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Chapter 1

OVERVIEW

1.1 Measurement of Cross Section

$$\sigma_Z \times \text{BR}_{Zee} = \frac{n_{Zee}}{\mathcal{L} \times \epsilon}$$

where

$$\epsilon = \epsilon_{acc} \times \epsilon_{trig} \times \epsilon_{reco} \times \epsilon_{sel}$$

particles? although that's theory intro (but need SOME particle-specific stuff)

the practical purpose of MC – can simulate all stages of gen/sim/reco/etc and compare everything step-by-step with data, as well as of course getting some quantities that require extra knowledge, like acceptance (and predicting efficiencies, rates, etc) HA, that sounds like a few of those things in the pythia manual intro! and I came up with them myself!

glossary? (explanatory text, with true glossary in appendix?)

- * histogram? errors? (stat/syst) etc?

- * eta, phi, transverse quantities

- * “kinematic”

- * I think I (hopefully) got minbias already, and this isn't exactly the place for it...

- * signal, background

- * acceptance, efficiency (especially for that formula above)

- * invariant mass

- * HERE OR IN THEORY INTRO need to do on-shell/off-shell decays

- * statistical and systematic uncertainties or errors

- * “data-driven” stuff? need for efficiency, but also systs??

- * acronyms?

Chapter 2

THEORY INTRODUCTION**2.1** *Standard Model***2.2** *Electroweak Physics**2.2.1 Z Production*

Chapter 3

EXPERIMENTAL SETUP

3.1 CERN

The European Organization for Nuclear Research, or CERN, is an international laboratory just outside Geneva, Switzerland. It was founded in 1954 as a collaborative effort between twelve European countries. It now has twenty member states, as well as many observer and other non-member states, and is one of the world’s major particle physics facilities.

3.2 Large Hadron Collider

The Large Hadron Collider (LHC) is a circular particle accelerator near Geneva, Switzerland, with a circumference of 27 km. Two proton beams circulate in opposite directions around the ring and cross at several points, which are home to large particle detectors. Figure 3.1 shows a diagram of the LHC layout. The two general-purpose detectors, CMS and ATLAS, sit on opposite sides of the ring, while the two smaller specialty detectors, LHCb and ALICE, sit at the interaction points to either side of ATLAS. Each beam consists of a series of proton bunches, with a maximum of 2835 “buckets” in the beam to be filled by bunches. The bunch structure is such that the nominal bunch crossing rate is 40 MHz.

The proton beams are accelerated from injection energy by an RF chamber, which provides an energy boost with each circulation of the beam until the collision energy is achieved. The beams are steered around the ring by 8-Tesla magnetic fields produced in 15-meter-long superconducting niobium-titanium dipole magnets, and focused by quadrupole magnets, 5-7 m long. The LHC uses a design in which both proton beampipes are contained in the same housing, allowing the same liquid helium cooling system to serve both.

The LHC began colliding proton beams in March 2010, quickly reaching its 2010 center-of-mass operating energy of 7 TeV (3.5 TeV per proton beam). At this energy it delivered over 47 pb^{-1} of collisions, with a maximum instantaneous luminosity of over $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

The LHC maximum design energy is 14 TeV (7 TeV per beam), and its design luminosity is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

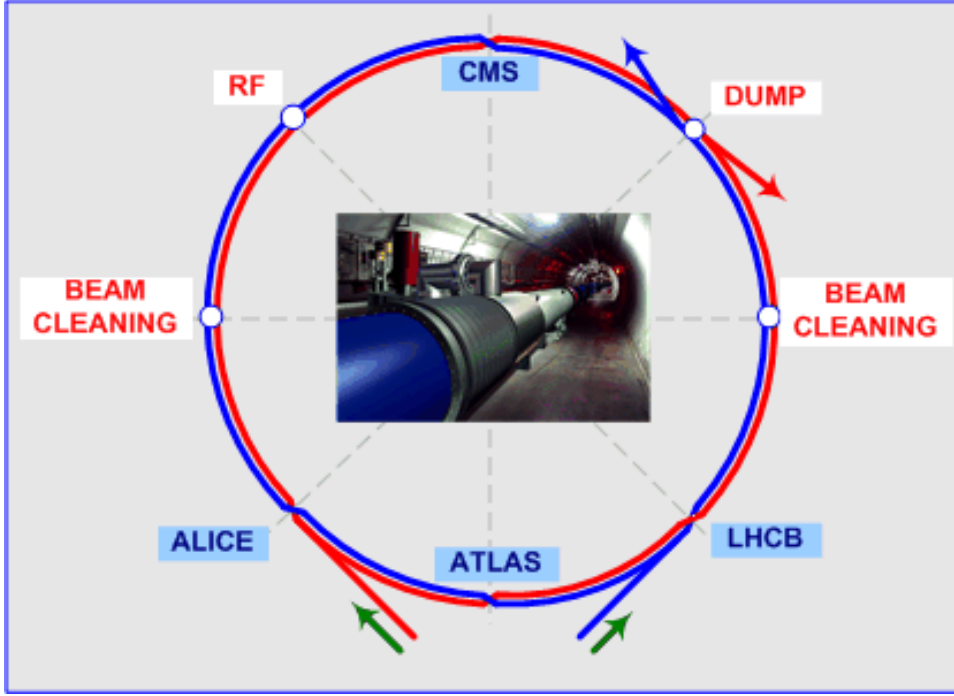


Figure 3.1: Diagram of the LHC layout.

3.3 Compact Muon Solenoid

The Compact Muon Solenoid (CMS) is one of the two general-purpose experiments for the LHC. Figures 3.2 and 3.3 show the structure of the CMS detector. It is cylindrical, 21.5 m long and with a 15-m diameter, and weighs 12,500 tons. The overall structure of the detector is formed by the iron yoke framework surrounding the inner detector, with the central section, the “barrel”, divided into five ring-shaped slices, while each end of the cylinder, or “endcap”, consists of several circular plates. These sections fit around the solenoid and inner detector, enclosing it completely.

Particle detection is done by several dedicated subdetectors. The electromagnetic and hadronic calorimeters fit inside the solenoid, with the tracking system inside the calorime-

ters. The three components of the muon system are outside the solenoid, integrated with the iron magnetic field return yoke: the drift tube chambers, resistive plate chambers, and cathode strip chambers.

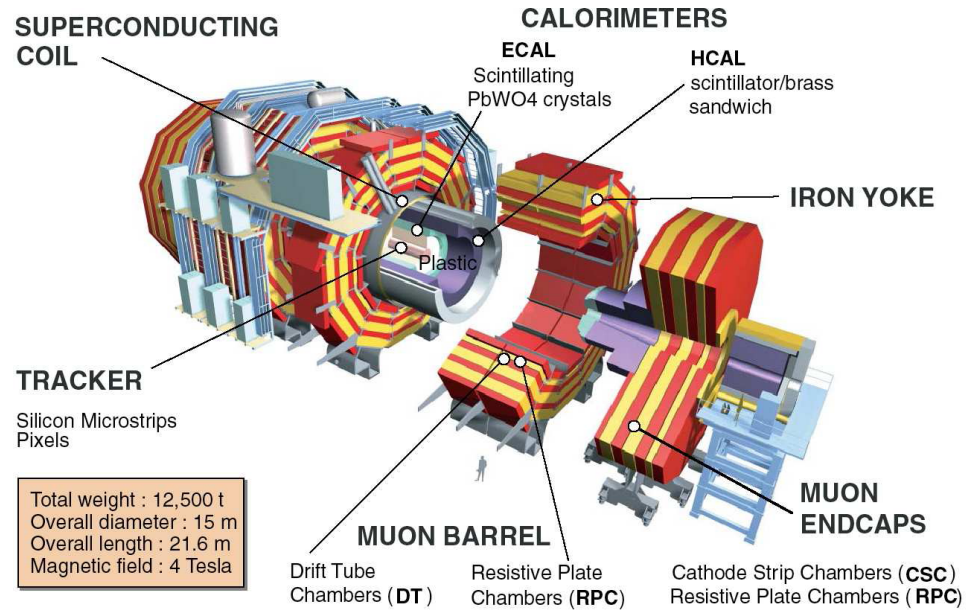


Figure 3.2: Expanded view of the CMS detector, showing the ring and slice structure as well as the placement of each subsystem.

3.3.1 Detection of Particle Interactions

Figure: Particle detection in CMS, Fig. 3.4

The various parts of the CMS detector work together to differentiate the end-products of proton interactions. As the end-product particles traverse their outward trajectory, they pass through the different subdetectors in turn. Figure 3.4 shows how end-product particles interact with the subsystems of the CMS detector. The innermost subdetector is the tracker, which reconstructs a particle's track through it from a set of points where it detected an interaction. The tracker only registers particles with an electric charge; neutral particles pass through undetected. The electromagnetic calorimeter detects particles that interact primarily electromagnetically. In this way the first two "layers" of the detector can

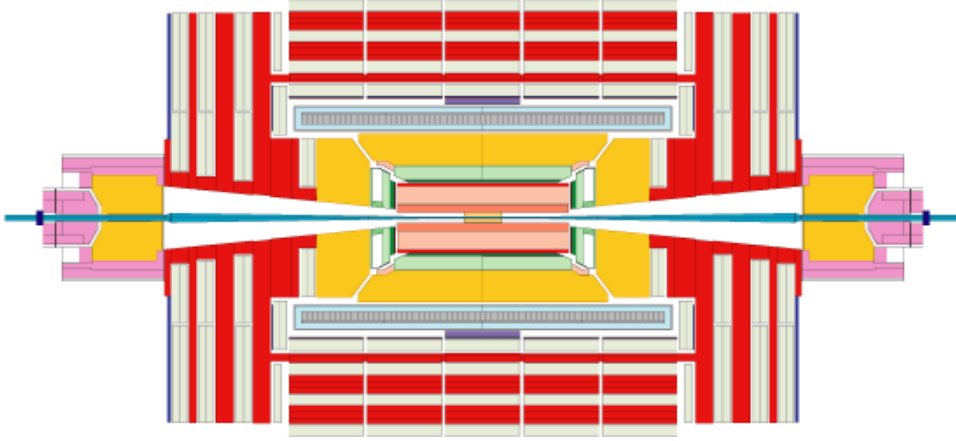


Figure 3.3: Cross-sectional view of the CMS detector.

differentiate electrons from photons: both are seen in the electromagnetic calorimeter, but only electrons leave traces in the tracker. Outside of the electromagnetic calorimeter is the hadronic calorimeter, which primarily detects hadrons. Hadrons are also detected in the electromagnetic calorimeter, but they leave the largest signature in the hadronic calorimeter, which differentiates the hadrons from the electromagnetic particles like electrons and photons. Hadrons are often found in large quantities called “jets”, so summing together the energy deposits from sizable electromagnetic and hadronic calorimeter regions is important in event reconstruction. Surrounding the tracker and the calorimeters is the solenoid, which generates the magnetic field. The charge of a particle can be determined from which way it bends in the magnetic field. Finally, outside the solenoid and interwoven with the panels of the iron return yoke, is the muon system. Muons leave traces in the inner subdetectors, but they are the only particles to live long enough to reach the muon system. This differentiates them from the other particles detected by the inner subdetectors. Since the muon system is outside the solenoid, the magnetic field points in the opposite direction, and hence the muon trajectories bend in the other direction from what they had inside the solenoid. The last category of end-product, neutrinos, generally cannot be detected. However, their direction and energy in the radial plane can be reconstructed by summing the energy of all the particles in the event. Because the initial protons have zero momentum in the radial

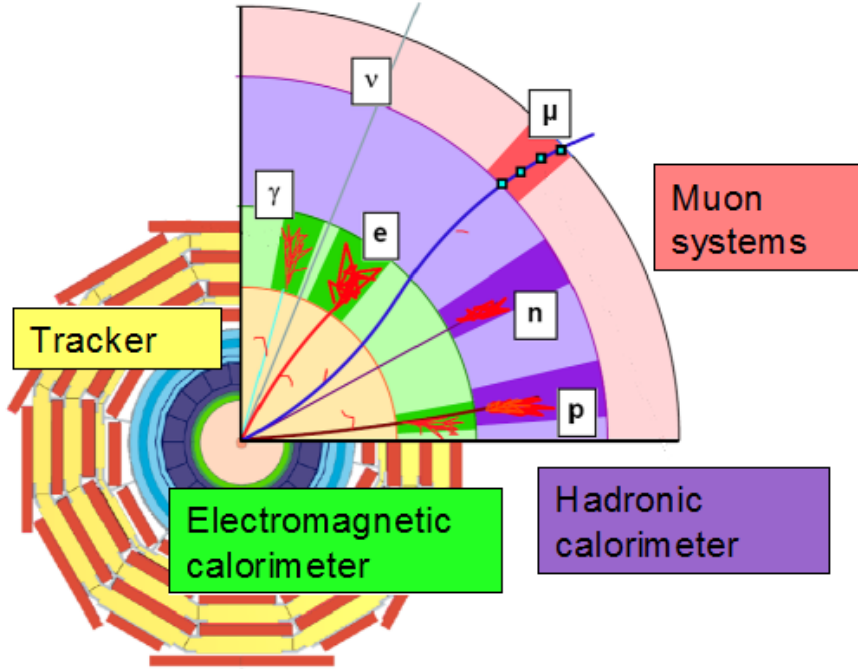


Figure 3.4: Detection of particles in the CMS detector.

plane, and momentum is always conserved, any significant “missing” component to the final energy can be taken to be due to a neutrino.

A CMS event display from 2010 running can be seen in Fig. 3.5.

3.3.2 Coordinate System

A standardized set of coordinates is used to describe points and directions within the CMS detector. The origin of the coordinate system is at the interaction point, with the x -direction pointing horizontally south towards the LHC center (ignoring the slight tilt of the LHC ring with respect to the vertical), and the y -direction pointing directly upwards. The z -axis points horizontally west along the beam direction, and the magnetic field inside the solenoid points in the positive z -direction. The azimuthal angle ϕ , measured in the x - y plane and ranging from $-\pi$ to $+\pi$ radians, is oriented such that $\phi = 0$ is equivalent to the

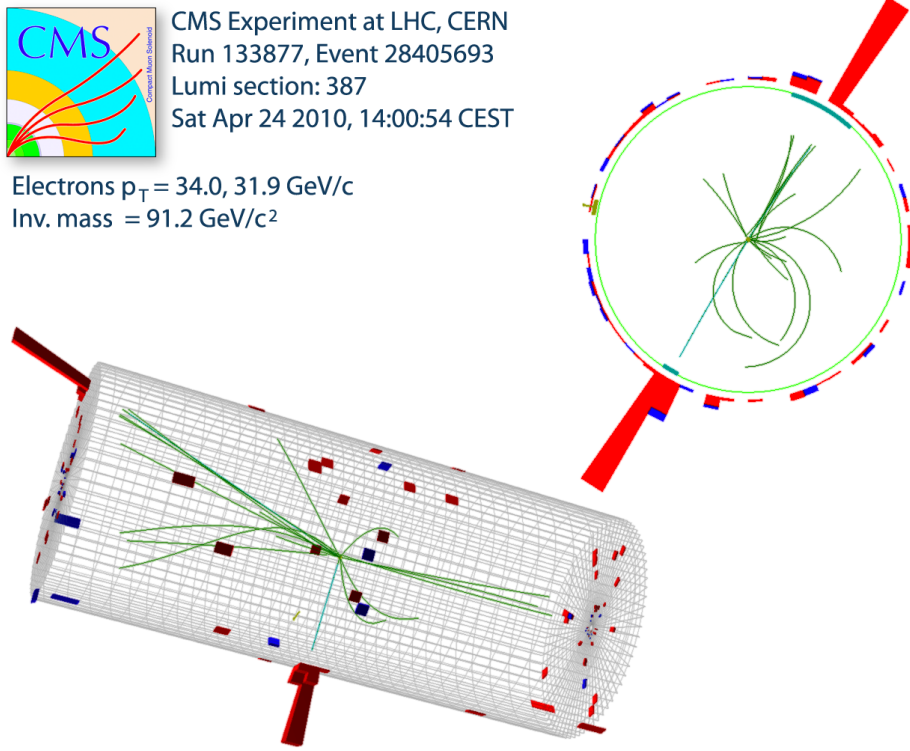


Figure 3.5: Three-dimensional display of a $Z \rightarrow e^+e^-$ event in the CMS detector.

positive x -axis and $\phi = \pi/2$ is equivalent to the positive y -axis. The longitudinal angle θ is measured from the positive z -axis, and the sign of $\eta = -\ln \tan(\theta/2)$ is equal to the sign of z .

3.3.3 Magnet

Since charged particles bend in a magnetic field, particle detectors use some sort of magnetic field to determine the charges of decay products. CMS uses a solenoid, or electromagnet in the shape of a coil, to produce a uniform magnetic field in the detector's inner region. The magnet coil is 12.5 m long with a 6 m diameter, and it weighs 220 metric tons. The CMS solenoid is made of a superconducting material, a niobium-titanium alloy, to handle the large amount of current necessary: it generates a field of 4 Tesla using a current of almost

20 kA in a four-layer winding.

The magnetic field is returned through a 10,000 metric ton iron yoke, which also serves as a support structure for the detector. The yoke consists of three concentric cylinders divided into the same 5-ring barrel and 3-disk endcap structure as mentioned previously.

3.3.4 Tracker

The purpose of the tracker is to detect the tracks from end-product particles; only those which are charged can be detected in the tracker. The CMS tracker contains 75 million channels and is specifically designed to get good performance using only a small number of hits per track. It is the innermost layer of the CMS detector and is made up of two different systems: the pixel detector, which is closest to the interaction point and hence has the finer granularity, and the strip tracker, covering the volume out to the calorimeter. Both systems are made of silicon and register charged particles in the same way. When a charged particle passes through the silicon, it knocks electrons out of the material, creating a net positive charge. The electric current needed to return the silicon to its neutral state is measured and amplified by the readout electronics. This readout technology is fast compared to the 25 ns bunch spacing of the LHC. A single track is reconstructed by stringing together the measurements from each of the layers.

Pixels

The silicon pixel detector has a very fine accuracy due to the high density of tracks near the interaction point. It consists of 65 million readout channels arranged on modules in several layers around the interaction point. In the barrel, the layers are cylindrical and situated at radii of 4, 7, and 11 cm, while each endcap has two disks, at 6 and 15 cm from the interaction point. Each module consists of a rectangular array of $100\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$ pixels, with a resolution of $15\text{ }\mu\text{m}$. The pixels on each module are read out by a dedicated chip attached to the module. The chip contains readout unit cells, one corresponding to each pixel, which are connected to the pixels with a small bump of solder in the so-called bump-bonding method.

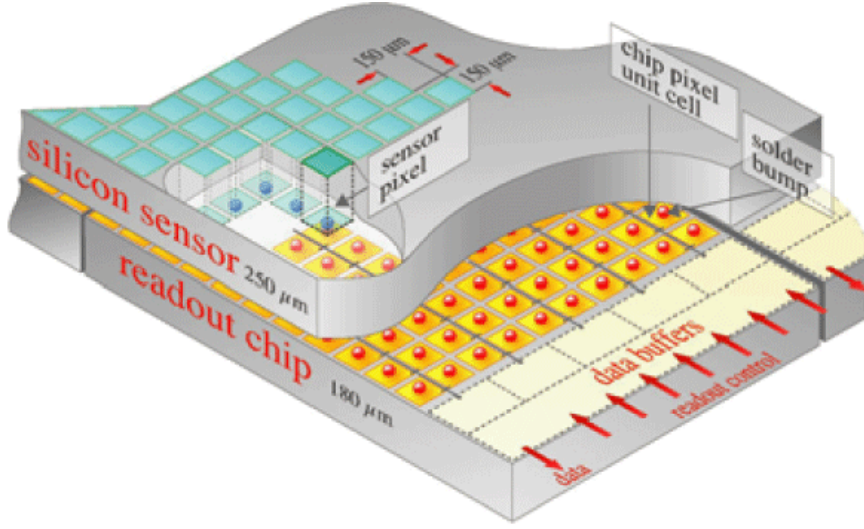


Figure 3.6: Structure of pixel detector layers.

Strips

The silicon strip detector consists of 10 million channels arranged in 10 layers of strips, in both the barrel and the endcap, and extends to a radius of 130 cm from the interaction point and to an $|\eta|$ value of 2.5. The track density at this stage is much less than in the pixel detector, so the granularity does not need to be as fine. Each strip is between about 12 and 16 cm long, with a resolution ranging from 15 μm in the inner barrel to 50 μm in the outer tracker. The strips are arranged in modules of 6 inches in length, with the geometry of each module dependent on its position in the tracker. The strip tracker consists of four different parts: the tracker inner barrel (TIB) with four layers of strips reaching to a radius of 50 cm, the tracker inner endcap disks (TID) with three layers to ± 90 cm in z , the tracker outer barrel (TOB) with six layers to 1.16 m radially, and the tracker outer endcap (TEC) with nine layers, extending to ± 2.8 m in z . Several of the layers are double-sided: they contain two sets of silicon modules. The two sets of modules are arranged in a stereo geometry to accurately measure the longitudinal (or radial, in the endcap) coordinate of the hit as well as the azimuthal.

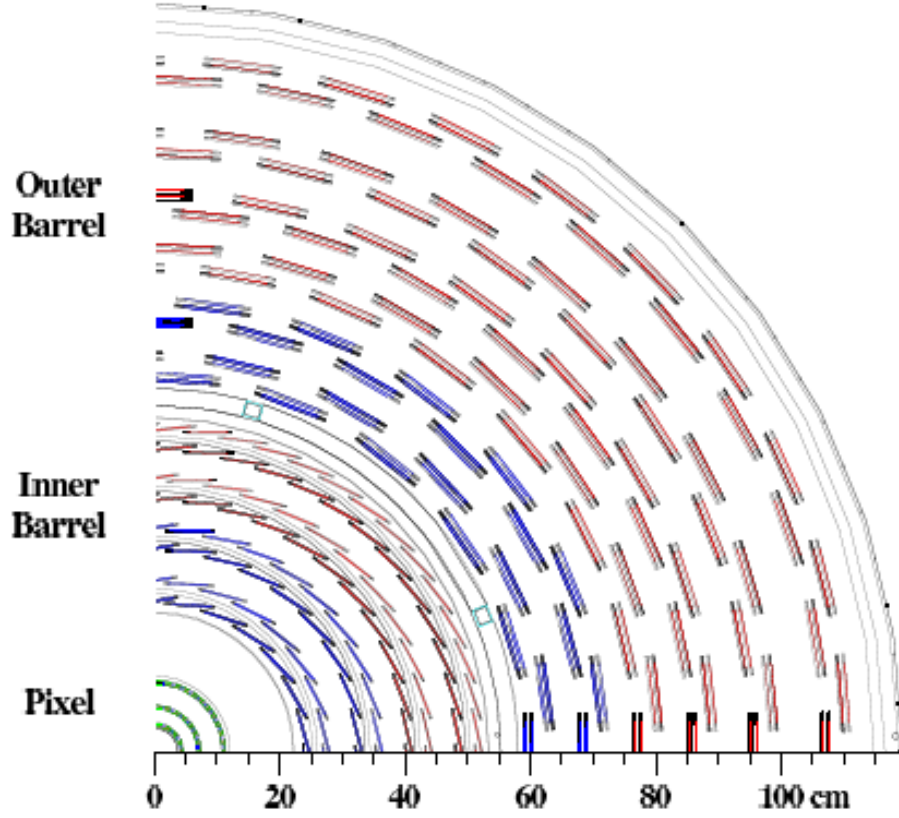


Figure 3.7: Diagram of layers in tracker barrel.

3.3.5 Calorimeters

The general purpose of a calorimeter is to measure energy passing through it. CMS measures the energy of decay products with a scintillating electromagnetic calorimeter (ECAL), situated just outside the tracker, and a sampling hadronic calorimeter (HCAL), surrounding the ECAL. Both calorimeters are contained within the solenoid. This solves a problem seen in other detector designs, in which energy lost in the magnet material leads to an uncertainty in the energy measurement.

ECAL

The ECAL is made up of 76,000 lead tungstate crystals, arranged in a cylindrical barrel and disk-shaped endcap geometry. The barrel is divided into 18 sections in ϕ and two in η , called supermodules. Each endcap is divided into two half-disks, called dees. Each lead tungstate crystal is 2.2 cm x 2.2 cm wide and 23 cm long for the barrel, and 3 cm x 3 cm wide and 22 cm long in the endcap. The dimensions were chosen such that the width of each crystal is approximately the characteristic size of an electromagnetic shower within it (Moliere radius of 2.19 cm), and the length is 25 times the radiation length of the material (0.89 cm for lead tungstate). The crystals are oriented with the long axis directed towards the interaction point. However, to avoid particles being lost in the cracks between the crystals, the crystals are offset by 3 degrees in both the ϕ and η directions. An electromagnetically-interacting particle will induce a shower inside the crystals, and the resulting light is captured by photodetectors situated at the back of each crystal. The energy resolution was measured to be

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2$$

A preshower detector, consisting of lead radiators and silicon sensors, is situated on the face of each endcap. The preshower serves to identify electron pairs due to low-energy pion decays and differentiate them from more interesting signatures. Pions typically decay on the scale of the distance between the interaction point and the ECAL endcap; therefore there is no preshower detector for the barrel, which is too close to the interaction point.

HCAL

The hadronic calorimeter surrounds the ECAL and covers $|\eta| < 3$ in the barrel and endcap (HB/HE) and up to $|\eta| < 5$ in the forward calorimeter (HF), both within the magnet coil. Additionally, the outer calorimeter (HO) is situated outside the solenoid and serves to detect and measure any leak-through. In general HCAL uses sampling calorimeter technology, with brass and scintillator layers interleaved in the barrel and endcap, and steel plates and quartz fibers for HF; quartz was used in the forward region because of its ability to withstand very

high particle fluxes. In a sampling calorimeter, the layers of metal absorber induce particle showers, which are then “sampled” by the layers of scintillator attached to photodetectors. Not all of the energy is directly detected, some being lost in the metal, so the energy measurement is scaled using experimentally-determined factors. The depth of the HCAL in terms of interaction length varies between $5.82 \lambda_I$ at $\eta = 0$ and $10.6 \lambda_I$ at the edge of HB and throughout the endcap, with the ECAL adding $1.1 \lambda_I$. The HO extends the HCAL depth to at least $11.8 \lambda_I$ in the barrel, with the magnet material acting as the absorber for the HO scintillator layer. (An additional layer of iron and a second scintillator exist at the $\eta = 0$ ring, where the HB depth is the least.) Since there is no ECAL in the forward region, the HF is equipped to distinguish electromagnetic objects from hadronic jets with different lengths of quartz fibers. The long fibers reach the entire depth of HF, while the short fibers only start halfway through the detector. Since electromagnetic showers tend to occur in the first half of the detector, and hadronic showers throughout the full HF, a shower detected only by the long fibers is likely to be electromagnetic in nature.

3.3.6 Muon System

The CMS muon system serves to identify muons, which are the only particles that leave a signature very far from the interaction point, and also to measure their momentum. The system is situated outside the magnet coil, within the iron return yoke, and provides coverage up to $|\eta| < 2.4$. The return yoke also functions as an absorber to filter out backgrounds to the muon signal. The muon system consists of three separate subsystems: drift tube chambers (DTs) in the barrel up to $|\eta| < 1.2$, cathode strip chambers (CSCs) in the endcap with an η range $0.9 < |\eta| < 2.4$, and resistive plate chambers (RPCs) in the region $|\eta| < 1.6$.

The DTs are used in the barrel due to relatively low muon rates in this area, in addition to a uniform magnetic field in the return yoke. Four stations of chambers are interspersed with the iron frame to form concentric cylinders around the beam pipe, with a total of 172,000 detection wires. Orthogonal positioning of the wires within each chamber provides measurement of both azimuthal and longitudinal position. Each wire detects charge that drifts toward it due to an applied voltage when a muon ionizes the surrounding gas, as

illustrated in Figure 3.8. Neighboring chambers overlap to ensure full coverage.

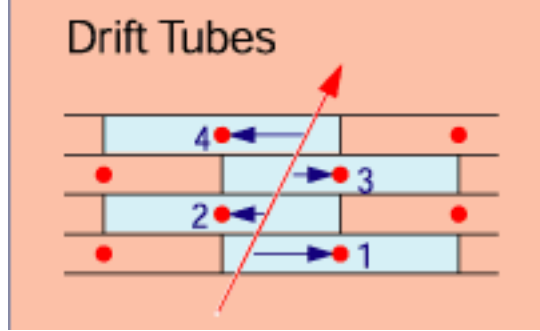


Figure 3.8: Conceptual diagram of drift tube chambers.

The CSCs are used in the endcap, where the muon rate and overall particle flux are higher. Cathode strips in each chamber measure the ϕ -position of a hit, while anode wires oriented perpedicularly measure the η -position. There are on the order of 200,000 readout channels for each type of measurement. Four stations of CSCs are used in each endcap; each muon in the range $1.2 < |\eta| < 2.4$ crosses either 3 or 4 stations. For $|\eta|$ between 0.9 and 1.2, muons are detected both by the CSCs in the endcap and the DTs in the barrel. Coverage is provided by overlapping layers of chambers at each station.

The RPCs provide redundancy for the previous two systems as well as a faster response time in place of a highly accurate position measurement. The RPCs measure the timing of a hit with a 1 ns resolution, compared to the 25 ns LHC bunch spacing and hundreds of ns drift time in the drift chambers. Six layers of RPCs are interspersed with the drift tubes in the barrel, while three layers are used in the endcap with the CSCs. Again, overlapping chambers ensures full coverage. Each chamber consists of two or three double-gap modules, each of which has a single readout module between two thin gas chambers. The readout module consists of metal strips, which capture the electric charge created when a muon ionizes the gas, causing an avalanche of charge. Figure 3.10 shows a diagram of the structure.

Overall, the muon system has a momentum resolution of 9% for relatively moderate- p_T ,

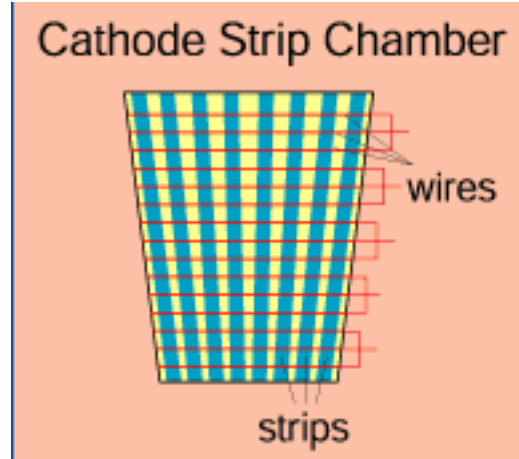


Figure 3.9: Diagram of cathode strip chamber, showing the cathode strips and anode wires for measuring the ϕ and η coordinates, respectively.

low- η muons, and ranging from 15% to 40% for very-high- p_T muons. When combined with the information from the inner tracker, however, this resolution improves to 1% and 5%, respectively.

3.3.7 Trigger

The purpose of the CMS trigger is to identify potentially interesting events. Storing the data from every collision is unfeasible; resources allow only a very small fraction of events to be kept. Therefore the trigger reduces the effective event rate, keeping only the events with an interesting signature, for example a large energy deposit. There are two levels to the CMS trigger. The Level-1 Trigger uses hardware-implemented algorithms to reduce the event rate from the LHC collision frequency of 40 MHz to a maximum of 100 kHz; this must be done quickly since the initial event rate is high. The High-Level Trigger reduces the rate further to 200 Hz, using a computer farm to process each event in more detail; having a lower input rate, it can afford more processing time per event.

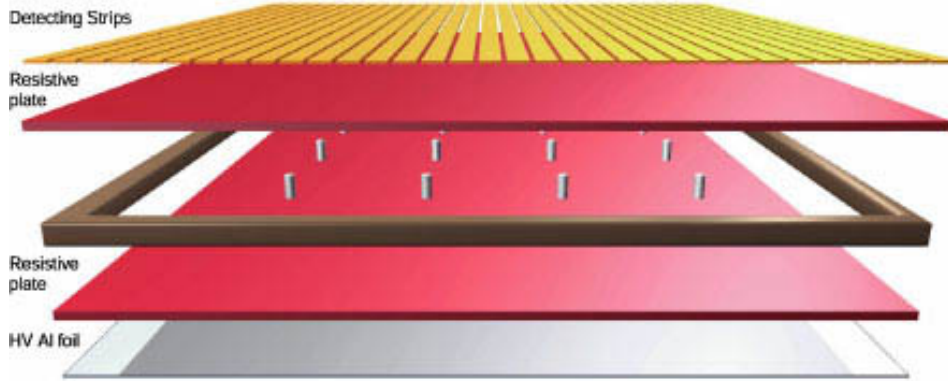


Figure 3.10: Diagram of resistive plate chamber.

Level-1 Trigger

The Level-1 trigger (L1) uses mostly programmable, hardware-based algorithms to identify and roughly reconstruct possibly interesting physics objects, such as electrons and muons. This is done within $3 \mu\text{s}$. The structure of the L1 is shown in Figure 3.11. Parallel chains process the muon system and calorimeter objects separately. Tracking information is not included in the L1, which means the L1 algorithms do not distinguish between electrons and photons. The first step of the Level-1 trigger is the generation of coarse versions of the readout information from each of the muon and calorimeter channels; this information is called trigger primitives. The trigger primitives are passed to regional trigger systems, which combine them into trigger objects. The objects for each region are then passed to a global system, which picks out the highest-energy (and therefore most interesting) objects of each type. The final set of objects gets passed on to the last level, the global trigger, which combines information from both the calorimeter and muon chains and makes a single decision based on the set of criteria implemented.

The trigger system must combine all the pieces of information according to which bunch crossing they originate from. This is complicated by the fact that the time it takes particles to reach the outer edge of the muon system is about that of the bunch crossing interval. In addition, the cable lengths between the subdetectors and the trigger subsystems and within

well as the ratio of HCAL energy to ECAL energy. If that ratio is higher than a certain value, too much energy has been deposited in the HCAL tower for it to contain a probable electron or photon. The RCT also calculates the total energy sums of square regions of the calorimeter, 4 trigger towers to a side, and sends these energy sums along with a list of possible electron or photons to the global calorimeter trigger level. A more detailed treatment of the electron/photon-finding algorithm exists in a later chapter.

High-Level Trigger

The High-Level Trigger (HLT) is implemented on a computer farm in the CMS above-ground control room building. It serves to reduce the L1 output event rate from 100 kHz to a rate suitable for transfer and storage to disk, around 200 Hz. An event must pass the HLT to be analyzed offline. The input rate at this stage is lower than that at the Level-1, so more time can be afforded to spend on the decision, and more detailed reconstruction can be done. The HLT uses versions of the standard offline physics-object reconstruction algorithms optimized for fast performance. The algorithms need to be more accurate than those of the L1, but absolute accuracy at the offline reconstruction level is not necessary. Still, the HLT algorithms are kept as close to the offline ones as possible. Specific algorithms are dealt with in more detail in a later chapter.

Trigger Menus

Both the L1 and High-Level Triggers use the concept of a trigger menu. There are different sets of criteria defining an “interesting” event at any one time; each set of criteria is called a trigger path. When an event fulfills all the criteria for a given path, that path “fires” and the event is accepted. Some paths may fire at a higher rate than desired, so a prescaling factor is implemented: only a fraction of events firing that path is kept. For example, a path with a prescale of 5 only has 1/5 of its passing events actually saved. In this way, events passing a certain path can still be studied without taking too much of the available resources. The set of paths that are being checked at any given time, along with their prescale factors, is called the trigger menu. The Level-1 and High-Level Triggers each have their own trigger

menus. Since the L1 must do things quickly, its criteria are simple, whereas the HLT may have more complex criteria. Passing a given L1 path causes related HLT paths to be run on that event.

At the beginning of collision running, the event rate was low enough to allow very loose trigger menus to be used. At the HLT, a “keep-everything” pass-through menu recorded essentially all activity. As the luminosity increased, however, more stringent criteria had to be applied to maintain an acceptable event rate, for example, raising the amount of energy needed to accept an “interesting” object. The successive algorithms have been studied in detail and commissioned successfully throughout the 2010 running conditions.

3.3.8 *Luminosity*

CMS measures luminosity with the forward calorimeter, which sits between $|\eta|$ of 3 and 5, close to the beam pipe. Two different methods of measurement are used. The first method counts the number of occupied towers in the HF (above some energy threshold to avoid noise), using the principle that that number is proportional to the luminosity. However, at high luminosity the number of occupied towers may begin to saturate, making this method less accurate. The second method does not saturate in this way: it measures the total energy deposited in the HF, which is also proportional to the luminosity. The information from both of these methods is combined into one luminosity value.

Fig. 3.12 shows the total integrated luminosity at CMS as a function of time for the 2010 running period.

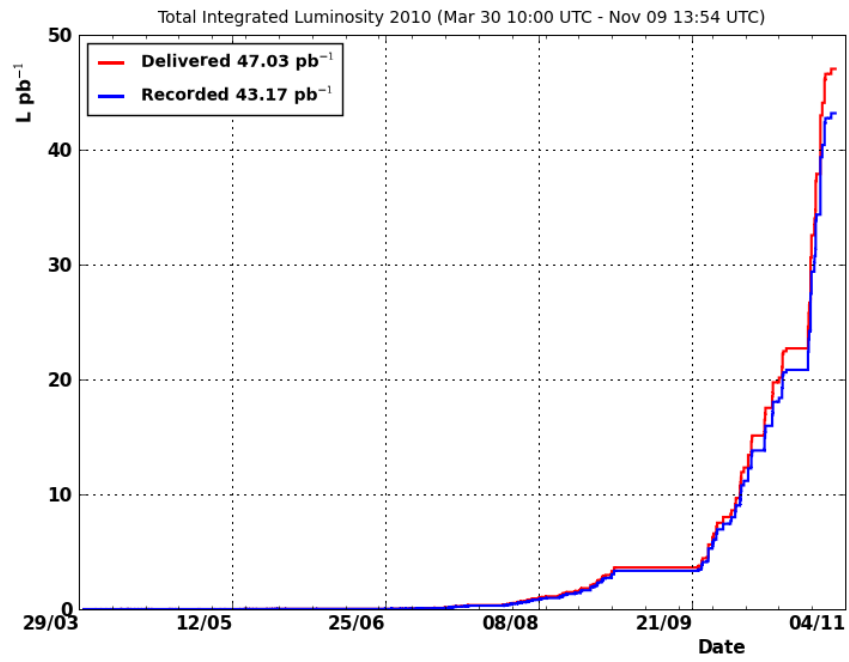


Figure 3.12: Luminosity collected by CMS as a function of time, 2010.

Chapter 4

EVENT SIMULATION

somewhere have the pretty picture from matt mc tutorial on how generators/geant/etc fit in with everything else (reco, whatever)

points of event simulation: compare with data (description of current understanding as is) design detectors

4.1 Monte Carlo Event Generation

put why called “monte carlo” multiple types: shower vs matrix element?

4.1.1 some explanation of the black box

modular structure here? that pretty picture showing all the different steps to an interaction that need to be simulated. all those steps can be done by separate packages, which is the philosophy. (pythia manual) pdfs -> hard scatter (underlying event, multiple interactions in parallel) -> [parton] shower (both isr and fsr, incl QED) -> hadronization (not directly applicable to my process, but applicable for bg's) -> decay resonances -> interactions with detector material ...

4.1.2 Monte Carlo Generators

PYTHIA

POWHEG

Other Generators

Like, whichever other samples I check

4.2 Detector Simulation

4.2.1 GEANT Detector Model

4.2.2 Level-1 Trigger Emulator

talk about how emulator necessary for l1, but not for hlt (duh)

Chapter 5

EVENT RECONSTRUCTION

The information from the detector for any given event gets read out over millions of channels from the many different subdetectors. These signals must be combined to provide meaningful physics information about the interaction that took place within the detector, namely the measurable quantities (like direction and energy) of the outgoing decay products.

5.1 *Detector Object Reconstruction*

The first step of the particle reconstruction involves translating the information from each detector channel, such as position and electronics signal, into useful quantities such as position in η - ϕ space and energy or momentum. This is done by algorithms mapping each individual detector cell to its η - ϕ placement and calculating its energy, which necessarily takes into account the position of each cell. The second step involves connecting information from different channels to build up a more complex picture of the particles that passed through the detector.

5.1.1 Electromagnetic Calorimeter Reconstruction

The information coming directly from the ECAL is read out in terms of each cell's electronics response. The ECAL reconstruction algorithms translate this into an energy value, which is then calibrated according to the the cell energy as well as its η -position. The algorithms also calculate quantities relevant to the quality of the deposit, in particular whether or not the deposit happened at a time consistent with the LHC bunch collisions, i.e. if it was “out of time”. This information is especially useful in identifying apparent energy deposits that have been found to come from the electronics themselves; these fake deposits were discovered during commissioning and are known as “ECAL spikes”. Since the spikes can imitate energy deposits from actual decay products, they must be removed from the

information used to reconstruct electrons and other particles. They can be distinguished from real particle deposits due to their timing as well as the fact that the surrounding crystals have no trace of a deposit. Therefore, if a high-energy deposit has no or very little energy in its neighboring crystals, or if its timing is not consistent with a bunch crossing, it is considered a spike and taken out of the reconstruction.

5.1.2 Track Reconstruction

A track is a sequence of hits in the tracker, reconstructed to trace the trajectory of a passing particle. The Kalman Filter algorithm used by default for CMS tracks, but not good at catching abrupt changes in electron trajectory due to bremsstrahlung. Therefore, GSF algorithm used for electrons – able to find those hits in unexpected directions.

Kalman Filter

The Kalman Filter (KF) tracking method is seeded by pairs of hits in the pixel detector. The seeding algorithm first searches for a hit in one of the outer layers of the pixel detector. If a hit is found, another hit is sought in a layer closer to the interaction point, looking in an η - ϕ window around the original hit. Only two out of the three pixel layers are required to have hits in order to maintain a high efficiency. Once a track seed is found, further hits are sought in each successive tracking layer. The Kalman filter method is used to predict possible locations for hits in the next layer based on the currently-known track parameters. Hits in that area are then sought and included in the track, combining each hit with the predicted location for that layer and weighting each value depending on the value's uncertainty. If there are multiple candidate hits in the next layer, a possible trajectory is calculated for each hit, along with a trajectory accounting for the case in which the hit in that layer was lost. This procedure is repeated for each layer: each of the calculated trajectories for a given layer is matched to hits in the next layer, for which new trajectories are calculated. To prevent the number of necessary calculations from growing too large, the number of possible trajectories at each step is capped at five. In the case of multiple possible trajectories for a given fully-reconstructed track, defined by two trajectories sharing more

than half of each of their hits, the track candidate with fewer hits (or, in the case of the same number of hits, the track with the worse fit) is discarded.

Gaussian Sum Filter

The Kalman Filter track-fitting does not accurately account for the behavior of particles in a material, specifically energy lost in the material and changes in direction due to radiation. The KF description is in particular inadequate for electrons, which readily interact with matter in these ways. The Gaussian Sum Filter (GSF) algorithm was therefore developed: essentially a Kalman Filter with a more sophisticated energy loss modeling. Instead of approximating the energy loss (which is non-Gaussian) with a Gaussian distribution, which KF implicitly does, the GSF method models it as a weighted sum of Gaussian distributions. This greatly improves the performance of the track-fitting for electrons.

5.2 Electron Reconstruction

As an electron passes through the CMS detector, it leaves a signature pattern in the sub-detectors. Characteristically, electrons produce a track in the tracker system, as well as an energy deposit in the electromagnetic calorimeter. Therefore an electron is reconstructed by matching tracks and energy clusters that appear to have been made by the same particle. There are currently two approaches used to initiate electron reconstruction: the “ECAL-driven” method and the “tracker-driven” method, named according to which subdetector’s information initiates the reconstruction. Each method produces a collection of basic electron candidate objects, each consisting of a calorimeter cluster and hits in the first few layers of the tracker. These collections are then combined into one and used as seeds to reconstruct the electron tracks, producing fully-reconstructed electrons.

5.2.1 ECAL-driven Electron Seeding

The ECAL-driven electron reconstruction method starts with an energy deposit (or “super-cluster”) in the ECAL and searches for hits in the pixel system that matches the position of the calorimeter deposit.

Superclusters

The calorimeter energy deposit used in the electron reconstruction is called a supercluster: a cluster of clusters. A single electron or photon deposits most of its energy in a 5×5 square of ECAL crystals, as shown in Fig. 5.1. However, an electron passing through the tracker material in a strong magnetic field produces bremsstrahlung and electrons from converted photons, causing the original electron's energy to have spread out in ϕ once it reaches the calorimeter. The process of creating a supercluster gathers these energy deposits to form the initial energy of the electron.

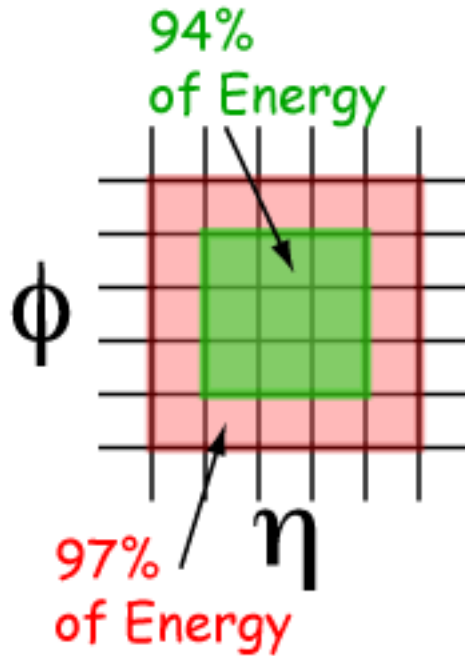


Figure 5.1: Typical energy distribution in a basic cluster.

The electron reconstruction currently uses two different superclustering methods, the “hybrid” supercluster method in the barrel, and the “multi5x5” clustering method in the endcap. The hybrid algorithm forms superclusters and basic clusters from the same energy deposit information, while the multi5x5 algorithm first forms a single collection of basic clusters, which are then separately combined into superclusters.

The hybrid algorithm starts with a list of all ECAL crystals with an energy greater than a threshold; these crystals are considered seeds. Beginning with the highest seed crystal, the area around each seed is searched for energy deposits in steps of one crystal in ϕ . For each ϕ step, a “domino” of crystals is formed in η : one crystal to each side of the central crystal, or, if the energy sum of those three crystals is greater than a threshold, two crystals to each side of the central crystal, for a total of five crystals per domino. The process is done for a given number of ϕ steps in both the positive and negative directions (currently 17 steps). As other seeds are encountered in this process, they are removed from the list of available seeds. Each domino with a higher energy than its two neighbors is considered as the seed for a basic cluster, and the collection of dominos formed by the search process is the basis for the supercluster. The basic clusters are formed by summing the energy of each local-maximum domino with those of its neighboring lower-energy dominos, excluding dominos that have already been used. The supercluster is then formed by summing the energies of the constituent basic clusters, with its seed considered to be the highest-energy basic cluster and its position given by the energy-weighted positions of the constituent clusters.

The multi5x5 algorithm first creates a collection of basic clusters from seeds, which are ECAL crystals with an energy higher than a given threshold. If a seed represents a local maximum, then its energy deposit is combined with those from the crystals in the surrounding 5x5 square to form a basic cluster, ignoring any crystals that have already been used to form the central 3x3 part of another cluster. The basic clusters are then used as seeds for the superclustering algorithm. For each seed cluster with energy higher than a threshold, the energies of any other clusters within an η - ϕ window of the seed (longer in ϕ than in η) are combined with its own energy to create the supercluster, leaving out clusters that have already been used to form another supercluster. The position of the supercluster is given by the energy-weighted position of the individual clusters.

Pixel Hit-matching

To reconstruct the full electron, the supercluster must be matched with a track. This is done by extrapolating the probable position of tracker hits from the supercluster’s position,

as illustrated in Fig. 5.2. Given the supercluster energy and the fact that a non-radiating electron would have hit the calorimeter at the energy-weighted center of the supercluster's energy spread, the electron's initial (pre-radiation) trajectory through the tracker can be calculated for both the positive and negative electron charge cases. The reconstruction algorithm then looks for a matching hit in the first pixel detector layer within a ϕ - z window of this position for each charge case. If a hit is found, another hit is sought in the second pixel layer within a different ϕ - z window of the hit in the first layer.

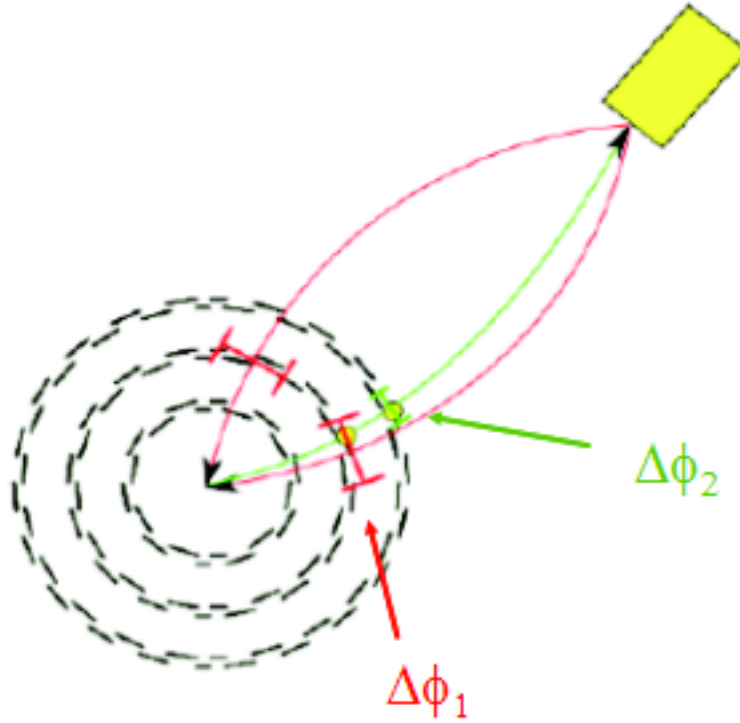


Figure 5.2: Schematic of pixel-hit search algorithm in electron-seeding. For both the positive and negative electron charge cases, a possible trajectory is extrapolated back from the calorimeter deposit given the deposit's energy. A hit is sought along either trajectory in either the inner or middle pixel layer within a window ($\Delta\phi_1$). If a hit is found, a second hit is sought along that trajectory in the next pixel layer(s) ($\Delta\phi_2$).

5.2.2 Tracker-driven Electron Seeding

In the tracker-driven electron seeding method, electron-finding is seeded by tracks, which are followed out to the ECAL to search for calorimeter clusters associated with each track. This method was developed to better deal with low- p_T electrons, for which the energy deposits from bremsstrahlung may be too widely separated to be matched, and non-isolated electrons within jets, whose energy deposits are not necessarily distinguishable from those of surrounding hadrons. For these electrons the calorimeter cluster-based seeding does not perform as well as for isolated, high- p_T electrons.

The tracker-driven electron seeding method takes as input the default collection of tracks, obtained by an iterative usage of the KF algorithm. The method first tries to follow each track all the way to the calorimeter and search for nearby energy clusters. All clusters with an acceptable E/p ratio with respect to the track are tested, and the cluster closest in η - ϕ space to the track is the one chosen.

Out of the tracks that were not well associated to any energy cluster, a preselection is applied to select those tracks that may have resulted from radiating electrons, which would not have been found by the cluster-matching method. If the track was not matched because it had too few tracker hits and could not be traced to the calorimeter, or if the KF algorithm did not fit the track well enough because of possible bremsstrahlung, the tracks are passed on to the next step of the selection. A reduced GSF track-fitting algorithm is then run on these tracks, in an attempt to recover the bremsstrahlung-induced changes in track direction. This reduced version of the GSF algorithm runs much faster than that with the default parameters, but the performance is slightly reduced. Finally, a multi-variate analysis using boosted decision trees is performed on these candidates. The MVA is trained on a sample of electrons from $b\bar{b}$ events, which are primarily non-isolated, and a sample of $Z \rightarrow e^+e^-$ events, which provides high- p_T electrons. The output of the MVA is a number indicating the likelihood of the object being an electron. Those whose MVA output is greater than a threshold are considered electron candidates. These candidates are then combined with those previously identified from the cluster-matching to produce the final collection of tracker-driven electron seeds.

5.2.3 *Electron Track Reconstruction*

The full collection of electron seeds, both ECAL- and tracker-driven, are used as the basis for reconstructing the electron track and hence completing the electron reconstruction. As mentioned previously, the electron reconstruction uses the GSF algorithm to reconstruct tracks. The electron kinematics are assigned to be a weighted combination of those of the constituent supercluster and track, and the final electron collection is saved for further analysis.

5.3 *Beam Spot Reconstruction*

The region where the beams overlap and protons may interact, the “luminous region”, is called the beam spot. The beam spot location can be used as an estimate for the initial position of tracks measured in the detector, and is therefore useful in track-seeding. Its position can be determined from measurements of tracks in the general track collection. This is done by making a distribution of each track’s distance of closest approach to the nominal beam spot $(0,0,0)$ as a function of the track’s ϕ angle at its closest approach. If the beam spot is far from $(0,0,0)$, the distribution looks sinusoidal. This distribution is then fit with a sine curve parametrized in the beam spot’s actual x - and y -positions, and these values are extracted.

5.4 *Primary Vertex Reconstruction*

Since protons may collide anywhere within the region of beam overlap, the main interaction in a given event may not necessarily happen at the exact center of the detector. In particular, there may be a significant displacement in the z -direction. Determining the location of the main interaction, also called the primary vertex, is an integral part of reconstructing the event. For example, an electron may leave a deposit in a given calorimeter cell that has a fixed η position relative to the nominal interaction point, the very center of the detector $(0,0,0)$. However, if the interaction producing the electron actually takes place at a different point, the electron’s actual η position will be different relative to the interaction. Therefore the position of the primary vertex should be taken into account when calculating η .

The process of reconstructing the primary vertex involves creating primary vertex candidates from the tracks in the event, matching each track to the interaction that likely produced it. This is done by grouping the tracks according to their z -position at the point at which they pass most closely to the beam spot. The tracks are required to pass relatively close to the beamline, and they are also required to have a p_T greater than some threshold (with a default of 1.5 GeV). Tracks within a small distance (default 1 mm) of each other at the beam spot are considered to have come from the same vertex, and the primary vertex candidates are formed from these groups of tracks. At this point a fit is applied to each primary vertex candidate, and tracks found to be incompatible with the candidate are discarded until all tracks meet a given compatibility level. Finally, vertices that are incompatible with the position of the beam spot are discarded. (A second algorithm uses the beam spot as constraint on the position of the vertex fit itself, but this algorithm was not fully commissioned at the time of this study.) If no reconstructed primary vertex candidates are found in an event, a “fake” primary vertex is added at the position of the beam spot. Since more than one interaction per event is possible but generally only one is of interest (the “primary” interaction), multiple candidates are ordered according to transverse energy of their constituent tracks, and the highest of these is taken to be the primary vertex.

Chapter 6

EVENT SELECTION

Most analyses, including this one, are only interested in particle interactions that happen relatively rarely during proton collisions. Therefore, methods have been developed to sort through all the events and select the interesting ones for further study. This selection takes place both “online”, in real time as the detector is running, and “offline”, after the previously-selected data has been stored. The online selection serves primarily for reducing the volume of data enough to feasibly store it, and so it is done centrally. In addition, the online selection is fairly general, while the offline selection is much more detailed and specific to individual analyses, and hence it is mostly done by the user of the data.

6.1 Online

The online selection consists mainly of the trigger system, described in technical detail in Section 3.3.7. The implementation of the trigger system’s algorithms that are relevant to this analysis is discussed in the following sections, including both the Level-1 and the High-Level Triggers. Both levels reconstruct possible physics objects and apply criteria to select the interesting events. In general, the processing at the Level-1 is quicker and coarser in order to sort through a larger volume of data, while the High-Level Trigger processing can afford to be longer and more thorough because it only deals with data not already discarded by the Level-1. In addition, as a last step, the information from the High-Level Trigger is used to group the data into primary datasets which are used as the basis for the offline selections.

6.1.1 Trigger Eras

Since the LHC began taking data the event rate has changed by several orders of magnitude, and the trigger menus have evolved accordingly to deal with the changes. Initially, the

collision rate was so low that minimum bias triggers ran unprescaled. However, it soon increased to the point where the minimum bias trigger rate became too high and had to be prescaled, and photon triggers were used instead. Eventually the photon trigger rate at the desired threshold also became too high, necessitating the extra constraints of the electron trigger at the same threshold. The rate for that trigger also increased, so to avoid prescaling the rate or increasing the threshold, tighter selection criteria were applied to the objects that fired the trigger. These criteria are looser than those applied in the course of analysis and so are not expected to seriously affect the trigger efficiency.

6.1.2 *Level-1 Trigger*

Reconstructing and triggering on an electron with the Level-1 Trigger involves information from the calorimeters, Regional Calorimeter Trigger, Global Calorimeter Trigger, and Global Trigger. Electrons and photons are indistinguishable in the L1 and are therefore treated the same, as “ e/γ ” objects.

The ECAL trigger primitive generation system (TPG) combines the energy deposits from a 5x5 square of ECAL crystals into a single energy value corresponding to one trigger tower. In addition, for each tower the ECAL TPG calculates a “fine grain veto” bit: if most of the tower’s energy is deposited in a 2x5 strip of crystals, then the energy pattern is considered inconsistent with that of an electron or photon, and the veto bit is set. Similarly, the HCAL also combines energy deposits into trigger towers; however, the HCAL fine grain structure bit is not used in electron-finding. The information from the ECAL and HCAL is compressed and sent to the Regional Calorimeter Trigger. The RCT does the main job of electron finding using several algorithms. The decompressed ECAL energy of each trigger tower is examined and compared to that of its four adjacent neighbors. If the energy of the tower is greater than that of its neighbors, it is considered an e/γ candidate. The candidate energy is set to the energy of the tower in question plus that of its highest-energy neighbor. However, if the tower’s fine grain bit is set, or if the ratio of the tower’s HCAL energy to ECAL energy is too high, it is vetoed as a candidate. A candidate is additionally considered “isolated” if, out of the eight towers directly surrounding it, there are five contiguous towers

forming an L-shape whose energies are low and who pass the fine grain and HCAL/ECAL ratio veto. Otherwise, the candidate is “non-isolated”. The RCT sends the collections of isolated and non-isolated candidates to the Global Calorimeter Trigger, which sends the highest-energy ones to the final step, the Global Trigger. The Global Trigger then applies the criteria determining whether or not this event passes the current set of trigger paths, for example, “two e/γ objects with energy above 10 GeV” or “one e/γ object with energy above 17 GeV”.

6.1.3 High-Level Trigger

The algorithms used to reconstruct trigger objects in the High-Level Trigger are the same as those used in the offline analysis and are described in Chapter 5. However, because of timing considerations, the algorithms are combined and configured differently at the HLT. The HLT has a limited amount of time in which to make a keep/discard decision for a given event in order to keep up with the flow of events. Therefore the algorithms are optimized for the best performance in the shortest time, which in practice means fewer steps and less complexity than the implementation at the offline level, where no such constraint exists. In particular, while offline-reconstructed electrons include tracker-driven electrons, those reconstructed at the HLT are ECAL-drive only, and the supercluster reconstruction algorithm uses a lower number of steps in the search process. Also, the size of the windows in which to search for hits in the pixel-matching part of the reconstruction is larger than that used offline.

The luminosity increase and consequent evolution of trigger menus described in Section 6.1.1 required incremental changes in the definitions of the current HLT paths. However, a few requirements remained common to all the paths used. In particular, the execution of each path begins by taking the Level-1 objects that passed the given L1 seed path and retrieving the information from the ECAL regions around those objects. From this information, clusters of energy deposits are identified, and clusters having too narrow a spatial distribution are rejected as being spikes. The trigger paths used in this analysis, shown in Table 6.1 all required (at least) one e/γ or electron candidate above a certain energy

Table 6.1: Trigger paths used to select data.

Trigger
HLT_Photon15_Cleaned_L1R
HLT_Ele15_LW_L1R
HLT_Ele15_SW_L1R
HLT_Ele15_SW_CaloEleId_L1R
HLT_Ele17_SW_CaloEleId_L1R
HLT_Ele17_SW_TightEleId_L1R
HLT_Ele17_SW_TighterEleIdIsol_L1R

threshold, with possible other criteria applied to the candidate as well.

Initially, the LHC collision rate was low enough that loose requirements and low thresholds could be used without overwhelming the system. The first trigger used did not require any matches to hits in the pixel part of the tracker, in contrast to all subsequent trigger paths used – without tracking requirements, it was by definition a photon trigger. In addition, after a few menu iterations the energy threshold applied to the candidate increased from 15 GeV to 17 GeV. The size of the window used to search for potential pixel matches also decreased (from “large-window” to “startup-window”). Later, various further criteria were applied to the shape of the total energy deposit ($\sigma_{i\eta i\eta}$, H/E) and to the quality of the match between the energy cluster and the track that make up the electron ($\Delta\eta_{in}$, $\Delta\phi_{in}$), as well as to the amount of energy surrounding the electron candidate (isolations). These further criteria are described in more detail in Section 6.2.1; in the current section it is sufficient to say that they were added in steps to the trigger paths to gradually tighten the selection.

6.1.4 *Primary Datasets*

The final step done centrally is the grouping of events passing similar HLT bits into primary datasets for storage. For example, in early running, all events passing a minimum-bias trigger were put into the MinimumBias dataset. Once the event rate increased and physics triggers fired more often, events were put into more specific datasets such as EG for all events passing e/γ (electron or photon) triggers, or later, Electron for all events specifically passing electron triggers. These primary datasets are the groupings of stored data that the offline analyses begin with.

6.2 Offline

The offline selection consists of any criteria applied to the data after it has already been stored, i.e. criteria applied to an already-existing primary dataset. This analysis uses data from two consecutive primary datasets: the EG dataset gathered during earlier data-taking (Run2010A, from run 135821 to run 144114), and the Electron dataset from later data-taking (the Run2010B era, runs 146240 to 149711). In addition, it was required that the primary vertex of each event be “good”: that is, within 24 cm of the nominal interaction point in the longitudinal direction and 2 cm in the transverse direction, and having a minimum of 4 degrees of freedom, which is a measure of the quality of the vertex fit. More detailed selections were made on the event contents, which will be discussed in the following sections. The electrons in these events were required to pass a series of criteria to determine “good” electrons. Finally, specific selections were made to the characteristics of the event as a whole in order to get the final collection of $Z \rightarrow e^+e^-$ candidate events.

6.2.1 Electron Selection

The electron selection starts with the full set of objects reconstructed as electrons, i.e. ECAL energy deposits with nearby tracks. The objects in this collection are not necessarily real electrons but are consistent with the electron signature at a low level. In order to select the reconstructed objects most likely to be real electrons from a Z, sets of further conditions are applied. First the electrons are required to be within the η region of ECAL in which they can be fully measured, in the barrel, $0. < |\eta| < 1.4442$, and in the endcap, $1.566 < |\eta| < 2.5$. A 25-GeV cut on the supercluster transverse energy is applied, followed by a set of cuts designed to reject electrons from photon conversions. Another set of cuts aims to distinguish real electrons from other energy deposits which may mimic electrons, and finally a set of cuts to make sure the electron is isolated, i.e. not part of a jet unrelated to the Z.

The collaboration (or egamma group) created several different electron selections of varying tightness of cuts, based on a given efficiency of the cuts (ref to iterative algo stuff). A tighter selection in general results in a purer sample of true electrons, but throws away many

more real electrons than a looser selection. These “working points” have target efficiencies ranging from 95%-efficient at the loosest (WP95) to 60% at the tightest (WP60). For early data-taking the WP95 and WP80 selections were chosen as the baseline selections for the Zee and Wenu analyses, respectively. As more data accumulated, it became clear that WP80 provided better performance than WP95 for the Zee analysis, as well. A deciding factor in the switch was the fact that the evolving trigger paths eventually used selections that were tighter than those used in the offline (WP95) analysis. This analysis uses the WP80 set of cuts for the complete dataset.

The selection cuts are displayed in the following cuts applied only to simulated data. The QCD Monte Carlo sample has effective electron isolation cuts already applied, so until the corresponding selection cuts are applied to data, the data does not agree with the Monte Carlo distributions. However, after all cuts have been applied the agreement is good; this will be demonstrated in a later section.

Conversion Rejection

The conversion rejection step of the electron selection aims to eliminate photons that have converted into electron pairs. Several variables have been chosen to distinguish between conversions and prompt electrons, focusing on the track properties. Since prompt electrons are expected to hit the first layer of the tracker, any electron-associated track that is missing initial hits can be rejected as a conversion that occurred within the tracker. The looser requirements of the 95 percent efficient working point allow an electron to have one missing hit; tighter working points such as WP80 require zero missing hits. Fig. 6.1a shows the number of missing hits for each electron. In addition, the conversion rejection algorithm searches for candidate electron-pair partner tracks, i.e. track pairs that appear to come from the same point. Every electron track is compared to all opposite-charge tracks within a dR cone of 0.3, and two values are calculated: a measure of the difference in the angles in the r-z plane between the two tracks ($\Delta \cot \theta$, Fig. 6.1b), and the distance of closest approach between the two tracks in the x-y plane ($dist$, Fig. 6.1c). Electron pairs from conversions are expected to have low values for both quantities, since both electron tracks begin at the

point of conversion and initially have the same direction as the converting photon. The WP80 requirements apply a threshold at 0.02 for both quantities.

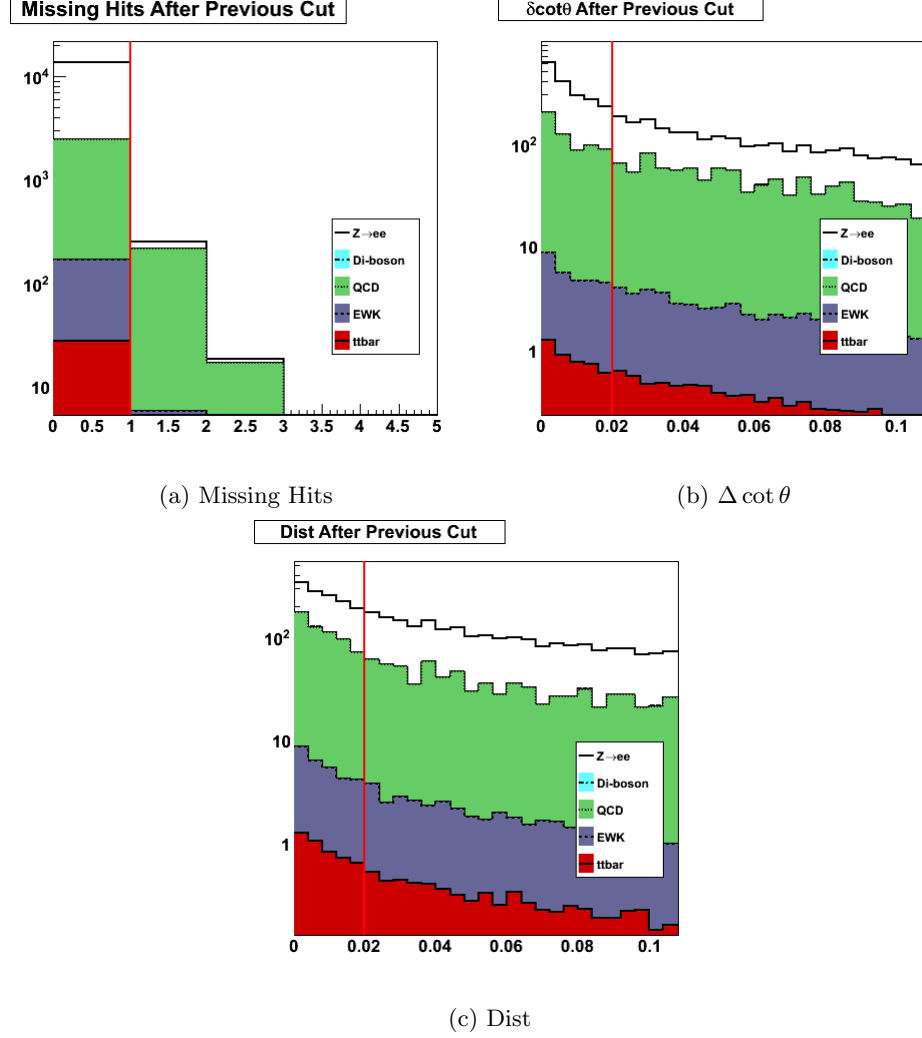


Figure 6.1: Conversion rejection variables after previous cuts.

Electron Isolation

It is expected that the products of a Z decay will not exit the interaction region in the vicinity of many other particles, since the Z decay products are not part of a jet. We want to select

those real electrons that are most likely to be prompt decay products, not those that come from some secondary interaction with many other end products. Therefore we apply a set of cuts requiring little detector activity in the area immediately surrounding the reconstructed electron. The so-called isolation cuts look at the energy deposits in the electromagnetic and hadronic calorimeters separately, as well as the total p_T of neighboring tracks, within specified ΔR cones around the electron-associated deposit/track. These energies are divided by the p_T of the electron itself to arrive at a relative value, which allows for higher-energy particles that may deposit more energy in the surrounding area. The thresholds for each of the three types of isolation is set separately for barrel and endcap, as given in Table 6.2. Plots of the separate isolation distributions for both barrel and endcap are shown after previously-applied selection cuts in Fig. 6.2 for track isolation, Fig. 6.3 for ECAL isolation, and Fig. 6.4 for HCAL isolation.

Table 6.2: Thresholds for WP80 relative isolation.

Cut variable	Barrel	Endcap
Track	0.09	0.04
ECAL	0.07	0.05
HCAL	0.10	0.025

Electron Identification

Several “electron identification” variables are used to differentiate genuine electrons from other particles or conditions that may mimic electron behavior. Since an electron is reconstructed from a supercluster matched to a track, it is desired that the match is a good one. The quality of matching can be estimated by looking at measures of the distance between the two components. The position in η and ϕ of the supercluster is compared with the η and ϕ position of the track extrapolated back to the vertex, with the differences being labeled $\Delta\eta_{in}$ and $\Delta\phi_{in}$, respectively. It is expected that a supercluster and track from the same

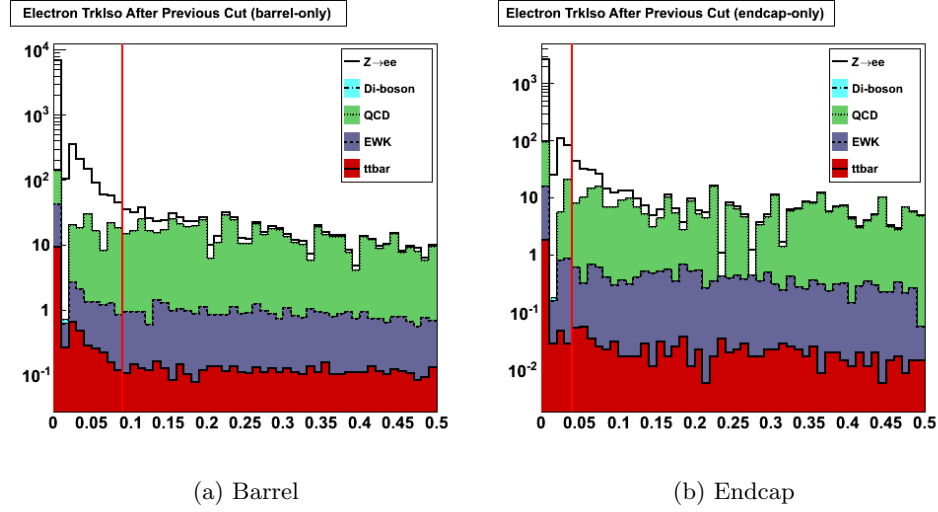


Figure 6.2: Electron tracker isolation variables before respective cuts.

electron will be close together, so upper limits on these quantities are defined as in Table 6.3. Distributions of electron $\Delta\eta_{in}$ and $\Delta\phi_{in}$, each plotted after the previous selection step, are shown in Fig. 6.5 and Fig. 6.6.

The electron's energy deposit is also expected to be narrow relative to that of a jet. A measure of the width in the η direction is therefore calculated using the energies and positions of the individual ECAL crystals, $\sigma_{\eta\eta}$, and this quantity is required to be below the thresholds listed in Table 6.3. (The ϕ direction is not examined because bremsstrahlung from the electron can cause a significant spread of the energy in ϕ .) The $\sigma_{\eta\eta}$ distribution for electrons after all previous cuts is shown in Fig. 6.7. In addition, an electron is expected to deposit most of its energy in the electromagnetic portion of the calorimeter. A large hadronic energy deposit is more likely to come from a jet, so a limit on the ratio of the energy deposit in the electromagnetic calorimeter to that in the hadronic calorimeter, H/E , is applied (values given in the table). The distribution of H/E for electron candidates is plotted after all previous selection steps in Fig. 6.8.

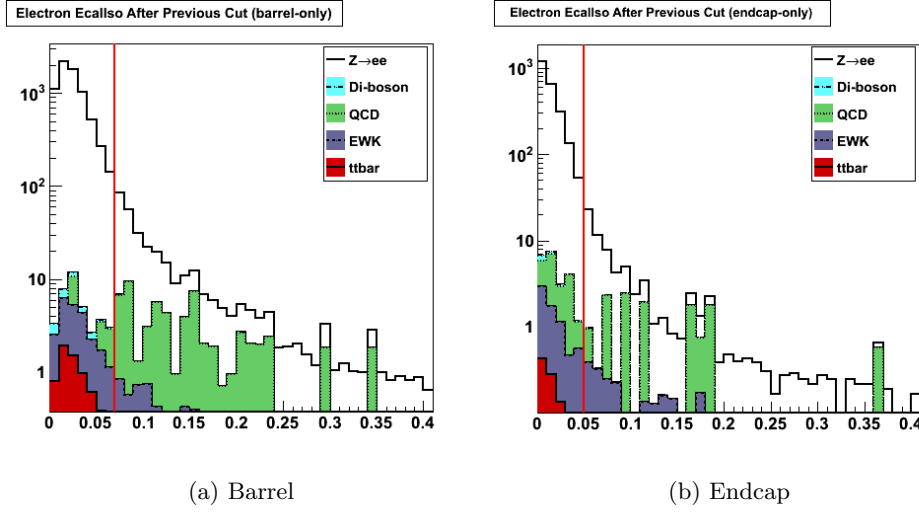


Figure 6.3: Electron ECAL isolation variables before respective cuts.

Matching Offline-Reconstructed Objects to Trigger Objects

In order to ensure that the offline-reconstructed objects being examined were also reconstructed by the trigger, each offline object is compared with the list of trigger objects firing a given path. If the offline object lies close enough to a trigger object (measured by ΔR), it is considered to have passed the trigger. Each event in this analysis was required to have at least one electron trigger-matched in this way, within a ΔR distance of 0.2. This demonstrates that the constituent objects in the event did in fact fire an appropriate trigger.

Table 6.3: WP80 electron identification cuts.

Cut variable	Barrel	Endcap
$\sigma_{i\eta i\eta}$	0.01	0.03
$\Delta\phi_{in}$	0.06	0.03
$\Delta\eta_{in}$	0.004	0.007
H/E	0.04	0.025

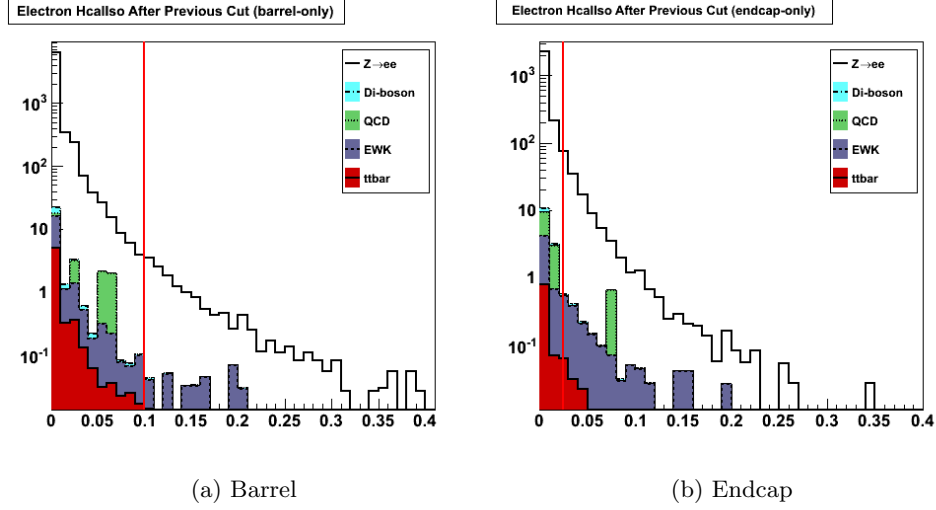


Figure 6.4: Electron HCAL isolation variables before respective cuts.

6.2.2 $Z \rightarrow e^+e^-$ Event Selection

In order to be included in the final selected sample of $Z \rightarrow e^+e^-$ events, an event must have two electrons passing the selection cuts described in Section 6.2.1. Only one of the electrons is required to match to a trigger object, however; even if only one electron fires the trigger, the event is kept and the trigger's purpose is served, and there is no extra necessity for both electrons to fire the trigger. The two electrons are also required to have an invariant mass between 60 and 120 GeV; this defines a window around the Z mass peak at about 91 GeV.

Acceptance for $Z \rightarrow e^+e^-$ Events

The acceptance (abbreviated A) is the factor representing the fraction of events theoretically able to be detected with the given experiment. It includes considerations related to a particle's kinematic quantities (its position and momentum) as well as to the precise definition of the signal interaction. In particular, the particle-detecting elements of any given detector, including CMS, do not fully cover the area around the interaction point – by necessity, some of that area is taken up by the beam pipe. This means that any end-product particle that goes into a “dead” space instead of a detecting element will not be detected.

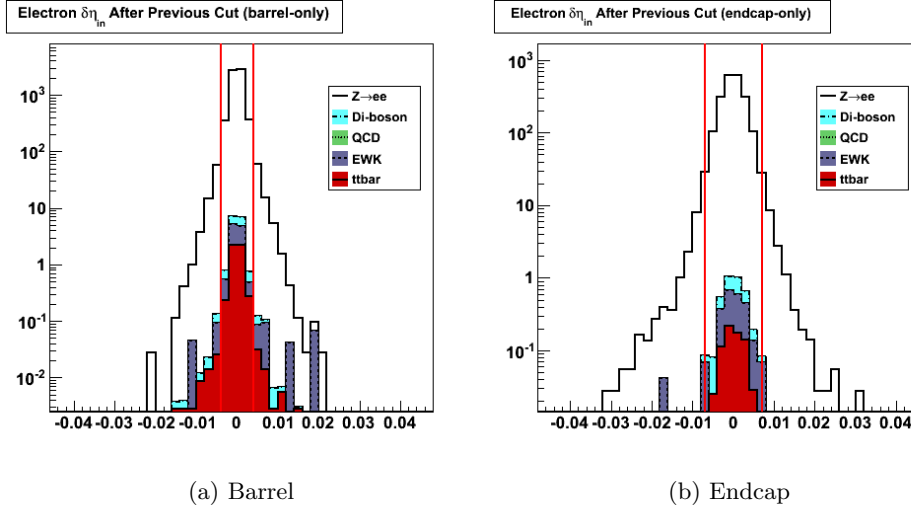


Figure 6.5: $\Delta\eta_{in}$ electron identification variables after previous cuts. A low $\Delta\eta_{in}$ indicates a good match between an electron candidate's supercluster and track. Values shown for (a) barrel and (b) endcap.

Therefore the acceptance factor takes into account the actual solid-angle area covered by the relevant parts of the detector. In addition, it is generally more difficult to distinguish very low-energy objects from background noise, so the acceptance also includes a lower limit on the energy of the particle.

In this analysis, the signal was defined to be those $Z \rightarrow e^+e^-$ events whose invariant mass was between 60 and 120 GeV; this captures the Z peak around 90 GeV. The acceptance was defined as the fraction of those signal events whose electron end products fall into the η region used for the analysis, $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$, and whose transverse energies were both above 25 GeV. These values can also be found in Table 6.4.

Table 6.4: Criteria for determining acceptance.

Kinematic quantity	Requirement
η	$ \eta < 1.4442$ or $1.566 < \eta < 2.5$
E_T	$< 25\text{GeV}$

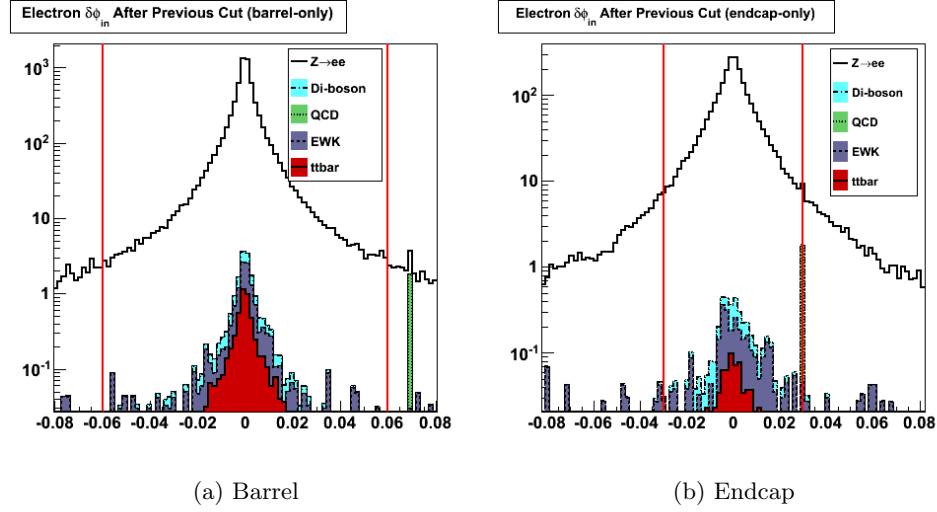


Figure 6.6: $\Delta\phi_{in}$ electron identification variables after previous cuts. A low $\Delta\phi_{in}$ indicates a good match between the electron candidate's supercluster and track. Values shown for (a) barrel and (b) endcap.

Acceptance cannot be calculated from data, because it is impossible to know how many events were missed – the only events we have are those which were not missed. Instead acceptance is determined by applying the defining criteria to a sample of simulated data, a sample large enough that statistical uncertainties become small enough to ignore. Since the simulated sample is expected to model real data well enough, this number is taken as the true acceptance for real data. However, the information used to generate the simulated sample is only a theoretical model; there are many ways in which it may actually differ slightly from what is used in the generation. These possible differences are taken into account in the uncertainty calculated for the acceptance, which will be detailed in a later section.

It is also useful to combine the supercluster reconstruction efficiency with the acceptance. The supercluster reconstruction efficiency is impossible to determine from data for the same reason as for the acceptance – it would require knowing about events that were missed, in this case electrons that had impacted the detector (specifically ECAL) but which had not resulted in the formation of a supercluster. Therefore this is also determined from

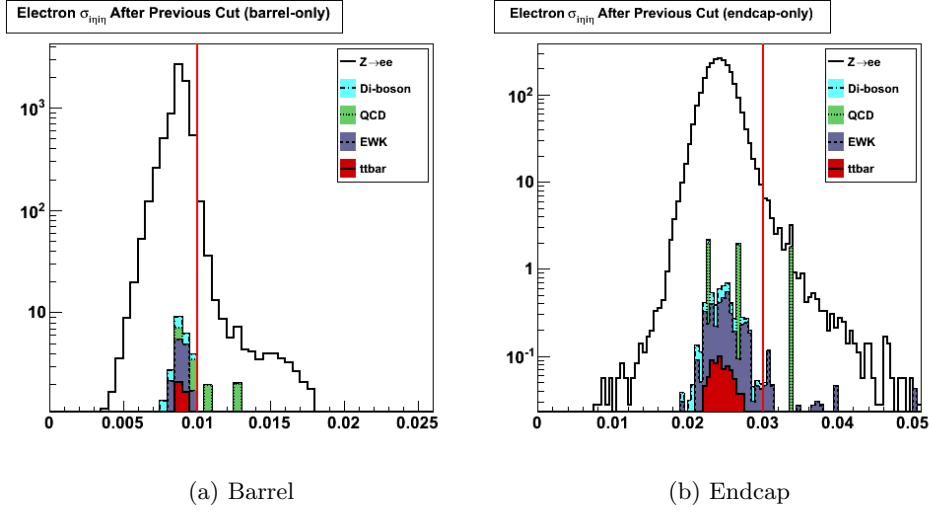


Figure 6.7: $\sigma_{i\eta i\eta}$ electron identification variables after previous cuts. $\sigma_{i\eta i\eta}$ is a measure of the spread of the electron candidate's energy deposite in η . A true electron is expected to be relatively narrow in η . Values shown for (a) barrel and (b) endcap.

simulated data. Effectively it is combined with the acceptance by applying an additional requirement on the acceptance: the simulated event should have two electrons passing the η and transverse energy requirements, and those electrons should also both be matched to reconstructed superclusters. The fraction of total events passing these combined criteria is referred to as “ECAL acceptance” or A_{ECAL} .

The pure kinematic acceptance for this analysis was determined with the POWHEG-generated Monte Carlo sample to be 0.423 and the ECAL acceptance was likewise calculated as 0.387. These values can also be found in Table 6.5.

Table 6.5: Acceptance values.

Quantity	Value
A	0.423
A_{ECAL}	0.387

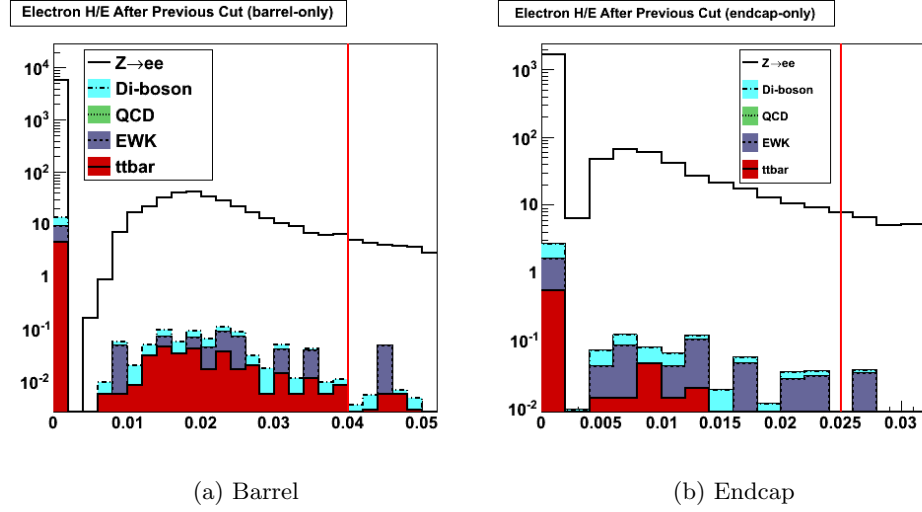


Figure 6.8: H/E electron identification variables after previous cuts. H/E is the ratio of the electron candidate’s energy deposited in HCAL to that deposited in ECAL. A true electron is expected to deposit relatively little energy in the HCAL. Values shown for (a) barrel and (b) endcap.

Efficiency of Selection for $Z \rightarrow e^+e^-$ Events

It is important to know how well the selection steps perform their task of keeping signal events; any signal events that are missed must be accounted for in the final calculation to get an accurate result. This factor is quantified in the efficiency, which is defined as the fraction of total objects or events passing a given selection. Simulated data can be used to calculate efficiency, since it contains the “truth” information – the true total number of events, whether or not they survive a given selection step. However, the simulation may not correctly model some aspect of the real data, which would cause a discrepancy with the real-data efficiency and a corresponding inaccuracy in the final result. Therefore it is desirable to use so-called “data-driven” methods, determining the efficiency as closely as possible using only the data itself. Because the truth information does not exist in real data, the number of events passing or failing a given selection must be determined with another method.

The tag-and-probe method is used to determine the efficiency of a given set of electron

selection steps. In this method, a set of data events is identified which appear to be good $Z \rightarrow e^+e^-$ candidate events. One of the electrons in each of these events must pass all selection cuts and essentially be identified as a golden electron; this is the tag. The criteria applied to the other electron are looser: it is not required to pass the selection cuts being tested. This is the probe electron. The event's status as a Z candidate is determined by enforcing a mass window cut on the invariant mass of the tag-probe system (this is sufficient to select a high-purity sample of events in which both legs are real electrons). The naive selection efficiency is then given by the fraction of probe electrons that pass the requirement being tested.

However, a more sophisticated analysis of the efficiency can be performed by fitting the invariant mass spectra of the tag-probe pairs for both passing and failing probes to a lineshape representing both the signal and the background. Then the distribution of passing probes can be represented as the signal lineshape multiplied by the efficiency and the total number of signal events added to the background lineshape multiplied by the number of passing background events. The failing probe distribution can be represented in the analogous way, using $(1 - \text{efficiency})$ instead. From this pair of fits the total number of events as well as the efficiency can be extracted simultaneously.

However, the tag-and-probe may possibly introduce a bias into the calculation, in particular if observing one leg makes it more likely that the other leg is observed. For example, if the electrons are essentially back-to-back, one is more likely to fall within the detector coverage if the other one does as well. In addition, there is a slight discrepancy between the efficiencies calculated using data and those using the standard Monte Carlo sample. Therefore, the strategy in this analysis is to calculate the “true” efficiency from the simulation sample, as well as the tag-and-probe efficiencies from the real data and simulation samples. The “true” efficiency is then corrected by the ratio of the data and simulation tag-and-probe efficiencies:

$$\epsilon = \epsilon_{MC}^{true} \times \left(\frac{\epsilon_{data}^{T\&P}}{\epsilon_{MC}^{T\&P}} \right)$$

This implies a certain amount of trust in the generator-level simulation of the interaction. The corresponding uncertainty in the efficiency due to the generator-level simulation is dealt

with in a later chapter.

The event selection efficiency in this analysis is determined by first obtaining the efficiencies of the individual selection steps given above. This also includes the initial step of reconstructing the electron objects from superclusters. Since each selection step is applied one after the other, the overall selection efficiency is given by the product of the individual efficiencies. In addition, since most steps are required to apply to both electrons, the single-electron efficiencies of these steps (the result of the tag-and-probe method) are squared to get the efficiency of both electrons passing that step. The trigger step, however, is a special case since only one electron is required to pass. In this case, the quantity used is the probability that at least one electron passes, which is equivalent to the probability both electrons fail subtracted from 1.

The formula used to calculate the overall event selection efficiency from the individual step efficiencies is therefore

$$\epsilon_{total} = \epsilon_{reco}^2 \times \epsilon_{isol}^2 \times \epsilon_{ID}^2 \times \left(1 - (1 - \epsilon_{trig})^2\right)$$

The efficiencies are given for each selection step in Table 6.6 and for all the triggers used in data individually in Table 6.7.

Table 6.6: Efficiencies of electron selection steps.

Step	True MC	MC T&P	Data T&P	Ratio	Efficiency
Reconstruction	0.965	0.972	0.971 +/- 0.002	0.999 +/- 0.002	0.964 +/- 0.002
Isolation	0.926	0.927	0.910 +/- 0.003	0.976 +/- 0.003	0.905 +/- 0.003
Identification	0.906	0.907	0.897 +/- 0.003	0.989 +/- 0.003	0.896 +/- 0.003
Trigger	0.959	0.941	0.972 +/- 0.001	1.032 +/- 0.001	0.991 +/- 0.001
Full Event selection	0.654	0.665	0.621 +/- 0.005	0.933 +/- 0.007	0.610 +/- 0.005

Table 6.7: Efficiencies of all the triggers used in data as determined with the tag-and-probe method.

Trigger	Efficiency	Error (fit)
HLT_Photon15_Cleaned_L1R	0.976	0.002
HLT_Ele15_LW_L1R	0.961	0.005
HLT_Ele15_SW_L1R	0.981	0.003
HLT_Ele15_SW_CaloEleId_L1R	0.986	0.003
HLT_Ele17_SW_CaloEleId_L1R	0.992	0.002
HLT_Ele17_SW_TightEleId_L1R	0.973	0.002
HLT_Ele17_SW_TighterEleIdIsol_L1R_v1	0.973	0.003
HLT_Ele17_SW_TighterEleIdIsol_L1R_v2	0.977	0.002
HLT_Ele17_SW_TighterEleIdIsol_L1R_v3	0.974	0.003
Overall	0.9763	0.0009

Distribution of Z Kinematic Variables

Since a significant number of $Z \rightarrow e^+e^-$ candidate events have been identified, it is useful to examine the kinematic properties of these events. Even though this analysis does not depend on these properties, comparing the distributions from the data with those from the simulated samples can provide an additional check of validity of the simulation.

Fig. 6.10 shows the distributions of standard kinematic variables for the reconstructed Z candidates: transverse momentum, rapidity, and azimuthal angle. The data (black dots) is compared with the simulation including background samples (lines/filled areas). As the ratio plots show, the agreement is good in general; large error bars indicate bins where the event count is not high enough to give a very precise estimate (such as the higher range of the Z p_T plot). However, there are areas in which there is an evident discrepancy between the data and the simulation, most notably along the outer edges of the Z rapidity plot. Possible causes might include a slightly inaccurate description of the particle interaction in

the generator, or a slight miscalibration of the detector. Since the difference is slight and does not affect this analysis, though, it can safely be ignored and the general agreement accepted.

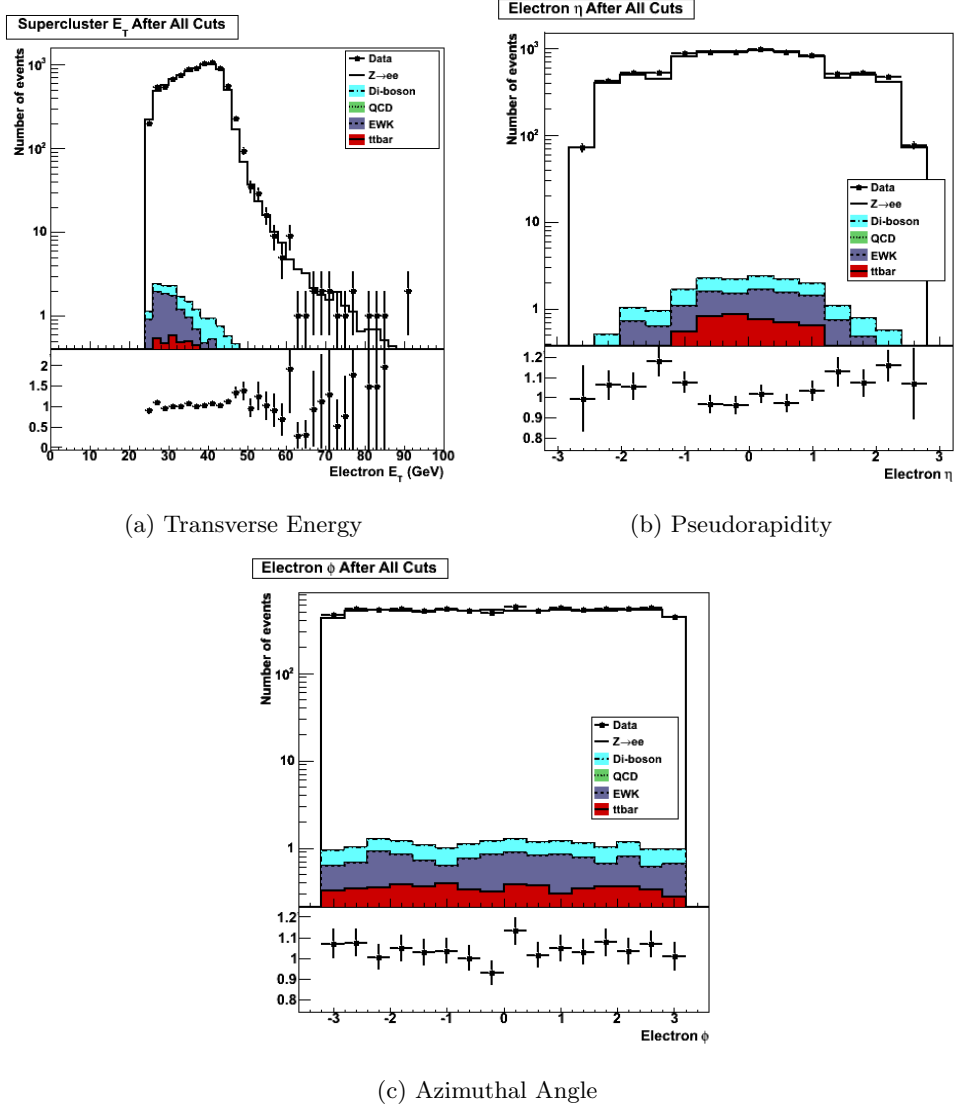


Figure 6.9: Spectra of reconstructed electron kinematic quantities after all electron selection cuts. The plots show distributions for electron p_T , η , and ϕ respectively. The agreement between real data and the simulated sample is good, demonstrating that the effects of the cuts on the data are understood.

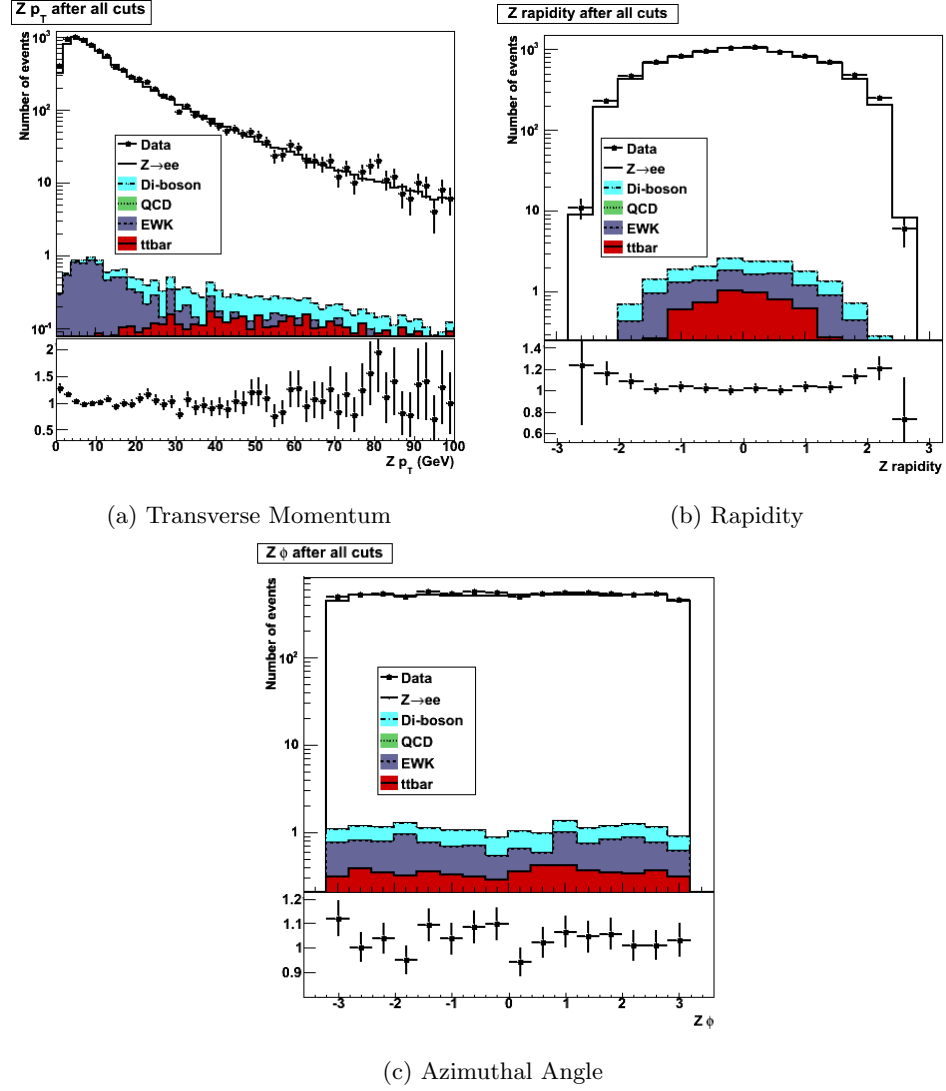


Figure 6.10: Kinematic quantities of Z candidates after full event selection.

Chapter 7

ANALYSIS METHOD

I guess this is the part of the analysis that's not included in event selection. SO, how to get the cross section, like the main formula, and where all the numbers came from (especially the ones we haven't calculated yet).

As explained in Section FIXME, the invariant mass of a set of decay-product particles is essentially the mass of the original particle that decayed. It is defined mathematically as

INV MASS FORMULA

where p momentum, E energy, etc. In our case, for a two-particle system, it can be written as

MORE FORMULA (this one necessary??)

The invariant mass distribution for the electron pairs in the events surviving all selection cuts is shown in Fig. 7.1. The peak around the Z mass ($\tilde{91}$ GeV) is clearly visible in both the Monte Carlo and data distributions.

Ooh, I do also have inv mass by eta plots

The total number of data events surviving the selection cuts is 8453.

ALSO TALK ABOUT HOW PLOTS SCALED??!

recap of formula:

THE FORMULA

* n_{total} * n_{bg} – THE DIFFERENT METHODS OF BACKGROUND SUBTRACTION
 * acc (event sel) * eff (event sel) – but talk about correcting for data/MC difference * Lumi
 (exp chapter or sth)

n_{total} comes from inv mass plot just shown, n_{bg} is what you need to calculate. 3 methods: * MC estimate * template method * sideband subtraction

You know, I don't think my analysis needs a whole giant section on data vs MC comparison. I didn't do a whole lot. Well, just write up what I did do, I guess.

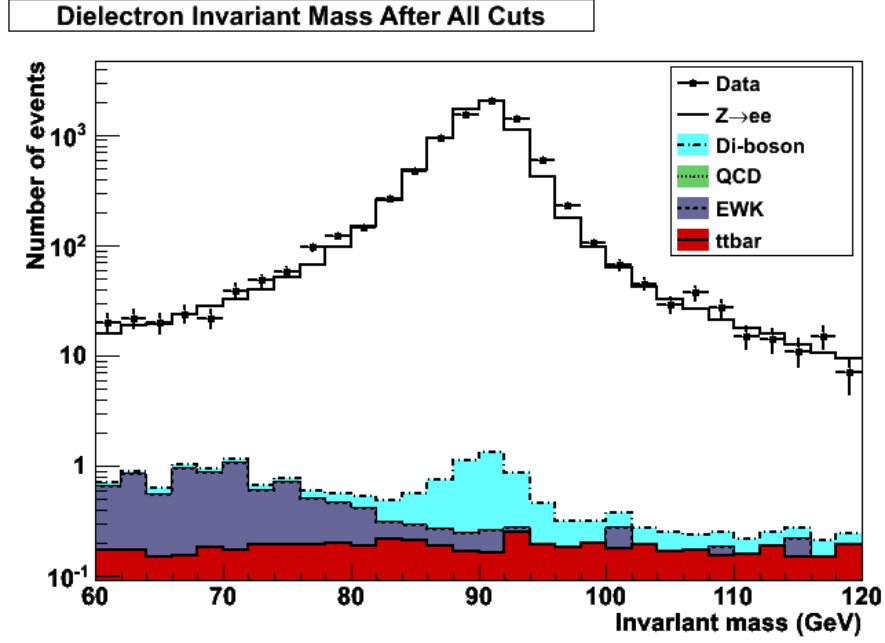


Figure 7.1: Electron-pair invariant mass after full selection.

7.1 Background Subtraction

It is expected that some number of non-signal events will look enough like signal events to pass the full selection. These background events need to be accounted for in the final calculation to arrive at the most accurate result. Therefore, the number of background events should be estimated and subtracted from the total number of events; This estimation can be done in a variety of ways. The methods used in this analysis are detailed in the following sections.

Figures: Background subtracted yield versus eta with a MZ mass window - comparison to MC, Fig. 7.2

Figures: Background subtracted Z PT distribution with a MZ mass window - comparison to MC, Fig. 7.3

7.1.1 Monte Carlo Estimation

One estimate of the number of background events can be made directly from the Monte Carlo simulation, by counting the number of simulated events that pass the full selection. The numbers of passing events for the simulated background samples used are in Table FIXME, with a total of 18.6 events. The accuracy of this method may be questionable due to unaccounted differences between the simulation and real data, however. In particular, the detector may not be correctly modeled in the simulation, causing slight differences in event numbers that are non-negligible at this level. Therefore, data-driven methods of background subtraction are also used, and the results from all the methods are checked against each other to confirm the accuracy of each method.

TABLE with MC-estimated number of events from each background source

7.1.2 Template Method

7.1.3 Sideband Subtraction

7.2 Estimation of Systematic Uncertainties

MAYBE MAKE WHOLE OTHER CHAPTER???

Woohoo, the whole thing

- * lumi

- * stat (but that's not syst)

- * theory syts (HOW TO REFERENCE?? Just reference VBTF paper, I guess...?)

my stuff:

- * electron energy scale

- * MC sample for efficiency

- * efficiency fitting

- * background subtraction/modeling (variation among the methods)

7.3 What Else?

Is this supposed to be random collection of methods used? e.g. tag and probe, template method, sideband fitting... although I guess the last two are actually background subtrac-

tion, which is somehow already determined to be part of this chapter.

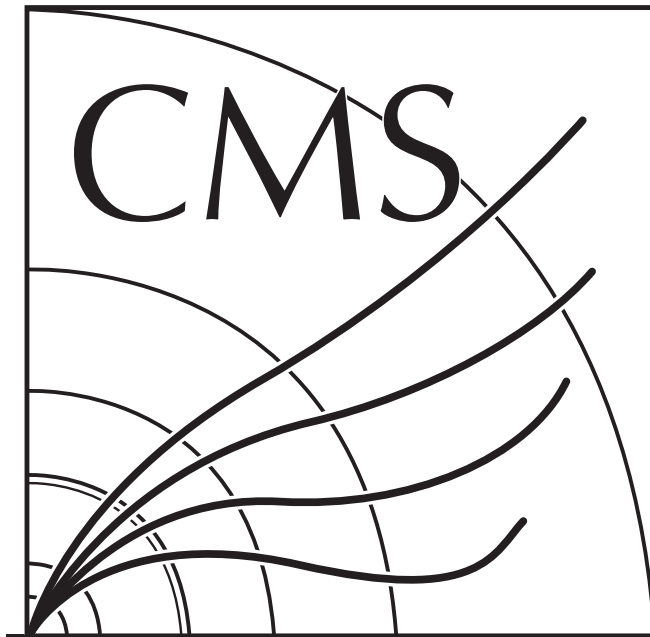


Figure 7.2: Background subtracted yield versus eta with a MZ mass window - comparison to MC.



Figure 7.3: Background subtracted Z PT distribution with a MZ mass window - comparison to MC.

Chapter 8

RESULTS**8.1 *Cross Section Measurement***

Cross section calculation

8.2 *Comparison to Theory***8.3 *Comparison to Previous Experiments***

Chapter 9

SUMMARY AND CONCLUSIONS