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D0 Note 777

A High Luminosity Trigger Design for The Tevatron Collider Experiment in D0

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A HIGH LUMINOSITY TRIGGER DESIGN

FOR

THE TEVATRON COLLIDER EXPERIMENT IN D0

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I. Introduction

In this paper we describe the triggering system for the D0 Experiment at the Tevatron proton-antiproton collider. In Section II we give an overview of the structure of the trigger and data acquisition systems with particular attention to the principal signal paths. The Calorimeter Trigger is described in Section III and in Section IV we discuss some of the Monte Carlo studies that were done to study the trigger performance and determine its design parameters. We end with a summary of our current status in Section V and acknowledgement of support in Section VI.

II. Overview

The D0 Experiment[1] at the Fermilab Tevatron Collider is based on a 4π uranium-liquid argon calorimeter surrounding an inner volume of tracking chambers and a transition radiation detector (TRD). Although there is no central magnetic field, a series of magnetized iron plates enclosing the calorimeters provide the means of momentum analyzing highly penetrating particles such as muons. The overall design stresses optimum measurement of the leptons and hadrons produced in high energy elementary particle interactions. This is accomplished by means of a highly segmented nearly hermetic detector with optimal resolution for both electromagnetic and hadronic energies.

Figure 1 is a block diagram of the major detector elements showing their connections to the triggering and data acquisition systems. Each of the major detector subsystems feeds signals to its own triggering circuitry and these are in turn connected to the First Level Trigger Framework which is discussed in more detail below. The Framework, in turn, has connections to the front end data acquisition system and various control computers and logic elements.

A. The Trigger System and its Elements

The trigger system in D0 is hierarchical in nature with four distinct, identifiable levels called Level 0, Level 1, Level 1.5 and Level 2. The first of these, Level 0, forms its decisions on the basis of information supplied by counter hodoscopes mounted on the end cap calorimeters. This information, derived from relative timing differences, includes a determination of whether one or more interactions have taken place in a given crossing and a measurement of the vertex position of a single interaction. This information is available rapidly (less than 130 ns after crossing) and thus can be included in higher level trigger decisions.

The Level 1 trigger, like Level 0, performs all its functions in the time between beam crossings (about 3.5 μs with six bunches of protons and antiprotons in the machine) and thus does not generate any deadtime. The inputs to Level 1, besides the information from Level 0, include information from the muon detectors and from the calorimeter. The muon detector supplies information on the charge and approximate transverse momentum of a found single muon, or a bit indicating the presence of more than one muon, for each of the three muon detector subdivisions. The calorimetric decisions are made by analyzing the patterns of energy deposits in the 1,280 projective trigger towers. This is discussed in more detail below.

An important feature of the D0 detector is the TRD, covering the central region of the detector. It is constructed of layers of thin plastic sheets organized in three concentric layers with 256 detector wires each and discriminates between electrons and hadrons by the characteristic energy deposited by highly relativistic electrons traversing regions of changing dielectric constant. At the trigger level, only the integrated charge on each wire is available as input and, therefore, electron identification requires information from the

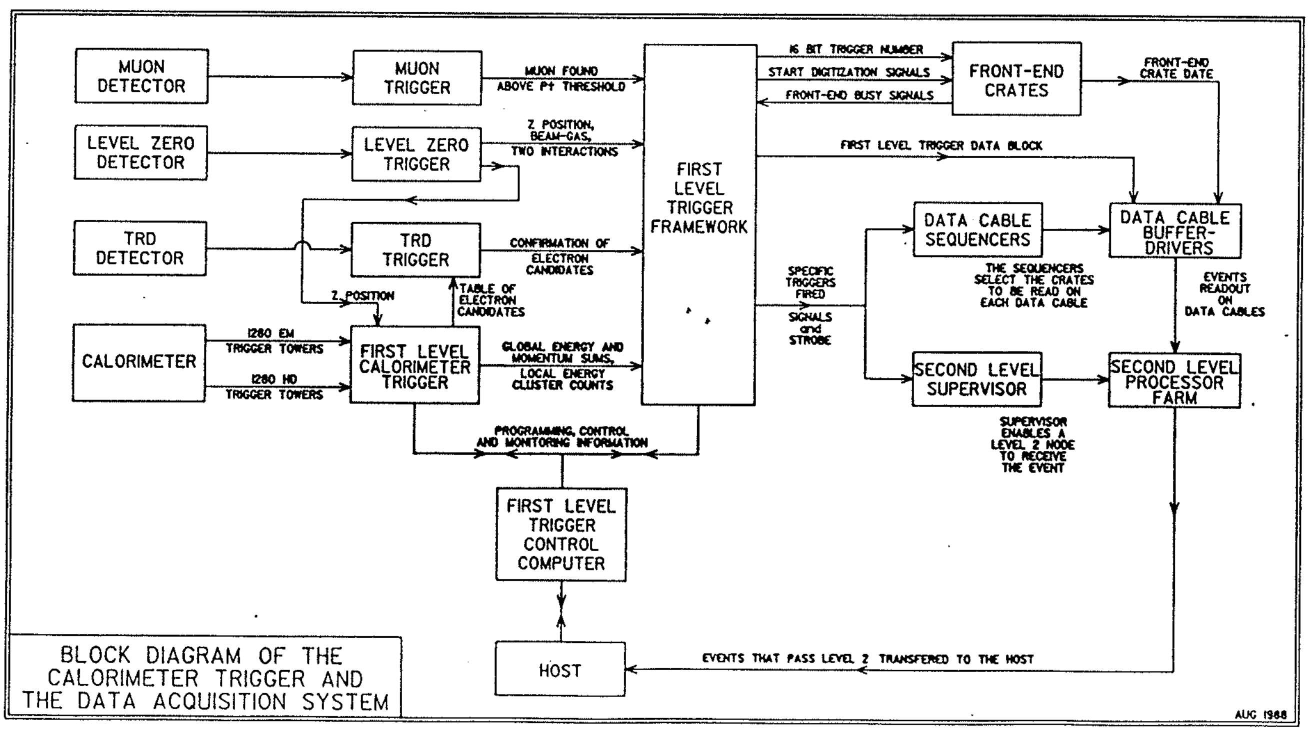

Figure 1. A schematic view of the triggering and data acquisition systems for D0.

calorimeter in the form of a list of electromagnetic (EM) shower candidates that could have generated the TRD signal. The computations necessary for these comparisons will take a few tens of μs, a time considerably longer than that available between crossings and therefore this trigger, called a Level 1.5 trigger, will generate deadtime. The rate of events subjected to this trigger will be carefully adjusted so that the deadtime is kept below about 10%.

The final trigger level, Level 2, is based on a large number (fifty) of high speed microprocessors (MicroVAX III's at this writing) which will subject the events to ever more stringent cuts to reduce their number to a few per second which will be recorded on a permanent storage medium. With a luminosity of 10^{30} $cm^{-2}s^{-1}$ and six bunches in the machine, the number of crossings is about 300,000 per second and the number of interactions (assuming an inelastic cross-section of 50 mb) will be about 50,000 per second. Essentially all of these will be examined by the Level 1 trigger and some subset by the Level 1.5. The function of the Level 1 trigger is to reduce this number to 200 - 400 for transmission to Level 2 where each of the 50 microprocessors will have from 4 to 8 events to discard per second to reach the tape-writing rate of 1-2 Hz.

B. The Framework

The functioning of the Framework can be understood by analysis of its principal signal paths shown in Figure 2. One set of inputs is the ensemble of trigger signals from the various detectors in the form of 256 bits. These are latched and used as one set of inputs to the AND-OR network with the other orthogonal set being the 32 programmed trigger configurations. Each of the 32 triggers can be programmed to require the presence or absence of any of the 256 trigger bits as well as to ignore them altogether. If the specific trigger is satisfied and if it is not vetoed by either a front end busy signal or a specific disable request, then this trigger decision, formed in the Final Specific Trigger Decision Card, is latched in the Trigger Latch Module. From there digitizing orders are issued and the rest of the system is notified about which specific triggers fired on this crossing. In the event of a Level 1.5 trigger, the Framework issues the necessary delays to await the trigger confirmation.

The Framework also embodies the bus structure by which the triggers can be programmed through messages from the host and trigger control computers. It also handles the transfer of Level 1 triggering information to the Level 2 nodes and decides which set of crates should be digitized if a specific trigger is satisfied. In addition, the Framework manages the large number of scalers used for monitoring system performance and reliability. A particularly important set of scalers are those counting beam crossings and events satisfying the individual triggers.

For monitoring purposes, the Framework has been designed so that the trigger control computer can read and write all of the registers used for trigger definition and control. A series of programs have been written for the trigger control computer to routinely check trigger performance as well as to diagnose faults in the event of system failure.

III. The Calorimeter Trigger

The D0 uranium-liquid argon calorimeter is constructed of projective towers covering the full 2π in the azimuthal angle, ϕ, and approximately 8 units of pseudo-rapidity[2], η, with eight or nine depth segments which provide convenient subdivision of the towers in electromagnetic (EM) and hadronic (H) sections. The segmentation in $\Delta\phi \times \Delta\eta$ is 0.1 x 0.1, which results in towers whose transverse size is larger than the expected sizes of EM showers but, considerably smaller than typical sizes of jets. As a compromise, for triggering purposes, we add four adjacent towers to form trigger towers with a segmentation of 0.2 x 0.2 in $\Delta\phi \times \Delta\eta$. This yields a total of 1,280 EM and 1,280 H tower energies as inputs to the Calorimeter trigger.

An important design decision was when to convert the analog signal stream from the calorimeter to digital signals for use in the triggering logic. In view of the improved noise immunity and despite the increase in the number of signal lines, we decided to digitize the signals with eight bit flash analog to digital converters (FADC's) immediately after reception at the trigger. The limitations in the number of bits imposes some constraints on our choice of least count and full scale which are discussed below.

It is expected that the current six bunch operation at the Tevatron Collider will be changed in the near future in an effort to achieve higher luminosities. A number of proposals have been advanced to accomplish this with most of them going to a larger number of bunches in the machine. In our trigger design we have attempted to anticipate these developments and have designed a trigger capable of operating at the highest bunch crossing rates consistent

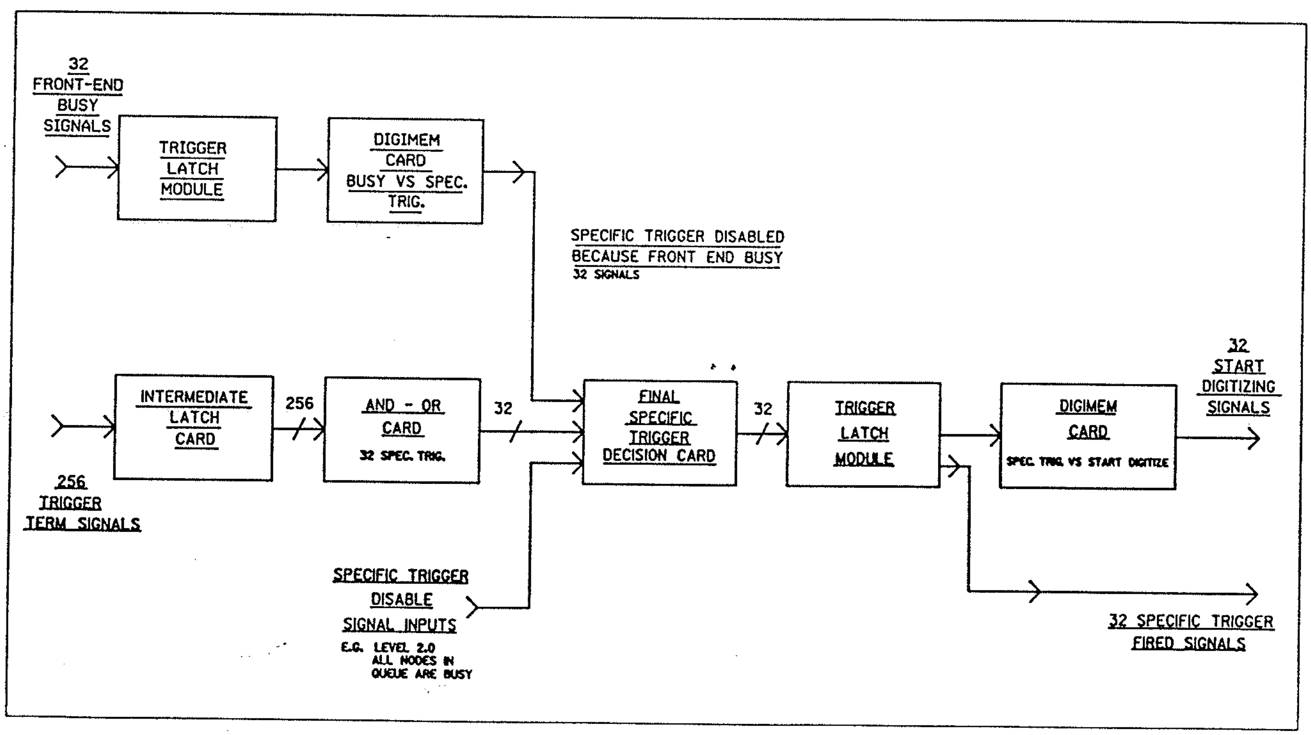

Figure 2. The principal signal paths in the D0 Trigger Framework.

with available electronics and the overall constraints imposed by finite budgets. In doing this we have adopted a "pipe-lined" design which is a scheme of dividing the trigger logic into a number of short steps with successive events marching through synchronously one after another. When the final trigger decision is made after a large number of steps, the pipe-line is stopped, and the event, which has been stored in either digital or analog form pending this decision, is recorded. This design permits the maximum crossing rate to be determined by the time of one step in the decision path.

The information from the calorimeter can be used to calculate a number of quantities that can be useful in triggering on specific physics processes. Among these are quantities such as the total transverse energy and the missing transverse energy which we will designate as "global" and information relating to "local" or cluster aspects of the energy deposits in the calorimeter. The latter would include the number of EM and H-like clusters exceeding a set of preprogrammed thresholds. We discuss each of these in more detail below.

A. Global Triggers

Potentially interesting global quantities include the total energies (EM and H):

$$Eem = \sum_{i=1}^{1280} Eem_i$$

and

$$Eh = \sum_{i=1}^{1280} Eh_i$$

the total transverse energies:

$$E_t em = \sum_{i=1}^{1280} Eem_i \sin \Theta_i$$

$$E_t h = \sum_{i=1}^{1280} Eh_i \sin \Theta_i$$

and

$$E_t = E_t em + E_t h$$

We have also found useful the missing transverse energy:

$$MP_t = \sqrt{E_x^2 + E_y^2}$$

where:

$$E_x = \sum_{i=1}^{1280} (Eem_i + Eh_i) \sin \Theta_i \cos \Phi_i$$

and

$$E_y = \sum_{i=1}^{1280} (Eem_i + Eh_i) \sin \Theta_i \sin \Phi_i$$

In the equations above the Eh_i and Eem_i refer to the H and EM energies deposited in the individual towers and the angles Θ_i, Φ_i to the usual polar co-ordinate angles describing the line connecting the interaction vertex with the energy deposited in tower "i".

All of the six quantities Eem, Eh, $E_t h$, $E_t em$, E_t and MP_t can be used in constructing triggers. Each of them can be compared to as many as 32 thresholds and the results of these comparisons passed to the Framework for inclusion in any of the 32 possible triggers.

B. Cluster Triggers

The D0 detector was designed with the intent of optimizing the detection of leptons, quarks and gluons. One family of leptons, the neutrinos, will pass through the detector without trace with their presence inferred by some missing transverse energy. The charged leptons will manifest themselves as localized EM energy deposits and the quarks and gluons as localized hadron-like clusters. An energy in a tower is called EM-like if it exceeds one of the minimum EM transverse energy cuts and if it is not vetoed by the H energy behind it. Both the EM cuts and the H veto cuts are set by the trigger control computer.

The trigger control computer also sets up four thresholds each for the EM+H towers to which their transverse energies are compared. If a tower E_t exceeds a given threshold, a corresponding tower sum is incremented. Trigger bits are derived from comparisons of the tower sums with four preset minimum count limits for both EM and H towers. These bits are once again passed to the Framework for inclusion in specific triggers.

C. Level 2 Connections

Our Level 2 trigger consists of a large number (50) of fast microprocessors whose function is to further reduce the trigger rate to a level supportable by the permanent recording media. A great deal of time can be saved in this process if the triggering information from Level 1 is made available to Level 2. To this end, a Level 1 trigger data block is created which contains, in considerable detail, the information on the basis of which the trigger decision was made as well as the trigger decision itself.

D. Hardware Implementation

1. Front End Cards

The analog signals from the calorimeter, representing energies, arrive at the calorimeter trigger over shielded differential signal wires and are connected to the analog front end section of a Calorimeter Trigger Front End Card (CTFE). A schematic diagram of one of the four cells of this card is shown in Figure 3. The front end section contains a differential line receiver and scales the energy signal to its transverse component using discrete resistors.[3] The front end also contains digital to analog circuitry for adding a positive bias to the tower energies in accord with downloaded values.

Immediately after the analog front end, the EM or H signal is turned into an 8 bit number by fast (20 ns from input to output) FADC's. With our current choice of 0.25 GeV least count this gives a maximum of 64 GeV for the single tower transverse energy contribution. Detailed Monte Carlo studies show that this choice does not adversely affect the trigger performance or efficiency.

The data are synchronized at this point by being clocked into latches and then follow three distinct parallel paths. One of these leads to a double buffered pipeline register for digital storage to await the trigger decision and a subsequent transfer to the data block for use by Level 2. On the other two paths, each 8-bit signal becomes the low order address to a look up memory. The full address for the look-up is formed by adding 3 bits of interaction vertex position information from Level 0. The contents of the memory at a specified address in one case is the transverse energy with all necessary corrections such as lower energy requirements etc. In the other case, the EM + H transverse energies are first added and then subjected to two look-ups to return the two cartesian components of the transverse energy for use in constructing MP_t. The extra look-up is accomplished by adding one more bit to the address. The inherent flexibility of this scheme has a number of advantages: any energy dependent quantity can be generated, individual channels can be corrected or turned off at this level and completely arbitrary individual tower efficiencies can be accommodated.

The CTFE card performs the function of adding the E_t's of the four individual cells for both the EM and H sections and passing the resulting sums onto the Adder Trees. In addition it tests each of the EM and EM+H tower transverse energies against the four discrete thresholds and increments the appropriate counts. These are then passed onto the EM cluster counter trees and the total E_t counter trees, respectively.

2. Adder and Counter Trees

The adder and counter trees are similar in that they both quickly add a large number of items to form one sum. A typical adder tree is shown in Figure 4.

3. Physical Layout

The physical organization of the Framework and calorimeter trigger in the moving counting house is shown in Figure 5. The subdivisions in η and ϕ connected to specific crates is indicated. This organization is essential for constructing intermediate sums over larger contiguous sections of the detector which may become useful in later trigger developments. It is also important in keeping together the same sign transverse energy vector components necessary to construct

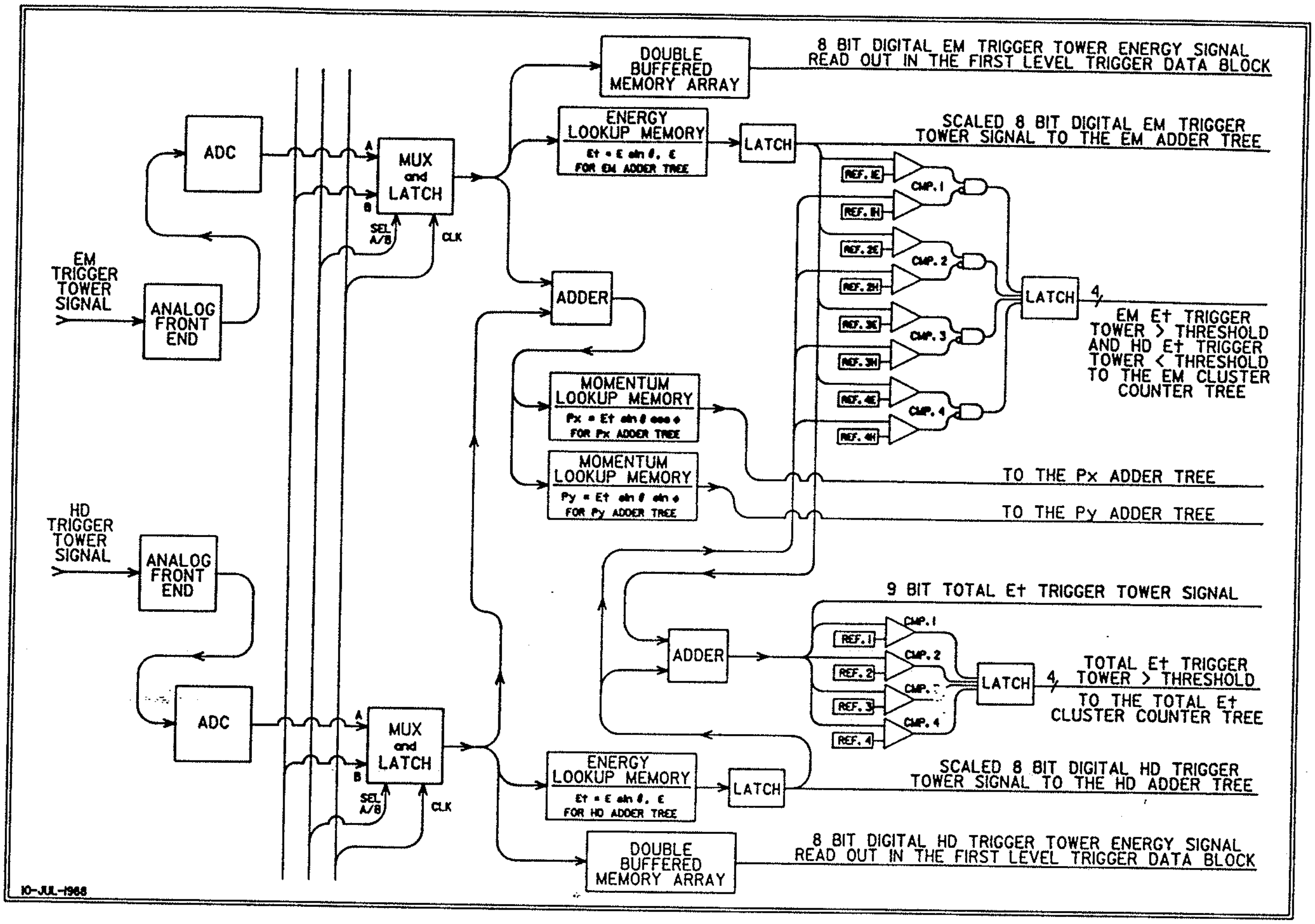

Figure 3. A schematic view of a front end cell for the D0 Level One Calorimeter Trigger.

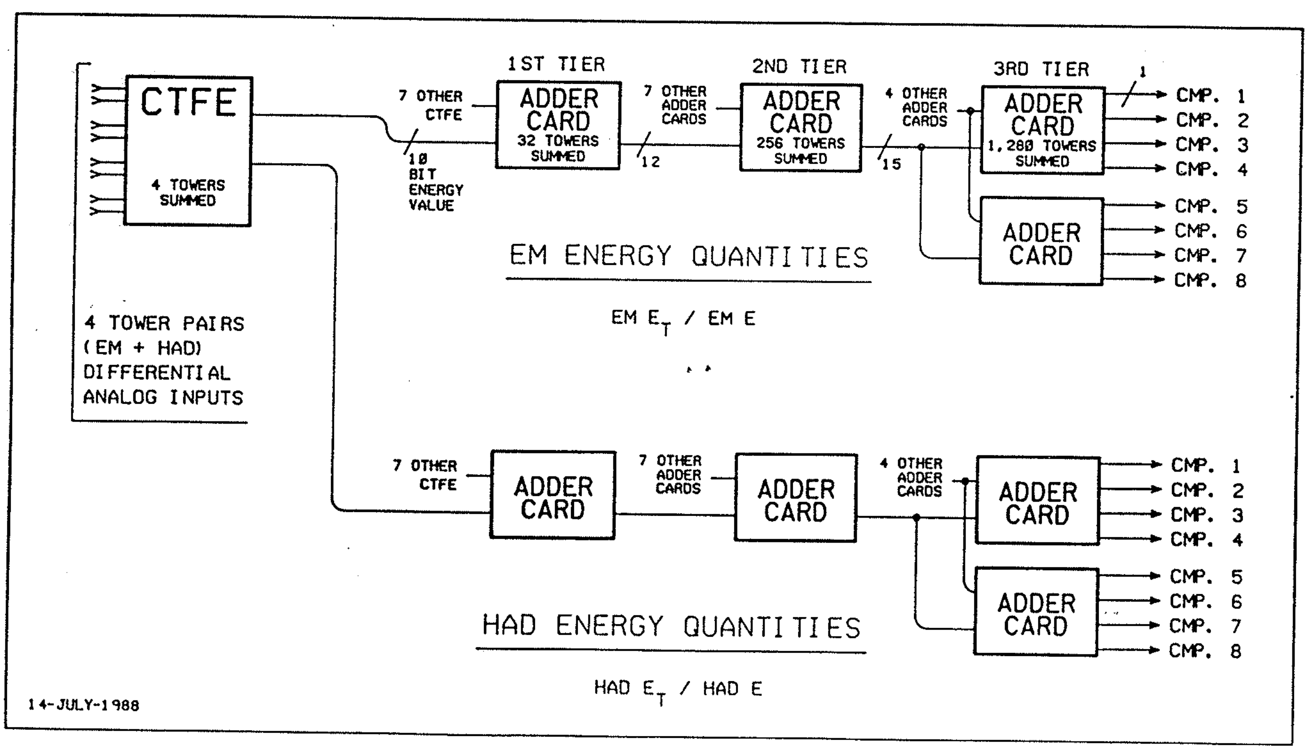

Figure 4. A block diagram of a scalar adder tree.

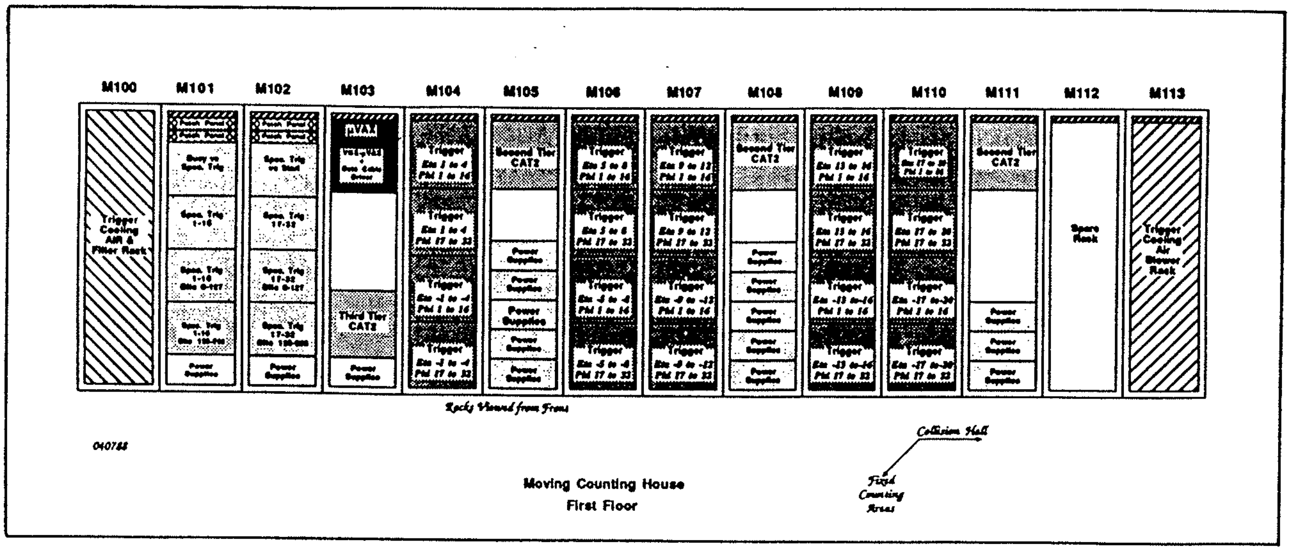

Figure 5. Organization of the trigger racks in the D0 moving counting house.

the missing transverse momentum since, for reasons of simplicity, we choose to use unsigned addition in forming the sums over the detector.

IV. Monte Carlo Studies

The essential features of the trigger design, the granularity of the calorimetry and the basic elements for trigger construction, were chosen on the basis of extensive Monte Carlo studies. The Monte Carlo was used also to subject the detector and trigger to various kinds of events embodying interesting physics and backgrounds in order to measure the efficiency of the trigger discrimination between signal and background.

Our method was to generate a large number of events over a wide range of parton transverse momenta using ISAJET[4] and then to make these events interact with a computer model of our detector using GEANT[5].

As examples of this work we show in Figure 6 a plot of the efficiency for triggering on Z° events, as a function of the requirement on EM transverse energy, on the left hand axis and the rate of "background" two-jet events satisfying the trigger on the right hand axis. As the number of events that the Level 2 trigger can process is limited, it is essential to reduce the background as much as possible while at the same time not sacrificing any signal.

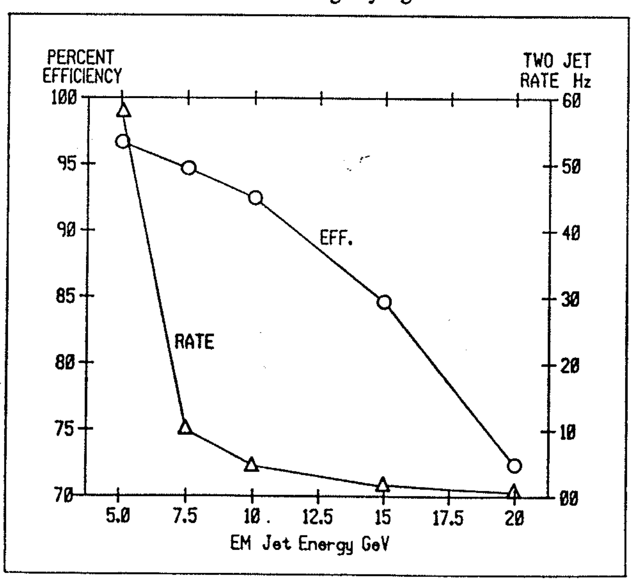

Figure 6. Efficiency for the detection of $Z^\circ \rightarrow e^+ e^-$, on left-hand axis and trigger rate for 2-jet events on right-hand, plotted vs. minimum EM energy requirement for two clusters.

The choice of the granularity of the trigger towers is a compromise between the very small size of electromagnetic showers and the large size of typical jets. For reasons of simplicity we decided to use the same size towers for both the EM and H energies and chose a granularity of 0.2 x 0.2 in $\Delta\eta \times \Delta\phi$. An example of the detector's response to electromagnetic radiation is shown in Figure 7 where we plot the ratio of detected to input transverse energy for electrons of fixed transverse energy but variable energy incident on the detector. In the plot, the finite resolution of the detector displays itself in the width of the peak centered at 1. Note also the small number of events

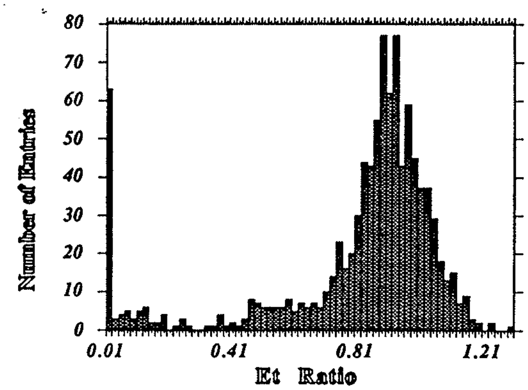

Figure 7. Ratio of measured to input EM E_t for incident electrons.

with diminished or zero response corresponding to events striking the cracks between individual EM detector modules. As this fraction is small and as the measured resolution is adequate at the trigger level we judged the trigger performance to be satisfactory for EM showers.

We also performed a large number of tests to gauge the performance of the trigger with hadronic jets, whose characteristic size can be substantially larger than the trigger towers. In one of the tests we generated two-jet events with a variety of parton transverse momenta and then studied the fraction of the parton E_t that was captured in calorimeter cells of various sizes. Figure 8 shows this fraction plotted against the mean parton E_t for two different trigger tower sizes, our trigger towers and towers nine times larger. The plot shows that the larger towers capture about twice as much transverse energy on the average, but also, that both are proportional to the actual parton E_t.

On the basis of our studies we concluded that our cell size was adequate and that we had sufficient flexibility in our triggering to achieve the required trigger rate reductions without compromising the

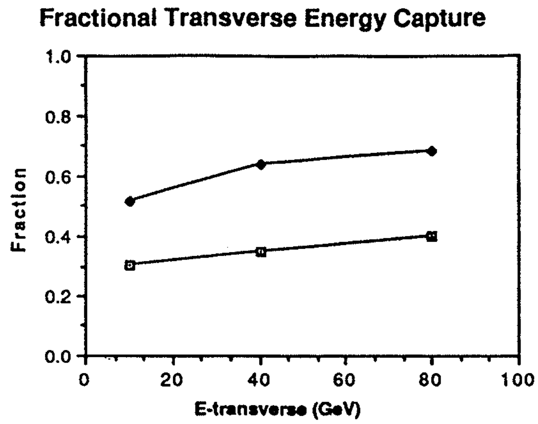

Figure 8. Captured hadronic jet transverse energy fractions, for two tower sizes, plotted vs. the parton transverse energy.

study of any of the physics processes that we examined. These included two-jet events with variable transverse momenta, W and Z events, "top" events with varying assumptions about its mass and events with super-symmetric particles.

V. Current Status

The Trigger Framework is finished and installed in the D0 experimental hall after undergoing extensive tests in the test beam. All of the principal features of the Calorimeter trigger have been designed and tested in the test beam. Final board design and prototyping is underway and the complete system is expected to be finished within a year. Similar progress is being made by the muon, Level 0 and TRD trigger systems. All systems are scheduled to be finished and installed well before the first data taking with D0 which is scheduled for 1990.

VI. Acknowledgements

The support of the National Science Foundation with grants PHY 8414172 and PHY 8716794 as well as equipment funding from the Department of Energy are gratefully acknowledged.

VII. References

[1] For a complete description see Fermilab Publication "Design Report: The D0 Experiment at the Fermilab Antiproton-Proton Collider", November 1984.

[2] The pseudo-rapidity is defined as $\eta = -\ln(\tan \Theta/2)$, where Θ is the polar angle relative to the beam axis.

[3] The scaling is done by multiplying the energy by $\sin\Theta_i$, where Θ_i is the angle the i^{th} tower makes with the beam line.

[4] ISAJET, a QCD-inspired Monte Carlo event generating program written by F. Paige and S. Protopopescu of Brookhaven National Laboratory.

[5] GEANT, a Monte Carlo program developed at CERN for the simulation of particle interactions with detectors.