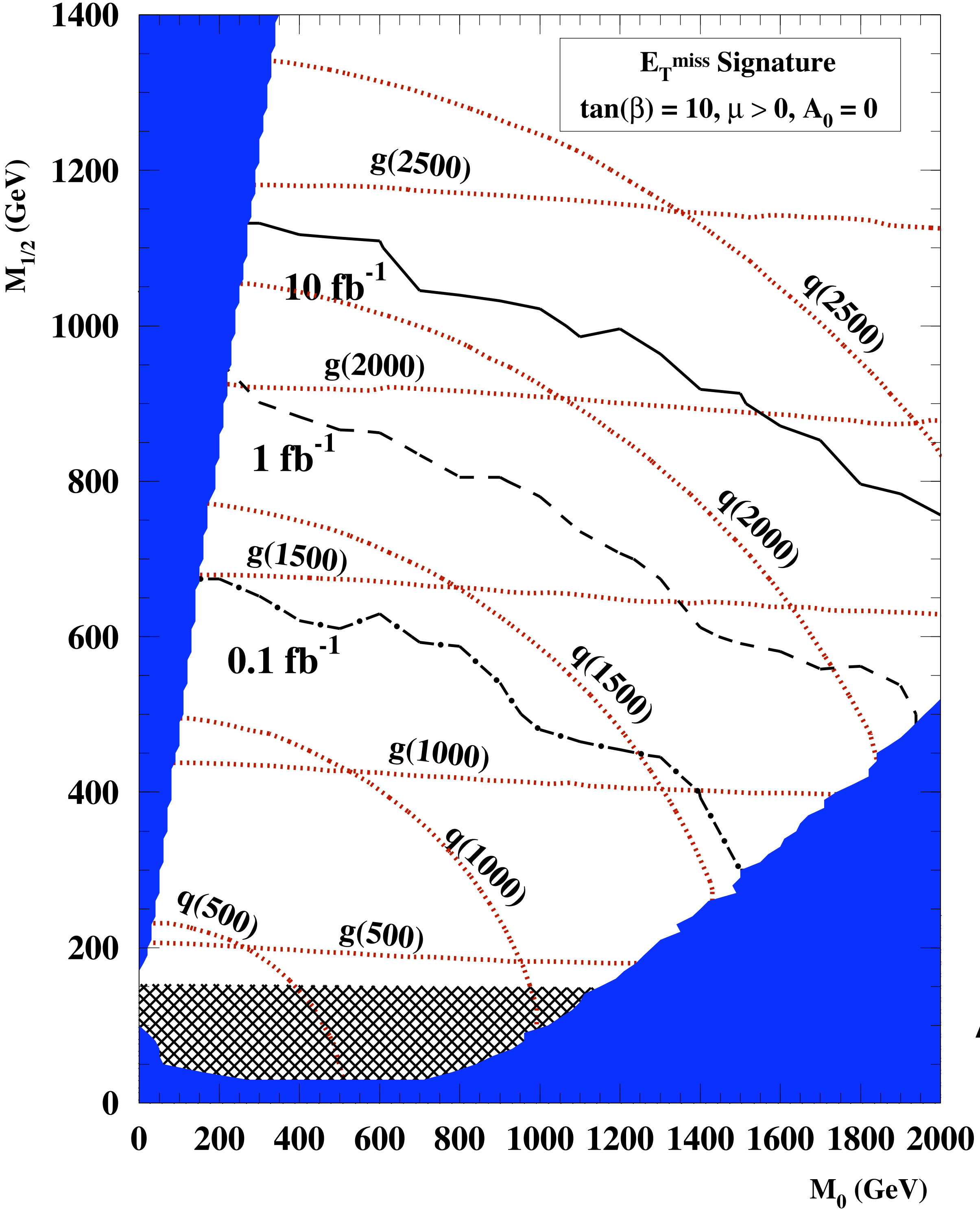
The new physics events should be quite complex. A typical event would have the form shown. Particle labels are for supersymmetry, but this type of event can appear in all three scenarios discussed earlier.



It is expected that events of this kind will appear as a very significant signal above background.

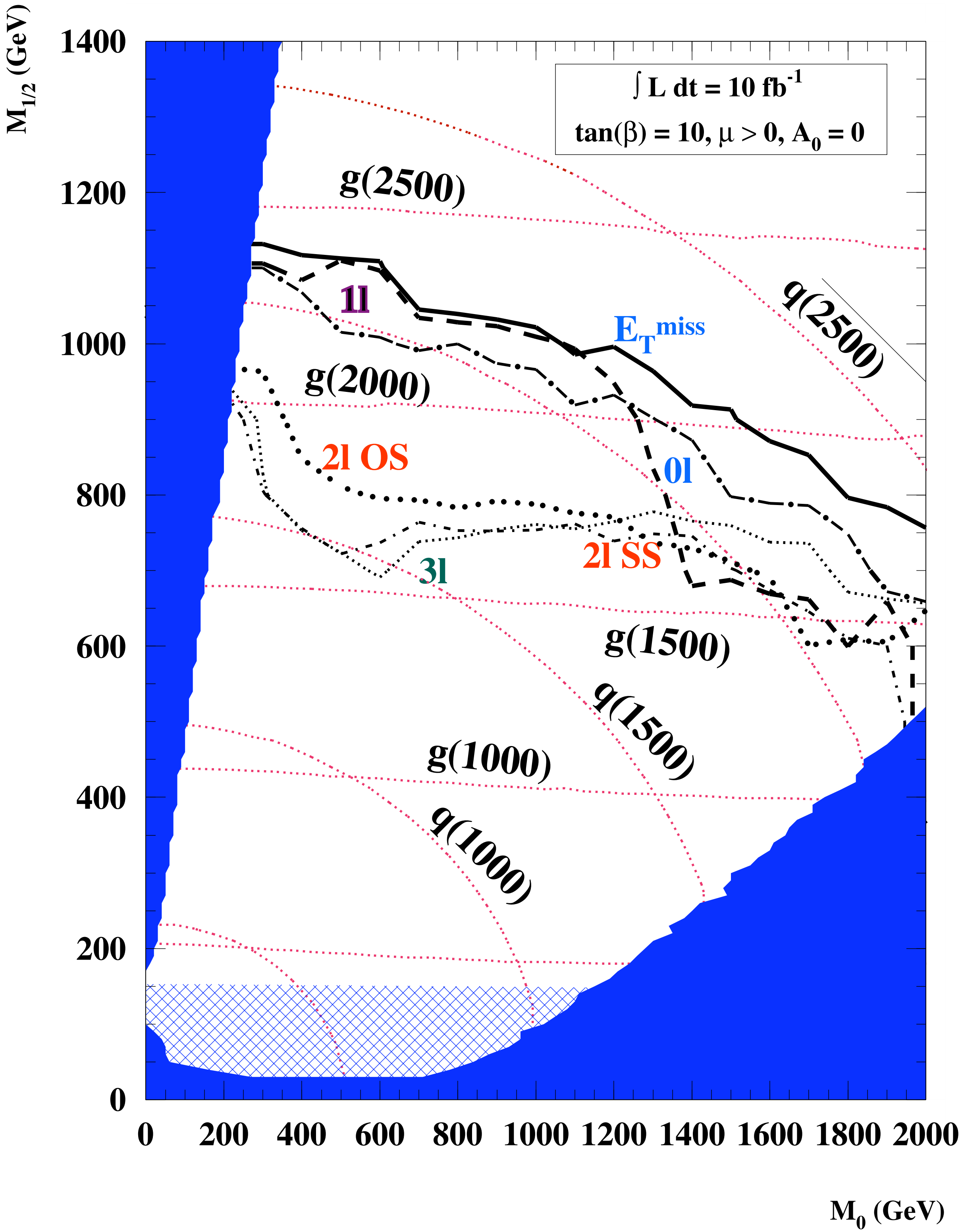
Here are the estimates of Tovey (2003) for supersymmetry models with universal scalar and gaugino masses at the GUT scale.

For squark and gluino masses below 1 TeV, the missing energy signature should be significant with a very small amount of integrated luminosity.



ATLAS

At the same time, many different signatures of new physics should be seen above the Standard Model expectation.

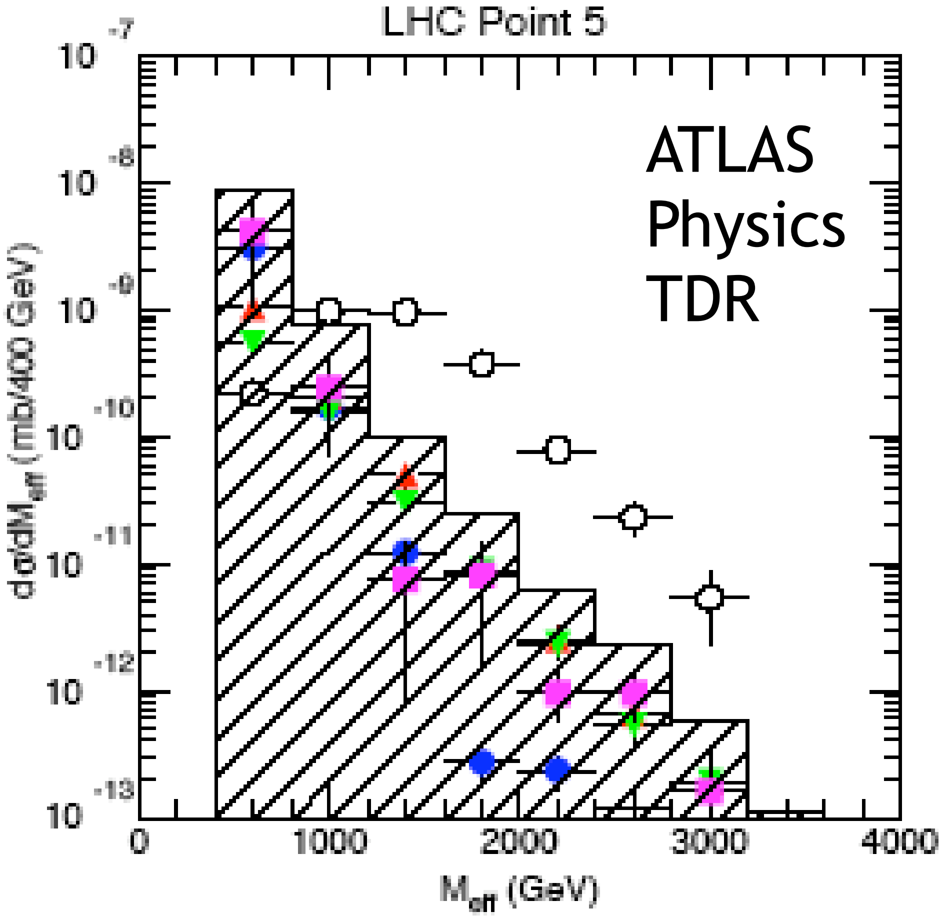


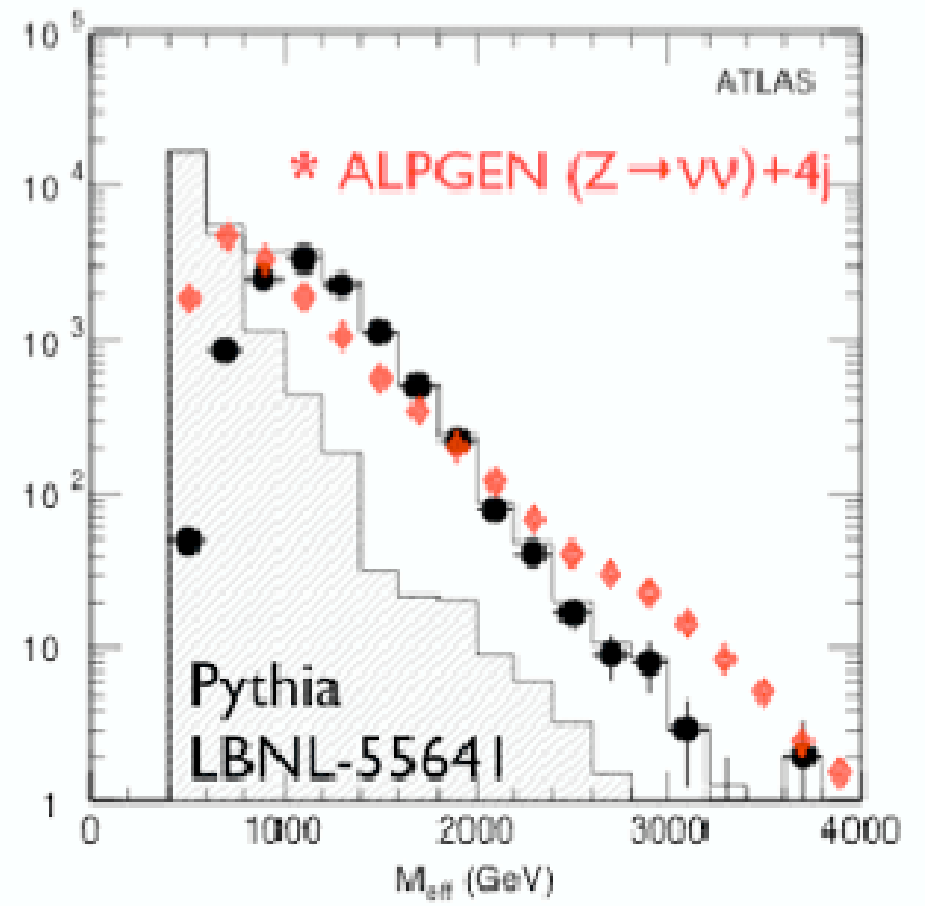
ATLAS

However, the expectation of large signals above Standard Model background does not mean that we can be complacent.

The theoretical background levels must be understood very well both absolutely and in relation to the actual data.

Gianotti and Mangano (2005):





"Not only is the rate larger than previously expected, but the shape of the distribution is different, and much closer to that of the signal itself."

An enormous amount of work has been done on the theoretical calculation of these background rates.

But still all particle physicists - even string theorists - should be engaged with this problem.   We need clearer ways to think about the prediction of backgrounds, and to verify our models of them from data.

In order to reach the level of new physics signals, we will need to work down through a series of levels dominated by Standard Model processes of different types.

Here is an idea of the hierarchy:

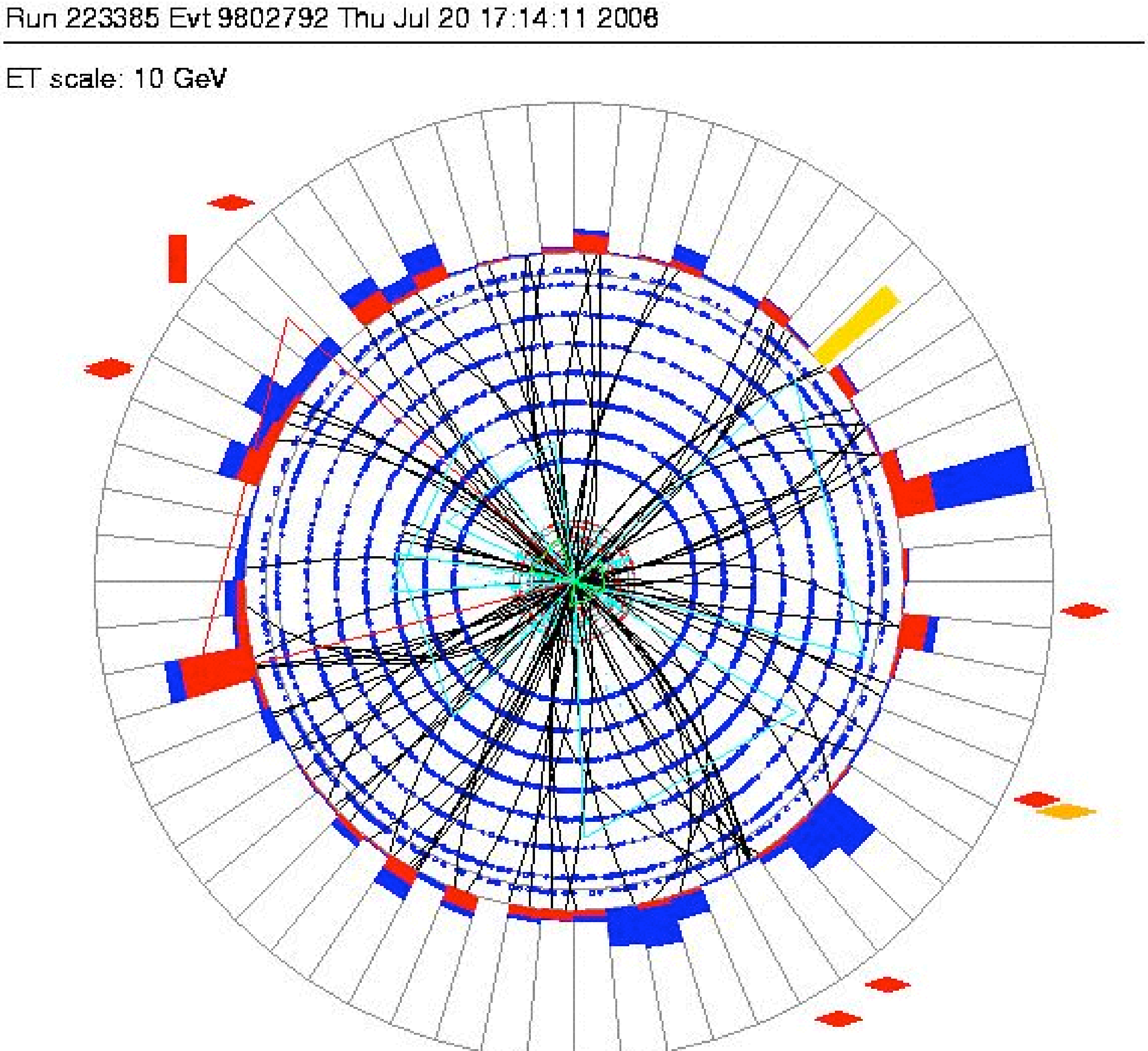
σ_{tot}	100 mb
jets w. $p_T > 100$	1 μb
Drell-Yan	100 nb
$t\bar{t}$	800 pb
SUSY ($M < 1$ TeV)	1-10 pb

The first challenge comes with the realization that the processes that we are looking for occur at rates of order

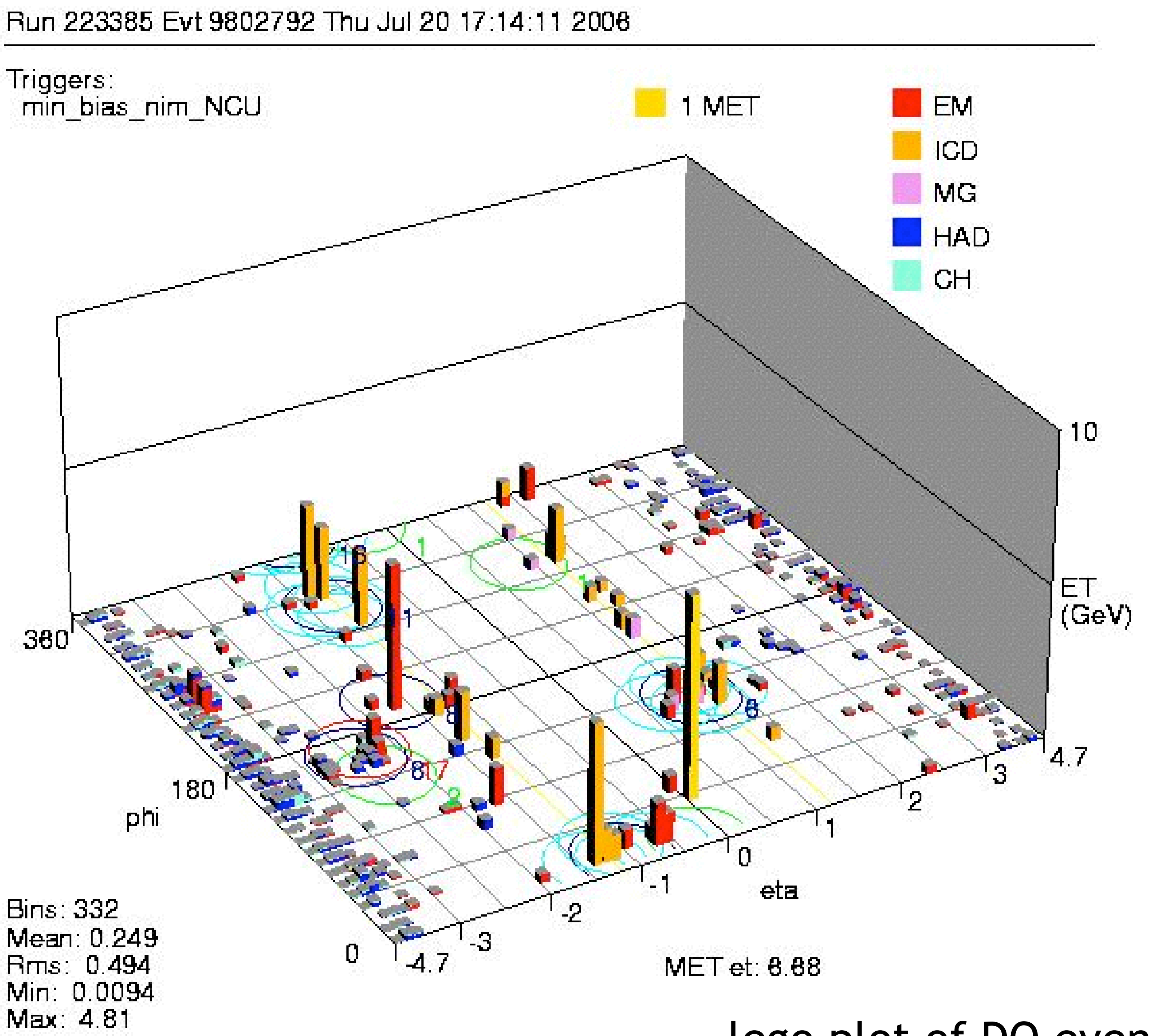
$$10^{-11}$$

of the total pp cross section.

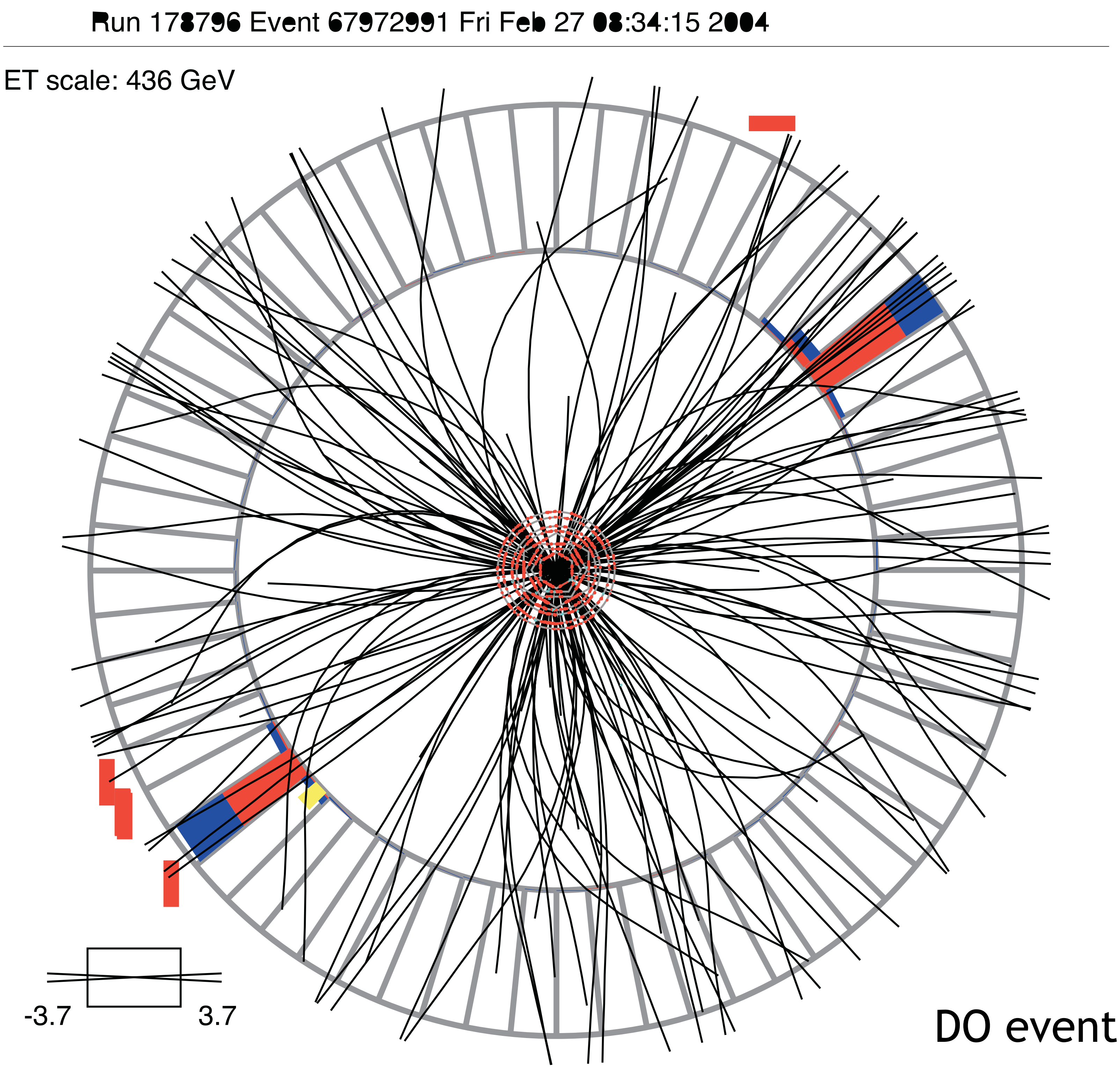
Still, the interesting events have several jets with large values of pT. To find jets, we can look at the 'lego plot' of pT deposited in the plane of θ and ϕ - or, better, rapidity y and ϕ . If we look for these objects instead of simply searching for large energy deposition, we already win about 6 orders of magnitude.

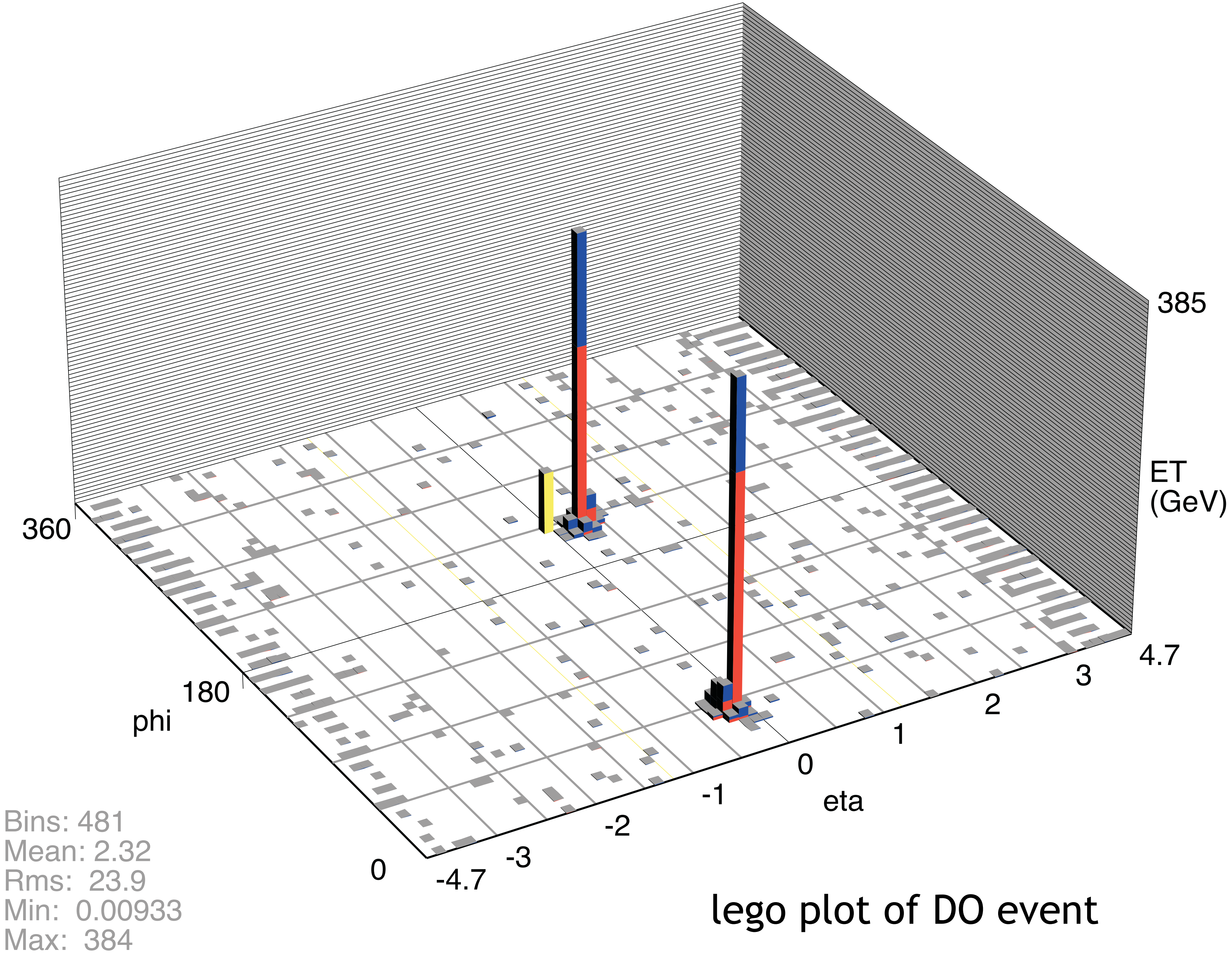


DO event



lego plot of DO event


Run 178796 Event 67972991 Fri Feb 27 08:34:15 2004
ET scale: 436 GeV
-3.7
3.7
DO event

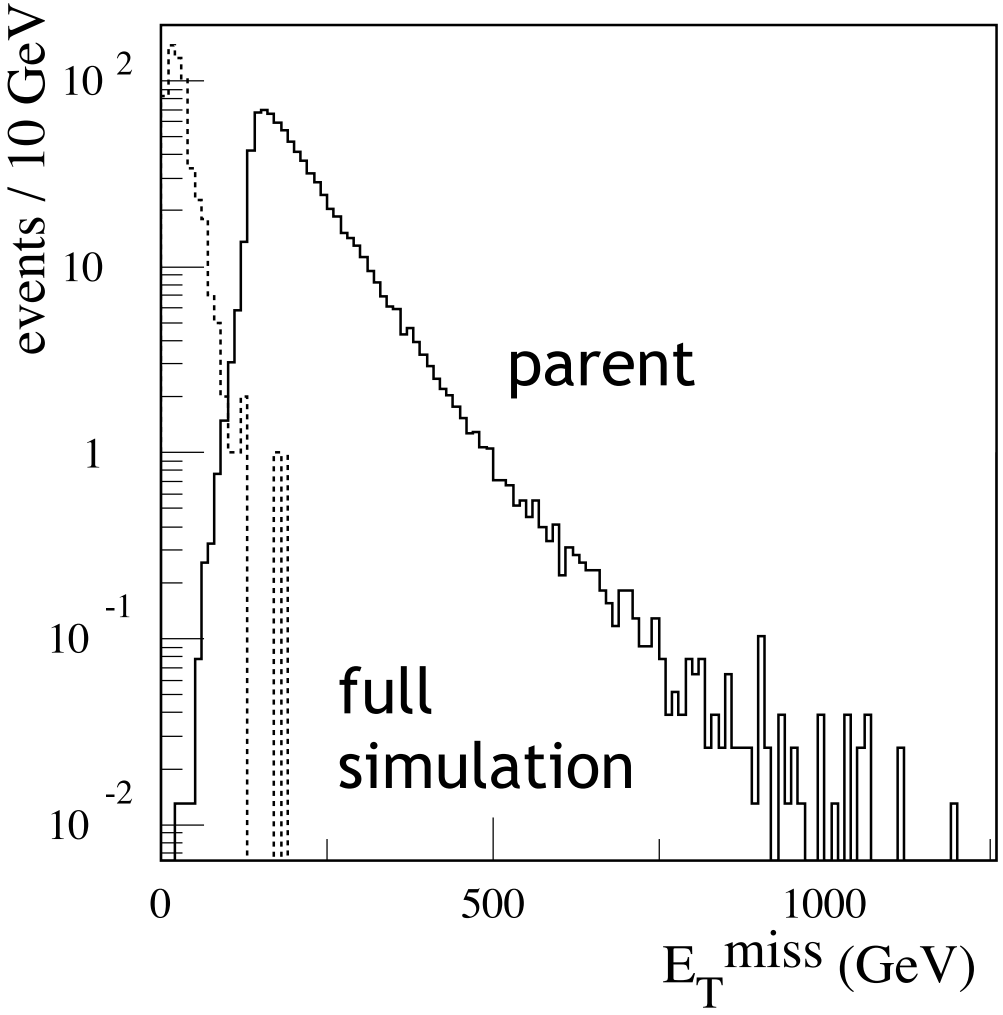


lego plot of DO event

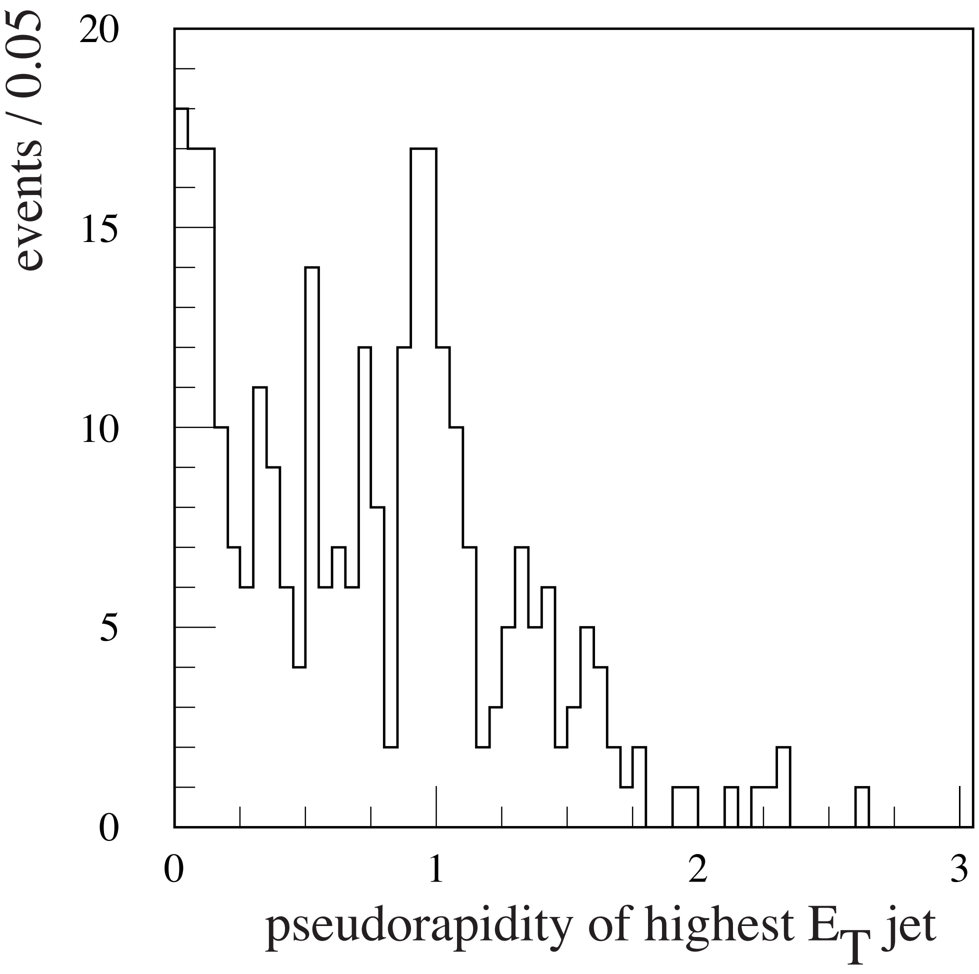
To go further, we need to search for events that do not belong to the classes generated by QCD. These should be events with multiple jets, plus leptons or unbalanced visible momentum.

QCD will generate unbalanced momentum if jets are mismeasured. To control this effect, it is necessary to understand the detectors, to eliminate noise and electronic signals unrelated to the physics events, and to correct for cracks and geometric inefficiencies.

CMS and ATLAS claim that they can control these effects to the required level. That story is expressed in these figures from the ATLAS TDR.



ATLAS simulation of missing ET in $Z(\rightarrow \mu^+\mu^-) + jet$

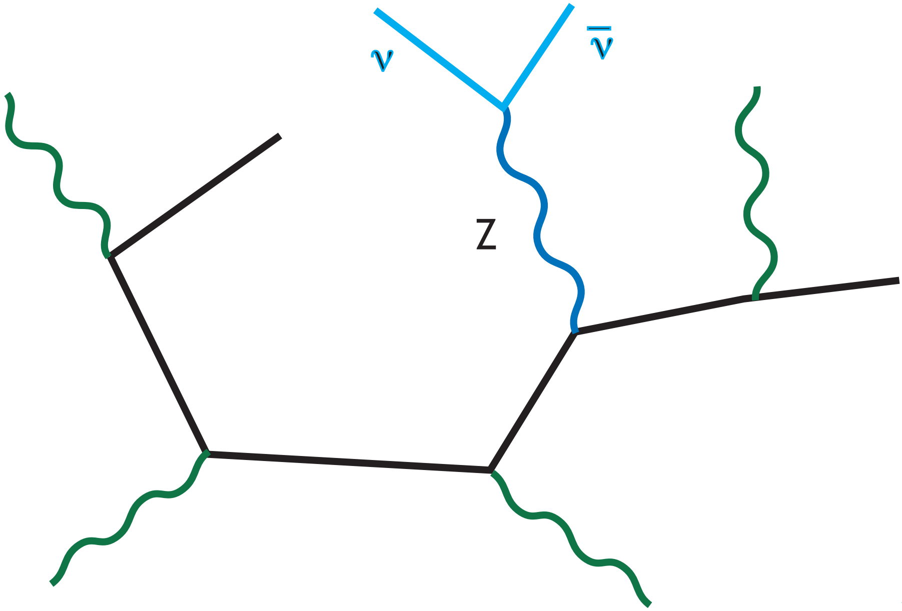


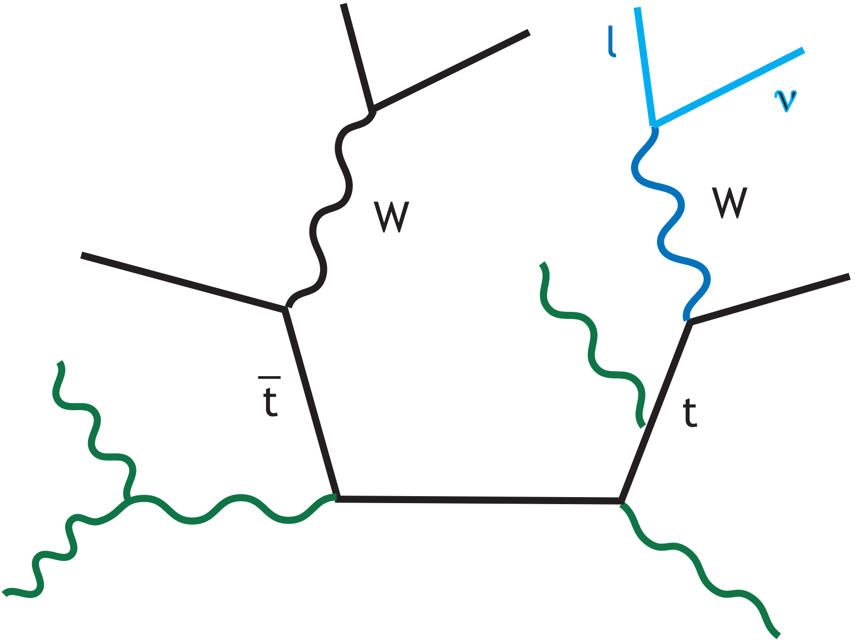
η of the jet w. the highest ET in events w. ET > 50

In the physics studies of ATLAS and CMS, the dominant backgrounds to new physics come from a different source, heavy particle production within the Standard Model, production of $W, Z, t\bar{t}$ plus jets.

These reactions already offer missing energy, leptons, and hadronic activity. They populate the region of large HT associated with new physics to the extent the additional jets are radiated along with the heavy particles.

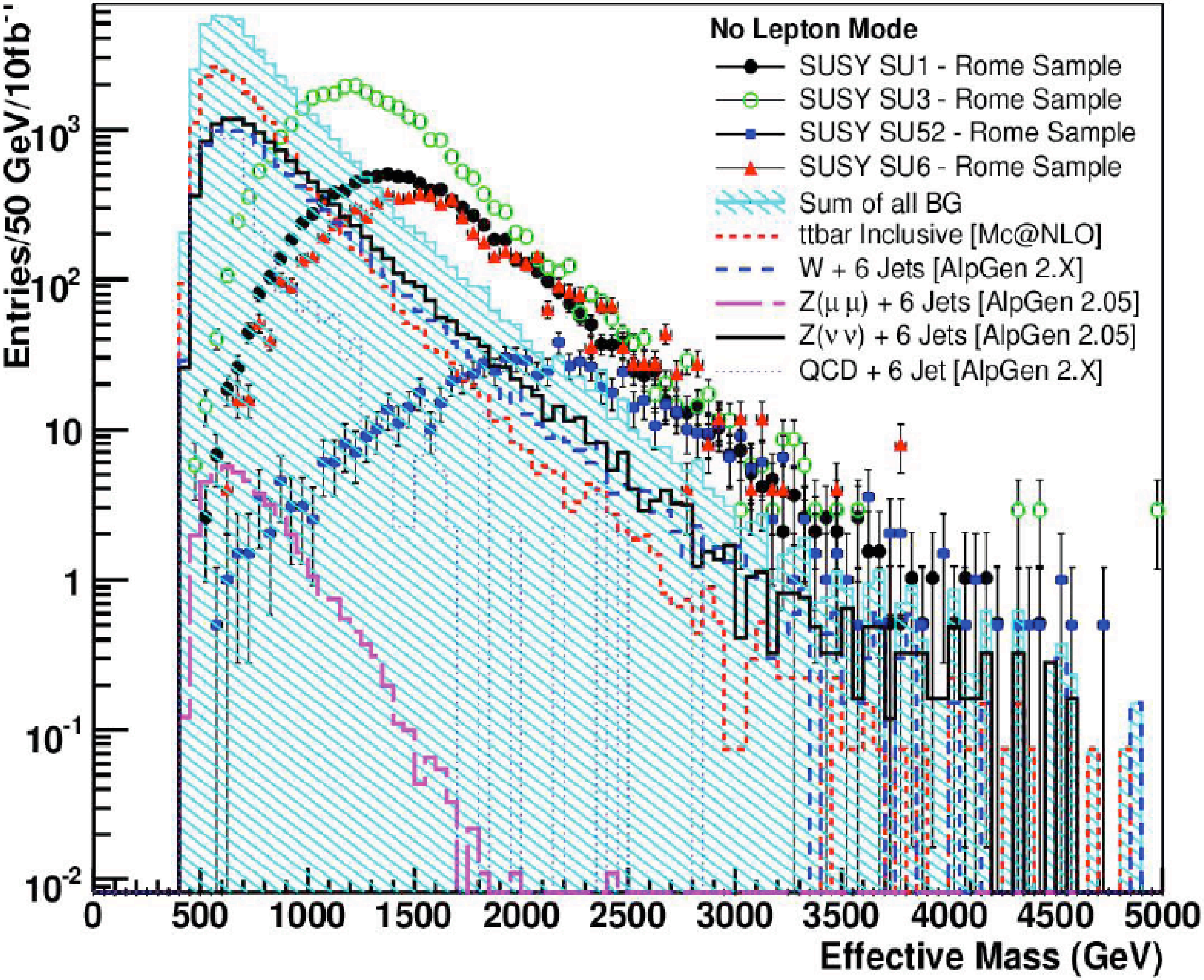
This is genuinely scary. Processes such as





have cross sections comparable to the SUSY signal and might compete with it.

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.

$E_T > 100$

To understand heavy particle + multijet backgrounds to new physics, there is a methodology that has been used successfully in the Tevatron, especially in the CDF and DO analyses of top quark production.

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 a now a standard part of the Tevatron culture.

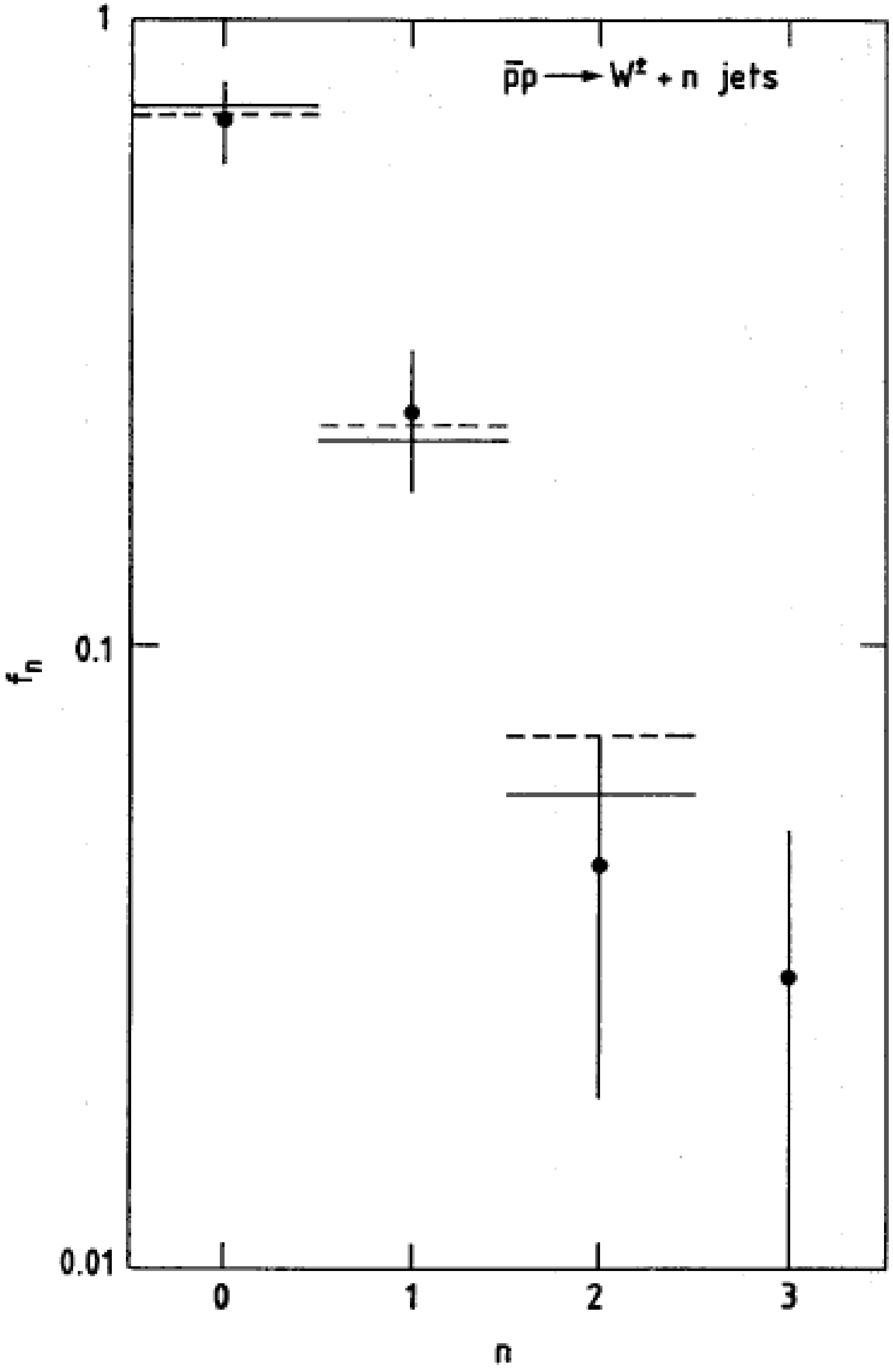
It apparently originated in UA2, where the systematics of jet counting was called "Berends scaling". The name did not stick, and there are are earlier references.

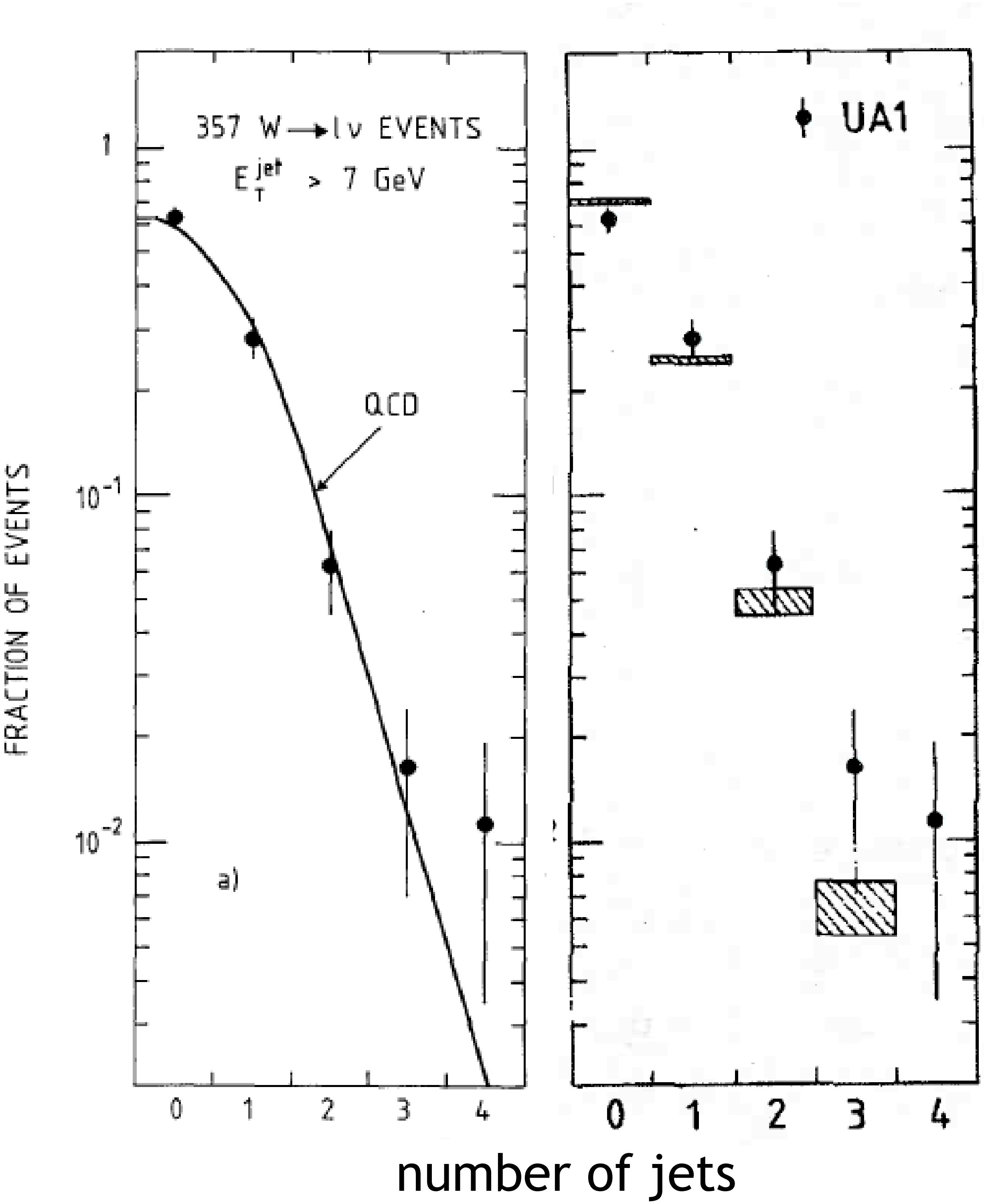
I think that the concept--in its original context, and in greater generality--is very important for carrying out and evaluating experimental results from the LHC. I would like to present a new name for it: the staircase.

Here is - to my knoweldge - the original staircase presented by Ellis, Kleiss, and Stirling:

Ellis-Kleiss-Stirling staircase (1985)

compared to preliminary data from UA1.





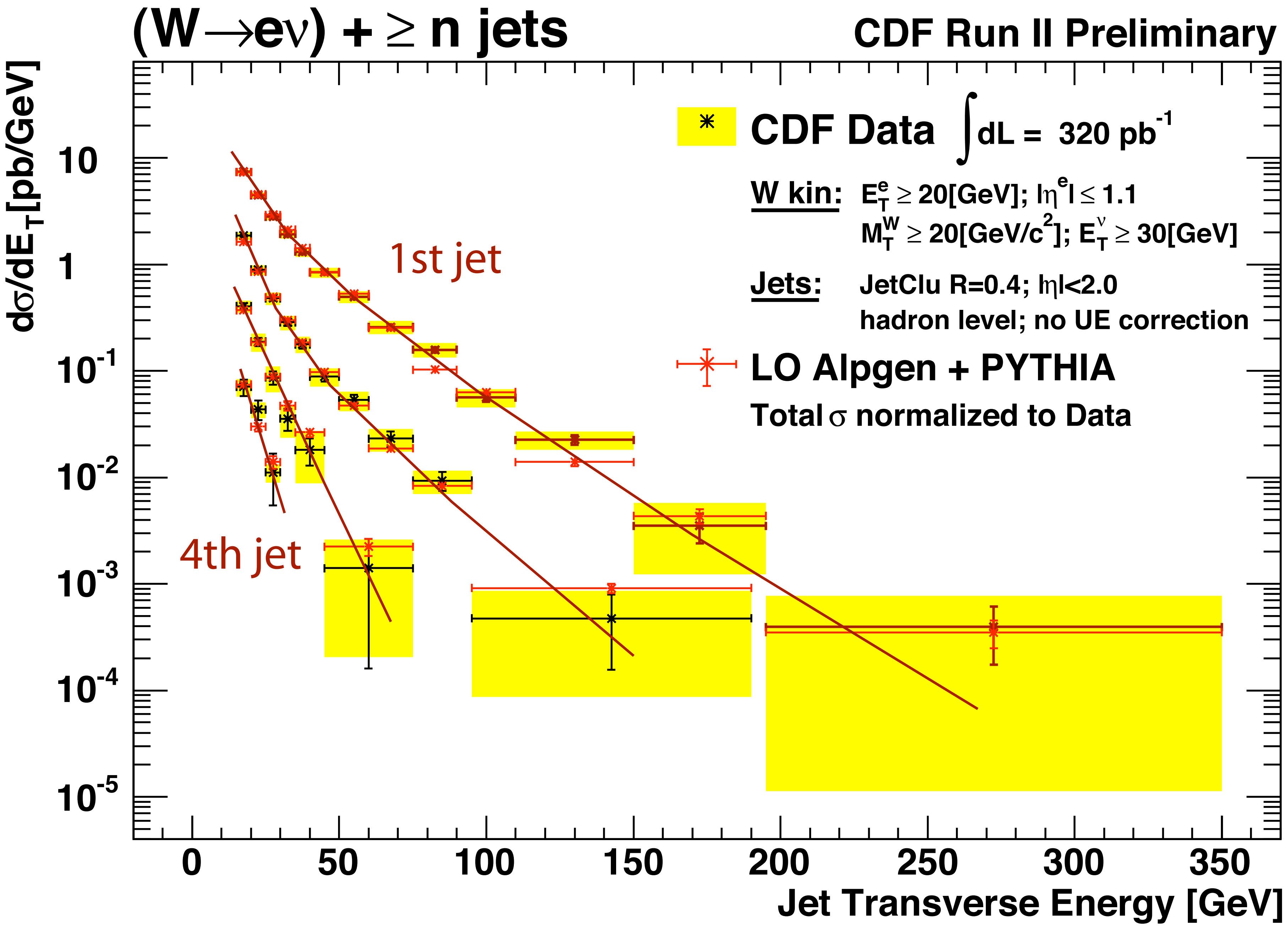
Here is the published UA1 data, compared to a calculation based on the Berends-Giele technology for multijet computation :

UA1
1988

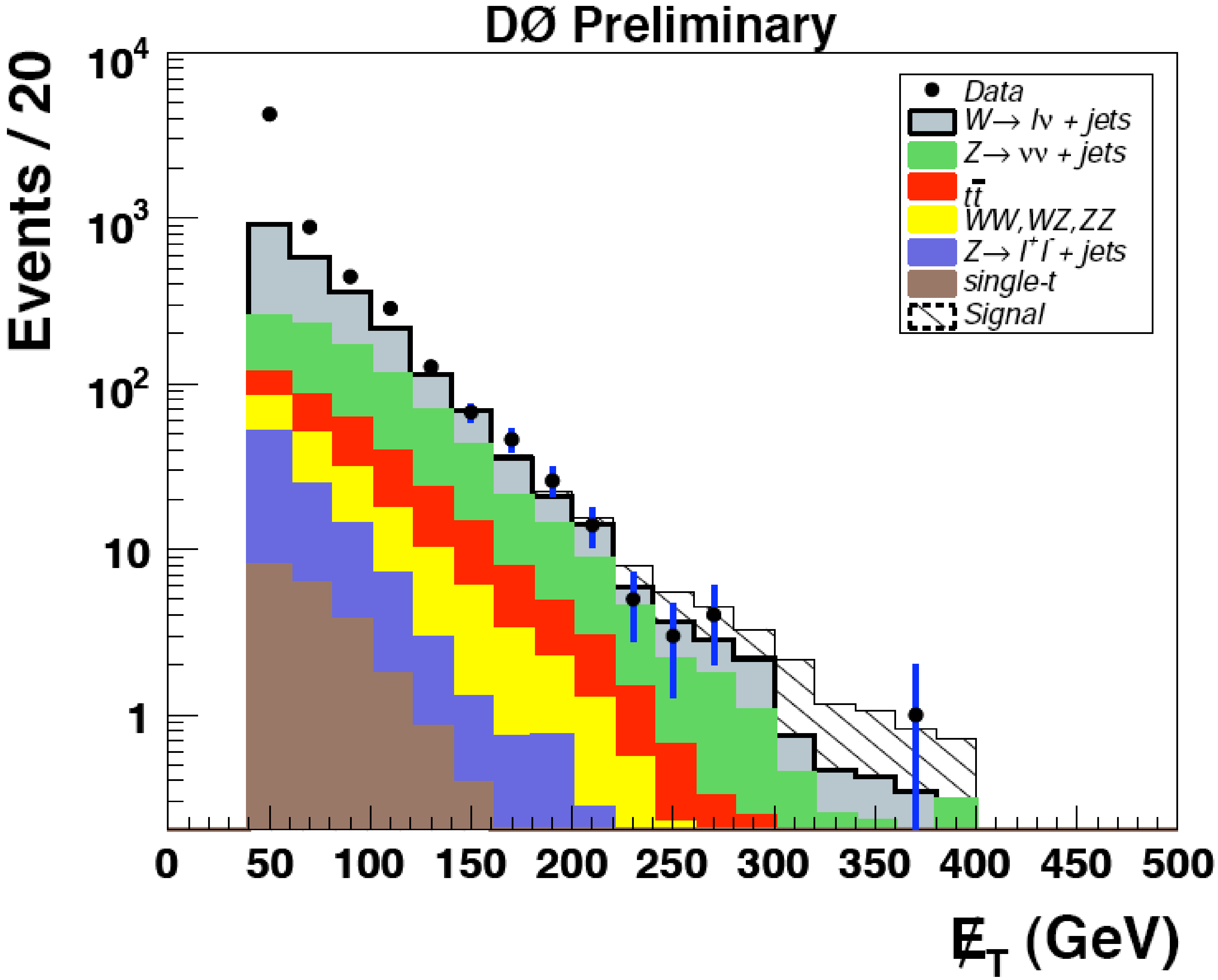
Berends,
Giele,Kuijf,
Kleiss, Stirling
1989

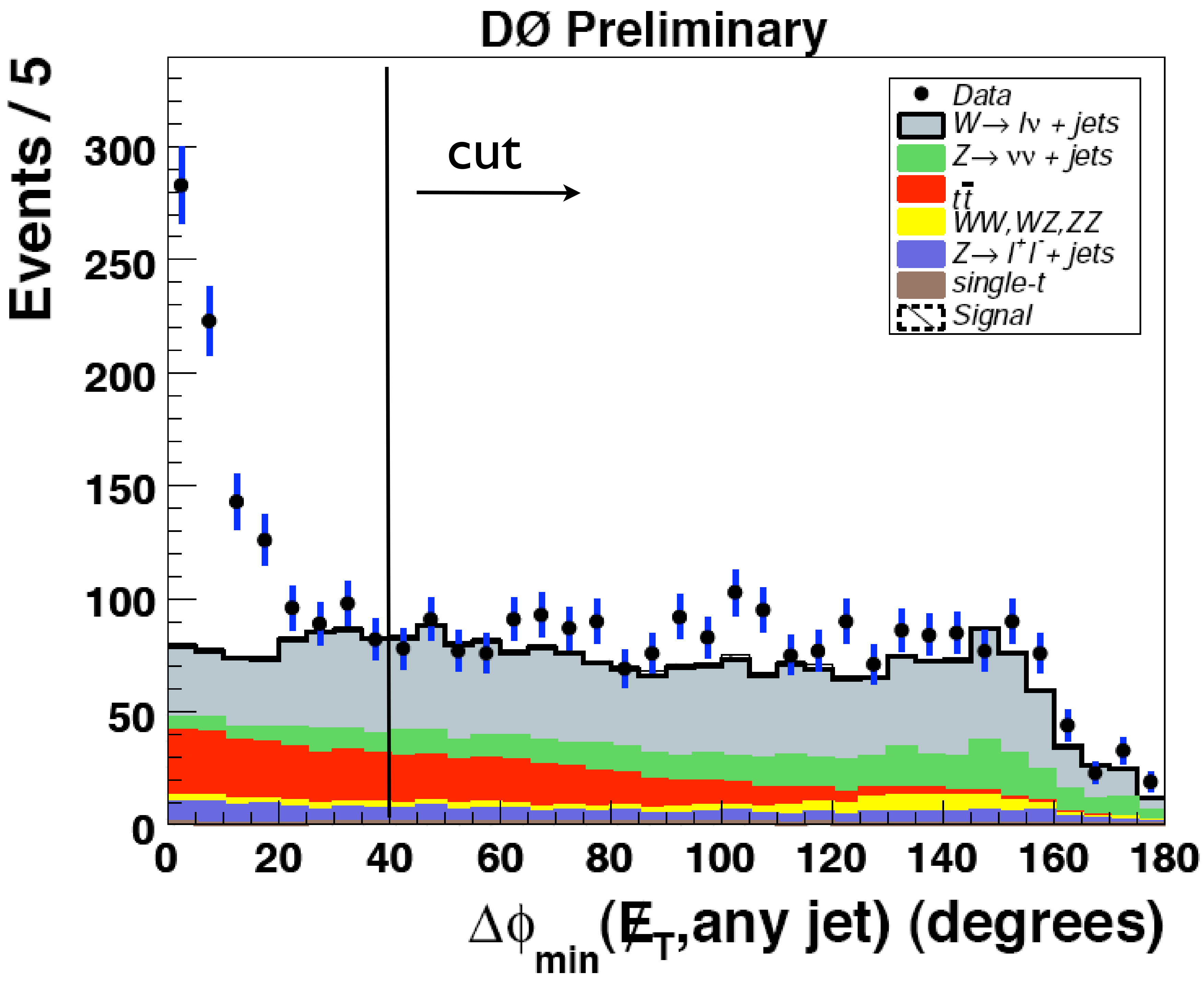
Let me show you a series of recent figures from the Tevatron experiments that illustrate this concept.

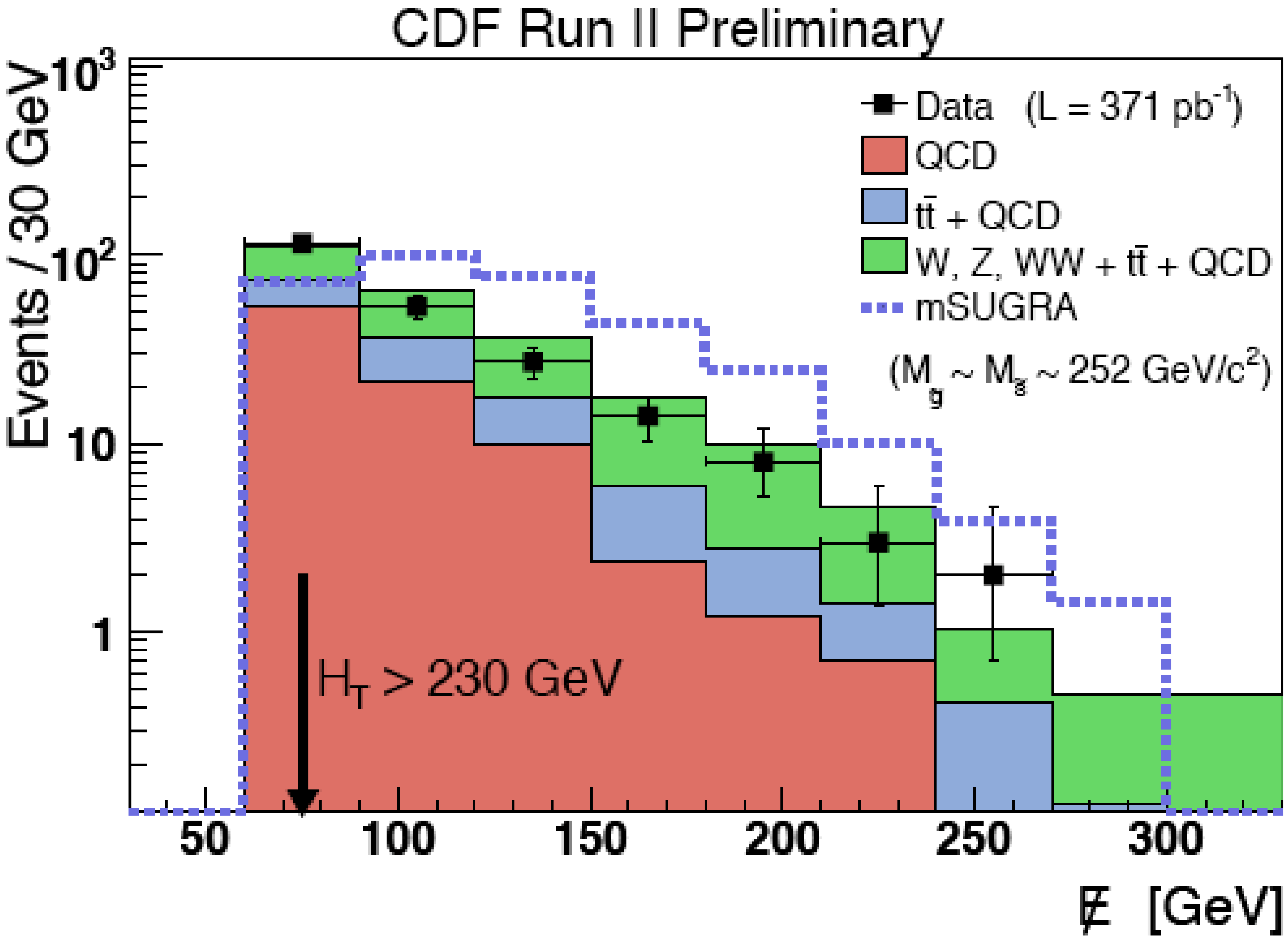
systematics of W + jets



search for SUSY in acoplanar di-jet events

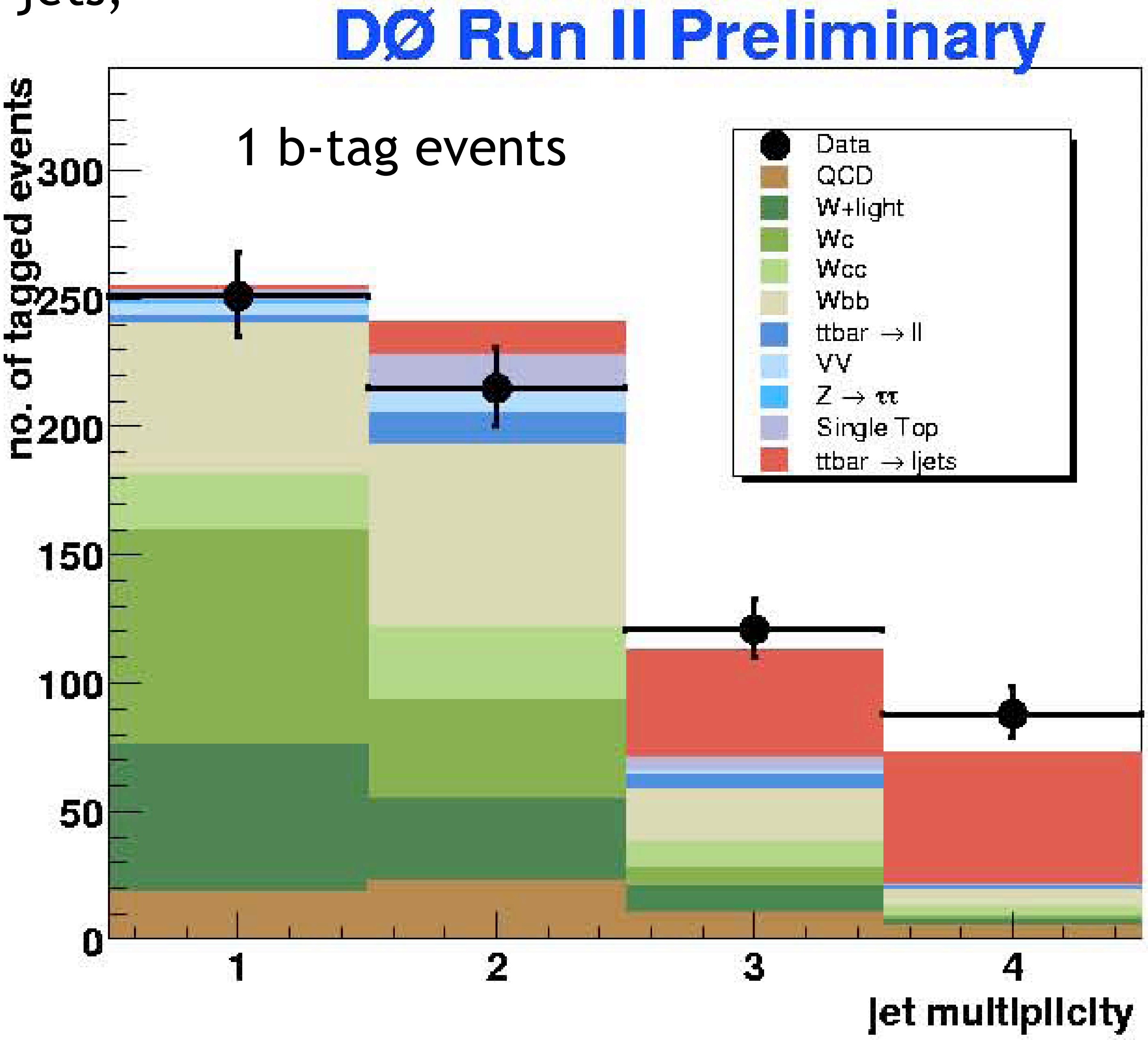



DØ Preliminary
Events / 5
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
160
180
cut
Data
$W \rightarrow l\nu$ + jets
$Z \rightarrow \nu\nu$ + jets
$t\bar{t}$
WW,WZ,ZZ
$Z \rightarrow l^{+}l^{-}$ + jets
single-t
Signal
$\Delta\phi_{min}(\not{E}_T$,any jet) (degrees)

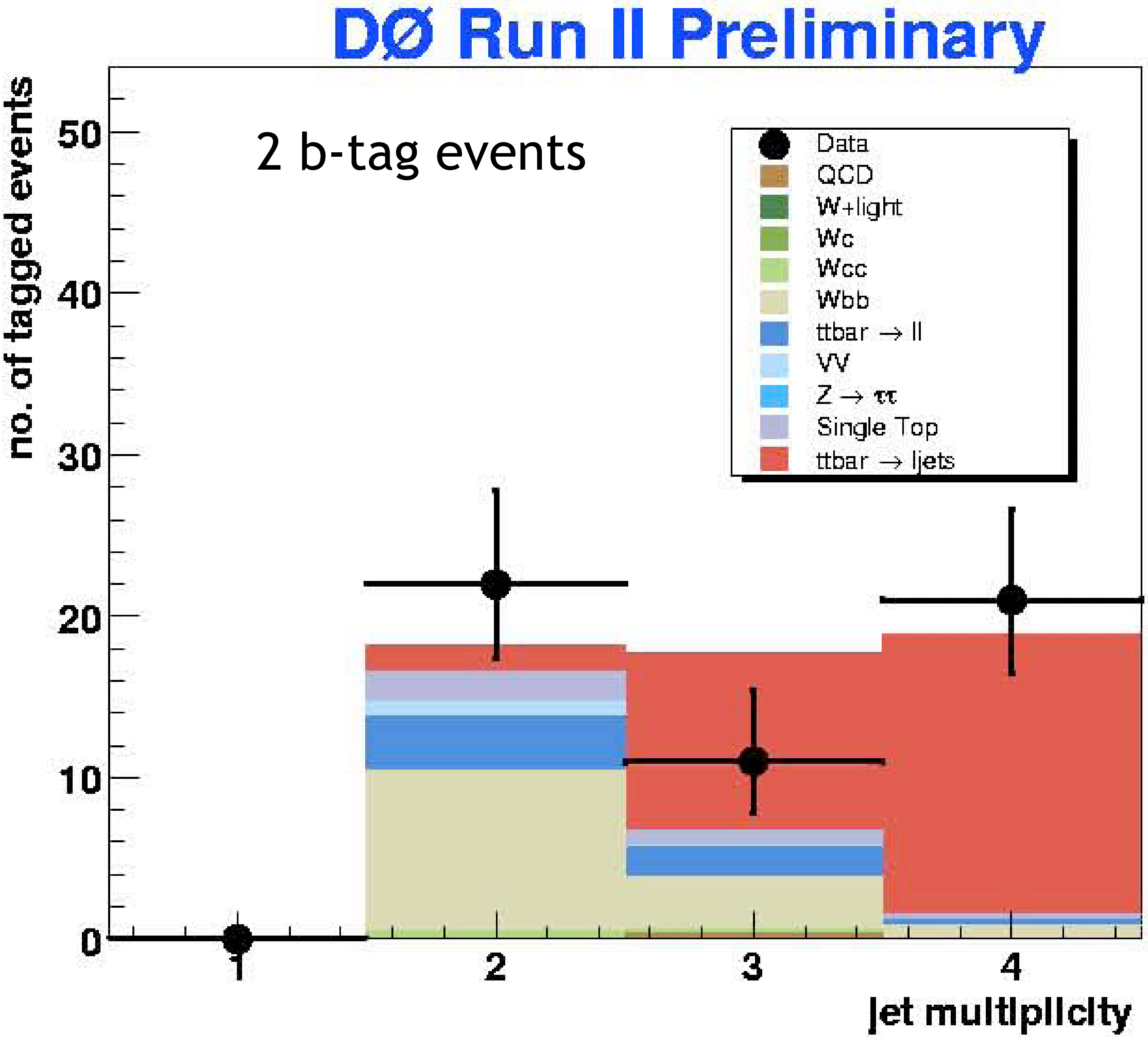

CDF Run II Preliminary
Events / 30 GeV
10^3
10^2
10
1
50
100
150
200
250
300
$\not\!\!E_T$ [GeV]
Data (L = 371 pb^{-1})
QCD
$t\bar{t}$ + QCD
W, Z, WW + $t\bar{t}$ + QCD
mSUGRA
($M_{\tilde{g}} \sim M_{\tilde{q}} \sim$ 252 GeV/c^2)
H_T > 230 GeV

top quark: require 1 b tagged jet

Here there are staircases both with respect to the number of jets,

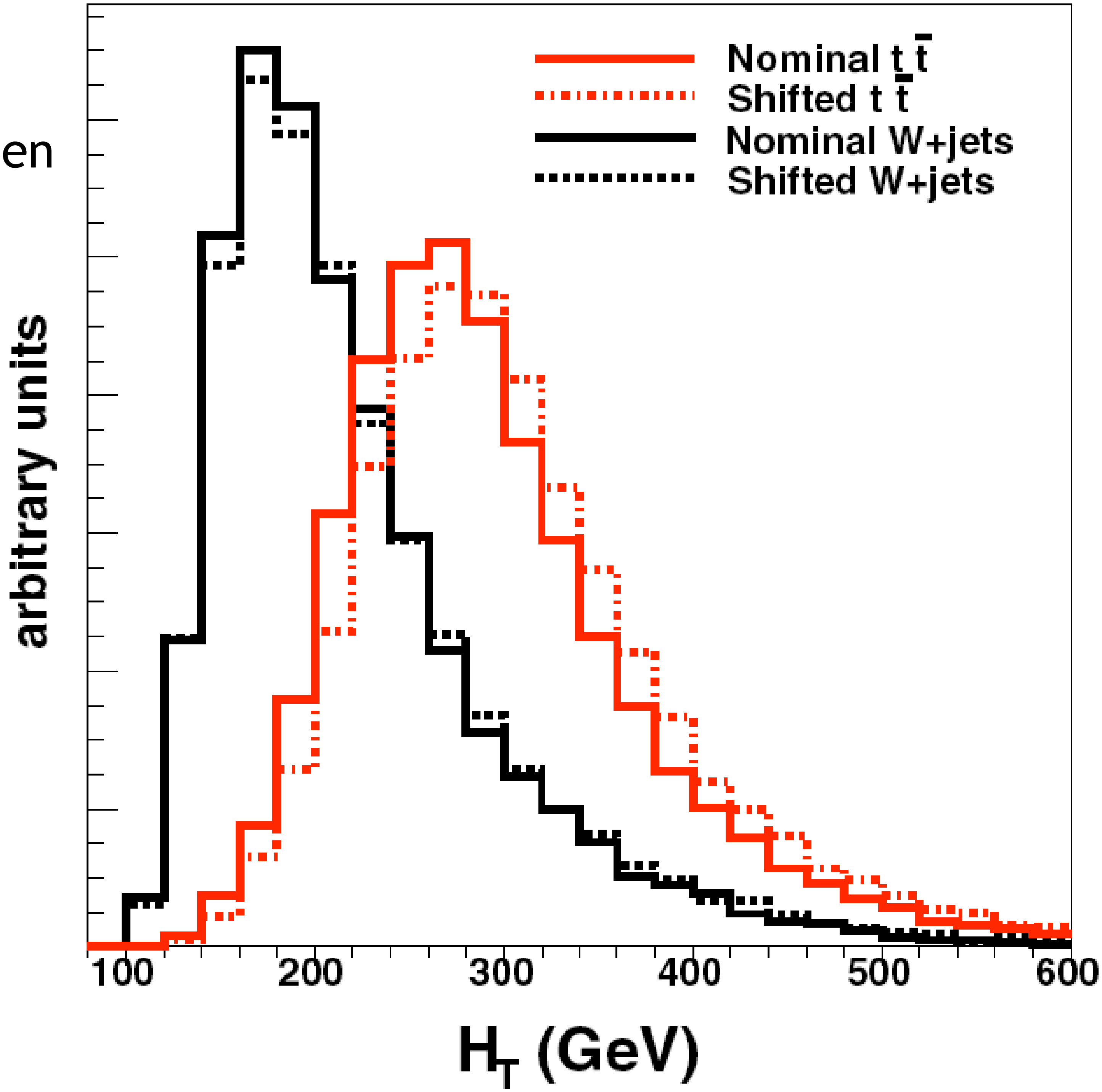


and with respect to the number of b-tagged jets.

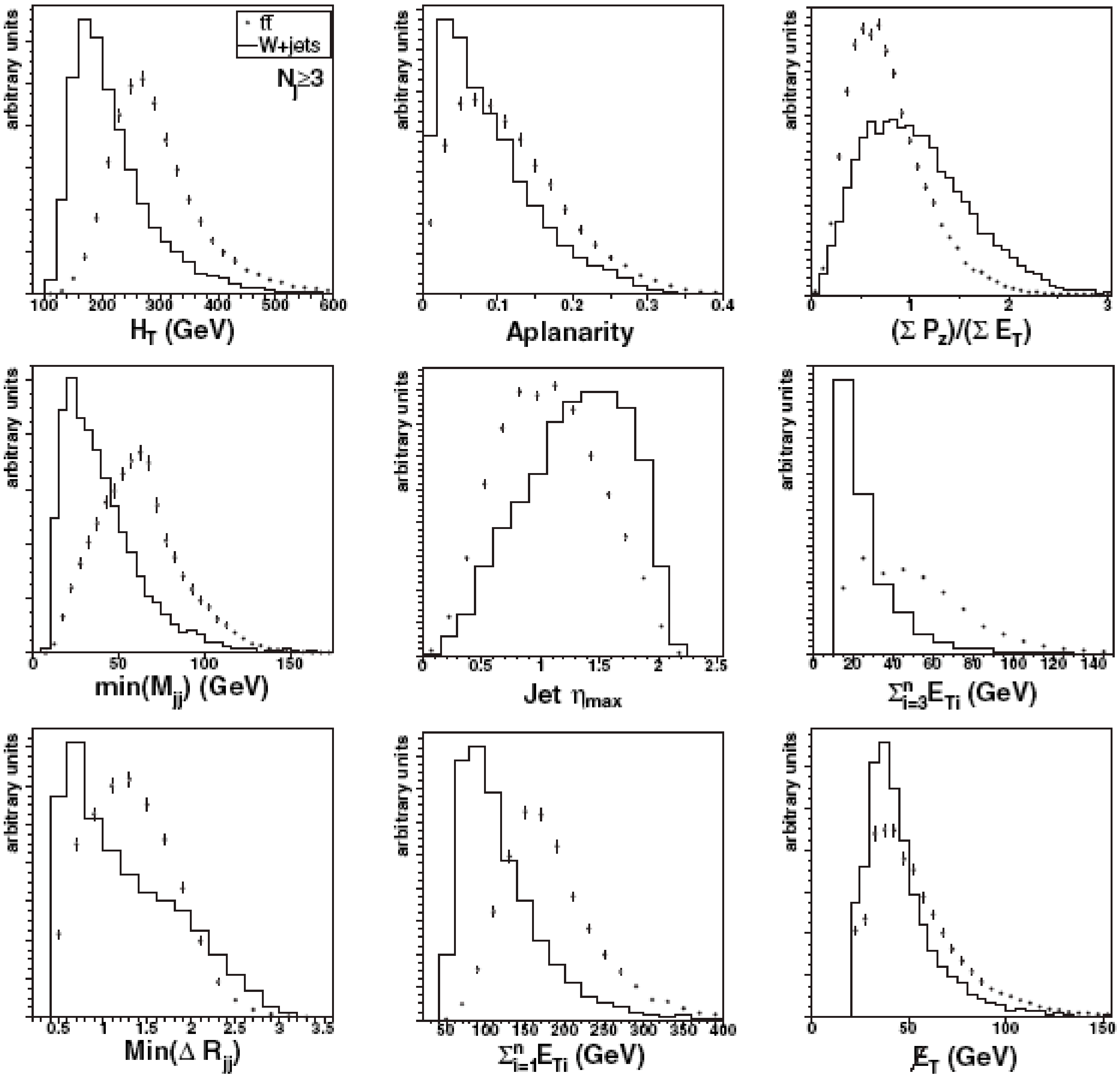


CDF

Comparison of HT distributions between ttbar and W + jets events



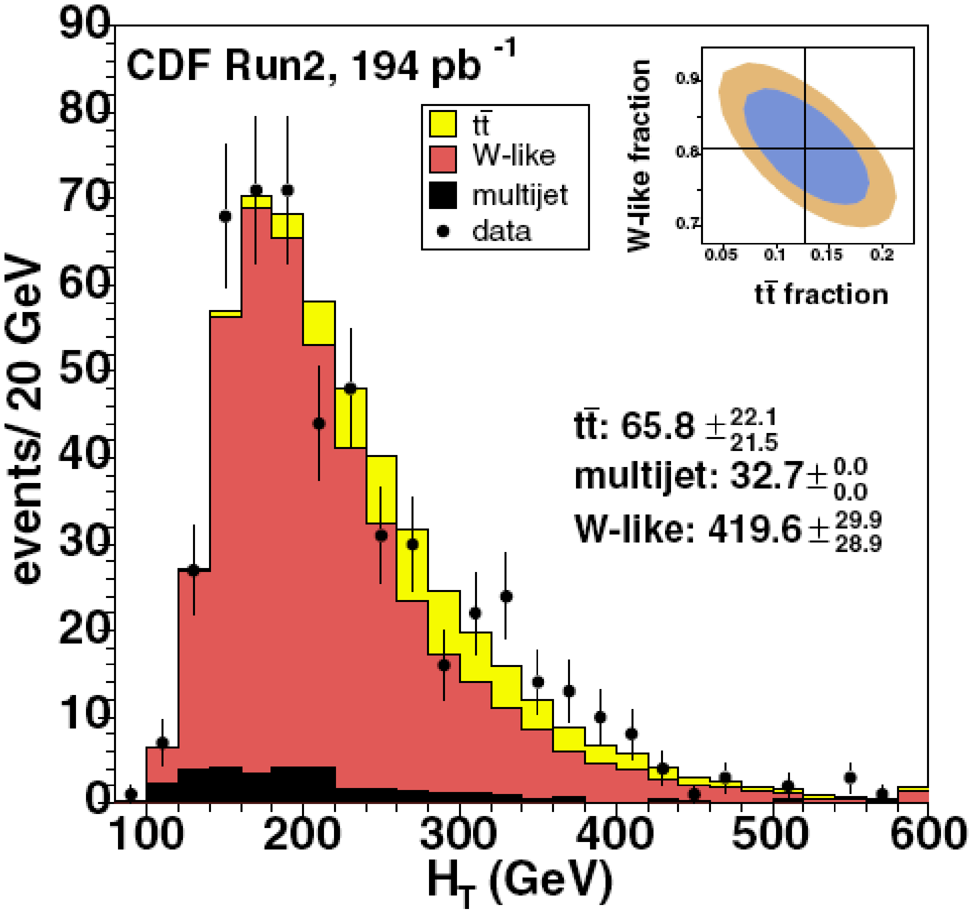
ttbar/W+jets shape comparisons for 9 kinematic observables.



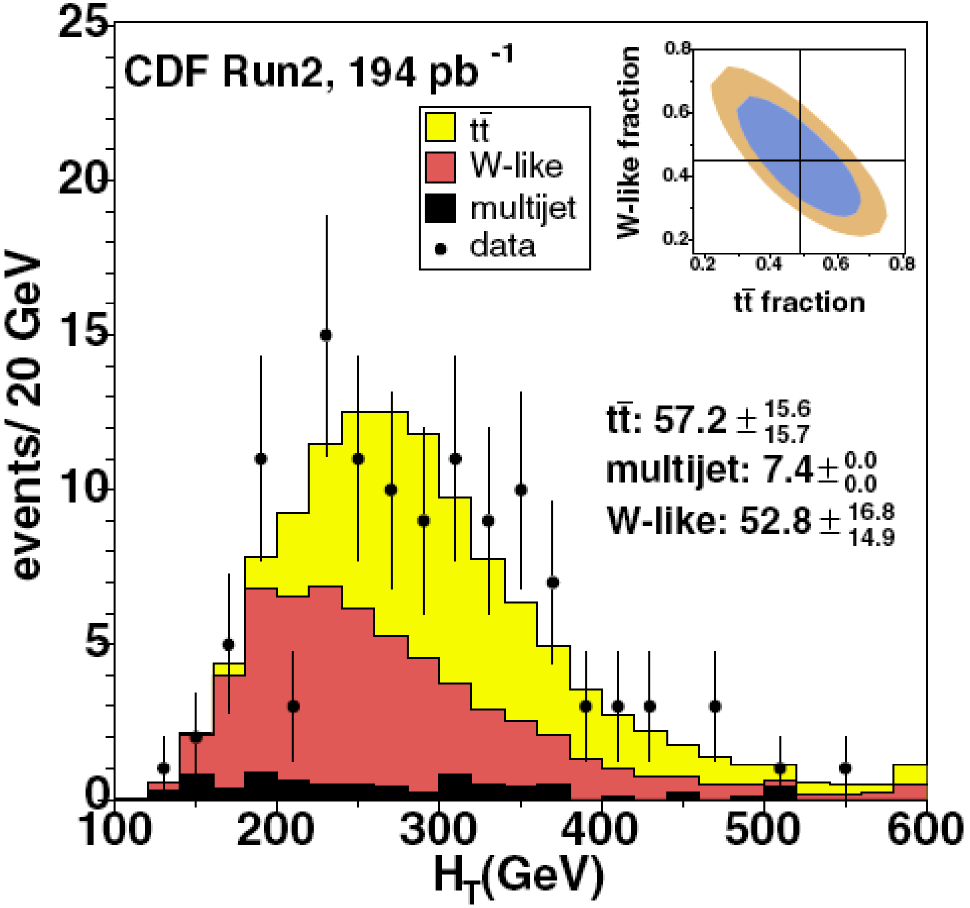
CDF

Using these and 10 more variables input to a neural network classfier, 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



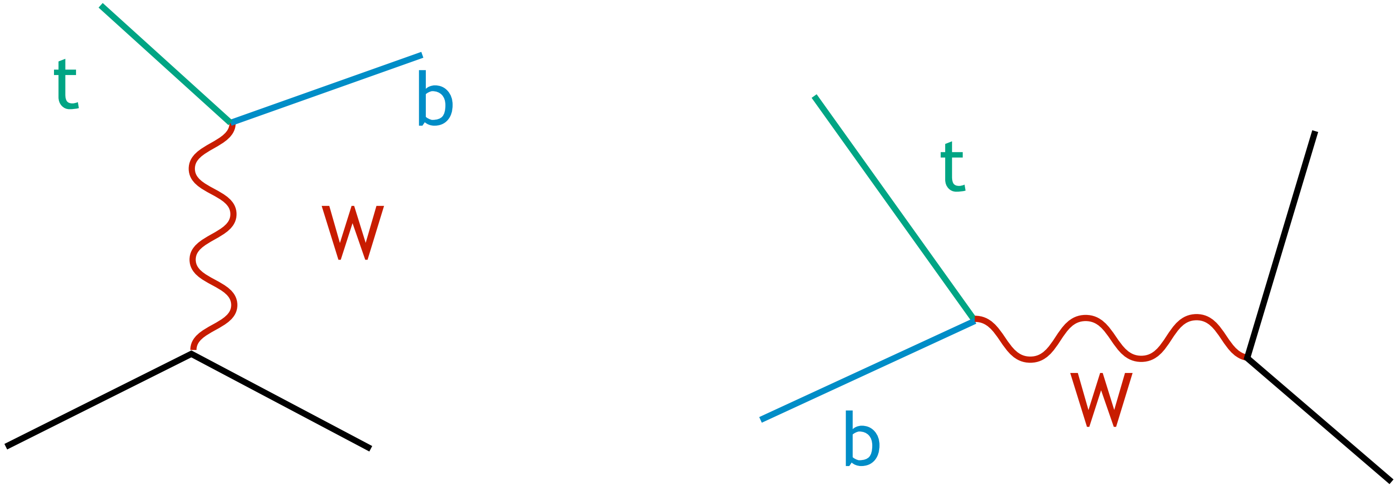
W + 4 jets



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

The CDF and D0 experiments reached an important milestone this past year with the observation of single top production.

This process has a rate about 10% of the rate for top quark pair production.   It is actually two distinct processes, one with an s-channel pole, one with a t-channel pole:



The signature of single-top production is intermediate between those of W + jets and top quark pair production.

The analyses are based on

$$\ell + \not{E}_T + (2,3)\ \mathrm{jet}$$

events with 1 b-tag.

To extract the single-top events from within these backgrounds, the CDF and DO events use automatic classifiers.

One method is to assign a weight to each event based on the lowest order matrix elements for the signal and background processes:

$$D(x) = \frac{P(x|\mathrm{signal})}{P(x|\mathrm{signal}) + P(x|\mathrm{background})}$$

Other analyses use neural networks or boosted decision trees trained with Monte Carlo signal and background state.

I will show some figures from the matrix element based analyses.

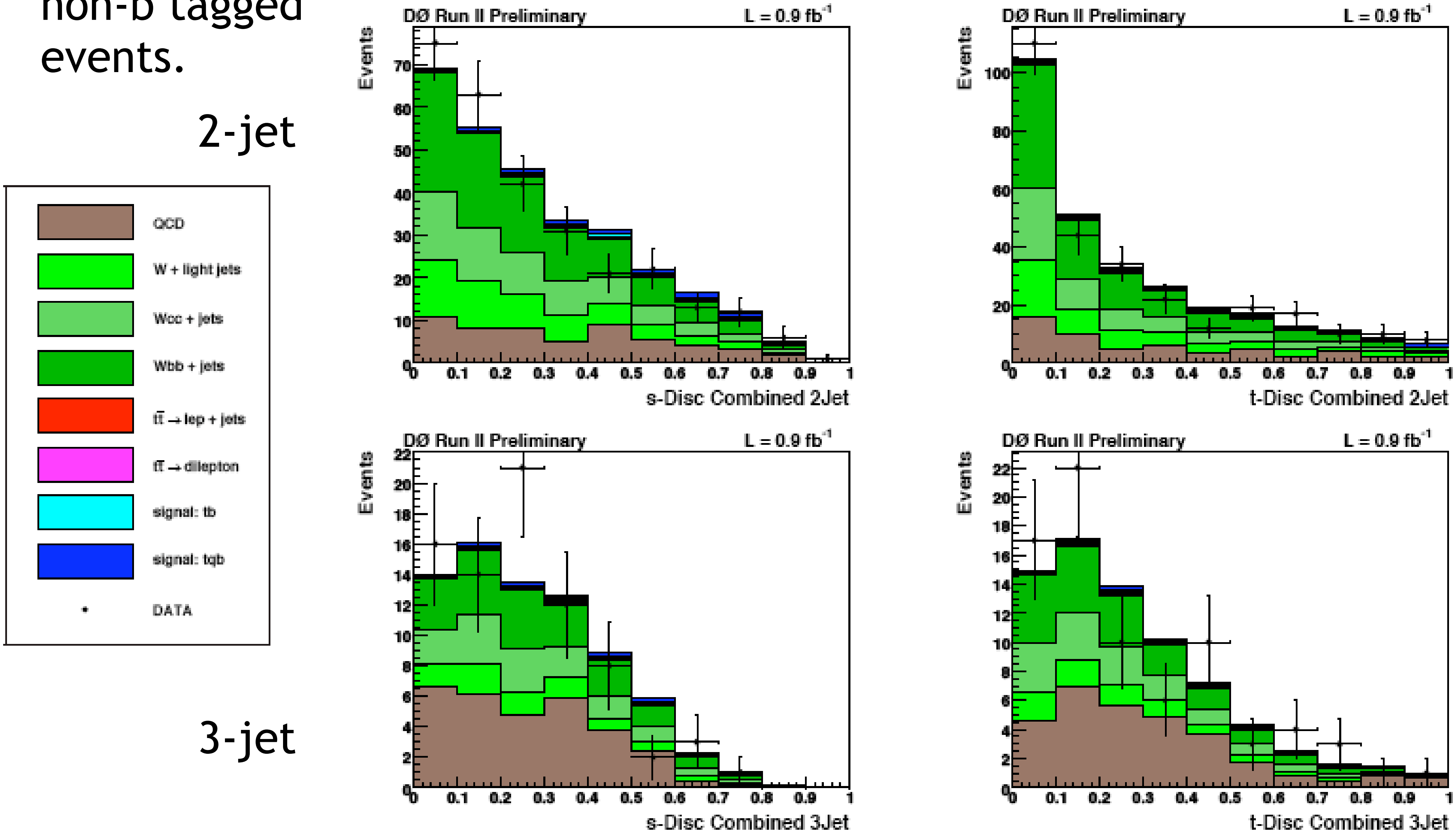
First, apply the classifier to non-b tagged events.

s-channel

t-channel

2-jet

3-jet

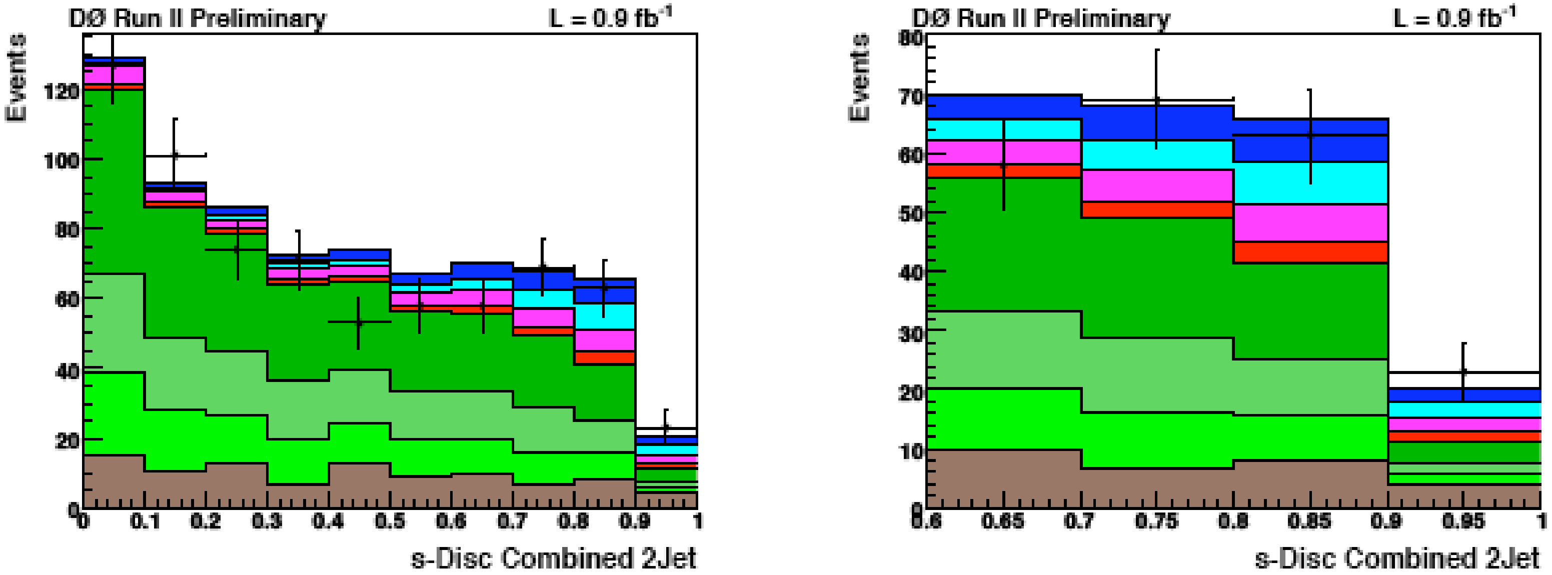


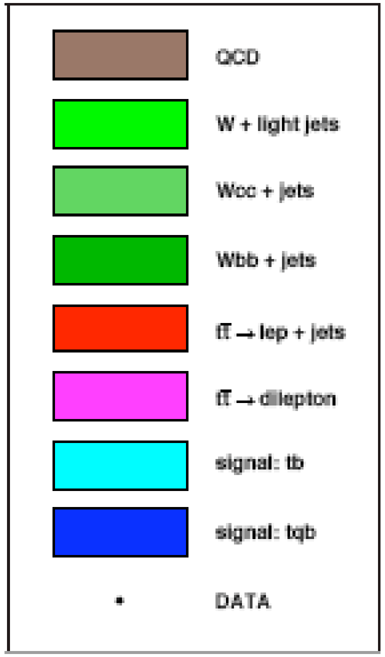
D0

then to the possible
signal events:

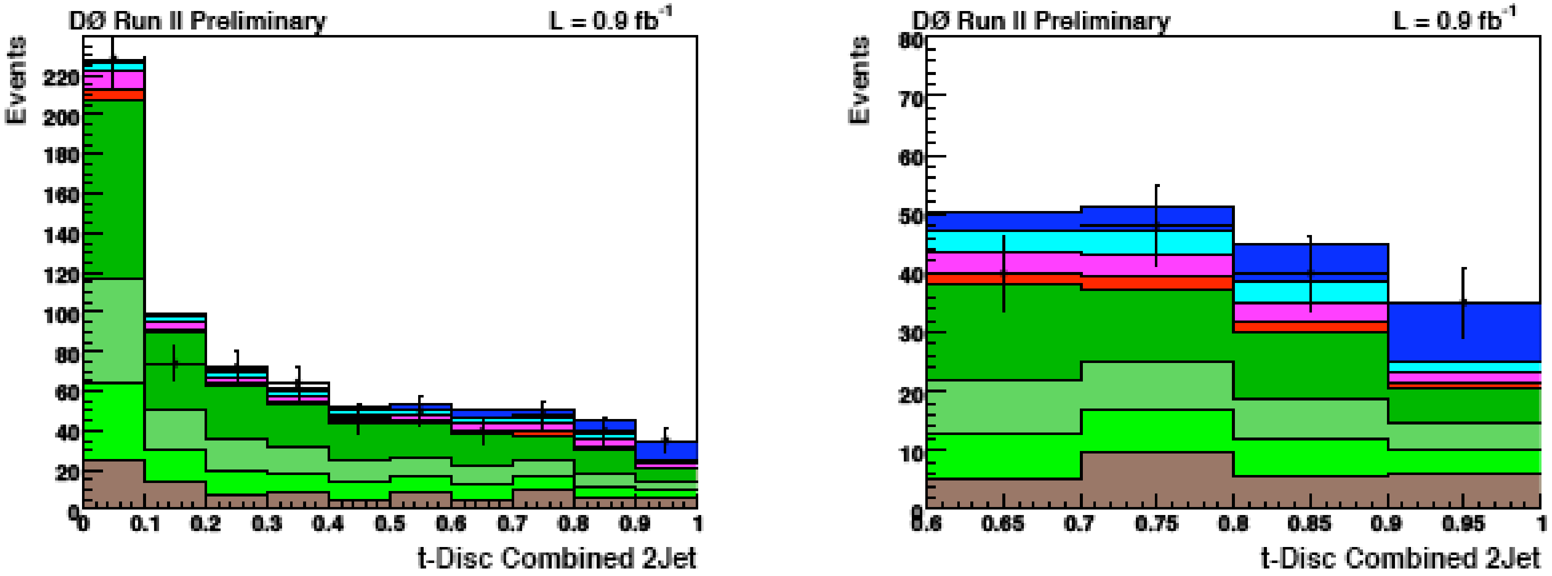
2-jet events

s-channel





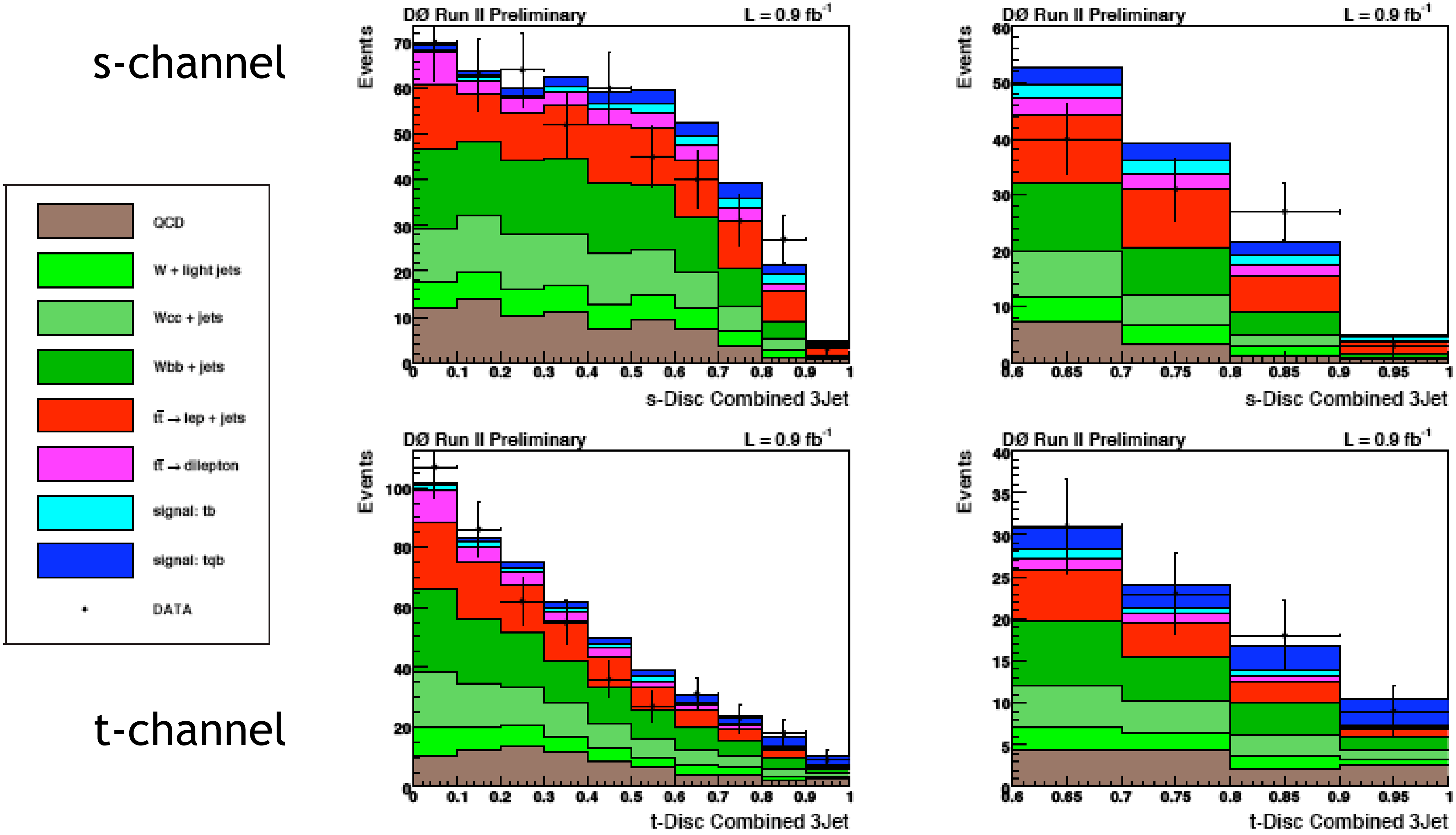
t-channel



D0

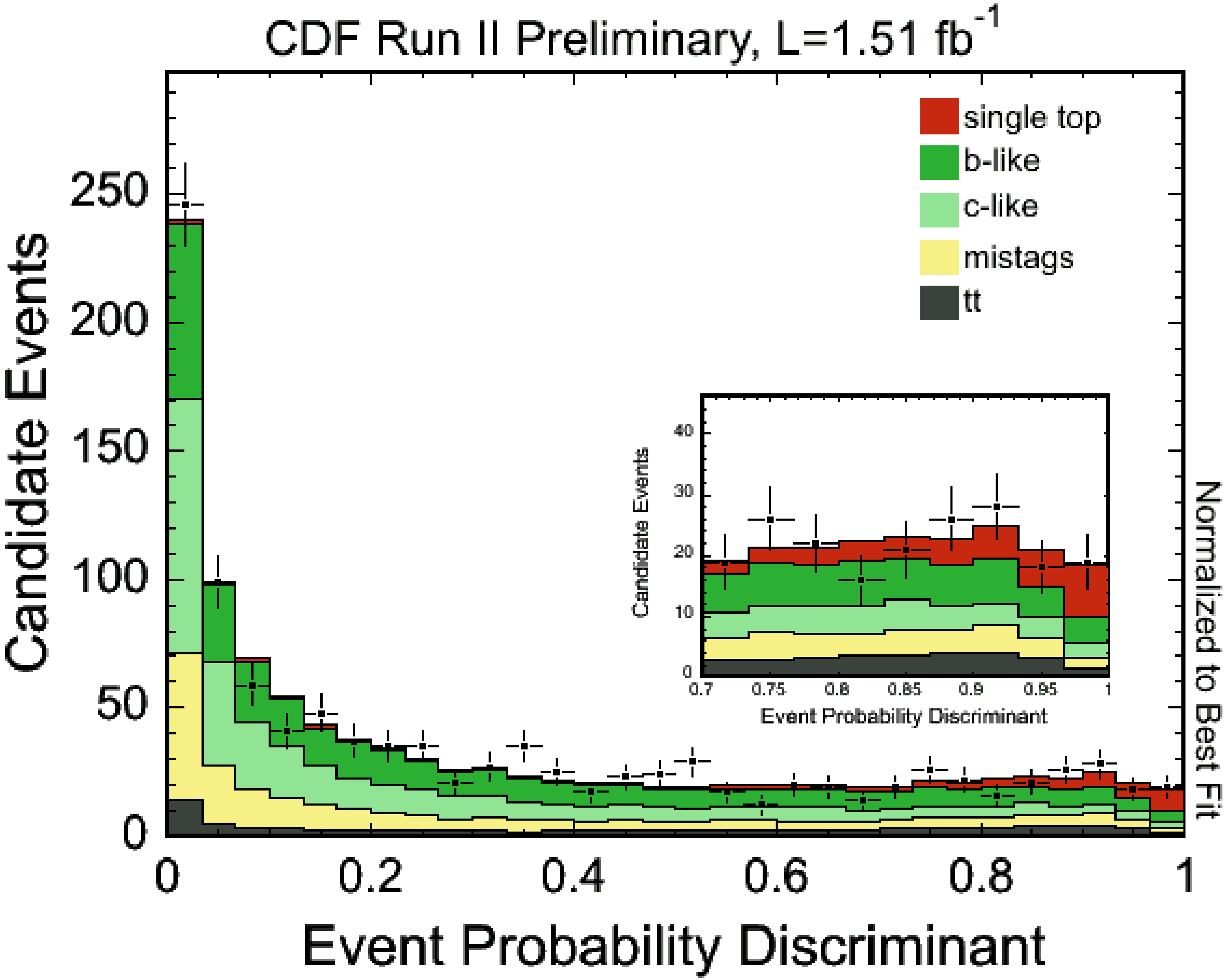
3-jet events

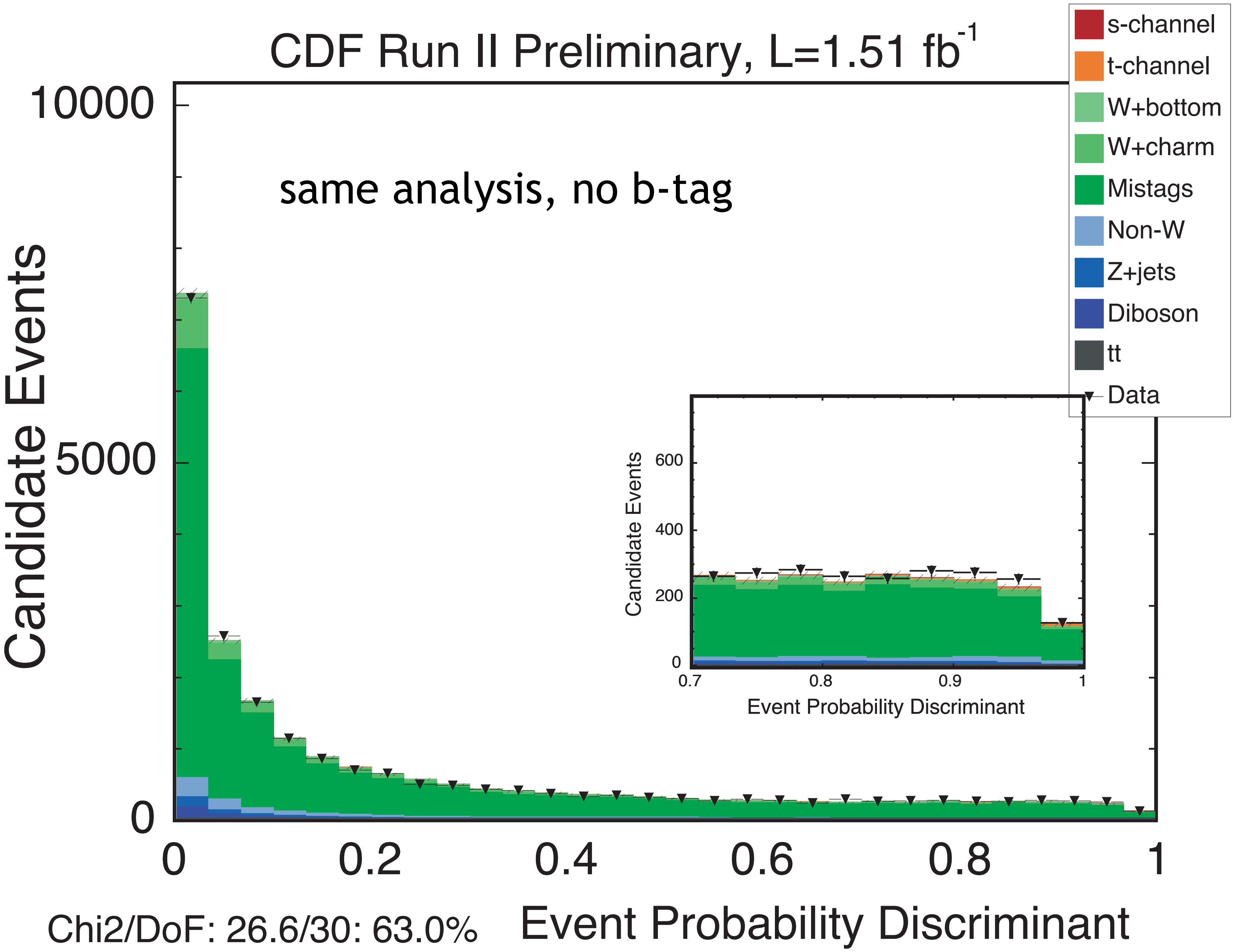
s-channel



t-channel

D0


CDF Run II Preliminary, L=1.51 fb^{-1}
Candidate Events
0
50
100
150
200
250
0
0.2
0.4
0.6
0.8
1
Event Probability Discriminant
single top
b-like
c-like
mistags
tt
Normalized to Best Fit
Candidate Events
0
10
20
30
40
0.7
0.75
0.8
0.85
0.9
0.95
1
Event Probability Discriminant



same analysis, no b-tag

Chi2/DoF: 26.6/30: 63.0%

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

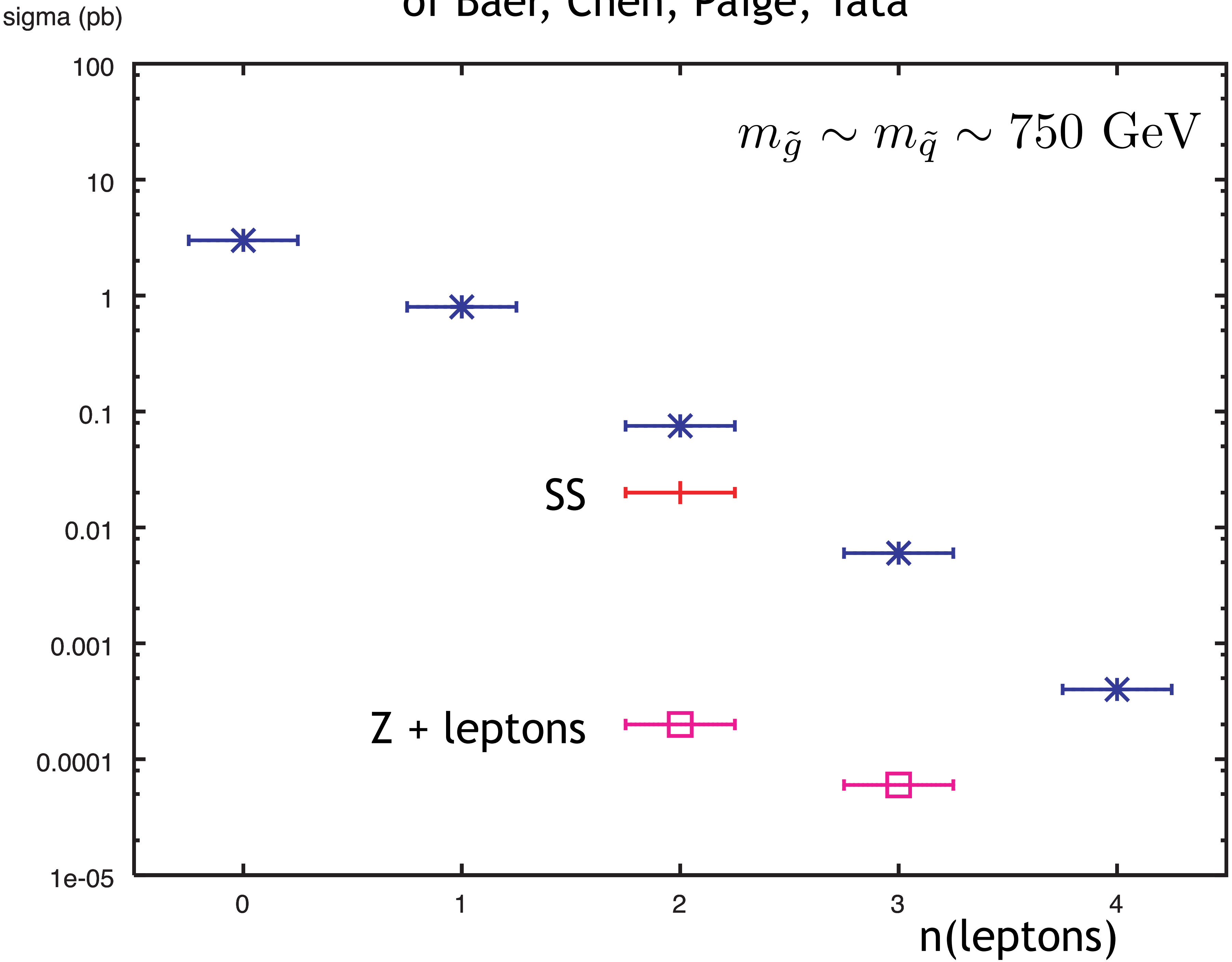
Many new physics models such as supersymmetry predict 2, 3, 4 - lepton events in a steadily decreasing progression.

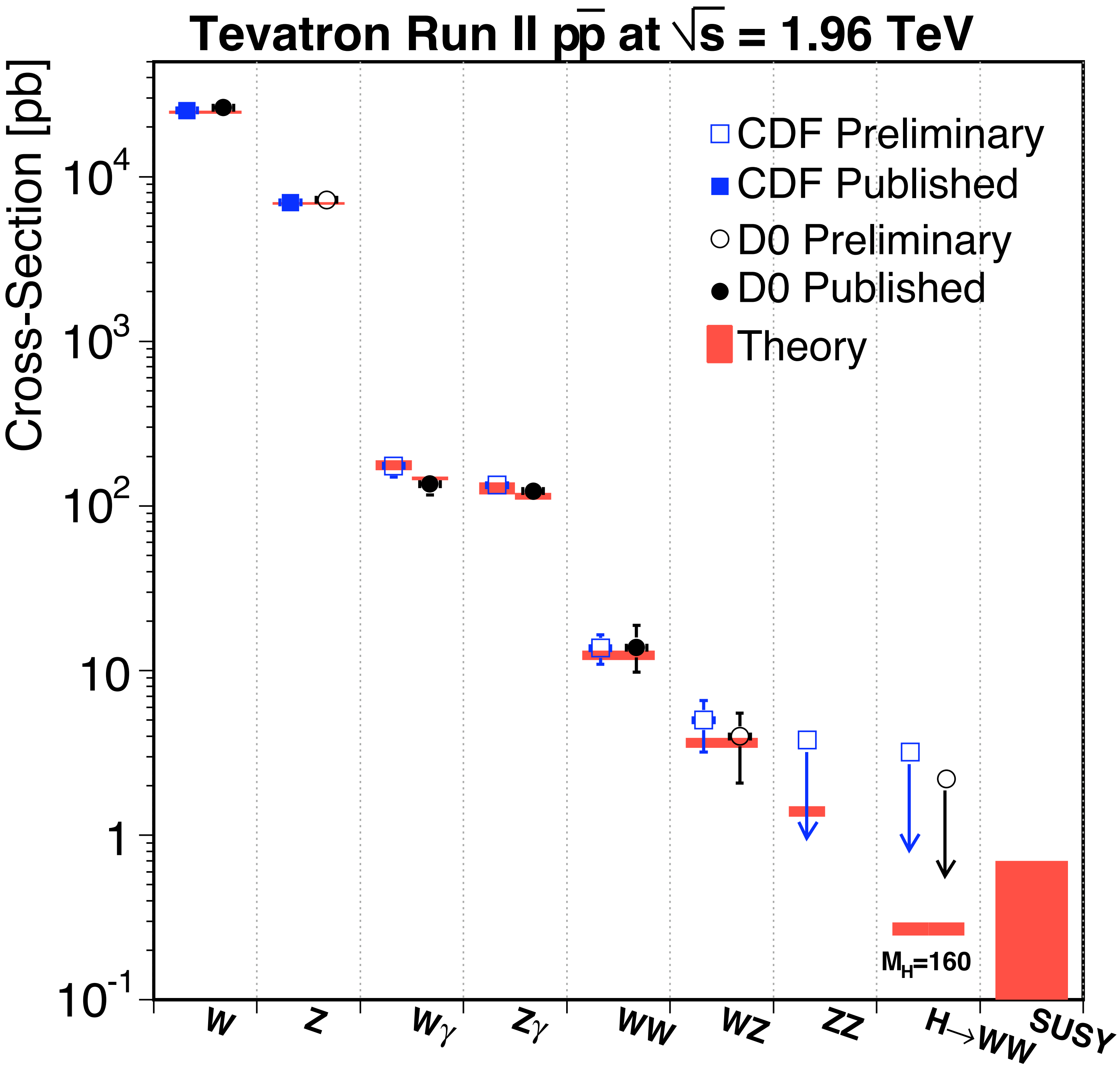
The Standard Model also produces such events, from multiple heavy-quark decays and jets faking leptons.

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

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

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





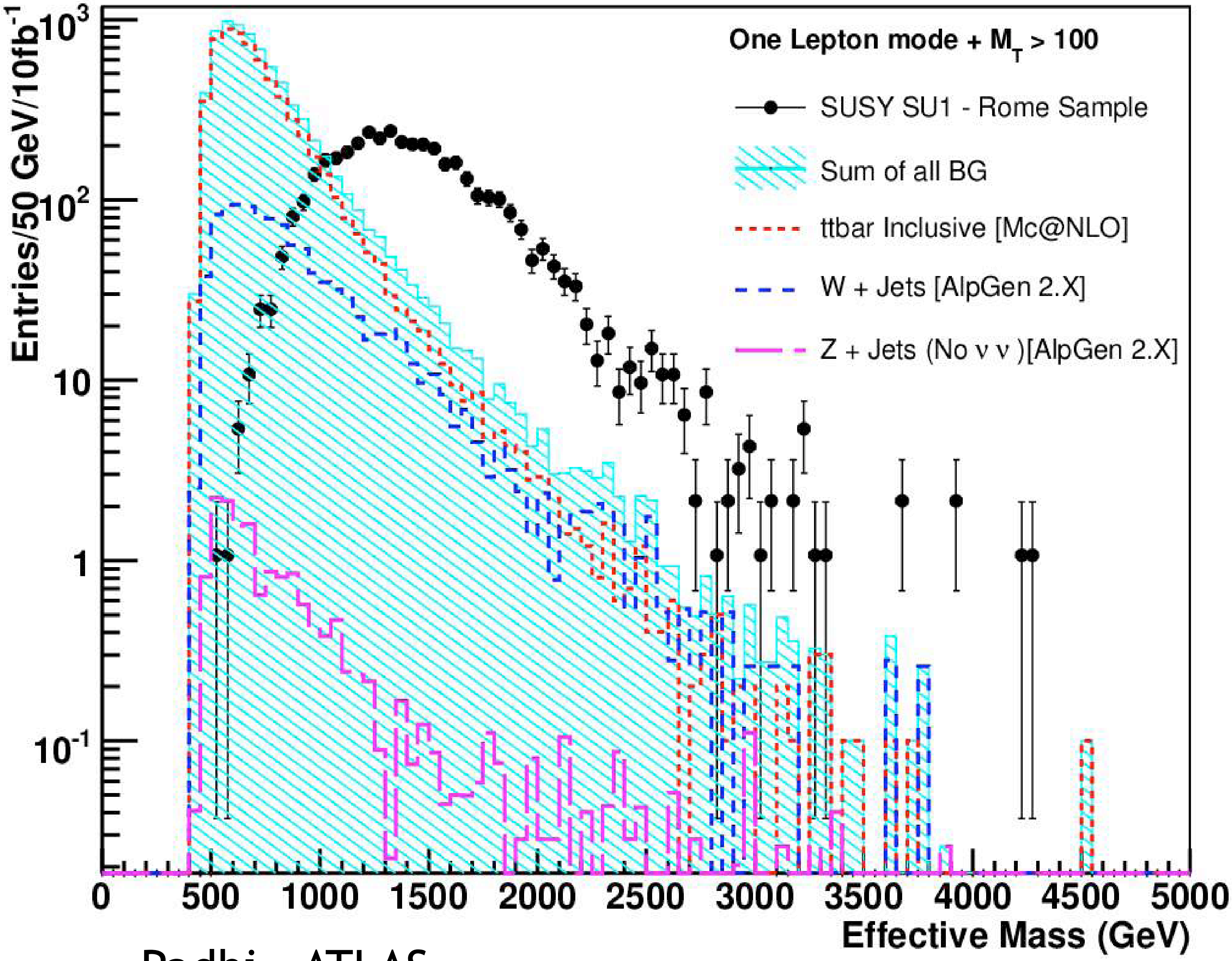
thanks to M. Neubauer

These studies at the Tevatron give us confidence that we will be able to sort new physics events with heavy particles from the background due to Standard Model heavy particle production.

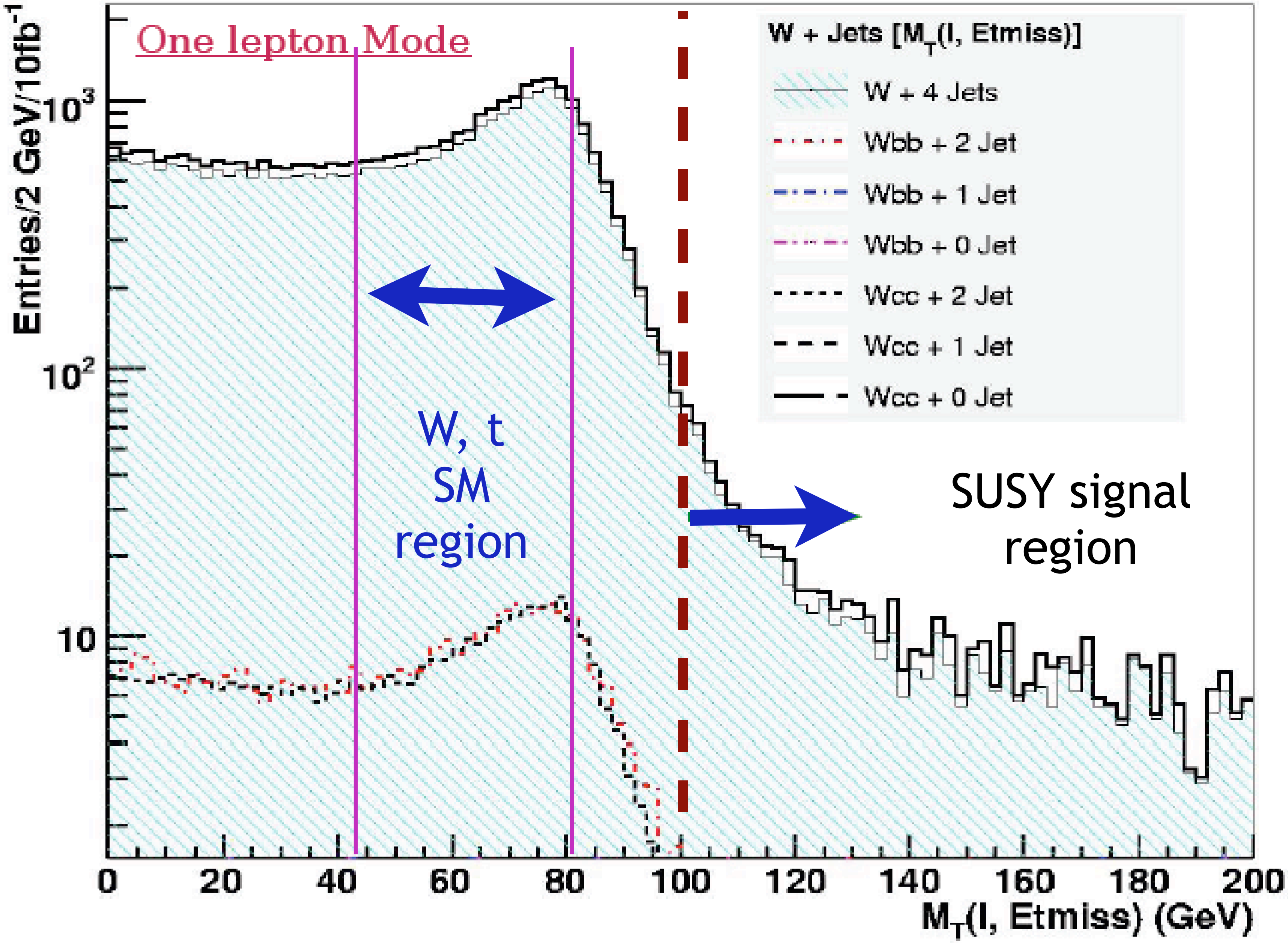
There is one genuinely new issue at the LHC. At the Tevatron, top quark pair production is at the pb level -- though already it is an important background in new physics searches. At the LHC, top quark pair production is at the nb level!

We need a way to obtain a relatively pure sample of $t\bar{t} + \text{jets}$ events to validate the theoretical models of this process used to estimate these backgrounds.

For example, in Padhi's simulation of the single-lepton + MET signature:



Padhi - ATLAS



W, t
SM
region

SUSY signal
region

Padhi

Once we have convincingly established that new particles are produced at the LHC, it is another challenge to work out the properties of these particles and measure their masses and couplings.

This could fill another lecture, one that I will not have time for here. This is Prof. Nojiri's subject, so I hope you can learn about it at another time.

In short, there are methods to find the masses of new particles at the 10% level, and some qualitative indications of spin and chirality assignments.

Instead of discussing this, I will rush into the future.

Tomorrow, we will talk about precision new particle spectroscopy at the ILC.