ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

HYBRID PHOTO-DIODE NOISE LIBRARY AT CMS HADRON CALORIMETER

M.Sc. THESIS

Hüseyin BAHTİYAR

Department of Physics Engineering

Physics Engineering Programme

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

CMS HADRON KALORİMETRESİNDE HİBRİT FOTODİYOT DETEKTÖRLERE GÜRÜLTÜ KÜTÜPHANESİ YARATILMASI

YÜKSEK LİSANS TEZİ

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Hüseyin BAHTİYAR, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID **509101127** successfully defended the thesis entitled **"HYBRID PHOTO-DIODE NOISE LIBRARY AT CMS HADRON CALORIMETER"**, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Defense : **8 June 2012**

To my fiancee and my family,

FOREWORD

I would like to express my thanks to my co-advisor Dr. Taylan Yetkin for his patience and endless helps. I would like to thank to my advisor Kerem Cankoçak providing me to go to CERN. I also thank to Mehmet Erhan Emirhan, Mete Yücel and Esra Barlas for helping me during my research.

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ABBREVIATIONS

ADC : Analog to digital converter
ALICE : A Large Ion Collider Experiment
Apd : Avalanche photodiodes
App : Appendix
ATLAS : A Toroidal LHC Apparatus
CERN : European Organization for Nuclear Research
CMS : Compact Muon Solenoid
CMSSW : CMS Software
ECAL : Electromagnetic Calorimeter
HB : Hadron Barrel Calorimeter
HCAL : Hadron Calorimeter
HE : Hadron Endcap Calorimeter
HF : Hadron Forward Calorimeter
HO : Hadron Outer Calorimeter
HPD : Hybrid Photo Diode
LHC : Large Hadron Collider
LHCb : Large Hadron Collider beauty Experiment
LHCf : Large Hadron Collider forward Experiment
MC : Monte Carlo
PMT : Photomultiplier Tube
QCD : Quantum chromodynamics
QED : Quantum electrodynamics
QIE : Charge-integrator and encoder
RBX : Readout Box
RM : Readout Module
SUSY : Supersymmetry
TOTEM : Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC

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LIST OF SYMBOLS

η	:	Pseudorapidity
ϕ	:	Azimuthal angle
θ	:	Horizontal angle
E_T^{miss}	:	Missing Transverse Energy
P_T	:	Transverse Momentum

HYBRID PHOTO-DIODE NOISE LIBRARY
AT CMS HADRON CALORIMETER

SUMMARY

The European Organization for Nuclear Research (CERN), is an international organization located in Geneva on the France–Switzerland border. Most of the activities at CERN are currently directed towards operating the new Large Hadron Collider (LHC), and the experiments for it. There are six experiments at the LHC. Two of them are high luminosity experiments namely A Toroidal LHC Apparatus (ATLAS), Compact Muon Solenoid (CMS). The remaing ones are A Large Ion Collider Experiment (ALICE), Large Hadron Collider beauty Experiment (LHCb), Total Cross Section, Elastic Scattering and Diffraction Dissociation (TOTEM) and Large Hadron Collider forward Experiment (LHCf).

CMS is a general-purpose detector which is designed to observe wide range of particles at proton or heavy ion collisions. CMS is built around a huge solenoid magnet. Like a an onion but in cylindrical shape, different layers of detectors measure different type of particles, and each detector use these data to build up a picture of what happened during the collision.

There are four sub-detectors in CMS which are, Tracker, Electromagnetic Calorimeter (ECAL), Hadron Calorimeter (HCAL) and Muon System. The HCAL has four sub-detector as well, named as, Hadron Barrel (HB), Hadron endcap (HE), Hadron Outer (HO) and Hadron Forward (HF) detectors. HB, HE and HO use Hybrid Photo Diodes (HPDs) for photon detection, where as HF uses photo-multiplier tubes (PMT).

The HPDs are found to generate signal even when there is no light coming from the detector channels [10]. These signals are called as “noise” and can be divided in three categories; thermal emission, ion feedback, and discharge.

This thesis focuses on HPD noise library production for HB and HE HPDs within CMS Software (CMSSW). Based on collected noise data, it provides details on how to mix noise data from the library with Monte Carlo events or collision events.

The HPD Noise Library package is a ROOT based framework and includes three different programs, library producer, library reader and a event mixer. The producer makes a simple analysis of the HPD noise data collected by special triggers and produces a ROOT file which is in the HPD noise data format. Reader is an interface code to the user. It is responsible from reading and returning collection of noisy HCAL channels with data for each 25ns time interval. Event mixer’s main purpose is to mix the created library noise with Monte Carlo (or data). The user can observe and study the effect of HPD Noise to data with the event mixer.

To show the importance of HPD Noise Library package a simple Missing Transverse Energy and Invariant Dijet mass analysis were made. Analysis’ clearly shows the HPD Noise effect.

As a result, based on local (HCAL only) and global (CMS) monitoring data HPD Noise Library Producer and Reader successfully upgraded to newest version of CMSSW. Noise mixing with data (or Monte Carlo) was made possible at the RecHit level. User can add HPD noise to any physics process with the provided tool. This enables users to study the effect of noise rare collision events.

CMS HADRON KALORİMETRESİNDE HİBRİT FOTODİYOT DETEKTÖRLERE GÜRÜLTÜ KÜTÜPHANESİ YARATILMASI

ÖZET

Kısaca CERN olarak bilinen, Avrupa Nükleer Araştırmaları Merkezi, Cenevre'de, Fransa – İsviçre sınırında bulunan, dünyanın en büyük parçacık fiziği laboratuarıdır. Laboratuarın temel işlevi, yüksek enerji fiziği araştırmaları için gereken parçacık hızlandırıcıları gibi deneysel altyapıyı sağlamaktır. Atom çekirdeğini araştırmak amacıyla kurulduysa da, CERN kısa sürede daha yüksek enerjilere erişmiş ve artık atomaltı parçacıkları ve bunlar arasındaki etkileşmeleri inceleyen bir kurum haline gelmiştir.

Son dönemde CERN'in ana amacı Büyük Hadron Çarpıştırıcı'sını ve bu çarpıştırıcının yardımıyla yapılan deneyleri yürütmektir. Bu deneylerin amacı Standart Model olarak bilinen, bilimsel otoritelerce kabul gören modeldeki bulunmamış parçacık olan, maddeye kütlesini veren Higgs bozonunu gözlemlemektir. Büyük Hadron Çarpıştırıcısında altı ana deney bulunmaktadır. Bu deneyler ATLAS, CMS, ALICE, LHCb, LHCf ve TOTEM dir.

ATLAS ve CMS deneyleri, genel amaçlı deneylerdir ve Standart Model Higgs bozonunu araştırmaktadırlar. ALICE deneyi bir ağır iyon deneyidir ve büyük patlamadan saniyeler sonra oluşmuş olan kuark-gluon plazmasını incelemektedir. LHCb, güzellik kuarkının yapısını ve yük parite bozunumunu inceleyen bir deneydir. TOTEM ve LHCf deneyleri parçacıkların ileri bölgedeki (protonların çarpıştığı bölgeye yakın olan bölgedeki) fiziği incelemektedirler.

CMS deneyi, CERN'deki genel amaçlı deneylerden biridir. CMS'in ana tasarım amacı Standart Model Higgs bozonunu gözlemlemektir. CMS dedektörü büyük bir bobin olarak tasarlanmıştır. Bu devasa bobinin içinde 4 Tesla'ya kadar manyetik alan oluşturulabilir, ayrıca bobinin içinde her biri farklı şekilde, farklı yapıdaki parçacıkları gözlemlemeyi amaçlayan alt dedektörler konulmuştur. CMS'in yapısı silindir şeklindeki bir soğan gibi düşünülebilir, her bir katman farklı bir alt dedektördür.

CMS'in alt dedektörleri genel olarak iz sürücü, elektromanyetik kalorimetre, hadron kalorimetresi, müon sistemi ve mıknatıstan oluşmuştur. İz sürücü, protonların çarpıştığı noktaya en yakın dedektördür, silikondan yapılmış olan dedektörün ana amacı, yüklü parçacıkların konumunu ve hareketini gözlemlemektir. Böylece parçacığın momentumu tayin edilebilir. İz sürücünün dışında elektromanyetik kalorimetre (ECAL) bulunmaktadır ve elektromanyetik etkileşimden oluşan olan foton ve elektronların enerjisini belirler. Elektromanyetik kalorimetrenin üstünde hadron kalorimetresi (HCAL) vardır ve hadron adı verilen kuark ve gluonlardan oluşmuş kompozit parçacıkların enerjisini ölçmek amacıyla tasarlanmıştır. Müon sistemi ise hadron kalorimetresinin üstünde bulunan mıknatısın dışındadır. Müon dedektörleri sayesinde, elektromanyetik ve hadronik kalorimetrede iz bırakmadan geçen müonların manyetik alan değişimi sayesinde momentum ve enerjilerinin belirlenmesi amacıyla tasarlanmıştır.

Hadron kalorimetresi kendi içerisinde dört altdedektörden oluşmuştur Bunlar hadron merkez (HB), hadron kapak (HE), hadron ileri (HF) ve hadron dış (HO) olarak adlandırılır.

Hadron merkez kalorimetresi, dedektörün orta kısmında bulunmaktadır, içi boş bir silindir görüntüsündedir. İçinde elektromanyetik kalorimetrenin merkez kısmını ve silikon iz sürücülerini barındırmaktadır. Örnekleme kalorimetresidir, her bir katmanında bir soğurucu ve sintilatör bulunmaktadır. Sintilatörden çıkan fotonları taşımak için dalga boyu kaydırıcı fiberler kullanılmaktadır. Çarpışma noktasına göre HB+ ve HB- olarak ikiye ayrılır. Foton algılayıcı olarak hibrit fotodiyotlar kullanılmaktadır.

Hadron kapak kalorimetresi, hadron merkez kalorimetresinin - ve + kısımlarının sonunda birer kapak gibi tasarlanmıştır. Merkez kalorimetre gibi bir örnekleme kalorimetresidir, aynı şekilde sintilatörden çıkan fotonlar dalga boyu kaydırıcı fiber ile taşınır. Foton algılayıcı olarak hibrit fotodiyotlar kullanılmaktadır.

Hadron dış kalorimetresi, mıknatıs ile müon sistemi arasına kurulmuştur. Hadron dış kalorimetresinin ana amacı hadronik serpintilerin, kuyruk adı verilen son kısmını saptamaktır. Bu bilgi yardımı ile geç oluşmuş olan hadronik serpintiler gözlemlenebilir. Hadron dış kalorimetresinde foton algılayıcı olarak hibrit fotodiyotlar kullanılmaktadır.

İleri hadron kalorimetresi, CMS dedektörünün iki kısmında da bulunmaktadır. Bu sayede CMS kapalı bir dedektör yapısına bürünür, böylece kayıp enerjinin daha iyi ölçülmesine yardımcı olur. İleri hadron kalorimetresinde çelik soğurucular ve özel olarak seçilmiş kuvartz fiberler kulanılmaktadır. Kuvartz fiberlerden oluşan fotonlar, kısa ve uzun fiberler ile foton algılayıcı olarak kullanılan foto çoklayıcı tüplere (PMT) iletilir.

Hadron kalorimetresinin alt dedektörleri olan merkez, kapak ve dış kalorimetreler foton algılayıcı olarak hibrit fotodiyotları kullanmaktadır(HPD). Hibrit foto diyotlar 1957 de icat edilmiştir. HPD nin optik penceresinin altında bir fotokatod vardır. HPD'nin altında silikon diyot bulunmaktadır. Silikon diyot ile fotokatod arasında 10 kV a kadar gerilim uygulanan vakum bölgesi bulunur.

Hadron kalorimetresinde HPD'lerin seçilme nedenleri, konum hassasiyeti olması, radyasyona karşı dayanıklı olabilmeleri, geniş bir algılama aralığının olması ve manyetik alan içerisinde sabit bir şekilde çalışabilmeleridir. Bazen dedektör kanallarından foton gelmediği halde hibrit fotodiyotlar sinyal oluştururlar. Bu tarz sinyaller gürültü olarak adlandırılır ve üç kategoriye ayrılır: Termal salınım, iyon geribeslemesi ve elektriksel boşalma.

Termal salınım, HPD'nin içindeki ısısal değişimden ötürü fotokatoddan elektronun kopması sonucunda oluşur. Kopan elektron vakum bölgesindeki yüksek voltaj ile hızlanır. Yaklaşık 10 KeV enerji ile gelen elektron, silikon diyoda çarparak enerjisini verir, silikon diyotta elektron boşlukları çiftleri oluşturur ve böylece sinyal oluşur. İyon geribeslemesi ise vakum sisteminin mükemmel olmamasından kaynaklı bir gürültü çeşididir. Vakum içerisinde gaz molekülleri bulunur, moleküllere çarpan elektronlar, molekülleri iyonize eder sonuçta daha yüksek bir sinyal ortaya çıkar. Elektriksel boşalma, manyetik alanın sapmasından ötürü oluşur, HPD'lerin duvarlarında biriken elektriksel yük boşalır ve eşik değerinden yüksek bir sinyal üretir. Bu gürültü çeşidi, genellikle HPD'de bulundan tüm kanallarda aynı anda görülür. Bu gürültü çeşitleri için kütüphane yapılmasındaki ana amaç, Monte Carlo'da oluşturulamaması ve fizik analizine etkisinin büyük olmasıdır.

Bu çalışmada Hadron kalorimetresi içindeki HB ve HE nin içerisinde bulundan hibrit fotodiyotlar için, kütüphane yaratılmıştır. HPD gürültü kütüphanesi her HPD için gürültü bilgilerini tutan, kullanımı kolay bir pakettir. Aynı zamanda gürültü bilgilerini Monte Carlo veya proton-proton çarpışmasından oluşan veriler ile karıştırabilme özelliğine sahiptir. Bu kütüphane HPD gürültülerinin fizik analizlerine etkisini gözlemlemek veya HPD gürültülerini filtrelemek için kullanılabilir. Paketin eski versiyonu CMS yazılımın tezin yazıldığı dönemdeki son versiyonuna yükseltilmiştir. Yükseltmedeki en önemli değişiklik HPDlerin tutulduğu ROOT dosyasındaki isimlerin, HCAL elektronik haritasından okunup yatarılmasıdır.

HPD gürültü kütüphanesi pakedi kütüphane üreticisi, kütüphane okuyucusu ve olay karıştırıcısını barındıran, ROOT temelli bir arayüzdür.

Kütüphane üreticisi özel olarak oluşturulmuş HPD gürültü verilerinden veya HB/HE yerel verileri üzerinden bir analiz yaparak, her HPD için gürültü bilgilerini kaydeder. Program okuma kutusu (RBX) ve okuma modülü (RM) bilgilerini elektronik haritadan alır, okuma kutusu ismi "_RM_" okuma modülü numarası şekilde (örnek: HBP12_RM_1) farklı bir isimle kaydeder. Hadron merkez ve hadron kapak dedektörlerinin + ve - kısımlarının her birinde 18 adet okuma kutusu bulunur, her okuma kutusunun içinde 4 adet okuma modülü bulunur, böylece 288 adet isim oluşturulur, böylece her bir isim bir HPD'ye karşılık gelmektedir. Kullanıcı kaydedilecek gürültünün eşik değerini belirler ve gürültü kütüphanesi bu verileri femtoCoulomb biriminde kaydeder. Oluşturulan ROOT dosyasında her bir HPD için, yük bilgisi, iyon geribesleme ve elektriksel boşalma gürültü bilgileri bulunmaktadır.

Kütüphane okuyucusu, oluşturulan kütüphanenin okunması için tasarlanmıştır, okuma işlemini yapar ve gürültülü olan kanalların bilgisini her bir 25ns'lik zaman dilimleri için oluşturur. Özel olarak alınan verilerde, zaman diliminin kayabilme olasılığına karşı, programın içinde zaman dilimi kaydırıcı da bulunmaktadır. Kullanıcının isteğine bağlı olarak iyon geribesleme simülasyonunu yapar.

Olay karıştırıcısı ise oluşturulan HPD gürültü kütüphanesini, veri veya Monte Carlo ile RecHit seviyesinde karıştırmaktan sorumludur. Digitize ortamda femtoCoulomb olarak tutulan gürültü bilgileri, CMS programındaki kalibrasyon katsayıları kullanılarak RecHit seviyesine getirilmiştir. Böylece kullanıcı, HPD gürütüsünün nasıl karıştırılacağını fiziksel verilere etkisini gözlemleyebilmektedir. RecHit derlemesi yapıldığında, jet, kayıp enerji gibi yüksek seviye nesnelerin yeniden yapılandırılması yapılabilir.

Sonuç olarak HPD gürültü kütüphane üreticisi ve okuyucusu yerel (sadece HCAL için) veya genel (CMS) verileri için CMS yazılımının son sürümüne başarı ile yükseltilmiştir. Veri veya Monte Carlo gürültü karıştırması RecHit seviyesinde yapılabilir. Kullanıcı olay karıştırıcısı yardımıyla HPD gürültüsünü herhangi bir sürece ekleyebilir, böylece kullanıcı nadir çarpışma olaylarında (Higgs bozonu araştırması gibi) HPD gürültüsünün etkisini gözlemleyebilir. Ayrıca bu çalışmada CMS yazılımının özel olarak tasarladığı simülasyon aracıyla 8 TeV kütle merkezi enerjide Monte Carlo verileri oluşturulmuştur. Oluşturulan Monte Carlo ile HPD gürültüsü karıştırılmıştır. Gürültü eklenmiş olaylar MET ve ak5CaloJet algoritmaları kullanılarak yeniden yapılandırılıp, HPD gürültü etkisi kayıp enine enerji için ve iki jet değişmez kütlesi için incelenmiştir.

1. INTRODUCTION

The European Organization for Nuclear Research (CERN) is an international organization [1] located in Geneva on the France–Switzerland border. Its main purpose is to operate the world's largest particle physics laboratory. Most of the activities at CERN are currently directed towards operating the new Large Hadron Collider (LHC), and the experiments for it.

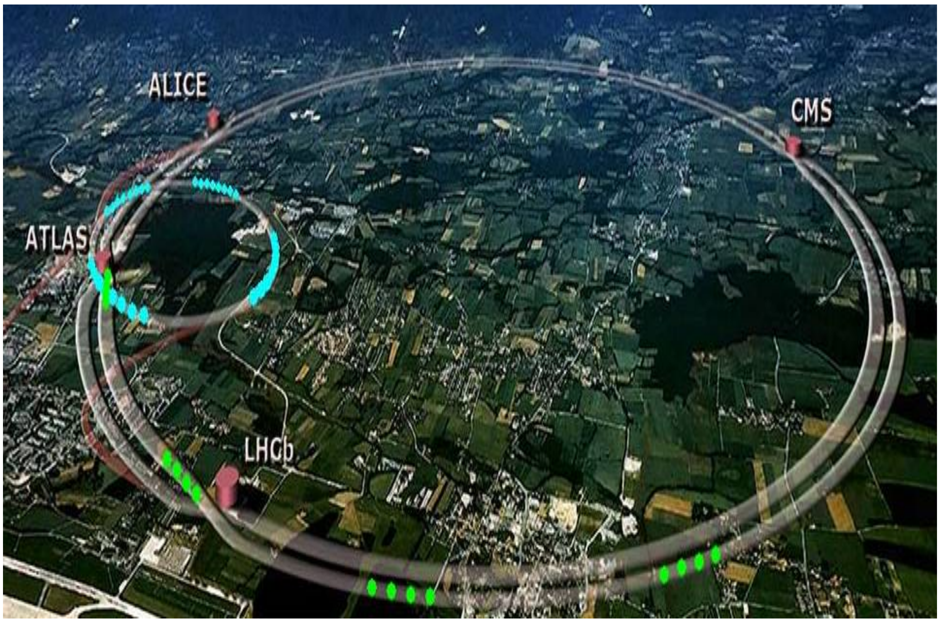

Figure 1.1: Large hadron collider and experiments view from above [1]

LHC is world most powerful two-ring-superconducting hadron accelerator and collider [1]. At LHC there are two rings of counter rotating beams. Protons are accelerated at the center of mass energy up to 14 TeV. LHC accelerates not only protons but also Pb ions up to 2.8 TeV. LHC recreates the conditions just after the Big Bang, by colliding high energetic protons or Pb ions.

The purpose of the LHC is to find physics beyond the Standard Model [11]. For this investigation LHC experiments focuses to understand electroweak symmetry breaking for which Standard Model Higgs mechanism is responsible. In theory Higgs mechanism can be discovered above 1 TeV energy. In addition to that, LHC experiments are capable of searching for new physics phenomena (such as Supersymmetry, extra dimensions, techni-colors) that are envisioned between electroweak scale and grand unification scale.

There are six experiments at the LHC. Two of them are high luminosity experiments namely A Toroidal LHC Apparatus (ATLAS) [12] and Compact Muon Solenoid (CMS) [8], which searching for Standard Model Higgs boson. A Large Ion Collider Experiment (ALICE) [13] is a heavy ion experiment, ALICE aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected [13]. Large Hadron Collider Beauty Experiment (LHCb) [14] focuses on beauty quark decays, looking for useful clues to explain why nature prefers matter over antimatter. Total Cross Section, Elastic Scattering and Diffraction Dissociation (TOTEM) [15] Experiment is dedicated to precise measurement of the proton-proton interaction cross section. Main purpose of Large Hadron Collider forward Experiment (LHCf) [16] is to investigate neutral-particle production cross sections in the very forward region of proton-proton and nucleus-nucleus interactions. Comparing to four other experiments, TOTEM and LHCf are much smaller in size and designed to focus on "forward particles" (protons or heavy ions).

1.1 The Purpose of Thesis

The thesis focuses on HPD noise library production within CMS Software (CMSSW). Based on collected noise data, it provides details on how to mix noise data from the library with Monte Carlo events or collision events.

Although most noises of HPDs are cleaned by using software based noise filters at High Level Trigger (HLT), the remaining noise is necessary to be understood for discoveries based on rare event counts. Since Monte Carlo simulations do not contain HPD noise, a software framework which can store and mix noise data with Mote Carlo is very useful to study background and signal during statistical analysis of rare events.

The goal of this study is to update older versions of programs to newest CMSSW version by naming ROOT branches taken from detector's electronic map in order to be global and practicable for users. The reason for update is to make HPD Noise Library to be able to determine and add ion-feedback and discharge rates for every HPD, using RAW data collected by HB/HE self trigger runs.

The effects of HPD Noise on dijet mass and E_T^{miss} distributions were investigated with the help of the library to demonstrate the importance of the library usage.

2. CMS DETECTOR

CMS is a general-purpose detector which is designed to observe wide range of particles at proton or heavy ion collisions. Since the main goal of CMS is to observe Higgs boson with its golden decay channel $H \longrightarrow \mu\mu$, it is built around a huge solenoid magnet to bend and measure momentum of muons. The same is also true for $H \longrightarrow \gamma\gamma$ decay where high resolution electromagnetic calorimeter becomes very important.

Like a an onion, but in cylindrical shape, different layers of detectors measure different type of particles, and each detector use these data to build up a picture of what happened during the collision.

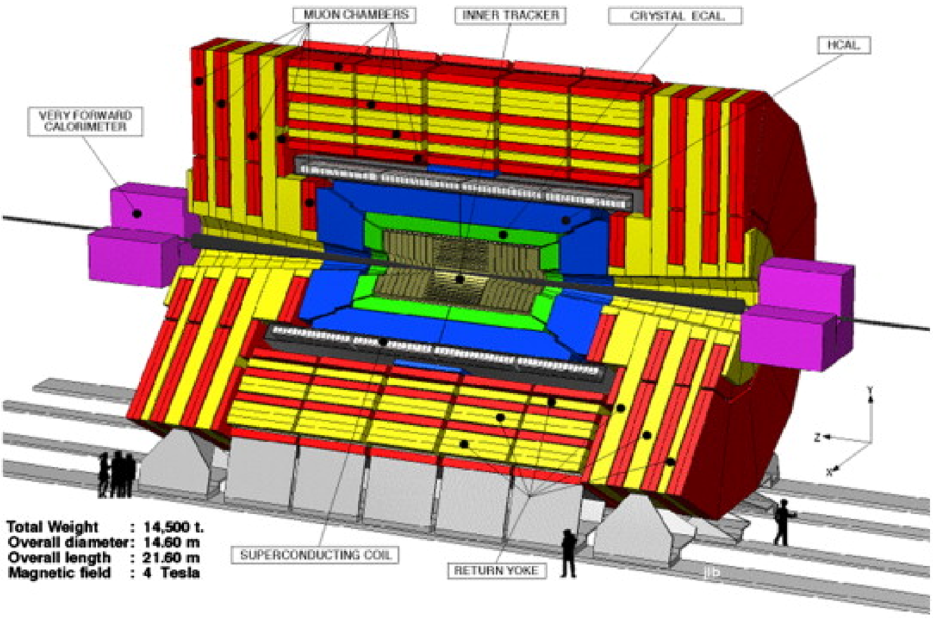

Figure 2.1: Perspective view of CMS detector [2].

Particles emerging from collisions first meet a tracker which is made of silicon. The tracker's main purpose is to chart the charged particles positions and measure the momentum.

Outside the tracker, there are electromagnetic and hadronic calorimeters that measure the energy of particles. The Electromagnetic Calorimeter (ECAL) - made of lead tungstate, measures the energy of photons and electrons. Outside the ECAL there is a Hadron Calorimeter (HCAL) which is designed principally to detect any particle made up of quarks. The size of the magnet allows the tracker and calorimeters to be placed inside the coil, resulting in a compact detector.

CMS is also designed to measure muons. The outer part of the detector, the iron magnet "return yoke", which confines and guides the magnetic field, also stops all remaining particles but muons and weakly interacting particles, such as neutrinos, from reaching the muon detectors. Four layers of detectors are interleaved with the iron, which also provides the detector's support structure [17].

2.1 Inner Tracking System

The inner tracking systems main purpose is to measure trajectories of charge particles and to reconstruct secondary vertices. Inner tracking system designed to have a very fast response since it is so close to interaction point (diameter of 2.5m), and faces a lot of particles in a bunch crossing (25ns) [6].

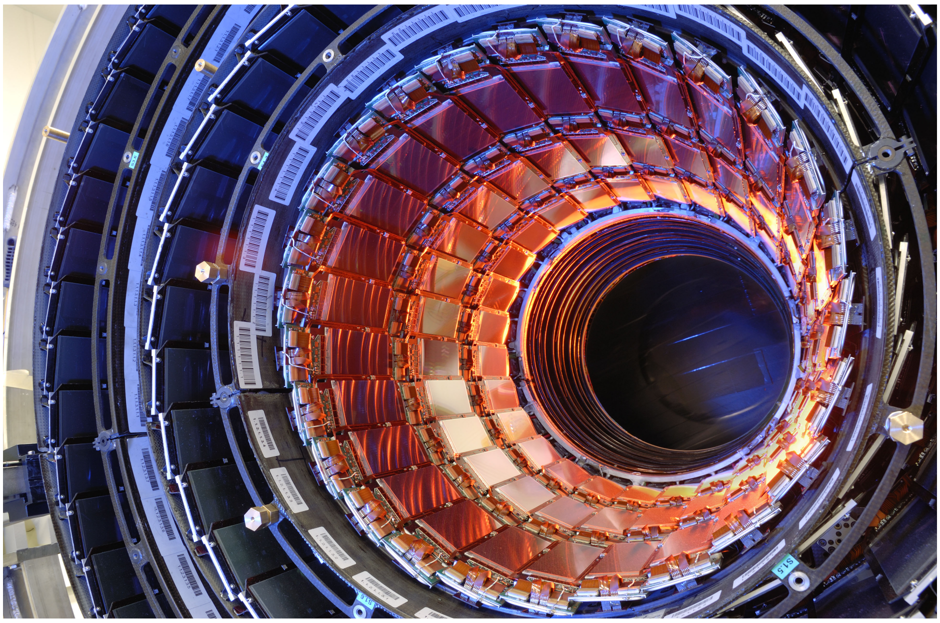

Figure 2.2: CMS tracker silicon strips detectors in the barrel module [3].

Tracker consists of a pixel detector with radius between 4.4 cm and 10.2 cm and a silicon strip tracker outwards with radius of 1.1 m [6].

2.1.1 Pixel detector

The pixel detector is closest detector to the interaction point, its pseudorapidity (see App A.1) range is $-2.5 < \eta < 2.5$. The detector, about the size of a shoe box, contains

65 million pixels. This allows to track the paths of particles emerging from the collision with extreme accuracy. It is vital in reconstructing the tracks of very short-lived (b and τ) particles. Detectors' tracks help outer track reconstruction and High Level Trigger [6].

2.1.2 Strip detector

After the pixels and on their way out of the tracker, particles pass through ten layers of silicon strip detectors, reaching out to a radius of 130 centimeters.

Silicon sensors are highly suited to receive many particles in a small space due to their fast response and good spatial resolution

The silicon detectors work as pixel detector does: When a charged particle crosses the material it knocks an electron, the applied electric field moves these giving a very small pulse of current, lasting for a few nanoseconds [17].

2.2 Electromagnetic Calorimeter

Electromagnetic Calorimeter (ECAL) is a hermetic calorimeter. It is made of lead tungstate crystal ($PbWO_4$) that scintillates when electrons or photons produce showers inside. The amount of scintillation light is proportional to the energy deposited by showering particle.

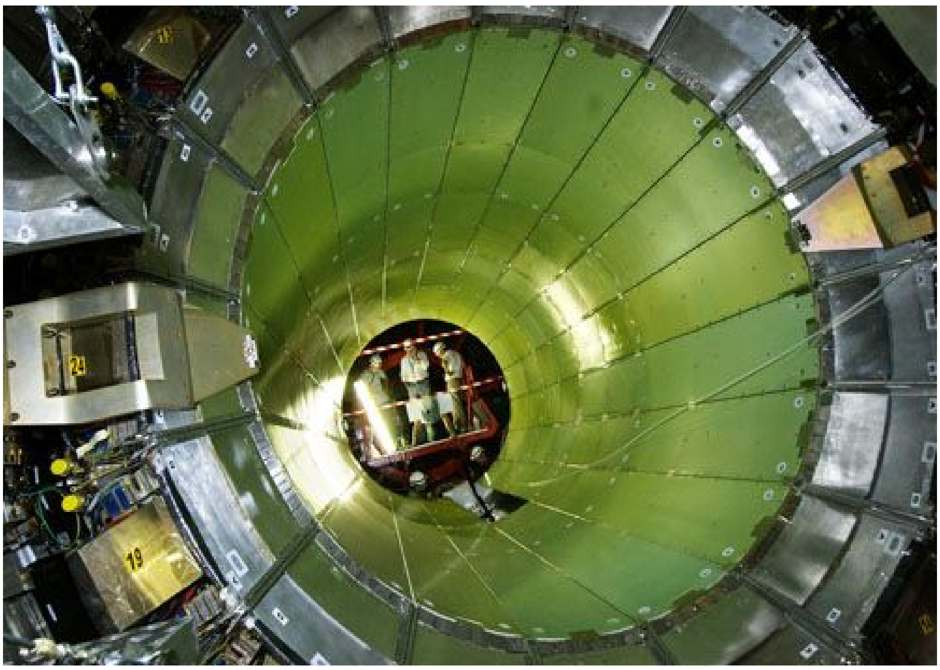

Figure 2.3: Electromagnetic calorimeter [4].

Main purpose of ECAL is to measure the energies of electrons and photons. The most important criteria is to detect Standard Model Higgs boson decays into two photon channel thats why ECAL is a hermetic calorimeter [6].

The ECAL is made up of a barrel section and two endcaps between the tracker and the HCAL. ECAL also contains preshower detectors in front of the endcaps. These allow CMS to distinguish between single high-energy photons and close pairs of low-energy photons.

There are two type of photodetectors in ECAL, they both are especially designed to work within the high magnetic field. In barrel section, there are Avalanche Photodiodes (APDs) and in endcaps, there are Vacuum Phototriodes (VPTs) [6].

2.3 Hadron Calorimeter

The Hadron Calorimeter (HCAL) [8] as the name implies, measures the energy of hadrons. Additionally, it provides indirect measurement of the presence of non-interacting, uncharged particles such as neutrinos. HCAL is very important to measure hadron jets, neutrino or exotic particles. HCAL is a hermetic calorimeter because it must detect hadrons as much as possible. That is directly important for missing transverse energy (E_T^{miss}) measurement.

HCAL has four sub-detectors which are named according to their rapidity coverage such as barrel (HB) $|\eta| < 1.4$, endcap (HE) $1.3 < |\eta| < 3.0$, outer (HO) $|\eta| < 1.26$ and forward (HF) $2.9 < |\eta| < 5$ regions [6].

When a particle passes through the HCAL that produce a rapid light pulse in readout electronics. Special optic fibers collect this light, and then optical signals are converted into electronic signals by HPDs (in HB/HE/HO) or PMTs (in HF).

2.3.1 Hadron barrel calorimeter

The HB [8] is a sampling calorimeter, which means the material that produces the particle shower is different from the material measures the deposited energy. HB consists of alternating plates of brass absorber and scintillator tiles with embedded wavelength shifting (WLS) fibers. It has two half-barrels located at each side of the interaction point (HB+, HB-). HBs' pseudorapidity range is $|\eta| < 1.4$. There are 18 wedges each of HB+ and HB- and each wedge is parallel to the beam axis and they are constructed out of flat absorber plates. When light comes out of the tile scintillators, it is carried by wavelength shifting (WLS) optical fibers. WLS fibers bring the light to clear fibers and they transport light to Optical Decoding Unit (ODU). ODU arrange fibers into read-out towers and bring the light to HPDs.

2.3.2 Hadron endcap calorimeter

As their name imply Hadron Endcap [8] calorimeters are like a lid and they are at the both side of the CMS. They are attached to the muon endcap. They cover $1.3 < |\eta| < 3.0$ range. At high η range, HE faces against high luminosity and high radiation. Because of these they must have high radiation tolerance and counting rate. Absorbers of HE designed specially minimize the cracks between HB and HE, and the absorbers are non-magnetic material so that calorimeter is so close to the 4T solenoidal magnet and they do not change the field lines at the edges.

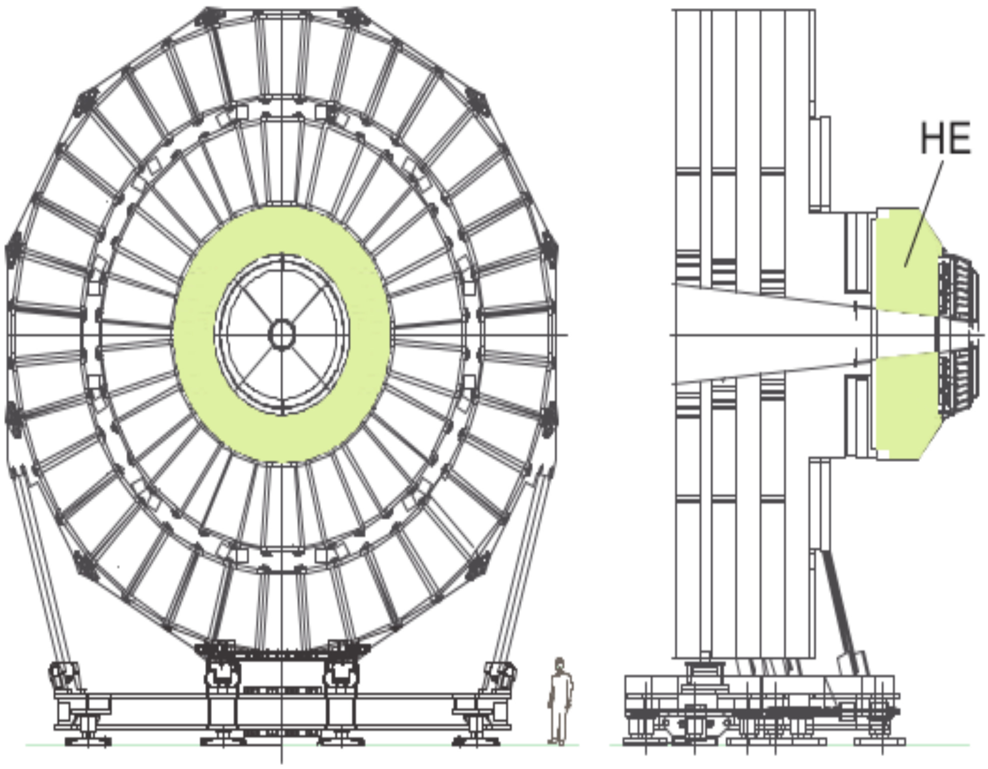

Figure 2.4: Hadron endcap calorimeter [5].

When the light comes out from trapezoidal shaped scintillators, it is captured and carried by wavelength shifting (WLS) optical fibers to the readout box. Like HB, clear fibers bring the light to ODU, and finally ODU bring the light to HPDs.

2.3.3 Hadron outer calorimeter

Hadron Outer Calorimeter [8] covers the | η | < 1.3 range, between magnet and muon system. Main purpose of HO is to detect the tails of hadronic showers. With the help this information the late showers are detected. Therefore, HO helps to improve the E_T^{miss} which has a crucial role in Higgs boson and beyond the SM searches.

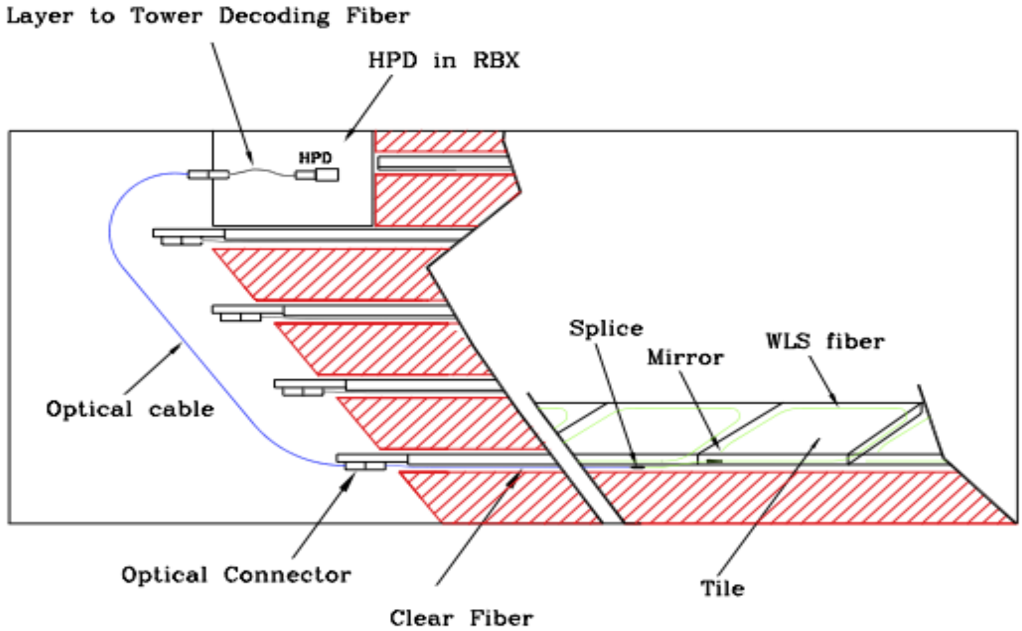

Figure 2.5: Scheme of the hb/he/ho optics [6].

The light coming out of the tile scintillators is collected by WLS, then it is carried by clear optical fibers to optical connectors. Optical connectors deliver the light to the HPDs. Because of the fringe and misalignment of magnetic and electrical fields, HPDs at HO are not working stably. In 2013 silicon photo multipliers (SiPM) will replace the HPDs.

2.3.4 Hadron forward calorimeter

The Hadron Forward Calorimeter (HF) [8] covers 3.0 < | η | < 5.0 range, and it is constructed on both sides of CMS detector. It is designed to make CMS a hermetic detector (thus better E_T^{miss}) measurement and to provide forward jet tagging, which are important for Higgs boson searches via vector boson fusion (VFB) processes. HF has steel absorber structure and especially selected quartz fibers were inserted in this medium. Hadron Forward Calorimeter has two types of fibers; long and short and they are read out with separate PMTs. Each read out box (RBX) has 24 PMTs.

Long fibers are inserted 22 cm in front of the short fibers. There are 18 wedges for HF+ and 18 wedges for HF-. When a particle comes to HF, it starts to interact with absorber and produce charged and light particles (usually electrons and positrons) inside shower produce cherenkov light when traversing quartz fibers. Cherenkov photons are captured inside quartz fibers if production angle is smaller than numerical aperture. The light is transmitted to the PMTs and an electronic signal is formed with the use of HCAL electronics.

2.3.5 Hcal read-out system

Read-out system of HCAL can be described as two different parts: Front-end and back-end electronics. Front-end electronics are inside the detector and consist of HPDs or PMTs, Charge-Integrator and Encoder (QIE) cards. Back-end electronics are located at the higher levels of the CMS cavern and it consists of HCAL Trigger Readout (HTR), trigger and data acquisition system (DAQ) [18].

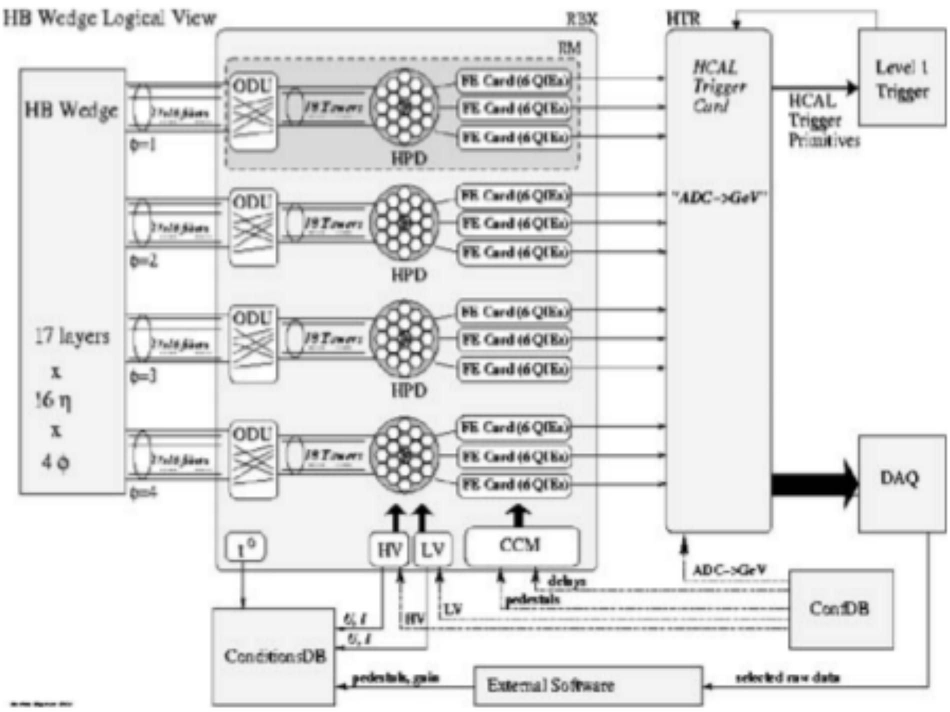

Figure 2.6: HCAL read-out electronics [6].

At HB/HE and HO the optical signals are transferred by clear fibers to HPDs. HPDs convert this optical signal to electric signal. At HF optical signals are transferred by quartz fibers bundles which carry the signal directly to PMTs and PMT signals are converted to electronic signal as well.

Analogue signal comes from HPDs or PMTs are converted to digital signal with Charge-Integrator and Encoder (QIE) cards. After the signal comes out QIE it is brought to HTR system at the CMS cavern [8].

Figure 2.6 shows overview of HCAL read-out/trigger chain.

2.4 Muon System

Most of the new physics models have muon in the final states, and as the name of the experiment implies detection of muons is very important for CMS. Muons are less affected by tracker and calorimeters than electrons, and they leave tracks on all of the detector. With the help of these tracks and powerful magnet bending power muon reconstruction is easily done [19].

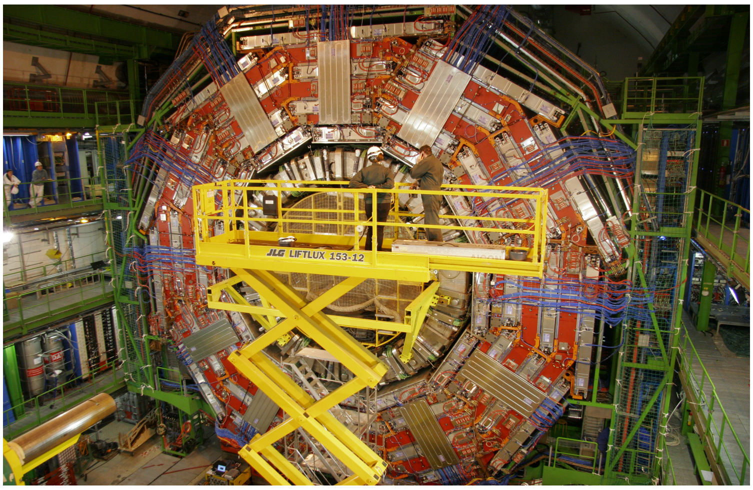

Figure 2.7: Muon chambers [7].

The muon system has three functions: identification, momentum measurement, and triggering. For these three functions the system has three types of detectors [6].

1) Drift Tubes: Drift tubes covers $|\eta| < 1.2$. They are inserted at the barrel region of muon system.

2) Cathode Strip Chambers: They are at the endcap regions, $0.9 < |\eta| < 2.4$.

3) Plate Chambers: The plate chambers are at the both barrel and endcap region.

2.5 Physics Aim of Cms Experiment

In the early of 1990s CMS design process was begun. The main purpose of the experiment is to detect Standard Model Higgs boson, so CMS was designed especially for this exploration in mind. Besides Higgs boson CMS provides a lot of research area in particle physics such as search for supersymmetric particles, extra dimensions, massive vector bosons, Heavy ion physics etc.

Standard Model studies contain QCD , electroweak and flavour physics. Through this studies it is possible to achieve more information beyond the Standard Model. E_T^{miss} might lead to lightest supersymmetric particle (LSP). Besides, the existence of extra dimensions can be useful for characteristic energy scale of quantum gravity [8].

In B quark studies, considerable progress has been achieved in understanding heavy-quark production at Tevatron energies. However some important theoretical uncertainties are still remaining. B-quark studies represent a test of theoretical approaches aimed to describe heavy flavor production [20].

Top-quark researches are very important for understanding of the $t\bar{t}$ production mechanism. Most of the new physics model contain top-quarks either as the background or in the main research. For instance top to tau dilepton channel is very important because it may enlight the existence of a charged Higgs boson [21].

Higgs physics is an important goal of LHC physics program. In the Standard Model electroweak symmetry breaking is explained via Higgs mechanism. But Higgs has not been observed yet. Main goal of the Higgs research is to find the channels containing rare events of this Higgs boson [22].

Supersymmetry (SUSY) is a theory beyond the Standard Model. It is preferred because SUSY solves the hierarchy problem and allows the unification of gauge couplings. Most of supersymmetric particles might be neutral, stable and weakly interact. Research of SUSY is focused on these particles that make up dark-matter which is most significant unsolved problem in particle physics [23].

The research of exotic physics contain various subjects: Microscopic black holes, which is the predictions of theories with low-scale quantum gravity. Dark matter researches investigates large P_T photon and E_T^{miss}. Extra dimensions is another theory of solving the hierarchy problem in Standard Model [24].

The main goal of heavy-ion collisions is to study the behavior of quarks and gluons at extreme condition of pressure, density and temperature similar with existed shortly after Big Bang [25].

3. HPD AND NOISE

Hybrid Photo Diode was invented in 1957 [26]. Since the silicon chip technology was not developed enough, HPD was not regarded as practical photodiodes. The motivation of HPD's rediscovery was the demand of position sensitive photodiode and insensitivity to magnetic field photodiode in 1987.

3.1 Hybrid Photo Diodes

HPD is a photodetector which has similar construction like PMT, and also it has noise-free gain and stability like photodiode [27]. Unlike PMT, in HPD the electron multiplier structure is replaced by silicon diode placed in the same vacuum housing [28]. This difference makes the HPD a vacuum photodiode tube.

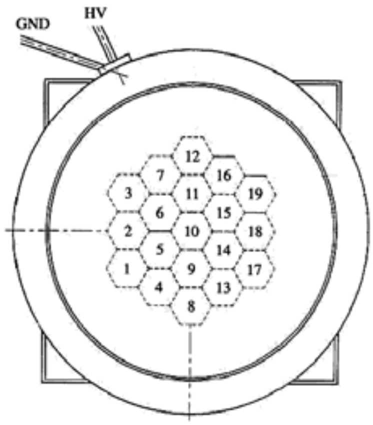

Figure 3.1: Pixels of hpd [8].

When light comes to photocathode, it gives its energy to electron and the excited electron is emitted from matter. But these photoelectrons have low energy, therefore high voltage (10-15 kV) is applied and this accelerates them in vacuum. The energetic photoelectrons lose their energy in the silicon diode through the creation of electron-hole (e/h) pairs [28], e/h pairs are freed at the rate of 1 for every 3.6 eV [27]. Also pixelation of the silicon diode makes HPD an effective position sensitive device.

Consequently HPD is a simple, stable, position sensitive and insensitive to magnetic field photodetector [27].

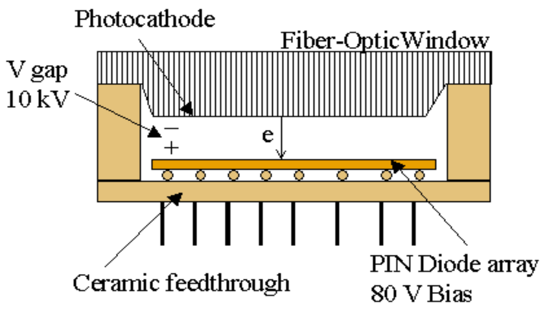

Figure 3.2: Structure of hpd [9].

3.1.1 Hcal hpd structure

The barrel, end-cap, and outer parts of the HCAL are read out by using specially designed pixelated hybrid photodiodes (HPDs) [29]. The main reason to use Hybrid Photo Diodes is that CMS is a enormous solenoid and inside the detector there is a huge magnetic field (up to 4 Tesla), so HPDs are specially designed to be able to work effectively in magnetic field. There had to be a silicon-based system because of the magnetic field. At that time there were two possibilities; multi-channel HPD or individual avalanche photodiodes (APD) in the same type of ECAL. This decision was made by observing pions, electrons an muons in 1995 beam tests at CERN. HPD has been chosen because of its better response and quantum efficiency than APD [29].

On the top side of HPD, there is an optical window that protects light sensitive photocathode. The light frees electrons by passing from the window through photocade surface due to the photoelectric effect. These free electrons are first accelerated inside vacuum tube by a potential difference, then they are slowed down hitting silicon diodes across the tube and finally the signal appears. The analog signal from the HPD is converted to a digital signal by QIE (Charge-Integrator and Encoder) [8]. The QIE has four capacitors which are connected in turn to the input, during 25 ns (time slice) period for each.

3.2 Hpd Noise

The HPDs are found to generate signal even when there is no light coming from the detector channels [10]. These signals are called as “noise” and can be divided in three categories, namely thermal emission, ion feedback, and discharge.

3.2.1 Thermal emission

In the photoelectric effect, electromagnetic radiation gives energy to electrons. When their excited energy is greater than work function of photocathode, they are emitted from the matter and they spread. These emitted electrons called as photoelectrons.

In a photocathode, thermal fluctuations occasionally give an energy to electron above the work function, which is the minimum energy that must be given to an electron to liberate it from the surface. In this case electron is emitted from photocathode and accelerated by the high voltage. This kind of noise is called thermal emission noise. The thermal emission signal is much smaller than the ion feedback and discharge.

Photocathodes work functions is obtained using Richardson-Dushman equation [30]:

$$J_s = AT^2 e^{-\frac{\phi}{kT}} \tag{3.1}$$

where J_s is current density of emission , A is Richardson's constant, T is temperature, ϕ is work function of photocathode, k is Boltzmann constant.

3.2.2 Calculation of thermal emission current density

The quantities in equation **3.1** has the following numerical values [9];

$A = 1202\ 10^2\ (\frac{mA}{cm^2K^2})$

$T = 300\ (K)$

$\phi = 1.55\ (eV)$

$k = 8.6173324\ 10^{-5}\ (\frac{eV}{K})$

Therefore the current density of emission can be found as

$$J_s = 9.95\ 10^{-17}\ (\frac{mA}{cm^2}) \tag{3.2}$$

In terms of electrons, $1\ (A) = 6.24\ 10^{18}\ (\frac{e}{sec})$, by using this J_s becomes;

$$J_s = 6.21\ 10^2 (\frac{e}{cm^2\ sec})$$

Since HPD's photocathode surface is 5.75 cm^2, it becomes

$$J_s = 35.71\ 10^2(\frac{e}{sec})$$

For 1 electron, HPD gives 0.33 (fC), therefore

$$J_s = 11.78\ 10^2(\frac{fC}{sec})$$

In LHC, there are 4 10^7 bunch crossing per second. This gives the thermal emission current density as

$$J_s = 2.945\ 10^{-5}(\frac{fC}{BX}) \quad \textbf{(3.3)}$$

With the help of this calculation, if the bunch crossing rate is determined, thermal emission rate can be easily computed.

3.2.3 Ion feedback

Vacuum system is needed to accelerate the photoelectrons properly but it is not possible to create a perfect vacuum between photocathode and silicon. Therefore, it may contain gas molecules that become ionized when they are hit by thermal electrons. These ionized particles cause more electrons to be freed from cathode surface and generates another noise component as a result of being accelerated by the energy field that is formed in high potential difference.

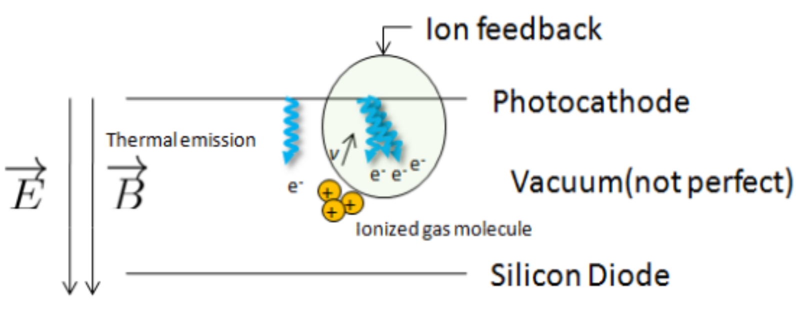

Figure 3.3: Illustration of thermal emission and ion feedback noise in hpd.

3.2.4 Discharge

Discharge noise is probably related to misalignment of magnetic field and electric field. As a result of this due to electrical discharge occurs and leaks from the wall of HPD.

All HPD channels gives noise greater than threshold but it does not effect all HPDs in the same readout box [10]. This is the major noise contribution over the 100 GeV.

4. HPD NOISE LIBRARY

The HPD Noise Library package is a ROOT based framework which includes 3 different programs:

Library producer: This code makes a simple analysis of the HPD noise data collected by special triggers and produces a ROOT file which is in the HPD noise data format.

Library reader: This is the interface code for the user. It is responsible to read and return collection of noisy HCAL channels with data in each time slice, including ion-feedback simulation, if requested. Measured noise rates are used for channel handling. A feature of time slice shifting for the noise is added. This allows user to adjust timing of the noise collected with special triggers.

Event Mixer: This code mixes the created library noise to Monte Carlo (or data).The user can see the effect of HPD Noise to data with this event mixer.

4.1 Hpd Noise Files

Except the HPDNoiseLibraryProducer, other HPD Noise files are stored in CMSSW SimCalorimetry/HcalSimAlgos Package structure.

The class structures are defined in the following source codes:

- HPDIonFeedbackSim
- HPDNoiseData
- HPDNoiseDataCatalog
- HPDNoiseDataFrame
- HPDNoiseLibraryReader
- HPDNoiseLibraryReaderTest
- HPDNoiseMaker

- HPDNoiseReader
- HPDNoiseLibraryProducer

HPDIonFeedbackSim is a class to simulate HPD ion feedback noise. The deliverable of the class is the ion feedback noise for an HcalDetId in units of fC or GeV.

HPDNoiseData is a class in HcalSimAlgos package. As the name implies it is responsible for creation of special HPD Noise Data frame. The data frame consists of HcalDetId and floating that corresponds noise.

HPDNoiseDataCatalog is an object to store HPD instance name and noise rate for the instance. The file contains setRate() function to set the user given noise rate.

HPDNoiseDataFrame is an object to store all timeslices of noise signal frame.

HPDNoiseLibraryReader is a class to read HPD noise from the library. The deliverable of the class is the collection of noisy HcalDetIds with associated noise in units of fC for 10 time samples.

HPDNoiseLibraryReaderTest is a test program for the user to show how to read from library.

HPDNoiseMaker consists of addHpd(), setRate(), newHpdEvent() and totalEntries() functions. The class uses HPDNoiseData and HPDNoiseDataCatalog classes. Duty of the class is creation of new HPD Noise Events, set information about rates and it also stores total entry number.

HPDNoiseReader is a class to read HPD noise events from the library that contains getHandle(), dischargeRate(), ionFeedbackFirstPeakRate(), ionFeedbackSecondPeakRate(), emissionRate(), totalEntries(), getEntry() functions.

HPDNoiseLibraryProducer uses HPDNoiseMaker and HPDNoiseData classes. Main task of producer is to generate a ROOT file that stores charge and rate information of each HPD.

4.2 Hpd Noise Library Producer

HPD Noise Library is aimed to give more specific information to the user by using HCAL electronics numbering scheme information instead of iϕ information that was used in older version. Library works effectively with HB/HE self trigger local data (which is taken using special triggers in CMS) and global raw data (which is taken using LHC's global triggers) (see App B.1).

The program obtains readout box (RBX) and readout module (RM) information by connecting electronic map function called logical map that is created for CMSSW, to Detector ID object. Then it is copied to the ROOT branches that were previously created with the name format rbx.name()+"_RM_"+rm.id() (i.e.: HBP12_RM_1)

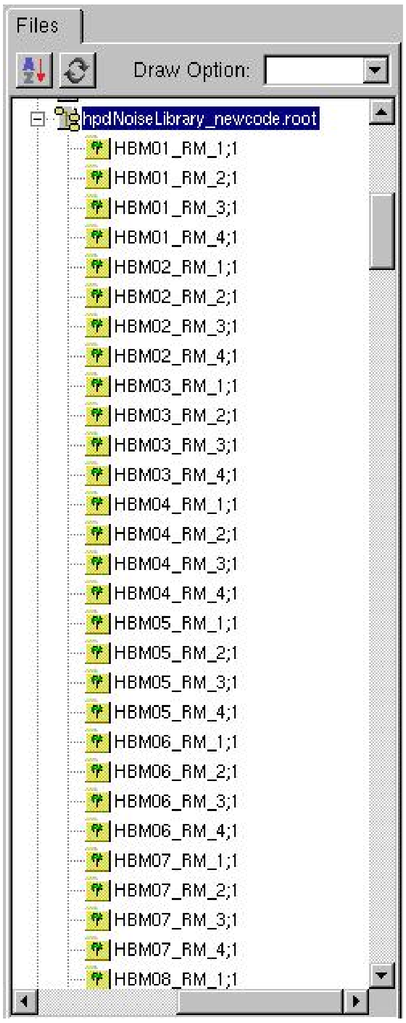

Figure 4.1: Root branches of created library

The program obtains the noises for HB-HE HPDs. There are four readout modules (pack of HPD and QIE cards) inside readout box. Each sub detector (HB±, HE±) has 18 readout boxes, making a total of 288 unique ROOT branches by following the naming scheme described above. During the run time, noise information is added to these branches according to their channel location. HO part can also be added with a parameter change without a need for recompilation.

Python configuration file provides parameters to user in order to determine event limit for the library, such as how many event to be written in total (event number), trigger rate and noise threshold. The noise in the library recorded in femtoCoulomb (fC) unit.

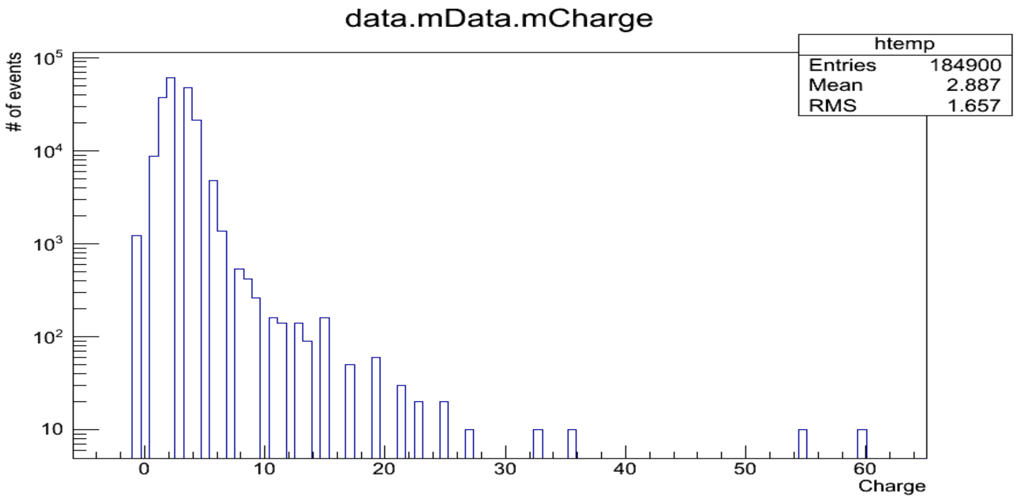

Figure 4.2: Example histogram from library

4.2.1 Noise data frame

HPD Noise Library Producer uses Noise Data Frame, which contains HPD Noise Data and HPD Noise Maker classes. The stored noise data type is defined at HPD Noise Data class. The type is a map which contains HCAL detector id and charge values in fC for noisy HPDs. HPD Noise Maker's function is to add HPD information, store total entry number for each HPD, and set the rate information for each HPD.

4.2.2 Hpd noise library producer working system

HPD Noise Library Producer operates under CMS Software. The code is like a C++ class, consist both standard C++ functions and CMSSW special functions.

The code fundamentally contains beginJob(), endJob(), beginRun(), endRun() and analyze() functions.

In beginJob(), code calls MakeHcalPixelNames() function that creates a map in which there is special sting name corresponding to each detector ID ("Readout box"_"Readout Module"), uses HPD Noise Maker to add every HPD in HPD Noise Library uses further steps of the program.

In analyze() section the algorithm looks at every time slices event by event and calls hasPassed() function to check whether the noise is greater than user defined threshold.

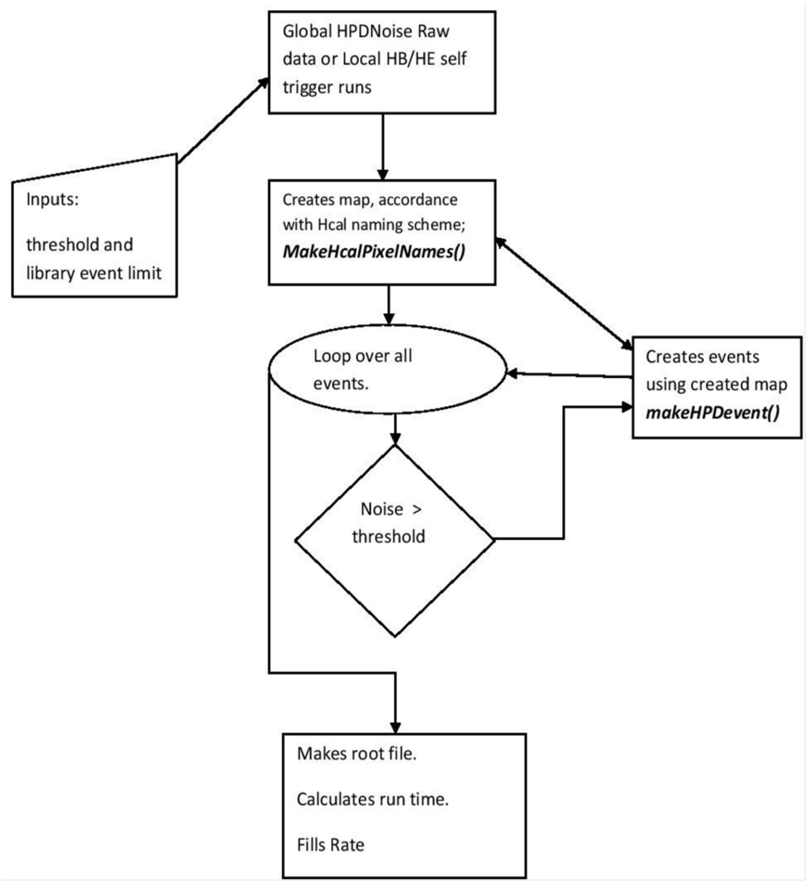

Figure 4.3: Flowchart of hpdnoiselibraryproducer program

If it is greater than threshold, hasPassed() function calls makeHPDevent() function to add the digi information.

In endJob(), class closes and deletes most of the pointers and functions, calls fillRate() function to perform rate calculations.

4.3 Tester Code

HPD Noise Library Reader is configured for HPD Noise Library Producer which is successfully updated for CMSSW_5_2_3.

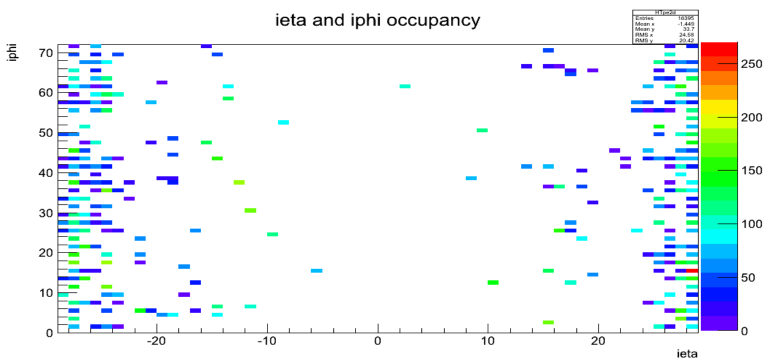

Figure 4.4: An example histogram for hpdnoiselibraryreadertest output

Library's validity is tested by HPD Noise Library Reader. For a cross-check, the values read from data file are evaluated in terms of being noisy or not, based on prerequisited criteria. User gets the values in HPD noise data format. Also user can choose biased or not biased noise, using functions getBiasedNoisyIDs() or getNoisyIDs(). Furthermore user can shuffle the data using shuffleData() function, which is very helpful for user to adjust timing of the noise collected with special triggers. The purpose of this test code is to show user how to use library and to demonstrate which results can be obtained.

4.3.1 Hpd noise library reader working system

The tester code uses HPDNoiseLibraryReader class, which operates NoiseDataFrame of created library. First of all for cross-check, it compares ROOT branches and fills HcalPixelNames vector with them. After that, it calles fillRates() function, obtains the discharge and ion feedback rates.

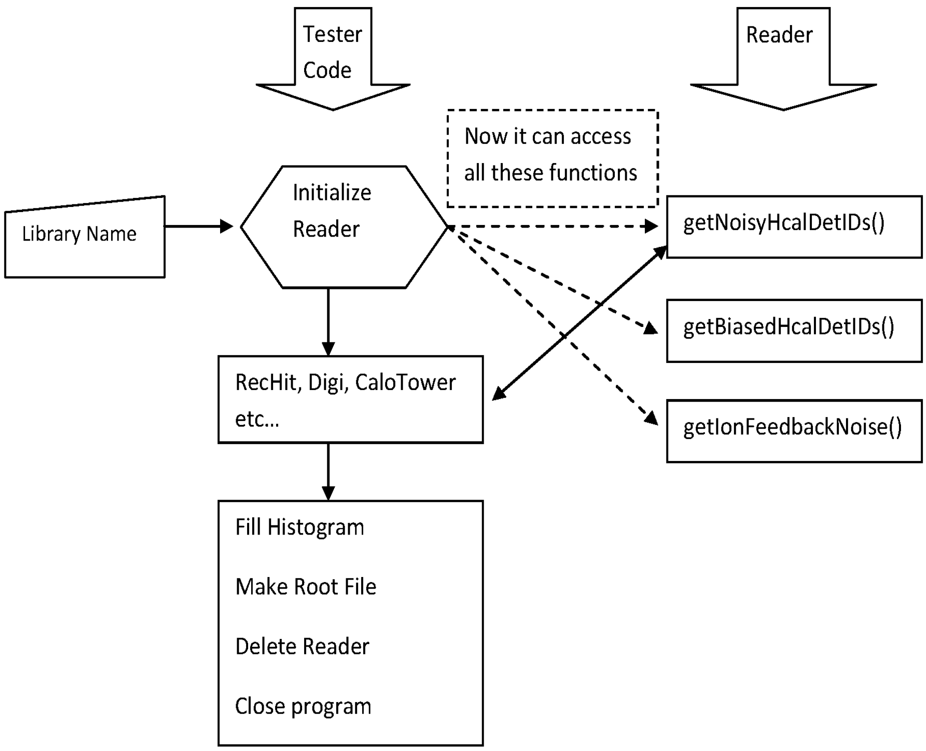

Figure 4.5: Flowchart of hpdnoiselibraryreader program

With the initialization of HPDNoiseLibraryReader, user can access, getNoisyIDs(), getBiasedNoisyIDs(), getIonFeedbackNoise() functions. This library can be used to mix noise for HCAL objects containing HCALDetId information (RecHit, Digi, CaloTower etc...).

4.4 Rechit Mixer Code

RecHit Mixer code serves as an example to demonstrate how the HPD noise can be mixed with RecHit obtained from Monte Carlo processes for physics simulations. Once a new RecHit collection is made, high-level object such as jets, missing transverse energy, can be reconstructed by using them.

Since the noise in library is stored in fC units, it is converted to energy (GeV) before altering original RecHit collection of Monte Carlo process. The conversion constants from fC to GeV are used from the HCAL database during runtime. An example code is given in the Appendix B.2.

4.4.1 Rechit mixer working system

The RecHit Mixer code is a class using both standard C++ functions and CMSSW functions. It is an EDProducer, that means code does not analyze but it produces an Event Data object.

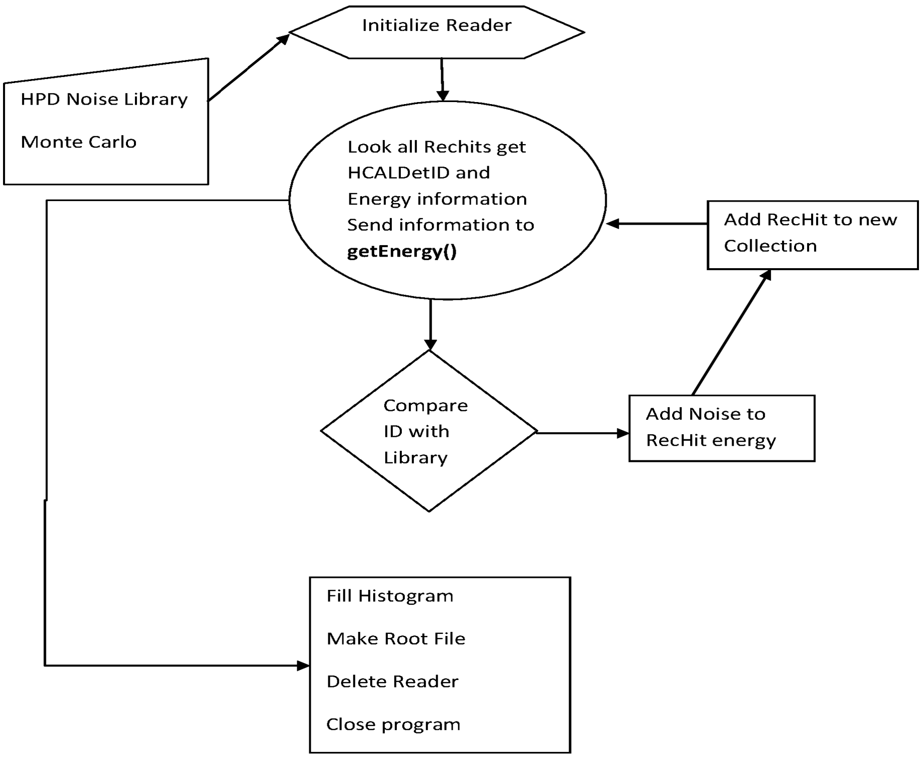

Figure 4.6: Flowchart of rechit mixer program

The code operates on created Monte Carlo events and HPD Noise Library data. In beginJob(), it initializes the HPDNoiseLibraryReader to get biased noise. In produce() function, it looks at every HB/HE RecHit events, takes detector id and energy information, after that it sends this information to getEnergy() function. In getEnergy function, code looks at Biased HCAL detector ids which is retrieved from HPD Noise Library reader. Furthermore it compares ids, determine whether they match or not. If they match, it adds noise to RecHits energy. Finally code adds this new energy information to the RecHit.

5. PHYSICS RESULTS

In the analysis, QCD Monte Carlo data used because of the high cross section production at the LHC. The python file created using the QCD_Pt_170_230_8TeV_cfi.py file with cmsDriver program. With this config file, total of 98000 event created. The mixed noise data produced with HPDNoiseLibraryProducer using 161351st run in HCALHPDNoise Raw dataset threshold selected as 50 fC. Total of 3800 noisy events created.

5.1 Quantum Chromodynamics

When the bubble chambers were invented in 1950s, hadrons were discovered but most of the particles were not fundamental. At first they were classified by using their properties such as charge and isospin, then strangeness. In 1963 the structure of the groups could be explained by the existence of three flavors of smaller particles inside the hadrons which are named as quarks. There are six types of quarks (up, down, strange, charm, bottom, top). Quarks carry charge known as color (red, blue and green).

QCD explains interactions between quarks. The color forces are mediated by gluons, they also carry charge. Electromagnetic force between photon and electron is described at QED (U(1)) which has a U(1) group structure. Strong force between quarks and gluons are explained in QCD based group SU(3) and weak electromagnetic interactions explained gauge group SU(2)xU(1) [31].

5.2 Missing Transverse Energy

Missing Transverse Energy (E_T^{miss}) refers to energy that is not detected in detector although it is expected because of the conservation of conservation of transverse momentum. At LHC, protons collide each other same energy, so initial momentum of the system is zero. Due to conservation of momentum, the final total momentum must be zero.

E_T^{miss} might be caused by some particles (such as neutrino) that can not be detected with detectors. Not only neutrinos but also some particles predicted by the theories beyond the Standard Model might cause E_T^{miss} as well. So E_T^{miss} is very important for beyond the Standard Model investigations.

5.3 Dijet Mass

The theory of strong interactions in QCD, the scattering of a pair of partons (quarks or gluons) gives the most energetic collisions. In simple case showering partons hadronize and produce two jets (dijet), that may be reconstructed to determine the dijet invariant mass, the mass of the two-parton system. The dijet Mass analyses are sensitive to the high mass scales accessible with hadronic final states. Dijet analysis is very important physics process at the LHC and it is used for looking the signals of new physics [32].

5.4 Results

QCD Monte Carlo file was created with cmsDriver software which uses pythia 8 [33] and GEANT 4 [34] programs. QCD data energy selected as 8 TeV, P_T selected as 170 to 230 GeV to see the effect of noise at hadronic states clearly. Noise data were created with HPDNoiseLibraryProducer program. The Monte Carlo and noise data mixed via RecHitMaker.

5.4.1 Missing transverse energy analysis

The noise + Monte Carlo data reconstructed with CaloMETCollection for Missing Transverse Energy Analysis.

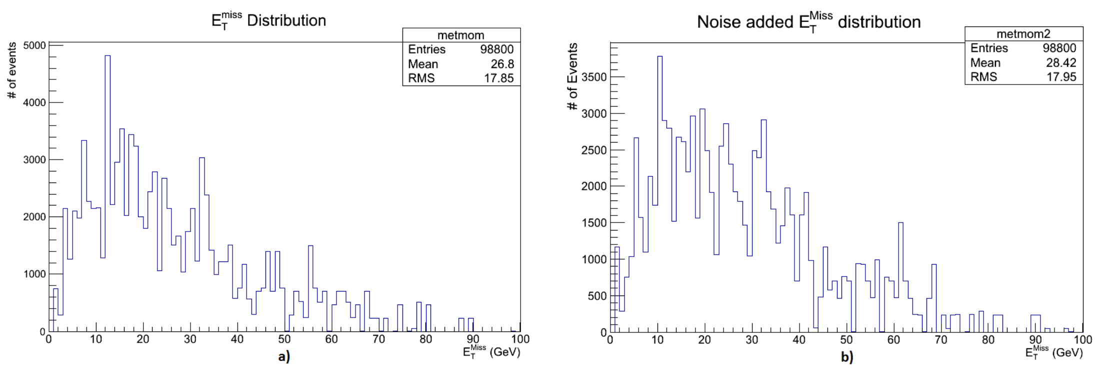

Figure 5.1: a) E_T^{miss} distribution without noise b) Noise added E_T^{miss} distribution.

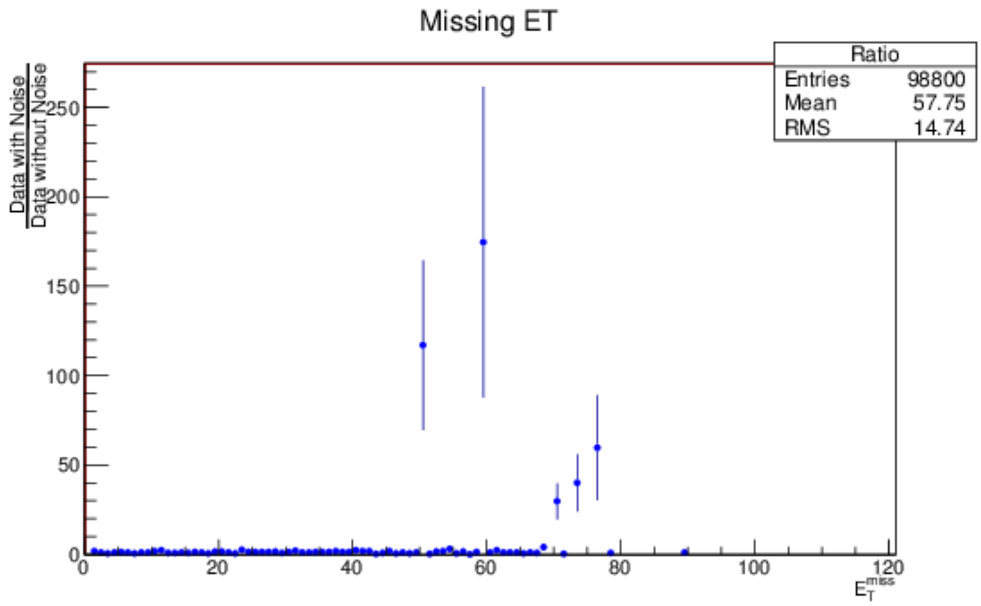

Figure 5.2: Ratio of E_T^{miss} distribution, data with noise / data without noise

The plots clearly show noise effect to E_T^{miss} between 40 and 80 (GeV).

5.4.2 Dijet mass analysis

For dijet analysis jets were reconstructed with antikt jet clustering algorithm [35]. The analysis made for barrel region ($|\eta|$ <2.5), leading two jets' of each event which P_T > 30 GeV were selected.

Invariant dijet mass calculated using Energy - Momentum equation.

$$M = \sqrt{(E_1 E_2) - (\vec{P}_1 \vec{P}_2)} \quad \textbf{(5.1)}$$

where $E_1, \vec{P}_1$ energy and momentum of first leading jet and $E_2, \vec{P}_2$ energy and momentum of second leading jet.

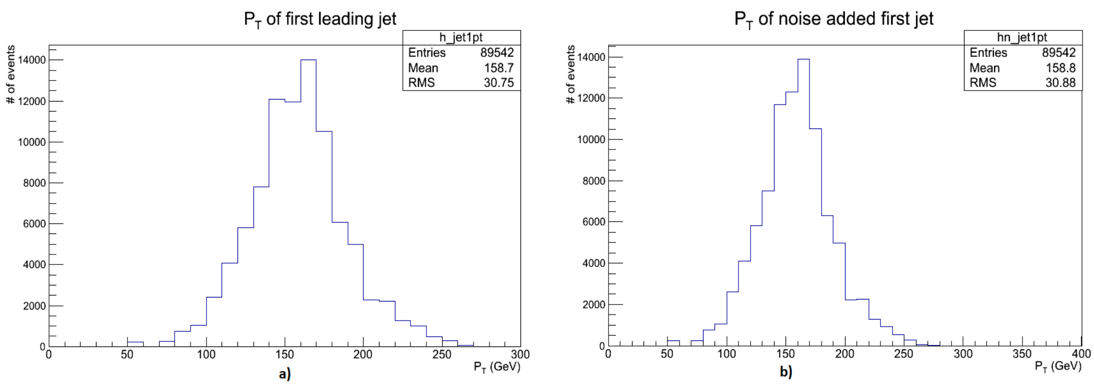

Figure 5.3: a) First leading jet P_T distribution b) Noise added first leading jet P_T distribution.

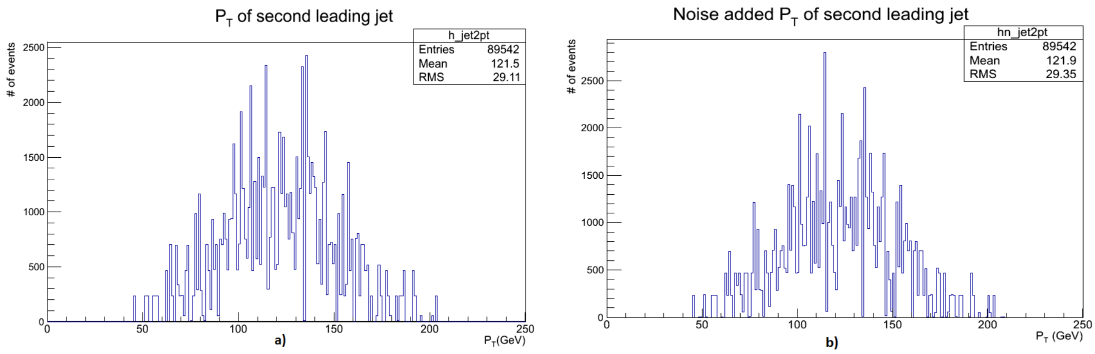

Figure 5.4: a) Second leading jet P_T distribution b) Noise added second leading jet P_T distribution.

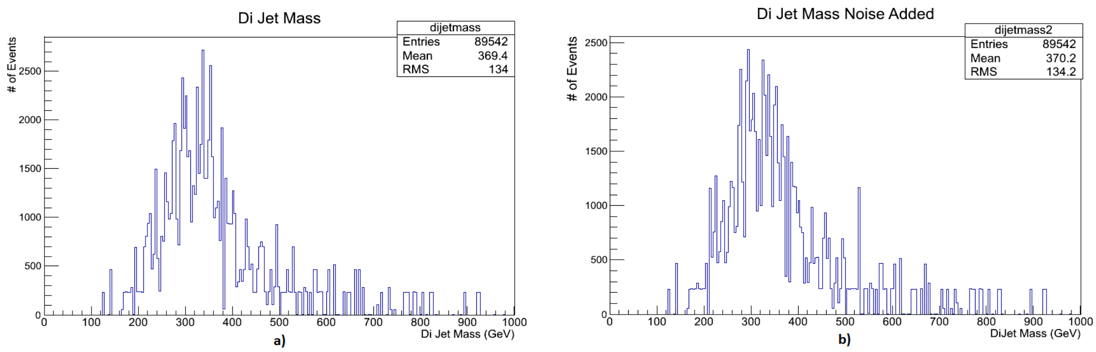

Figure 5.5: a) Dijet mass distribution b) Noise added dijet mass distribution.

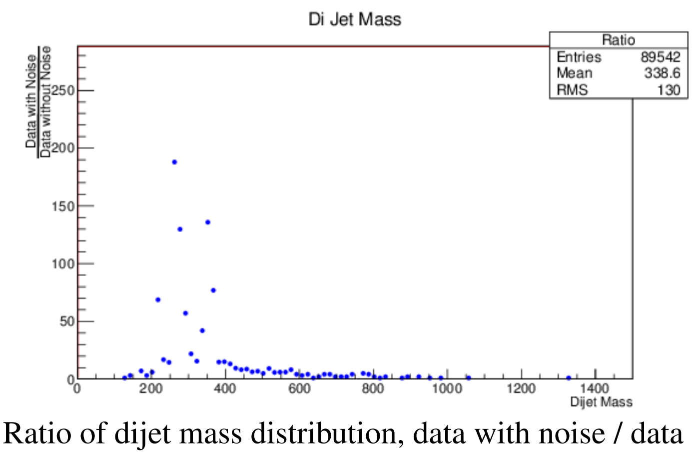

Figure 5.6: Ratio of dijet mass distribution, data with noise / data without noise

The plots clearly show noise effect to dijet mass between 200 and 600 (GeV).

6. CONCLUSIONS AND RECOMMENDATIONS

Based local (HCAL only) and global (CMS) monitoring data HPD Noise Library Producer and Reader successfully upgraded newest version of CMSSW. The noise mixing with data (or MC) is possible at the RecHit level. User can add HPD noise to any process with the provided tool. This enables users to study the effect of noise rare collision events.

The HPD noise effect to E_T^{miss} can be easily seen from figure 5.1 and figure 5.2. The effect focused between 40 and 80 (GeV) though statistically improved results might be more enlightening.

The effect of Noise to Jets' P_T, is shown at figure 5.3 and figure 5.4, effect of the noise is very slight, with the available data, it is not possible to give any definite conclusions. Also Dijet mass effect can be seen at figure 5.5 and figure 5.6, noise effect to dijet mass focused between 200 and 600 (GeV).

For clearer results, number of events might be improved for both noise and Monte Carlo data. Also threshold of the noise might be increased when creating the library.

Library will use at HLT Noise Clean-up tests at HCAL.

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APPENDICES

APPENDIX A.1

CMS is using origin as the collision point. The y-axis is vertically upward, and the x-axis is radially inward. The z-axis points along the beam direction.

The azimuthal angle ϕ is angle between the x-axis in the x-y plane. Pseudorapidity η is defined as $\eta = -\ln(\tan\frac{\theta}{2})$ or $\eta = \frac{1}{2}\ln(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z})$ where p_z is momentum of the beam direction. The polar angle θ is measured from the z-axis. [8]

APPENDIX B.1

Since it takes substantial CPU time to perform dedector simulations, lxplus batch system used for analysis. User must have CMS account to work HPDNoiseLibrary.

CMSSW_5_2_3 must be installed

```
scramv1 p CMSSW CMSSW_5_2_3
cd CMSSW_5_2_3/src
```

SimCalorimetry/HcalSimAlgos copied from cvs.

```
cvs co -d SimCalorimetry/HcalSimAlgos
UserCode/hbahtiyar/SimCalorimetry/HcalSimAlgos

cd SimCalorimetry/HcalSimAlgos

scram b
```

HPDNoiseLibraryProducer must be copied.

```
cvs co -d Analyzers/HPDNoiseLibraryProducer
UserCode/hbahtiyar/HPDNoiseLibraryProducer

cd Analyzers/HPDNoiseLibraryProducer

scram b

cd test
```

Inside this directory there are 2 python files.

hpdLocalnoiseAnalyzer_cfg.py : config file for local data

hpdnoiseanalyzer_RawToDigi_cfg.py : config file for global raw data

User can run files writing;

```
cmsRun hpdLocalnoiseAnalyzer_cfg.py
```

or

```
hpdnoiseanalyzer_RawToDigi_cfg.py
```

APPENDIX B.2

HPD Noise Analyzer Config file for Local Data

```
import FWCore.ParameterSet.Config as cms
import sys
process = cms.Process("Local")
process.load
("FWCore.MessageService.MessageLogger_cfi")
process.maxEvents = cms.untracked.PSet
( input = cms.untracked.int32(10))

process.load
("Configuration.StandardSequences.Geometry_cff")
process.load
("Configuration.StandardSequences.RawToDigi_Data_cff")
process.load
("Configuration.StandardSequences.FrontierConditions_
GlobalTag_cff")
process.GlobalTag.globaltag = 'GR_P_V28::All'

print "Enter Runnumber: "
rn = sys.stdin.readline()

RUNNUMBER = int(rn.strip())

OUTFILE = 'Localoutfile_' + str(RUNNUMBER) + '.root'
process.source = cms.Source("HcalTBSource",
    fileNames= cms.untracked.vstring(
     'rfio:/castor/cern.ch/user/c/cchcal/usc_2008/
     USC_0' + str(RUNNUMBER) + '.root'

    )
)

process.TFileService = cms.Service("TFileService",
    fileName = cms.string(OUTFILE)
)


process.hpdNoise = cms.EDAnalyzer('HPDNoiseAnalyzer',
    isLocal= cms.untracked.bool(True),
    HPDNoiseThreshold = cms.untracked.double(-1000.),
    HPDNoiseLibraryEventLimit = cms.untracked.int32
    (1000),
    HPDNoiseLibraryName = cms.untracked.string(OUTFILE),
    OutFileName =
    cms.untracked.string('summary_' + str(RUNNUMBER) +
```

```
    '.txt')
)

process.p  = cms.Path
(process.hcalDigis * process.hpdNoise)
```

HPD Noise Analyzer Config file for Global Data

```
import FWCore.ParameterSet.Config as cms
process = cms.Process("Rec")
process.load("FWCore.MessageLogger.MessageLogger_cfi")

process.load("CondCore.DBCommon.CondDBSetup_cfi")

process.maxEvents = cms.untracked.PSet
(  input = cms.untracked.int32(-1) )
readFiles = cms.untracked.vstring()
secFiles = cms.untracked.vstring()
process.source = cms.Source ("PoolSource",fileNames =
readFiles,
secondaryFileNames = secFiles)
readFiles.extend( [
       'data.root'
] );


secFiles.extend( [
               ] )

# output module
process.load
("Configuration.EventContent.EventContentCosmics_cff")
process.MessageLogger.cerr.FwkReport.reportEvery = 1

process.load
("Configuration.StandardSequences.MagneticField_38T_
cff")

#Geometry
process.load
("Configuration.StandardSequences.Geometry_cff")

# Real data raw to digi
process.load
("Configuration.StandardSequences.RawToDigi_Data_cff")

# reconstruction sequence for Cosmics
process.load
```

```
("Configuration.StandardSequences.ReconstructionCosmics
_cff")

#L1 trigger validation
process.load
("L1Trigger.HardwareValidation.L1HardwareValidation_
cff")
process.load
("L1Trigger.Configuration.L1Config_cff")
process.load
("L1TriggerConfig.CSCTFConfigProducers.CSCTFConfig
Producer_cfi")
process.roadSearchSeedsP5.MaxNumberOfCosmicClusters =
200
process.siPixelClusters.ChannelThreshold = cms.int32
(100)
process.siPixelClusters.SeedThreshold = cms.int32(20)

process.hpdNoise = cms.EDAnalyzer('HPDNoiseAnalyzer',
    isLocal= cms.untracked.bool(False),
    HPDNoiseThreshold = cms.untracked.double(50.),
    L1BitsToAccept = cms.untracked.vint32(),
    L1BitsLogic = cms.untracked.string("OR"),
    TriggerRate = cms.untracked.int32(50),
    HPDNoiseLibraryEventLimit =
    cms.untracked.int32(100),
    HPDNoiseLibraryName =
    cms.untracked.string
    ("hpdNoiseLibrary_newcode.root"),
    OutFileName = cms.untracked.string
    ("summarynewcode.txt")
)
process.load
("Configuration.StandardSequences.Geometry_cff")
process.load
("RecoJets.Configuration.CaloTowersES_cfi")
process.load
("Configuration.StandardSequences.RawToDigi_Data_cff")
process.load
("RecoLocalCalo.Configuration.hcalLocalReco_cff")
process.load
("Configuration.StandardSequences.
FrontierConditions_GlobalTag_cff")
process.GlobalTag.globaltag = 'GR_P_V28::All'
process.p = cms.Path
(process.RawToDigi_woGCT * process.hpdNoise *
process.hcalDigis)
```

APPENDIX B.3

```
MakeNewRecHits::MakeNewRecHits
(const edm::ParameterSet & iConfig)
{
  using namespace std;
  rand = new TRandom ();
  reader = new HPDNoiseLibraryReader (iConfig);
  //register new collection
  produces < HBHERecHitCollection > ();

}


MakeNewRecHits::~MakeNewRecHits ()
{
  delete reader;
}


void
MakeNewRecHits::produce
(edm::Event & iEvent, const edm::EventSetup & iSetup)
{
  using namespace edm;
  using namespace std;
  iEvent.getByLabel ("hbhereco", hbhe_recHits_h);
  const HBHERecHitCollection *hbhe_recHits_old =
    hbhe_recHits_h.failedToGet ()? 0 : &*hbhe_recHits_h;
  if (!hbhe_recHits_old)
    {
      cout << "HBHE Rechits not found" <<
endl;
      return;
    }
  std::auto_ptr < HBHERecHitCollection >
  pOut (new HBHERecHitCollection ());
  for (HBHERecHitCollection::const_iterator
       hhit = hbhe_recHits_old->begin ();
       hhit != hbhe_recHits_old->end (); hhit++)
    {
      HcalDetId hcalDetId_rh = hhit->id ();
      int ieta = hcalDetId_rh.ieta ();
      int iphi = hcalDetId_rh.iphi ();
      int idepth = hcalDetId_rh.depth ();
      HcalCalibrations calibs =
conditions->getHcalCalibrations (hcalDetId_rh);
      HBHERecHit aHit = (HBHERecHit) (*hhit);
```

```
      float oldEnergy = aHit.energy ();
      float newEnergy =
      getEnergy (aHit.energy (), aHit.id ());
      HBHERecHit newHit
      (aHit.id (), newEnergy, aHit.time ());
      pOut->push_back (newHit);
    }
  iEvent.put (pOut);
}

void
MakeNewRecHits::beginJob ()
{
}

void
MakeNewRecHits::endJob ()
{
}

void
MakeNewRecHits::beginRun
(edm::Run & iRun, edm::EventSetup const &iSetup)
{
  iSetup.get < HcalDbRecord > ().get (conditions);
}
float
MakeNewRecHits::getEnergy
(float oldEnergy, HcalDetId id)
{
  using namespace std;
  HcalCalibrations calibs =
  conditions->getHcalCalibrations (id);
  vector < pair < HcalDetId,
  const float *>>NoisyHcalDetIds;
  NoisyHcalDetIds =
  reader->getBiasedNoisyHcalDetIds ();
  float total = 0.;
  float totalgev = 0.;
  vector < pair < HcalDetId,
  const float *>>::const_iterator itNoise;
  for (itNoise = NoisyHcalDetIds.begin ();
        itNoise != NoisyHcalDetIds.end ();
       ++itNoise)
    {
      HcalDetId theId = (*itNoise).first;
      if (id == theId)
{
  const float *noise =
```

```
  (*itNoise).second;
  for (int ts = 3; ts < 7; ++ts)
    {
      total += noise[ts] - calibs.pedestal (1);
    }
  float respcorrgain = calibs.respcorrgain (1);
  totalgev = total * respcorrgain; //for GeV
}
    }
  return (totalgev + oldEnergy);
}

//define this as a plug-in
DEFINE_FWK_MODULE (MakeNewRecHits);
```

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