# A Proposal to Increase the L1 Trigger Efficiency of Z-boson Detection in the CMS detector at the Large Hadron Collider

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## Abstract

As of May 2011, the L1_Single_EG12 bit of the Level-1 trigger for the Compact Muon Solenoid experiment is expected to be overwhelmed by projected luminosity increases at the Large Hadron Collider. The ensuing necessary prescaling of data would negatively impact Z-decay physics. It is proposed to implement a new trigger bit which utilizes leading HF rank to more efficiently identify di-lepton ECAL-HF Z-decay events. To establish the feasibility of this option, data containing known examples of these events is compared to the subset of background data where the L1_Single_EG12 bit had fired. It is shown that the leading HF jet ranks of desired 'signal' events are significantly higher than those of 'background events, suggesting inclusion of leading HF rank in triggering criteria. The proposed trigger bit would eliminate all events with a leading HF rank less than four, corresponding to less than 16 GeV of transverse energy in HF. This would reduce the triggering rate by a factor of 6.08 while still preserving 99.9 percent of signal events, rendering a prescale of di-lepton Z-decay data unneccesary.

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# Chapter 1

# Introduction

As of May 2011, it has become apparent that the L1_Single_EG12 trigger bit in the Level-1 (L1) trigger of the Compact Muon Solenoid detector at the Large Hadron Collider will require prescaling. This trigger is designed to save all data where a single electron with transverse energy greater than 12 GeV is observed in the electromagnetic calorimeter of CMS. Such a trigger is used for collecting events where a Z-boson has decayed into two electrons, including events where one electron has entered the HF detector, where the L1 electromagnetic trigger does not extend. However, such single-electron events are sufficiently common that the increasing luminosity of the LHC will lead to the trigger firing at an unacceptably high rate. The result would be a prescale of data by a factor of 2 or more, which would cause important data on Z-decay to be lost. However, it has been hypothesized that the L1 Forward Jet functions can be used to identify these events, if their energy is sufficient to distinguish them from background. Since this energy, deposited in HF, is available to the L1 trigger, using this information in a new trigger would allow Z-decay measurements to escape the effects of a L1_Single_EG12 prescale.

The objective of this paper is to make a conclusive argument for the establishment of a new L1 trigger bit at CMS that combines the requirements of Single_EG12 with a requirement for a minimum leading forward jet rank of four, which would reduce the triggering rate by a factor of six while keeping almost all (99.9 percent) of the desired Z-decay events. To do this, the concept and design of the CMS experiment, the principles behind the CMS triggering system, and the basic physics of Z-boson decay are all reviewed. Finally, it is shown through analysis of 2010 and 2011 CMS data that leading forward jet rank is a useful tool to distinguish Z-decay events from background. Various rank options for triggering are suggested, and the corresponding impact of each option on trigger rate and efficiency are presented.

# Chapter 2

# Physics at the Large Hadron Collider

## 2.1 Particle Accelerators

One of the most counterintuitive aspects of science is the fact that the largest experiments are often those that study the smallest subjects. The reason for this is simple: to probe ever-smaller distances, ever-higher energies are required. For example, living cells can be observed using visible-light microscopes, but their constituent molecules can only be observed via electron microscopy. To probe still deeper, electron particle accelerators were invented in the 1930s to investigate the structure of atoms[4]. Studying the nucleus, however, was more complicated. Electrons (being leptons and immune to the strong force) could provide information on the charge distribution of the nucleus, and eventually of the nucleon, which revealed its substructure. However, technical challenges with electron accelerators limited their energy, and so proton accelerators took the lead. By 1970, accelerators of 100 GeV could probe distances of $10^{-17}$meters[5], and showed that the nucleons were composed of constituent quarks. This discovery gradually led to the emergence of the present Standard

Model of particle physics, which is tested today with accelerator energies of order 10 TeV. In this way, accelerators are used like microscopes to investigate phenomena on the smallest possible scales.

## 2.2 The Synchrotron

The simplest form of particle accelerator is (or rather, used to be) quite common in daily life- the cathode-ray tube (CRT). In it, electrons pass through a voltage difference, and this potential energy becomes kinetic energy, much as a dropped ball accelerates as it loses the potential energy of its former height. To achieve higher velocities, a particle must pass through a larger potential difference. However, while a ball can be lifted higher and higher without limit (ignoring the $\frac{1}{r}$ behavior of the gravitational potential) there are practical limits to accelerating charged particles via ever-higher voltage differences. The most notable of these is dielectric breakdown, which occurs to air in thunderstorms.

The solution typically employed to bypass this problem is to use the same voltage difference repeatedly. This works much like the game of tether ball, where one accelerates the ball by striking it each times it passes. There are two common ways this is accomplished; the first is the linear collider. In this configuration, a particle is accelerated down a straight, evacuated beamline. Surrounding the beamline are a series of cylindrical conductors, called *drift tubes*, which a particle must pass through in sequence. By connecting these to an AC voltage source (with alternating drift tubes attached to alternating polarities) and strategically modifying the length of each drift tube to match the time-of-flight through it, a particle can be accelerated to high energies using relatively modest voltage differences between each conductor. Unfortunately, since particles pass through each drift tube only once, linear colliders scale linearly with their energy, and consequently are prohibitively expensive for producing the highest energies.

The second solution is the synchrotron. In a synchrotron, accelerated particles are made to travel in a large circular ring. This is accomplished by the use of bending magnets, as charged particles obey the Lorentz force law when moving through a magnetic field, and since the force experienced is perpendicular to the direction of motion,

$$\vec{F} = q\vec{v} \times \vec{B} \tag{2.1}$$

the path traveled will be circular for a uniform dipole field. With each orbit, the particles travel through the same accelerating region(s), gain the same increment of energy, and are brought back to the start by the bending magnets, which supply a slightly higher field for each return trip. In the case of proton accelerators, both the frequency and the field are altered as the protons are brought up to full energy. It should be noted, however, that synchrotrons are not as suitable for electron acceleration, as *synchrotron radiation* (discussed later) consumes an unacceptable amount of energy. Despite this, a clear advantage of the synchrotron is the ability to utilize colliding beams.

Ultimately, the purpose of any kind of particle accelerator is to collide the accelerated particles with some target, and use the energy released to create new particles. If the particles are collided with a fixed target, then conservation of momentum in the rest frame of the accelerator demands that a large portion of the incident energy be consumed in producing a moving product. However, if two counter-revolving beams are collided together, then the products are stationary in the lab frame, and the entire energy of the two colliding particles is available to produce new particles. For this reason, most large particle accelerators utilize counter-revolving and colliding beams. To achieve useful collisions, the beams are made to collide at fixed interaction points where the beams cross, and phase locking is used to ensure that “bunches” of particles interact these points rather than individual particles. Because of these advantages, synchrotrons have become the dominant tool in modern high-energy physics, most notably at the Tevatron and Large Hadron Collider.

## 2.3 The Large Hadron Collider

The Large Hadron Collider, or LHC, is a proton-proton colliding synchroton located at the European Organization for Nuclear Research (CERN) just outside Geneva, Switzerland. At a center-of-mass designed collision energy of 14 TeV and a circumference of some twenty-seven kilometers, it is both the largest and highest energy accelerator in the world. Before entering the LHC main ring, protons are accelerated through four pre-accelerators: starting with LINAC-2, 50 MeV protons enter the Proton Synchrotron Booster, then the Proton Synchrotron, then the Super Proton Synchrotron, which accelerates the protons to 450 GeV for injection into the LHC. Once there, it takes 20 minutes for the beams to be accelerated to the current peak energy of 3.5 TeV, and once there, the beams can be circulated for over 10 hours while collisions occur. During that time, the protons will have traveled farther than the distance from the sun to Pluto without touching the sides of the beam pipe, which is less than 5 cm across. The counter-rotating beams of the LHC cross at four points, which play host to four primary experiments: CMS, ATLAS, LHCb, and ALICE. The latter two are specialized, and the former two are general-purpose.

## 2.4 The CMS Detector

The Compact Muon Solenoid is one of two general-purpose detectors at the LHC. The name is somewhat disingenuous, as the solenoid is anything but compact, and got its name by being smaller than ATLAS, the other detector. The detector is cylindrical and symmetric about the collision point both radially and axially. At the heart of the detector is a superconducting solenoid that measures 13m in length and 7m in diameter, and produces a 3.8 Tesla magnetic field [6]. Since charged particles follow curved paths in a magnetic field (see equation 2.1), it is possible to measure the momentum of these particles by observing their tracks. Correspondingly, the innermost component is the tracker[1], which uses

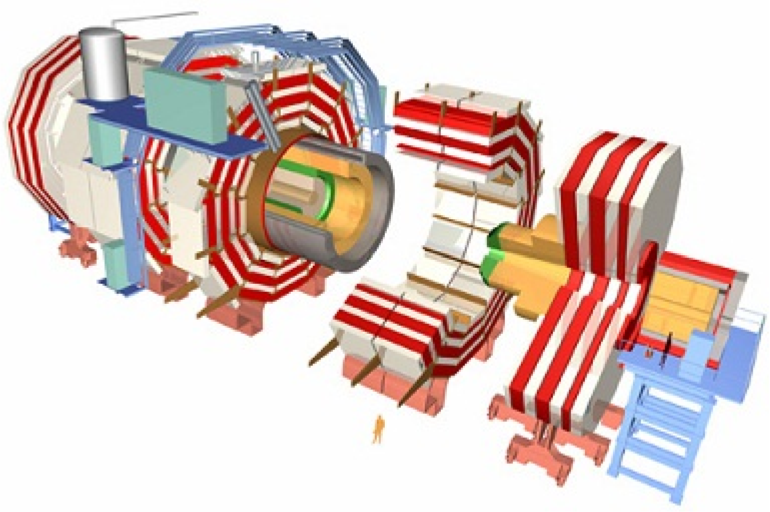

Figure 2.1: Exploded diagram of the CMS detector, with 2 m human for scale[1].

a shoebox-size pixel detector surrounded by ten layers of silicon strip detectors. Together, these establish precise paths for particles that emerge from the interaction point.

Outside the tracker is the ECAL, or electromagnetic calorimeter. This detector is composed of 78,000 lead tungstate crystals arranged into a cylindrical "barrel" and two flat "endcaps." These crystals scintillate, producing light in proportion to the number of passing particles. This indicates the energy of an incident particle, since particles are made to 'shower' through interactions with other nuclei, a process by which one high-energy particle becomes many lower-energy particles. The light is then amplified using avalanche photodiodes, and the electronic signals produced then provide precise information on the energy of electrons and photons produced in collisions.

The final layer inside the magnet is HCAL, the hadronic calorimeter. It measures the energy of hadrons, or particles composed of quarks. The detector works as a sampling calorimeter, with alternating layers of absorber and scintillator tiles- the former induces passing particles to deposit energy, and the latter measures how much energy was deposited in each layer. The detector is arranged into 4 sections, two concentric "barrel" segments (HB and HO), endcap (HE), and forward (HF). HF is unique in that most of the collision energy is deposited in HF, given its location at very high eta (which means it has a small angle from the beam line)[7], and therefore it must be very radiation-hard. For this reason, quartz fibers were used as the active material. They work when charged particles generate Cerenkov light, and the detector is correspondingly more sensitive to electrons. The way that HF determines whether an event is electromagnetic or hadronic is through the use of two sets of interleaved quartz fibers. One set traverses the whole length of HF, (165 cm) and the other does not start until 22cm from the front of the HF apparatus, but runs the rest of the way to the back. This makes it possible to distinguish between the two types of events because electrons and photons deposit the majority of their energy in these first 22 cm, and will then deposit significantly less energy in the short fibers than is deposited by hadronic events.

Outside the magnet, the muon system is a massive structure that doubles the diameter of CMS, and is composed of an iron return yoke with muon chambers in between each layer. It is placed at the outside of the experiment because muons are the most penetrating particles studied. Since muons will not deposit all of their energy into a calorimeter, the muon system functions much like the tracker, in that the momentum of each muon is determined by observing its path and how much deflection is observed due to the return magnetic field. Like the calorimeters, the muon system consists of a concentric "barrel" with ends covered by two "endcap" regions.

## 2.5 Physics Objectives

The purpose of the CMS experiment (and of the LHC) is ultimately to advance the understanding of physics. With that in mind, one of the purposes is to simply observe what happens when particles collide at unprecedented energies, and a general-purpose detector

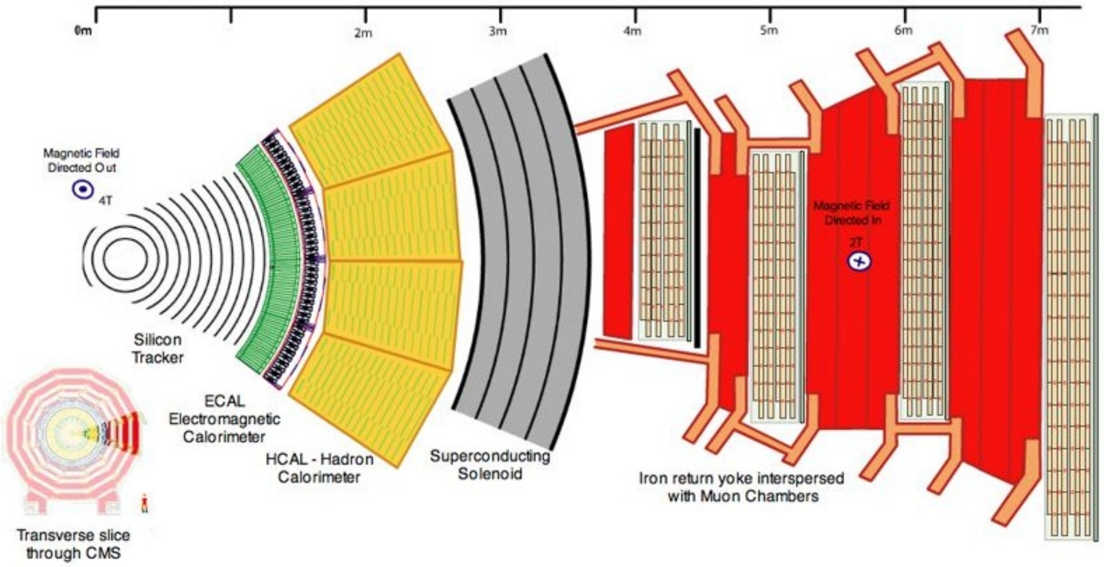

Figure 2.2: Transverse Slice of the Compact Muon Solenoid Detector[1].

like CMS is ideally suited to observe any novel phenomena that emerge. However, there are also more tangible objectives. One of the things that CMS should be able to do is verify the existence of the Higgs boson, or the lack thereof. If discovered, the Higgs would confirm the leading hypothesis on why particles have mass. Another physics objective is to look for evidence of sypersymmetry (SUSY), the idea that the unification of the three Standard Model forces at high energies leads each known particle to have a "super-symmetric" partner. Such a discovery could help identify the composition of the "dark matter" that composes much of the universe. The LHC experiments also hope to investigate the origins of the universe through the periodic collisions of lead nuclei instead of protons; it is thought that evidence for a new state of mater, the quark-gluon plasma, might be observed in such collisions. Finally, a more mundane purpose of the CMS detector is to conduct high-precision measurements of physics that is already known, and in essence "tighten the tolerances" of the Standard Model. It is this last task which is most relevant for the purposes of this paper.

# Chapter 3

# Triggering Systems in High Energy Physics

## 3.1 What is a trigger?

In common usage, a trigger is simply a device that causes something to happen when certain conditions are satisfied. In high-energy physics experiments, this is still the case; experimental triggers alter the way data is handled when certain patterns are observed in the detector's output. Most commonly, these triggers are utilized to ensure that only data which requires further analysis is recorded, just as a security camera might be programmed to write images to disk only when motion is observed.

## 3.2 Why are triggers needed?

Triggers are essential in high-energy physics for one simple reason – the volume of data is simply enormous. At CMS, the amount of data taken by the detector every time proton bunches cross is of order one megabyte, or about the size of a digital photograph. However, at full luminosity, the rate of bunch crossings is 40 million per second. Therefore, if the data from every bunch crossing were stored, many terabytes per second would have to be written to disk. Even if the problem of writing to disk that quickly could be solved, running the detector would still be prohibitively expensive. The purpose of a triggering system, then, is to automatically determine when 'interesting' data has been recorded, direct it to be saved for later review, and dispose of the rest.

## 3.3 Triggers in a hadron collider

In the Standard Model, there are two kinds of elementary fermions- quarks and leptons. Quarks, however, are unable to exist independently, and must be paired with either an antiquark, forming a meson ("middle-weight" particle) or two other quarks, forming a baryon ("heavy-weight" particle). Most of these combinations are unstable, and rapidly decay into other forms of matter; the only combinations that are stable on human timescales are two familiar hadrons, the proton and neutron. Since the neutron is uncharged, the Coulomb and Lorentz forces do not apply to it, and it therefore is unsuitable for use in particle accelerators. Therefore, the only choices for the particle physicist are the proton and electron (the only charged lepton stable for long periods).

In an electron collider, the only forces experienced are the Coulomb and weak interactions, so any time an event occurs with sufficient transverse momentum to be observed in the detector occurs, it is almost always 'interesting' and worth saving. This is because electrons merely passing close by each other will not experience enough force to be deflected through large angles, and will simply continue traveling down the beam pipe. By contrast, hadronic collisions often result in so-called 'soft scattering' since the constituent quarks experience the strong force, and consequently hadrons typically eject quarks and gluons in strong interactions, processes that are already well-understood. This is exaggerated further by the fact that protons are not point particles. Such events are not interesting from a physics perspective, but occur much more often than anything else. By counting the number of distinct chiral particle vertexes, we see that an average of 9 such events happen per bunch crossing. For this reason, in a hadron collider it is not sufficient to trigger only when 'something happened' in the detector. Rather, the trigger system must be configured to recognize patterns that characterize 'interesting' events, and distinguish them from simple scattering.

Given this daunting triggering problem, it is reasonable to ask why physicists bother with hadron colliders at all. The answer is that only hadron colliders can feasibly achieve high energies, because charged particles emit radiation when accelerated. The energy lost is inversely proportional to the fourth power of mass, and so electrons would lose energy due to centripetal acceleration at a rate $10^{13}$ times that of protons. Appropriately, this phenomenon is named *synchrotron radiation*.

## 3.4 The 2-level CMS Trigger

In CMS, the triggering problem has been solved by implementing a system of two layers of triggers, one after the other[2]. The initial trigger is aptly named "Level-1" or L1, and the subsequent trigger is known as the "high-level trigger," or HLT. L1 is extremely fast, and is entirely hardware-based. It has to be, because there is little time for processing; its task is to reduce the flux of data from the bunch crossing rate (40 MHz) to no more than 100 kHz of the most promising events and pass them on to the HLT. It is important to realize that to avoid a backlog, a decision on whether to accept or reject data from a bunch crossing must be made at the same rate as bunch crossings- once every 25 nanoseconds. The HLT then can analyze data at a much more leisurely pace, running more detailed tests to determine if the data match specific preprogrammed signatures. This second level, a bank of eight thousand computers, then reduces the 100 kHz influx of events to the most-interesting 100 Hz, which are then written to disk for later analysis.

For the purposes of this paper, the L1 trigger is the most important, with specific regard to the data available to it at the time an acceptance decision is made. The flow of data inside the L1 trigger system is outlined in Figure 3.1. From this, it is important to note several things for future use. First, the trigger primitives (initial inputs) come from “trigger towers,” which are physically-grouped clusters of detection elements, like the ECAL scintillator crystals. From these inputs, the regional calorimeter trigger does preliminary identification of signals, and passes along the most interesting to the global calorimeter trigger, which then performs sorting and presents information to the global trigger for a final L1 decision. Energies from the four highest forward jets are passed along from the regional calorimeter trigger as “ranks,” which correspond to predefined energy intervals, such that all possible energies can be assigned a rank of 0 through 63. Finally, when the global trigger makes a final decision, it has 128 possible algorithms to use. Each of these occupies one “bit” in a string attached to each event. If any of the algorithms yields a one, the event is saved; if all bits are zero, the event is rejected.

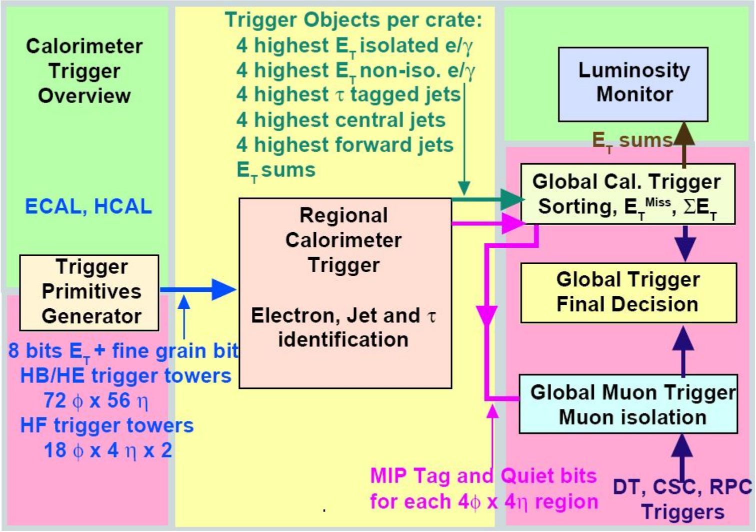

Figure 3.1: An overview of the functionality of the Level-1 Trigger [2].

# Chapter 4

# The Physics of Z-decay

## 4.1 The Z Boson

In the Standard Model of particle physics, three of the four fundamental forces are mediated by gauge bosons. The most familiar to the reader will be the photon, which mediates the electromagnetic interaction. The strong interaction, affecting only quarks, is mediated by the gluon, while the weak interaction is mediated by the W and Z bosons. The weak interaction affects both quarks and leptons, and is responsible for beta-decay, since it (uniquely among the forces) allows quarks to change their flavors. The name arises from the weak force being six orders of magnitude weaker than the electromagnetic force, which itself is much weaker than the strong force. Of course, all three forces dwarf the strength of the gravitational interaction, but gravity is negligible on the subatomic scale and not addressed by the Standard Model.

The W and Z bosons are massive particles; their rest masses are 80.4 and 91.2 GeV, respectively. Because of this, the weak force is short-ranged. The mass of the Z-boson is greater than the mass of a krypton atom! Despite this, in the force-carrier role conservation of mass-energy is not violated since the W and Z are virtual particle. This means that they are created and annihilated very quickly, in the window allowed by the uncertainty principle. However, in particle collisions of sufficient energy, free W and Z bosons may be created, and observing their subsequent decays can yield interesting physics.

The decay paths of the W and Z bosons are governed by charge conservation. The W boson carries either a positive or negative charge, while the Z has no charge. Consequently, while the W can decay into either a lepton and neutrino or a up-type and down-type quark pair, the Z can only decay into a fermion-antifermion pair. Each fermion with mass less than the top quark (which is too massive to be a decay product) constitutes a *decay mode* of the Z, and the probability of each decay mode is given by the *branching fraction* of that mode. This is influenced by the number of possible states within each mode (for instance, quark decay is more likely, since quarks can be produced in three distinct "colors" in addition to the various flavors).

## 4.2 Why Z-decay is Useful for CMS

Decay of the Z is observationally valuable [8] for several reasons. First, the lepton decay modes are very well understood and easy to recognize and measure in the detector. However, while muons are perhaps the most unambiguous particles to identify, muon coverage less extensive. Because of this, although electron decay accounts for only about 3.4 percent of all Z-boson decays, it is disproportionately useful in calibration of the detector.

Another reason is that Z decay can be used to make precision measurements of the *parton distribution functions*, or PDFs, for the proton[3]. These describe which constituents of the proton carry the momentum of the proton- for example, the valence quarks (two up quarks and one down quark) comprise a small fraction of the proton mass, the rest being so-called "sea quarks" and gluons. Since the Z is produced when partons inside the two colliding protons collide, the combined momentum of the partons involved influences the momentum of the Z, and thus its subsequent direction, or *rapidity* in the detector.

By utilizing conservation of transverse momentum, it is possible to calculate the initial momentum of the Z from the two lepton tracks that result from its decay. Note that this task is substantially more difficult with the quark decay mode, since the products are messy "jets" resulting from hadronization of free quarks, not single particles. A better understanding of the PDFs will improve our understanding of QCD at the scale of elementary particles. Additionally, the proton PDFs summarize our understanding of the CMS targets, and an excellent understanding of the targets is required to make accurate predictions of the results of collisions.

For the aforementioned reasons, observing as many di-lepton Z-decays as possible is a worthy physics goal at CMS. These observations require a trigger system that will recognize when such events have occurred. For events where two electrons are deposited in ECAL this is trivial, as electrons are easily recognized by that system. However, as illustrated in Figure 4.1, a substantial fraction of these events deposit one electron in ECAL and another in the HF detector, where electrons are not easily differentiated from other particles. A trigger system to recognize these events without overwhelming the system with background must be more subtle; this is the topic of the next chapter.

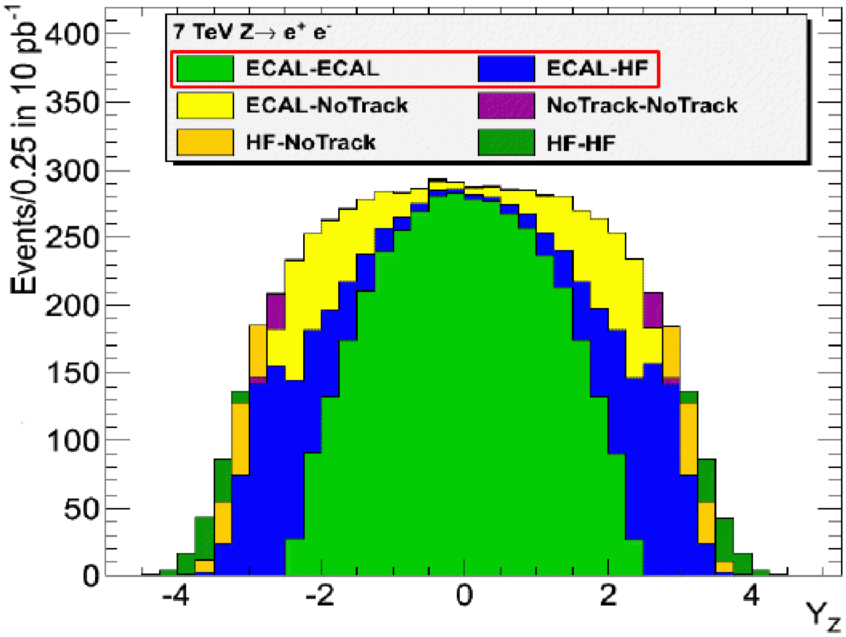

Figure 4.1: The simulated (Monte Carlo) frequency of di-electron Z-decay being observed in various parts of the detector, as a function of Z rapidity[3].

# Chapter 5

# A new L1 Trigger Bit for CMS

## 5.1 The current status of the L1_Single_EG12 bit

As of early 2011, bit 50 in the CMS Global Trigger is assigned to the algorithm "Single_EG12". It fires whenever an electron or photon with transverse energy greater than 12 GeV is observed in ECAL, and is useful for identifying di-electron Z-decay events (where one electron also enters the HF calorimeter). At current luminosity, this trigger bit is very active. For instance, in the recent run 163817 (May 2, 2011), the L1 trigger fired at an average rate of 38.2 kHz, while Single_EG12 triggered with an average frequency of 8.5 kHz, a substantial fraction of total L1 activity. With impending luminosity upgrades, it is almost certain that unless this rate can be brought down, the Single_EG12 bit must be prescaled, with corresponding impacts on Z-decay physics. In the following sections, it is proposed to link the 'single-electron' requirement with a 'minimum leading rank in HF' requirement, which could dramatically reduce the background rate with little impact on the desired signal.

## 5.2 The High-Level Trigger for HF

As described above, the role of the L1 trigger is to keep the rate of event readout by the data aquisition system (DAQ) below its limit of 100 kHz. The combination of the L1 and HLT triggers must limit the rate of writing data to disk. Currently, the Z-events with electrons in HF are collected based on the Single_EG12 L1 bit described previously, and the HLT trigger, `HLT_Ele17_CaloIdL_CaloIsoVL_Ele15_HFL`. This HLT trigger requires an ECAL electron which passes loose isolation and identification requirements, and has transverse momentum greater than 17 GeV. It also requires the presence of an HF electromagnetic object (with extremely loose ID requirements) and transverse momentum greater than 15 GeV. The goal of the effort described here is to adjust the seeding of this HLT trigger, without modifying the trigger itself.

## 5.3 The Usefulness of Leading Forward Jet Rank

For each bunch crossing, information on the rank of the four most energetic HF jets is available from the L1 Calorimeter Trigger. This information is useful because the desired di-electron Z-decays typically deposit a significantly larger amount of energy in a single HF jet than most background events, as is illustrated in the following subsections.

One point of caution is necessary when comparing thresholds for L1 forward jets to HF electromagnetic objects as reconstructed in HLT. The reconstruction in HLT and for analysis uses only the long fibers of HF, and clusters only 9 cells of HF. The L1 forward jets, by contrast, use both the long and short fiber energy, and combine 54 cells. The L1 forward jets will thus see more noise from both the detector and from other interactions in the same beam crossing. As a result, the thresholds cannot be simply compared and the effect of a given cut at L1 on the efficiency of the L1-HLT combination will be investigated below.

### 5.3.1 L1 Forward Jet Rank for Signal Events

To evaluate the effectiveness of L1 forward jet rank in differentiating signal-like events from background, the first step is to investigate known signal events. For the purposes of this discussion, a 'signal event' will be considered to consist of an electron in ECAL and one in HF, each with transverse momentum greater than 20 GeV and with a di-lepton mass between 70 and 120 GeV. The electron is required to pass WP80 identification criteria, ensuring that 80 percent of true electrons can pass. Meanwhile, the HF electron must pass loose identification requirements.

To justify these assumptions, Figure 5.1 plots a histogram of the reconstructed masses of signal-like events. The resulting curve is roughly symmetric about a peak at 90 GeV, implying that the source is Z-boson decay. Therefore, it is very likely that the particles entering HF are also electrons.

Finally, the rank of the leading forward jet in each of the remaining events can be recorded and compiled into a histogram, Figure 5.2. From this, it can be seen that very few events that meet the selection criteria have a leading rank in HF less than 5, which corresponds to 20 GeV at the current linear assignment of 4GeV/rank increment.

### 5.3.2 L1 Forward Jet Rank for Background Events

The second task is to investigate a sample of background events and verify that most have a small leading rank in HF. For the background sample, a large collection of events was accumulated from the data set "/Commissioning/Run2011A-PromptReco-v2/RECO," with the trigger requirement "HLT_L1SingleEG12_v1." This ensured that only events which were accepted by the current L1 trigger bit were considered. Then, a filter was added to remove any events that would be accepted by the current HLT. In this way, a sample of pure background events was obtained. Finally, as before, the leading rank of each event was obtained and plotted in a histogram, Figure 5.3.

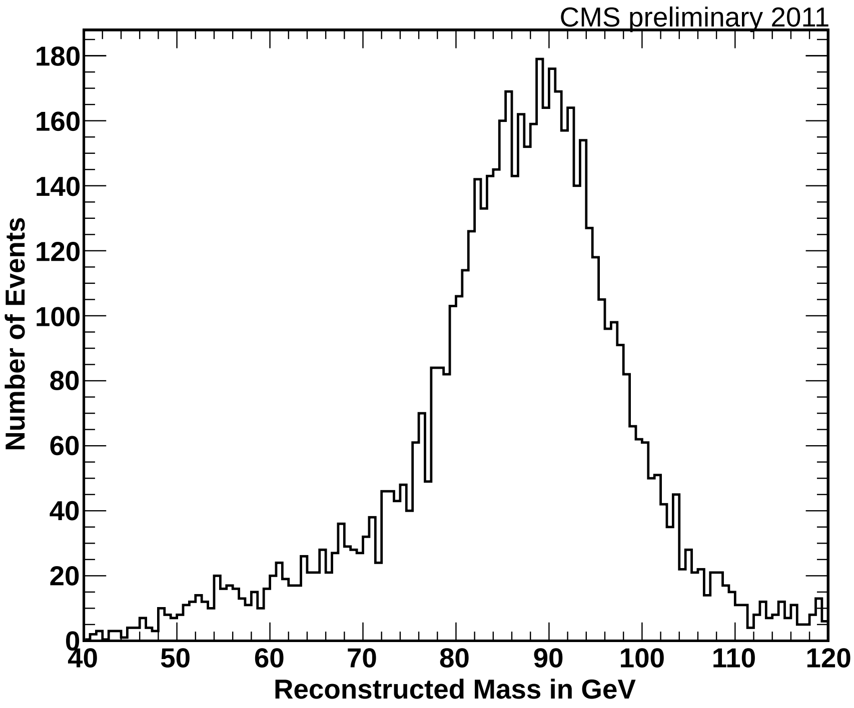

Figure 5.1: Reconstructed mass distribution of signal-like e-e events.

## 5.4 Improving L1_EG12 via Addition of an L1ForJet Cut

### 5.4.1 Rationale

From Figure 5.3, it is observed that the background distribution peaks at low rank and decays roughly exponentially, such that the amount of background events at rank 5 is already an order of magnitude lower than the peak. At the same time, the signal distribution is almost nonexistent before rank 5, and grows rapidly thereafter. This suggests that dramatic reductions in triggering rates can be achieved by implementing a leading-rank cut in the vicinity of rank 5. To better illustrate this, Figure 5.4 shows the efficiency of both signal and background on the same histogram. This was achieved by integrating everything greater than or equal to the rank in question, normalizing, and plotting the results.

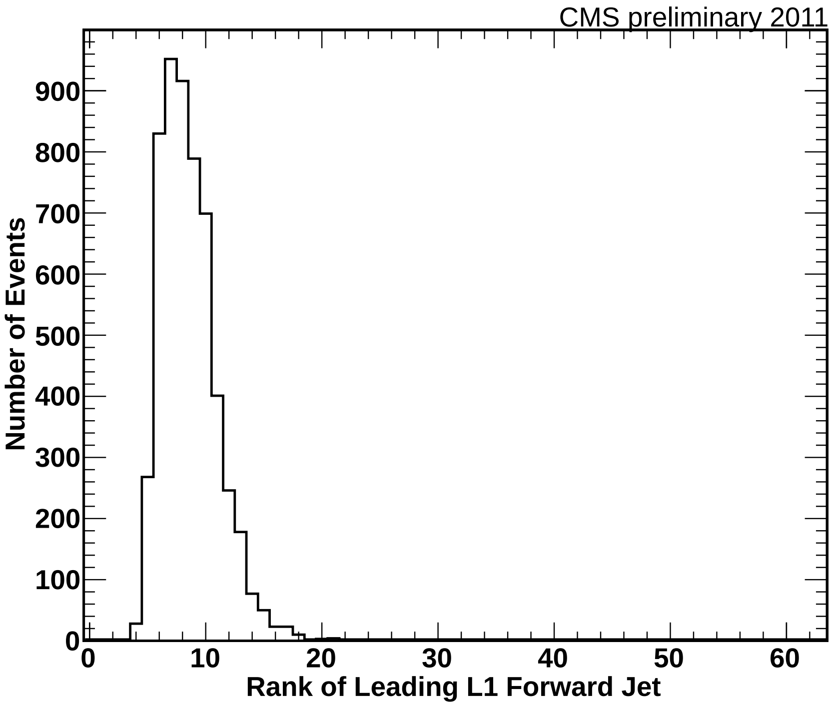

Figure 5.2: Distribution of leading rank in HF for signal events.

### 5.4.2 Avoiding HLT Overlap

Before an appropriate choice of leading rank cut can be made, there is one additional consideration- the threshold of the HLT. A trigger which sets the cut threshold too high will end up rejecting events that the HLT would have passed, which is unacceptable. Consequently, Figure 5.5 illustrates the overlapped efficiencies of events that would have passed the HLT and the same background as before. The HLT passing subset was accumulated from `/DoubleElectron/Run2011Av2/RECO`, a large set of electron-containing data, and was made by removing all those events that would not have passed the HLT. This is essentially the opposite of the procedure used to construct Figure 5.3.

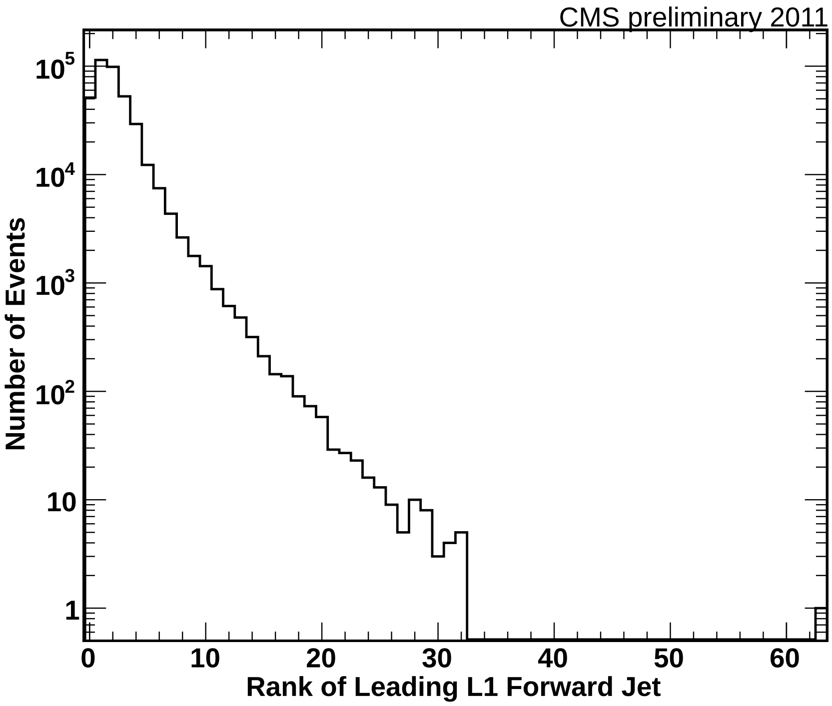

Figure 5.3: Distribution of leading rank in HF for background events.

### 5.4.3 Options for Leading Rank Cut Selection

To make a final selection of which leading rank number to cut on, it is essential to consider three items: the rate reduction of that rank, the amount of signal remaining after the cut, and the proportion of HLT-passing events which would be preserved. These items are summarized in Table 5.1 for all reasonable rank options. At the low end, keeping the cut at (below) rank zero corresponds to doing nothing, and at the high end, the rate reduction is almost a factor of 20, but the signal efficiency noticeably decreases and the proportion of cut events that would have passed the HLT becomes unacceptably high. Therefore, a reasonable compromise may be represented by cutting everything with a minimum rank below 4 (16 GeV). This would reduce the rate by a factor of six, preserve effectively all of

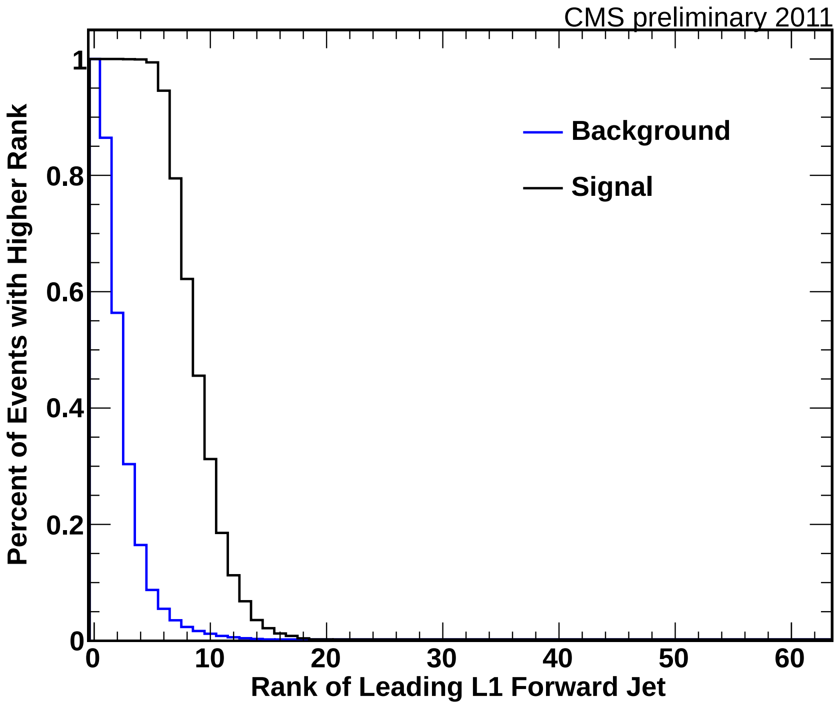

Figure 5.4: The efficiencies of both signal and background with respect to the leading forward jet rank.

the signal, and only lose one percent of events which would otherwise have passed the HLT. Such a cut would enable a prescale to be avoided while still preserving all the important data for Z-decay physics, and is therefore recommended.

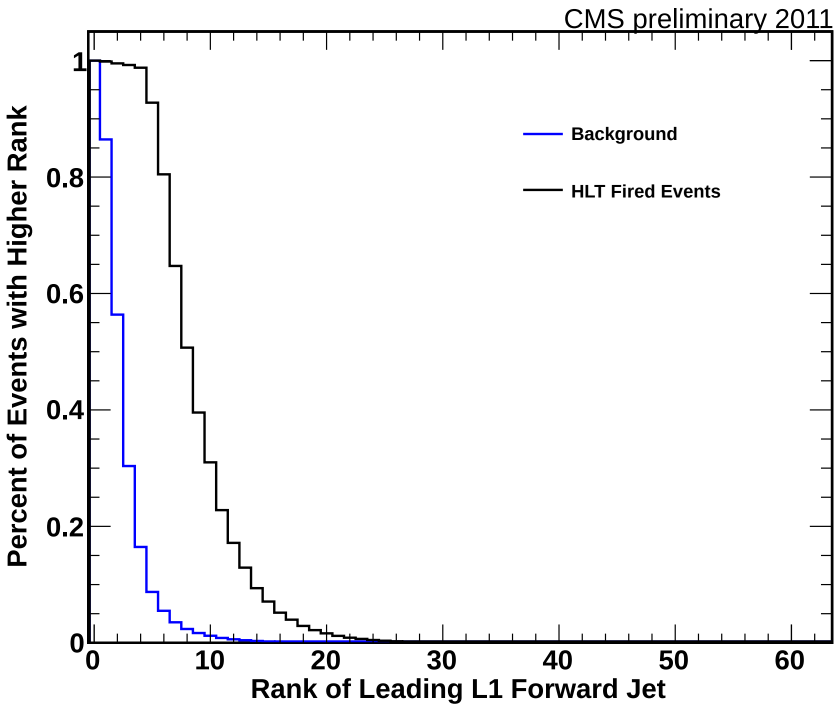

Figure 5.5: The efficiencies of events that pass HLT and background with respect to leading forward jet rank.

Table 5.1: Options for cut selection by rank number.

| Minimum Rank | Rate Reduction | Efficiency w.r.t. Signal | Efficiency w.r.t Current HLT |
|---|---|---|---|
| 0 | 1 | 1 | 1 |
| 1 | 1.16 | 1 | 0.998 |
| 2 | 1.77 | 1 | 0.995 |
| 3 | 3.29 | 1 | 0.992 |
| 4 | 6.08 | 0.999 | 0.988 |
| 5 | 11.45 | 0.994 | 0.928 |
| 6 | 18.20 | 0.945 | 0.805 |

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