Triggers and Missing Energy

David Kettler

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Abstract

First I give a breif overview and history of the D0 experiment at Fermilab with an emphasis on the trigger system. After explaining what triggers are for and how they work I explain the research I have done into modelling the Level 1 Calorimeter trigger while attempting to measure missing energy from an event and distinguishing it from the background. Finally I say a few words about the potential for future discoveries.

Contents

1 Overview of DØ

Fermilab is home to the world's highest energy particle accelerator, the Tevatron, and is the current state of the art in particle physics. The DØ experiment at Fermilab first came online for Run I on May 12, 1992. Run I took data until 1996, operating at 1800 GeV center of mass energy and a luminosity of 125 pb^{-1}. At this luminosity, events would occur every 3500 ns. Run I was the source of many exciting discoveries, including the discovery of the top quark.

After extensive upgrades, Run IIa began in early 2001, continues today, and is expected to finish in early 2004. For Run IIa the energy was increased slightly to 1960 GeV at the center of mass, but more importantly the luminosity was increased to 2 fb^{-1}. Events now occur every 396 ns. Once Run IIa is finished, one final upgrade, Run IIb, is planned. Expected sometime in 2005, the energy will stay the same but the luminosity will be increased again to 15 fb^{-1}. This will yield an event every 132 ns.

One of the most anticipated events in particle physics today is the discovery of the Higgs boson. Of course there is always the possibility that it will not be discovered, which is potentially even more important, however there are very good reasons for believing that the Higgs is there. The Higgs is the only particle in the Standard Model which has not yet been directly observed in experiment. Its most important contribution to the Standard Model is the fact that it can at least qualitatively explain particle masses. The standard Higgs theory says there is a Higgs field throughout space and different particles couple to this field differently giving the appearance of mass. The Higgs field can also couple to itself under certain circumstances yielding a Higgs boson.

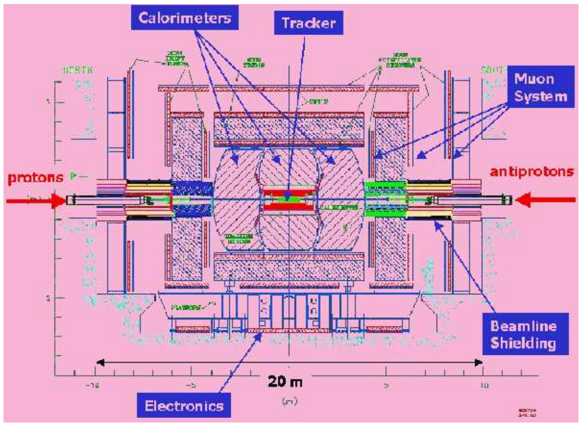
Unfortunately this is only a theory at this point. Even worse it is an incomplete theory. The above description is only, as I mentioned, qualitative and there are still precious few numerical predictions. Further, while most particle physics have some sort of Higgs boson, many theories actually predict several Higgs bosons with somewhat different properties. For instance, SUSY (supersymmetry) requires at least 4 different Higgs bosons. If we were to experimentally observe more than one Higgs boson than this would be a big win for theories like SUSY.

The reason reason the extra luminosity at Fermilab is desirable is because we are right on the threshold of being able to detect the Higgs boson. Previous data, from both Run I and LEP, have given us lower bounds on the mass of the Higgs of about 114 GeV, however theoretical predictions also give us an effective upper bound of not much over 200 GeV. Although the Higgs could in theory be heavier than we believe, the Higgs mechanism would break down if the mass was above a certain level. Even at its current energy Fermilab ought to be seeing something. The problem is being able to reliably distinguish similar background processes from a Higgs decay. I will go into more detail about this later, but what's important is that for now luminosity is important.

2 Description of Trigger System

Triggers are essential to managing the sheer quantities of data that is generated by an experiment like DØ. Currently Run IIa generated 2.5 million events every second. Each even consists of approximately 250 kilobytes of data. A simple calculation then tells us that 625 gigabytes of data is being generated every second, yet only about 50 events can be written to permanent tape storage every second. Furthermore, the vast majority of this data is not actually interesting to us. Most of it consists of common and therefore well understood processes. If we want to probe the frontiers of particle physics then we want to study the uncommon processes. Even at this massive data rate, an interesting event may only occur once every couple of days.

The trigger system is what is responsible for managing all this data. Since actually making a decision in only 396 ns is quite difficult, DØ's triggers come in three stages. Each stage throws out a certain number of events based on a certain set of criteria so that the next stage has more time to look at a given event. The Level 1 trigger takes in data at 2.5 MHz and outputs at 5 kHz. The Level 2 trigger takes that output as its input and outputs at about 1 kHz. Finally, the Level 3 trigger takes that output as its input and outputs at 50 Hz.



The first two levels of triggers require custom hardware and firmware and are very low-level. The Level 3 trigger actually runs on a farm of standard PC hardware and so all the design work is in the software. I am concerned primarily with the Level 1 trigger, so this is all I will say about the Level 3 trigger.

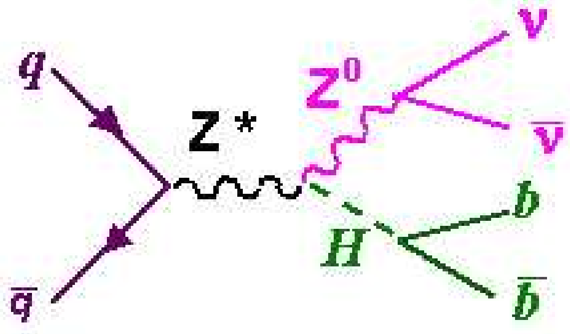
The Level 1 trigger can itself be broken down into many different components. L1Cal is the Level 1 Calorimeter trigger, which was the primary focus of my research and is used to trigger on events based on the energy readings in the calorimeter. The other Level 1 triggers include L1PS (Preshower), L1CTT (Central Track Trigger), L1Mu (Muon), and L1FPD (fiber preshower detector). Level 2 triggers include L2Cal, L2PS, L2CTT, L2STT (Silicon Track Trigger), and L2Mu.

The physical L1Cal trigger consists of stacks of heavy metal plates interspersed between gaps containing liquid argon. When an incoming particle hits one of the plates the result is a shower of particle which all slow down and finally stop in the liquid argon. The passage through the liquid argon produces ionization electrons proportional to the energy of the incoming particle. Most particle energies are measured this way, however this cannot be used to measure neutrino or muon energies. On the other hand, muon energies can be determined from the tracking chamber by seeing how much they bend. Therefore the only particles that do not have its energy measured at all are neutrinos.

3 Missing Energy

Missing energy is simply energy that must exist due to conservation laws but is not measured in the calorimeters. As explained above, this is usually a result of neutrinos. The reason we are interested in this is because of a particular hypothetical Higgs decay:

$$\mathrm{ZH} \rightarrow \nu\bar{\nu}\mathrm{b}\bar{\mathrm{b}}$$



This decay, if it occurs, should result in a combination of b quarks and neutrinos, and so long as neutrinos are one of the possible signs of a Higgs boson we are interested in triggering off of certain events that have missing energy.

While this is only one way to produce Higgs, it is one is likely to actually be seen at Fermilab. The problem is that there are other events that can produce neutrinos and b quarks and these events must be calculated to great precision theoretically so that the observations can be seen as a deviation from this baseline. Thus having as many data points as possible is extremely important. This is where the luminosity advances of Run IIb become most important since there must actually be a statistically significant contribution of events with missing energies.

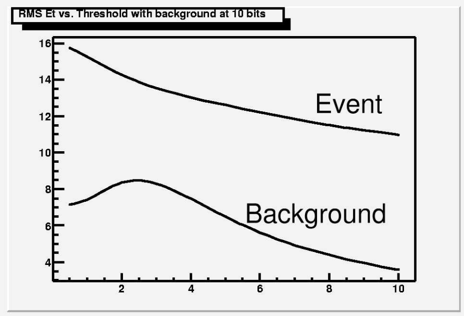
The actual calorimeter energy readings are spread across many different trigger towers in a circle around the beam pipe and end caps. Since the initial particles in the collision have no transverse momentum at all, a vector sum of the transverse momentum components of the particles measured in the calorimeters should in theory always yield zero. Of course since the neutrinos aren't being measured the net transverse momentum is nonzero for events that contain neutrinos.

There is another complication, however. There is noise in the signals that come from the trigger towers and when they are summed the random variations will often add up in ways that would give false positives. The key is to have some sort of threshold value before the data from the trigger tower is considered. One of the key parts of my research was to model the data from the trigger towers while varying the precision of the calculation and the threshold value to see how it affects the results.

The variation in the precision refers to the number of bits used to calculate the angle towards the trigger tower. For reference I have included graphs at many different bit values at the end of this paper, however my investigation has shown that the graphs tend to stabilize at 8 or 9 bits so the following discussion has been done at 10 bits.

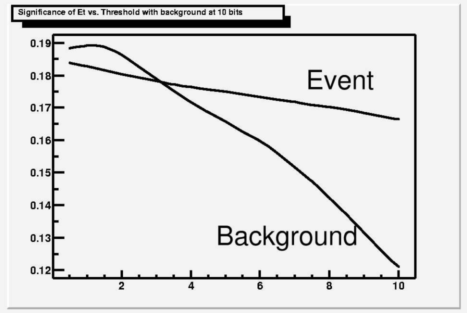
For reference I looked at both events that should have ZH → $\nu\bar{\nu}b\bar{b}$ decays as well as pure QCD events that should not involve neutrinos and therefore ideally should not have any missing energy. I refer to the $\nu\bar{\nu}b\bar{b}$ events as the "event", as it is the event we are interested in, and the QCD events as the background. All energies are in GeV unless otherwise noted.

Here we have the RMS Et vs. threshold with the event and background at a precision of 10 bits:



While the background is noticeably smaller than the measured event, it is still not trivial and therefore a relatively high threshold should be important.

Here we have significance (mean/RMS) of Et vs. threshold with the event and background also at a precision of 10 bits:



As you can see, for low thresholds the significance of the background is actually greater than that of the event. Even at the point where they are equal we cannot say with confidence that the background is not important. It is not until there is a relatively high threshold that we can begin to distinguish the event from the background with confidence.

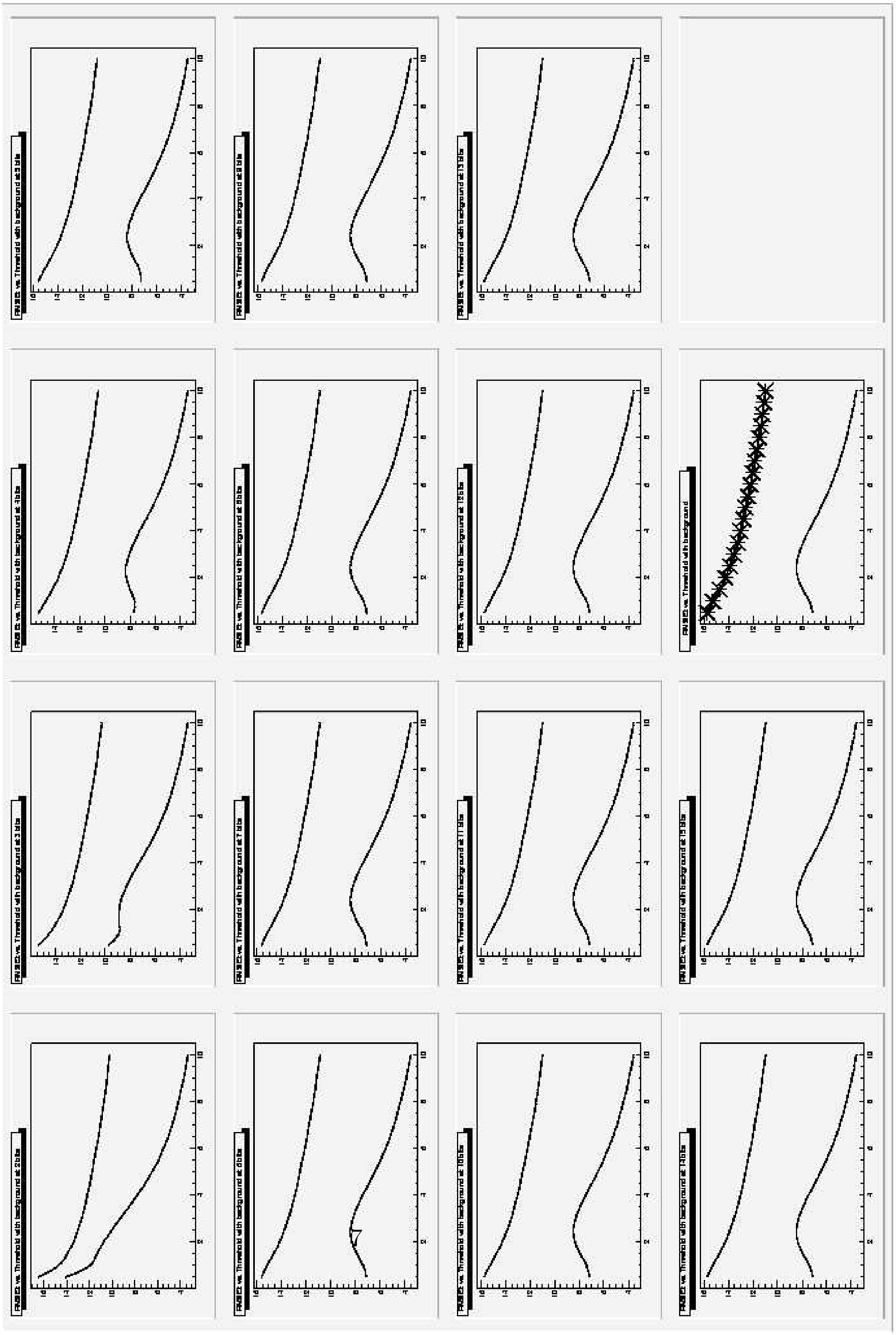
4 Conclusions

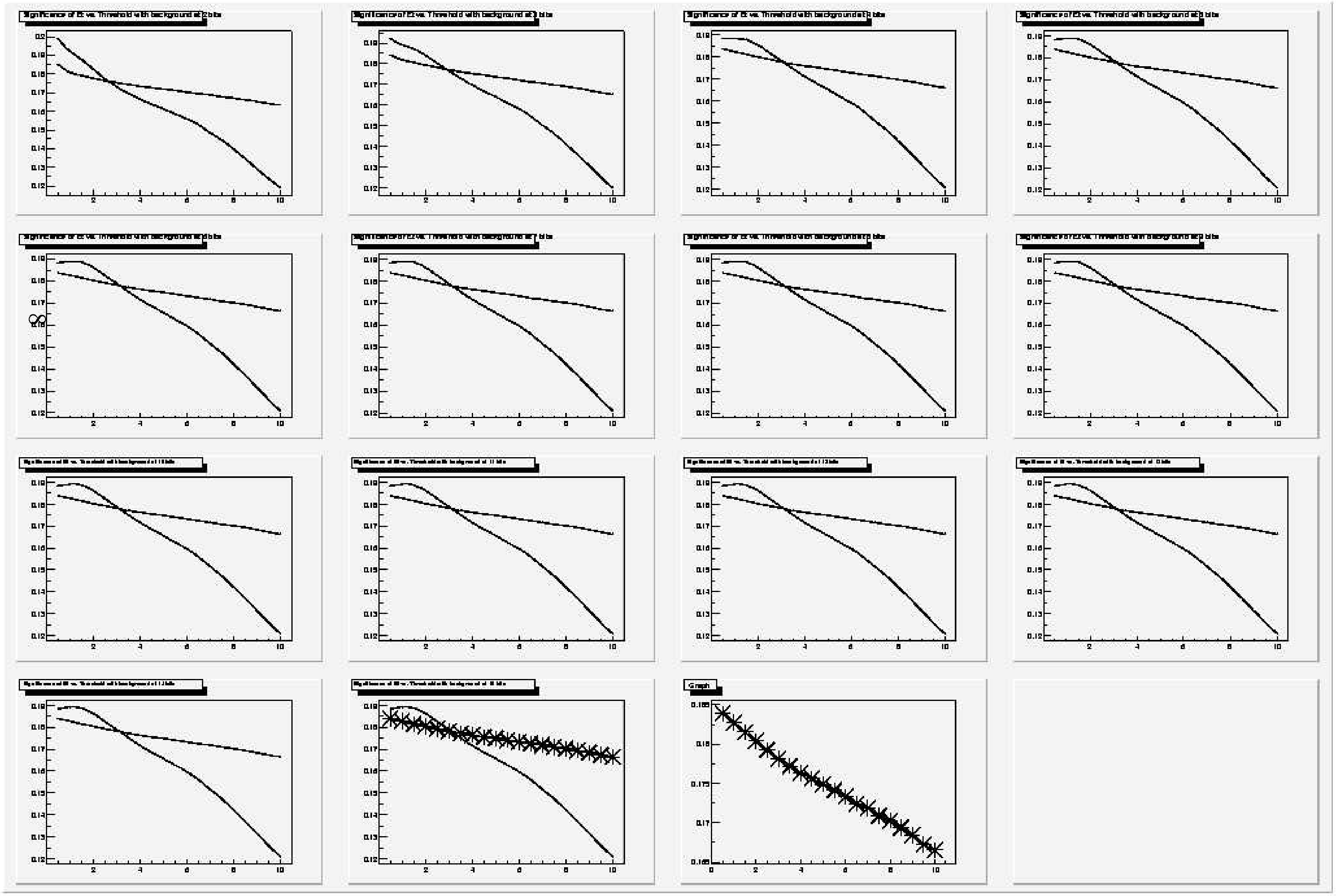
Right now we are on the verge of finding the Higgs boson, and either confirming the standard model or going beyond it. The key to finding the Higgs at Fermilab is to increase luminosity, and increased luminosity requires better triggers. That is what the Run IIb trigger upgrade is for and hopefully in a few years we will see some results from it.

Even though this paper is about the DØ experiment at Fermilab I cannot conclude it without at least mentioning the ATLAS experiment being constructed for LHC. LHC (Large Hadron Collider) is an accelerator currently being constructed at CERN. It is scheduled to be complete by 2007 (though this schedule may be optimistic) and promises to deliver both seven times the energy of Fermilab and roughly two orders of magnitude higher luminosity than what even Run IIb will deliver. It can achieve this amazing luminosity because it is a proton-proton collider and therefore they do not have to spend time producing antiprotons.

It will still be a number of years before we get any real results from ATLAS (they are scheduled to run at low luminosity at first before they reach the luminosity the machine was designed for), however when said results are available the question of the Higgs will be settled once and for all. While the Higgs is at least potentially heavy enough that it will never be seen at Fermilab, if the Higgs is too heavy to be seen at the LHC then its mass would have to be in a regime where the Higgs mechanism breaks down and the Higgs would no longer explain mass. In other words, while there could theoretically be some heavy particle in that regime, it would no longer serve any purpose and an alternate theory would be needed to explain mass anyway. Thus in a few years will will definitively know whether or not there is a Higgs.

5 Additional Graphs




Significance of Et vs. Threshold with background at 2 bits
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
2
4
6
8
10
Graph
0.185
0.18
0.175
0.17
0.165
0

References

[1] REU Program Lectures

[2] http://www-d0.fnal.gov/public/highlights/highlights1.html

[3] http://www.nevis.columbia.edu/~evans/talks/Collab_Meet_021011.pdf

[4] http://www.nevis.columbia.edu/~evans/talks/slac02.pdf