

**Search for Supersymmetry in opposite-sign
same-flavour dilepton events with the CMS
detector in proton-proton collisions at**

$$\sqrt{s} = 8 \text{ TeV}$$

Von der Fakultät für Mathematik, Informatik und Naturwissenschaften der RWTH Aachen University zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften genehmigte Dissertation

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Zusammenfassung

Abstract

Contents

Zusammenfassung	i
Abstract	i
1 Introduction	1
2 The Standard Model and its extension to Supersymmetry	3
2.1 The Standard Model of particle physics	3
2.2 Motivation for extending the Standard Model and Supersymmetry	3
2.3 Production of lepton pairs in supersymmetric models	3
2.4 Kinematic edges in the dilepton invariant mass spectrum	3
3 Experimental setup	5
3.1 The CERN Large Hadron Collider	5
3.2 The CMS detector	6
3.2.1 The tracking system	7
3.2.2 The electromagnetic calorimeter	8
3.2.3 The hadron calorimeter	10
3.2.4 The muon system	12
3.3 Trigger and data acquisition	14
4 Data analysis and event selection	17
4.1 Trigger and event processing	17
4.2 Object reconstruction	17
4.2.1 Muon reconstruction and selection	17
4.2.2 Electron reconstruction and selection	18
4.2.3 Observables reconstructed with Particle Flow	20
4.3 Datasets	25
4.4 Event selection	25
5 Estimation of Standard Model backgrounds	27
5.1 Flavour-symmetric backgrounds	27
5.2 Backgrounds containing a Z boson	27
5.3 Investigation of possible further backgrounds	27
5.4 Search for a kinematic edge with a fit	27
6 Results	29
6.1 Result of the counting experiment	29
6.2 Result of the search for a kinematic edge	29
7 Interpretation in simplified models	31
7.1 Simplified Models for Supersymmetric Signatures	31
7.2 The T6bbledge and T6bbslepton model	31

7.3 Interpretation of the counting experiment in simplified models	31
8 Outlook to LHC Run II	33
9 Conclusion	35

1 Introduction

2 The Standard Model and its extension to Supersymmetry

2.1 The Standard Model of particle physics

2.2 Motivation for extending the Standard Model and Supersymmetry

2.3 Production of lepton pairs in supersymmetric models

2.4 Kinematic edges in the dilepton invariant mass spectrum

3 Experimental setup

3.1 The CERN Large Hadron Collider

The Large Hadron Collider (LHC) [1], located at CERN near Geneva and stretching far into the french countryside, is capable of colliding protons and lead ions at higher energies than any of its predecessors. Also the instantaneous luminosity delivered to the experiments exceeds that of any previous machine at the energy frontier. It was constructed in the tunnel formerly inhabited by the LEP electron-positron collider in 100 m depths below the surface with a circumference 27 km. It was designed to collide protons at a centre-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$ with instantaneous luminosities of $10^{34} \text{ s}^{-1} \text{ m}^{-2}$.

The LHC consists of eight arcs, as shown in Figure 3.1, where superconducting dipole magnets are used to provide a magnetic field of up to 8.3 T at the highest planned energies to bend the charged particles along the curvature of the tunnel, while quadrupole and other specialised magnets are used to focus the beams. In straight segments between these arcs, LHC infrastructure and the experiments are located. The infrastructure components include the cooling facilities necessary to reach a temperature of 1.9 K around the ring, the superconducting cavities in which the protons are accelerated by standing electromagnetic waves, collimators for beam cleaning and the beam dump, where the beam is ejected from the LHC at the end of fills. In the other four straight segments the beam is brought into collisions, which are studied by the four large experiments at the LHC. Of these, CMS [2] and ATLAS [3] are multi-purpose detectors with a diverse physics program, while ALICE [3] and LHCb [4] are more narrowly focused on heavy ion collisions and flavour physics, respectively.

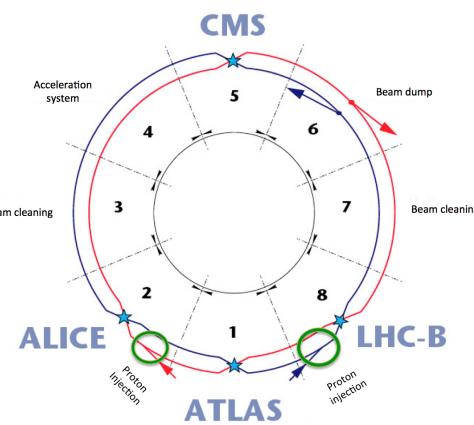


Figure 3.1: Schematic view of the LHC with its eight arcs. The four interaction points, where the experiments are located, are marked with blue stars. Other important parts of the LHC infrastructure are also indicated [5].

The protons circulating the LHC are injected at an energy of 450 GeV after running through a chain of pre-accelerators, the Linac2, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS). The proton beams are separated into bunches of about 10^{11} particles. Though being 25 ns by design, corresponding to up to 2808 bunches in the LHC, the smallest spacing between bunches in time was 50 ns throughout the running in 2012 and most of 2011. In these running conditions, after three years of running in the years 2010 to 2012, constituting the so called Run I of the LHC, a centre-of-mass energy of $\sqrt{s} = 8$ TeV has been reached. The instantaneous luminosities delivered to the experiments reached a maximum of $7.7 \cdot 10^{33} \text{ s}^{-1} \text{ m}^{-2}$ in late 2012, as can be seen on the left side of Figure 3.2. The integrated luminosity delivered to the CMS experiments in 2012 was 23.3 fb^{-1} , exceeding that of 2011 by almost a factor of four [6], as shown on the right side of Figure 3.2.

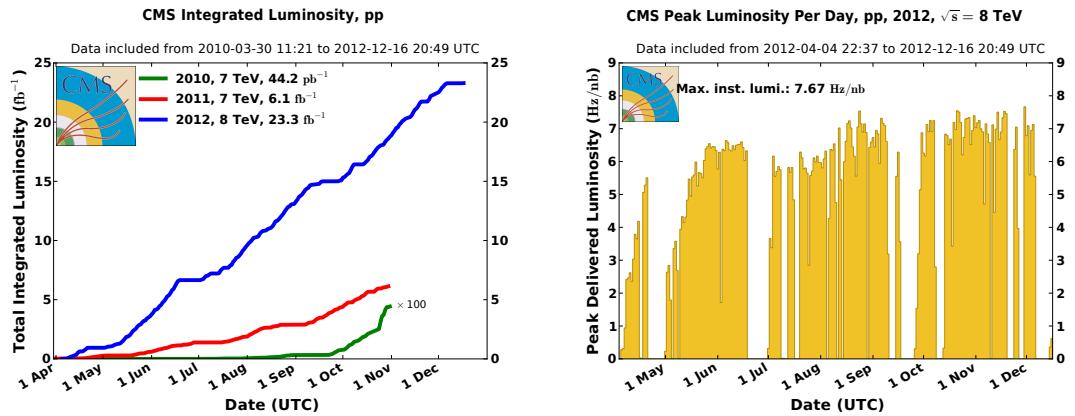


Figure 3.2: Development of instantaneous (left) and integrated (right) luminosity delivered to the CMS experiment. The left plots shows the results for all three years of data taking, while the right one only shows the 2012 data taking.

3.2 The CMS detector

Located in one of the four intersections of the LHC beams, the CMS detector is designed to measure the resulting collisions to high precision. Key ingredients are a high precision measurements of the properties of single particles as well as a good coverage of the 4π solid angle. The central element of the CMS detector is a superconducting solenoid. Cooled to 4.45 K, it is able to produce a homogeneous magnetic field of 3.8 T, which allows to measure the momentum of charged particle by bending their trajectories. As shown in Figure 3.3, the different components of the detector are layered in cylindrical shapes around the interaction point. The magnet encompasses most of the main subdetectors, namely the tracking system which measures the trajectories of charged particles and the electromagnetic and hadron calorimeters, designed to measure the energy of particles. Located outside of the volume of the solenoid are the iron return yoke and muon detectors. This cylindrical structure is complemented on both sides by endcaps, which close the solid angle in the direction of the beams and are partly located outside the volume of the solenoid. The different components are described in more detail in the following.

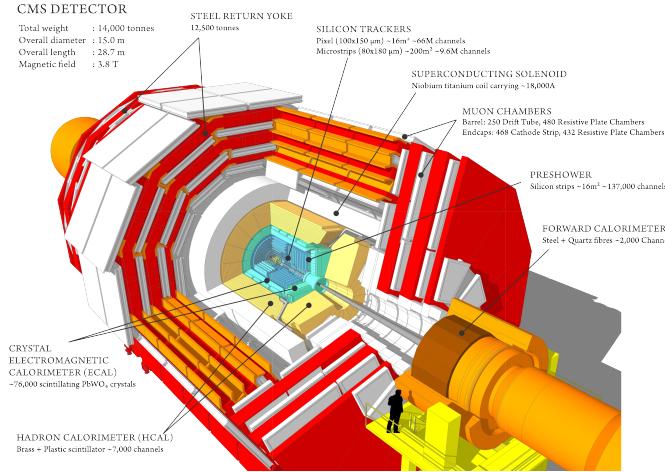


Figure 3.3: Schematic view of the CMS detector [7]. From the inside out, the tracking system is shown in blue, the electromagnetic calorimeter in green, the hadron calorimeter in light yellow, the superconducting solenoid in white, the return yoke in red and the muon system again in white.

3.2.1 The tracking system

The trajectory of charged particles can be determined by measuring the signal of the ionization they cause when traversing matter. The tracking system of the CMS detector consists of many layers of silicon pixels and strips. Combining the points at which a charged particle traverses the different layers, the trajectory of this particle can be measured. The bending of this trajectory under the influence of the magnetic field allows to determine the momentum of the particle. The tracking system has a diameter of 2.5 m and a length of 5.8 m, corresponding to a geometric coverage of $|\eta| < 2.5$. The tracking detector consists, as shown in Figure 3.4, of the pixel detector (PIXEL) surrounded by various components of the silicon strip tracker.

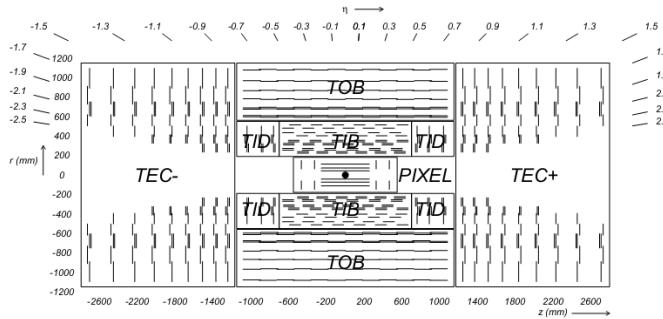


Figure 3.4: Schematic view of the CMS tracking detector. The innermost part shows the pixel detector (PIXEL), surrounded by the tracker inner barrel (TIB) and tracker inner discs (TID). The outermost parts of the tracking detector are the tracker outer barrel (TOB) and the two tracker endcaps (TEC+ and TEC-).

The silicon pixel detector

The innermost part of the tracking system in the pixel detector, which consists of three layers in the barrel region at radii between 4.4 cm and 10.2 cm, complemented by two discs perpendicular to the beam axis, located at $|z| = 34.5$ cm and $|z| = 46.5$ cm. As the particle density is highest close to the interaction point, a high granularity is needed to maintain a low occupancy of the pixel detector. Therefore the pixel detector consists of roughly 66 million pixels with a combined active area of about 1 m^2 . Each pixel has a size of $150 \times 100 \mu\text{m}^2$. The analogue readout of the pixels allows to combine the measurements of neighbouring pixels, bringing the spatial resolution down to 15 to 20 μm . This is especially important for the reconstruction of the interaction vertices and the tagging of the secondary vertices from the decay of b-hadrons.

The silicon strip detector

Further away from the interaction point, between 20 cm and 116 cm, the granularity of the tracking system is reduced. Silicon strip detectors are used, structured in four layers of the tracker inner barrel (TIB), complemented on each side with three discs of the tracker inner discs (TID). All this is surrounded by the six layers of the tracker outer barrel (TOB). The tracker endcaps (TECs) consist of nine discs each. The individual strips have a length of about 10 cm and a pitch between 80 μm in the two inner layers of the TIB and 183 μm in the four inner layers of the TOB. The single point resolution in TIB and TOB depends on the layout of the specific layer and varies between 23 μm and 53 μm .

Stereo modules, constructed by placing two modules back to back, rotated by 100 mrad, are placed in the first two layers of both TIB and TOB, the first two discs of TID and the first two and the fifth discs of the TECs. These allow for 2-D measurements, with a precision of the z position measurement of 230 μm in TIB and 530 μm in TOB.

For high momentum tracks of about 100 GeV in the region of $|\eta| < 1.6$ a p_T resolution of 1-2% is achieved, while the impact parameter of these tracks can be measured with a resolution of about 10 μm .

Compared to other tracking technologies, an all silicon tracking system as used in CMS consists of significantly more material. The material budget lies between 0.4 and 1.8 radiation length X_0 , as shown in Figure 3.5. For light charged particles such as electrons this leads to a significant probability to emit bremsstrahlung in while traversing the tracking detector, which has to be taken into account in the reconstruction of particles.

3.2.2 The electromagnetic calorimeter

The electromagnetic calorimeter (ECAL) measures the energy of electrons and photons. It uses lead tungstate (PbWO_4) crystals both as absorber and active material. The electromagnetic shower induced by the electron or photon leads to the emission of scintillation light in the crystal, which is measured at the end of the crystals by avalanche photo diodes (APDs) in

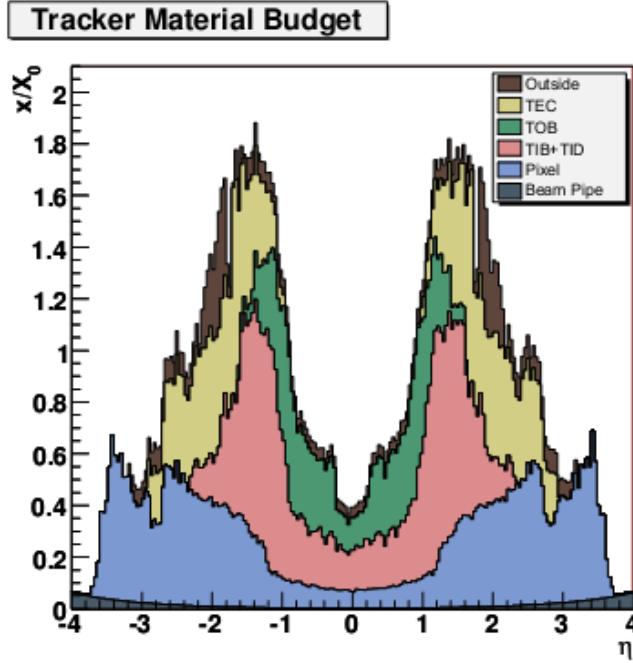


Figure 3.5: Material budget of the CMS tracking detector in units of radiation length X_0 as a function of η .

the barrel segment of the ECAL and more radiation hard vacuum photo triodes (VTPs) in the endcap region. The choice of lead tungstate was driven by the need for a material that is at the same time dense (8.28 g/cm^3), has a small Molière radius (2.2 cm) and is fast. About 80% of the scintillation light is emitted after 25 ns, which is the time between two LHC bunch crossing under design conditions. The structure of the ECAL is shown in Figure 3.6. The ECAL barrel (EB) covers the region of $|\eta| < 1.479$ and consists of 61200 crystals. They have a size of $2.2 \times 2.2 \text{ cm}^2$ at the front and $2.6 \times 2.6 \text{ cm}^2$ at the back, with a length of 23 cm, corresponding to $25.8 X_0$. In the ECAL endcaps (EE), consisting of 7324 crystal each, they are slightly larger ($2.862 \times 2.862 \text{ cm}^2$ to $3.0 \times 3.0 \text{ cm}^2$) and shorter (22 cm, corresponding to $24.7 X_0$). The EEs extend the geometric coverage of the ECAL to $|\eta| = 3.0$.

In the region of $1.653 < |\eta| < 2.6$ a preshower detector, consisting of two layers of silicon strips and two layers of lead absorber, is installed to distinguish between prompt photons and those from the decay $\pi^0 \rightarrow \gamma\gamma$. The strips, oriented perpendicular to each other, have a pitch of 2 mm, allowing to resolve the two showers of the photons from the π^0 .

The production of scintillation photons per energy deposit is temperature depend. Therefore the ECAL is kept at a temperature of $18 \pm 0.05^\circ\text{C}$, where it is about 4.5 photons per MeV.

The typical resolution of the ECAL is parametrized as

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2, \quad (3.1)$$

with three terms describing different sources of uncertainty. The first term includes statistical

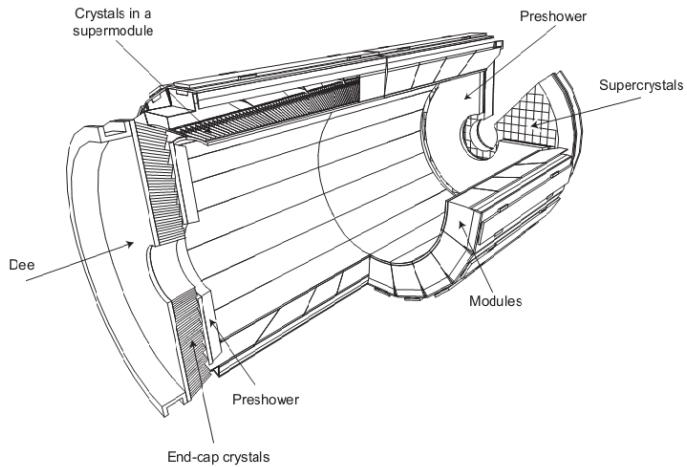


Figure 3.6: Schematic view of the CMS ECAL.

fluctuation in the production of scintillation light as well as the energy distribution over several crystals. The second term covers such sources of noise as electronic noise or pileup. The constant term accounts for other sources of uncertainties such as calibration errors. The size of the different contributions has been confirmed in test beam measurements [8].

3.2.3 The hadron calorimeter

The hadron calorimeter (HCAL) measures the energy of charged and neutral hadrons. In the barrel region of the detector it is situated between the back face of the ECAL and the coil of the solenoid, at radii between 1.7 m and 2.95 m, limiting the amount of material that can be used in its construction. Therefore additional detectors are placed outside of the volume of the magnet, forming the hadron outer calorimeter (HO). The HCAL barrel (HB) is complemented on each side by a HCAL endcap (HE) and the geometric coverage is extended to high values of $|\eta|$ by dedicated forward calorimeters (HF). The placement of these subdetectors relative to the other components of CMS are shown in Figure 3.7.

The HCAL barrel and outer detectors (HB and HO)

The HB covers the geometric region $|\eta| \leq 1.3$. It is constructed as a sandwich calorimeter, consisting of plastic scintillator as the active material. For the absorber material, the fourteen inner layers of the HB are made from brass, while steel is used for the front and back plates of the HB to increase the stability of the construction. The scintillator is divided in 144 segments in ϕ and 32 segments in η , resulting in a spatial granularity of 0.087 in both η and ϕ . The scintillation light produced in the active material is transported to hybrid photo diodes using scintillating fibres. As all layers of one tower in η and ϕ are read out by the same photo diode, there is no segmentation in the readout in r , except for the two towers closest to the HE on each side. The material of the ECAL in front of the HB corresponds to about 1.1

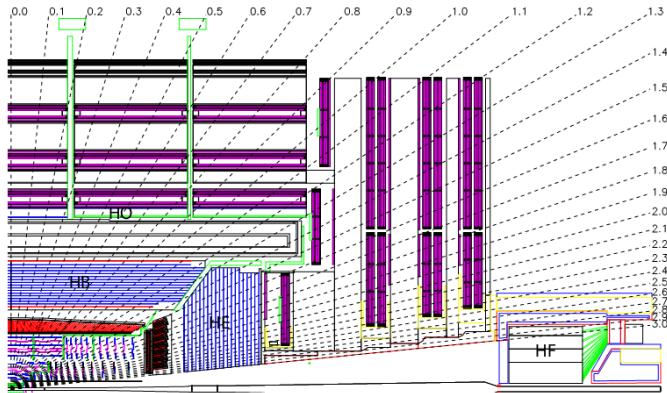


Figure 3.7: Schematic view of the CMS HCAL.

interaction length λ_i . The absorber material of the HB itself amounts to only $5.82 \lambda_i$ at $\eta = 0$, which increases to $10.6 \lambda_i$ at $|\eta| = 1.3$. To measure the energy of jets not contained in the HB, the HO is placed outside the vacuum containment of the solenoid. It consists of one additional layer of scintillator, with the magnet acting as absorber, except for most central part of the detector, where one additional layer of steel absorber and scintillator are installed. Hereby the material budget of the HCAL is increased to at least $10 \lambda_i$ over the whole barrel region.

The HCAL endcaps (HE)

The HE extends the geometric coverage of the HCAL up to $|\eta| = 3.0$, coinciding with that of the EEs. It is constructed from the combination of brass absorber and plastic scintillator as the HB and for the region $1.3 \leq |\eta| \leq 1.6$ also retains the $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ granularity in η and ϕ . For $|\eta| \geq 1.6$ the segmentation is coarser, resulting a granularity of $\Delta\eta \times \Delta\phi \approx 0.17 \times 0.17$. This structure again corresponds to about $10 \lambda_i$. The longitudinal segmentation of the readout of the towers differs based on the location of the tower. The two towers closest to the beam line are read out in three segments, while most others are read out in two segments. The two towers overlapping with HB are read out without longitudinal segmentation. Multipixel hybrid photo diodes have been chosen for the readout due to their low sensitivity to magnetic fields.

The hadron forward calorimeter (HF)

Of all subdetectors of CMS, the HF covers the highest values of $|\eta|$, reaching up to values of $|\eta| = 5.2$. This close to the beam pipe radiation hardness is the key feature of the design, as nearly 90% of the energy deposited in the detector as the result of a proton-proton interaction is allotted to the HF. It is constructed as two 3.5 m long cylinders with a radius of 1.3 m, located at $|z| = 11.2$ m. The first 1.65 m consist of plates of steel with a thickness of 5 mm, again

corresponding to about $10 \lambda_i$. The active material are quartz fibres, which are inserted into grooves in the steel plates. The particles created in showers in the absorber emit Cherenkov radiation in the fibres, which is detected by photomultiplier tubes at the end of the fibres. As the Cherenkov threshold is lowest for electrons, at 190 keV, the HF is more sensitive towards electromagnetic than hadronic showers. To separate the two, half of the fibres start only at a depth of 22 cm inside the absorber. As the electromagnetic shower develop faster, they deposit most of their energy before this point, which distinguishes them from hadronic showers.

3.2.4 The muon system

Muons are in general not stopped by any of the subdetectors of the CMS detector inside the solenoid. Therefore they can be measured with high precision in a clean environment outside of it. The muon detectors are therefore placed inside the return yoke of the magnet, both for the muon barrel (MB), covering up to $|\eta| = 1.2$ and muon endcap (ME) detectors, placed between $|\eta| = 0.9$ and $|\eta| = 2.4$. Being placed so far away from the interaction point, the muon detector have to cover a large area, which requires them to be rather inexpensive compared to other technologies used in the construction of CMS. Three different types of gaseous detectors are used to provide at the same time identification, p_T measurement and triggering for muons. In the barrel region, drift tubes (DT) are used as the main muon detectors, while in the endcaps cathode strip chambers (CSC) are used because they are faster and better equipped to deal with the larger and inhomogeneous magnetic field in this region of the detector. To provide a very fast muon tagging for the trigger, resistive plate chamber (RPC) complement the other two technologies in both the barrel and the endcaps.

Drift tubes (DT)

In the barrel, the TD chambers, each made of 2 or 3 super layers, which in turns are made up of four layers of TDs, are grouped together into four muon stations. Of these the first three contain 2 groups of 4 layers of chambers measuring in the $r - \phi$ plane and one group measuring the z coordinate. In the last muon station only the groups measuring in $r - \phi$ are present. The chambers in each chamber are offset by half of the width of a cell with respect to the next layer to not leave dead spots in the geometric coverage. The DT system consists of about 172000 sensitive wires. The drift tubes are filled with a mixture of 85% Ar and 15% CO_2 , and their structure is shown in Figure 3.8. The $r\phi$ resolution of a single layer of DT is about 250 μm , so that one chamber reaches a precision of 100 μm .

Cathode strip chambers (CSC)

The CSC are multiwire proportional chambers, consisting of 6 planes of anode wires interleaved with 7 panels of cathode strips. The chambers have trapezoidal shape and are arranged in four discs around the beam axis, each further segmented into two or three rings. The cathode strips measure the ϕ coordinate while the anode wires measure the radial coordinate. Figure 3.9

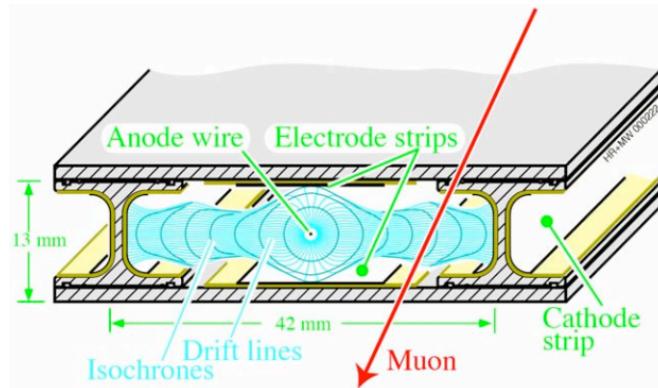


Figure 3.8: Schematic view of one DT.

shows the structure of one chamber on the left side and the creation of a signal due to a amplification of the initial ionization in an avalanche close to the anode wire.

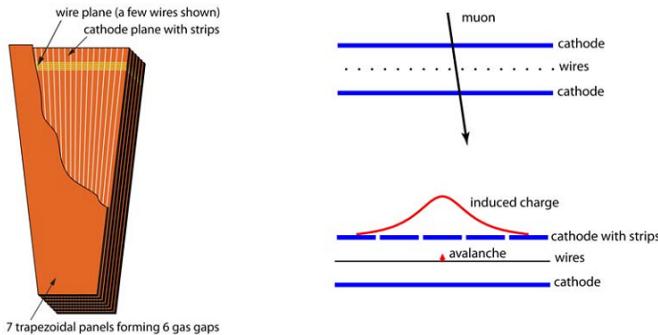


Figure 3.9: Schematic view of one CSC (left) and the creation of a signal (right).

Resistive plate chambers (RPC)

The RPCs consist of three layers of Bakelite, which form two small gas filled gaps and between which high voltage is applied. The amplification of the initial signal is very fast in this configuration, with drift times of about 5 ns. Therefore this technology is well suited to associate muon candidates to the LHC bunch crossings. In the barrel region six layers of RPCs are installed, while three layers are used in the endcaps for $|\eta| \leq 1.6$.

Momentum resolution

The p_T resolution of the muon system alone was expected to be about 10% for muons with p_T up to 200 GeV. Combined with the information from the inner tracking system, a resolution of about 1% was expected to be achieved in the central region of $|\eta| \leq 0.8$ for a p_T of 10 GeV, increasing to about 2% for a p_T of 200 GeV.

The p_T resolution for muons has been measured using data collected in 2010 [9]. Using the muon system alone, resolutions better than 10% have been found for the barrel region for muons with $p_T > 15 \text{ GeV}$. The muon resolution improves when combining the information from the muon system with those from the inner tracking system. The precision of the tracking system dominates for a wide p_T range and averaging over η and ϕ resolutions of $(1.8 \pm 0.3(\text{stat.}))\%$ at $p_T = 30 \text{ GeV}$ to $(2.3 \pm 0.3(\text{stat.}))\%$ at $p_T = 50 \text{ GeV}$ have been achieved.

3.3 Trigger and data acquisition

If the LHC is operated at the design bunch spacing of 25 ns, bunch crossings occur with a rate of about 40 MHz in the interactions points. Even if this has been reduced by at least factor of two during Run I of the LHC because of the increased bunch spacing, event rates of this magnitude can not be handled by the available means of data processing. The total event rate is therefore reduced by a factor of about 10^6 by two subsequent trigger systems. The Level-1 (L1) trigger consists of programmable electronics, allowing for a coarse reconstruction of physics objects in the calorimeters and the muon system. This system reduces the event rate to a maximum of 100 kHz. Following an L1 accept (L1A), the CMS data acquisition system (DAQ) collects the event information from the readout of the different subdetectors and passes it one to the High-Level trigger (HLT). The HLT is a software trigger and has access to the full detector readout [10]. It can perform a full reconstruction of the events to apply approximate versions of the algorithms used in offline data analysis. It accepts events at a rate of a few 10^2 Hz .

Level-1 trigger (L1)

The output of the different subdetectors are stored in pipelined buffers inside the readout electronics. This limits the time between the bunch crossing and the distribution of the L1 accept to the subsystems to $3.2 \mu\text{s}$. The L1 is therefore constructed from mostly custom-built programmable electronics either directly inside the detector or located close by in the underground facilities. As the readout of the tracker and track reconstruction are feasible on this time scale only calorimeter and muon system information are used. The L1 system is divided into local, regional and global components, as shown in Figure 3.10.

The calorimeter trigger the local component are the Trigger Primitive Generators (TPGs). For $|\eta| \leq 1.74$ they have an (η, ϕ) -coverage of 0.087×0.087 , corresponding to one HCAL tower and a 5×5 matrix of ECAL crystals in front of it. The TPGs communicate the energy deposits in the trigger tower and the number of the bunch crossing to the Regional Calorimeter Trigger. One calorimeter region consists of 4×4 trigger towers. Candidates for electrons or photons (e/γ) are formed by selecting the towers with the highest E_T in the ECAL. Based on information about the energy distribution inside the ECAL tower, the ratio of energy in ECAL and HCAL in the trigger tower and the overall distribution of energy in the neighbouring trigger towers the candidates are classified as isolated or non-isolated. Per region four isolated and four non-isolated e/γ candidates, the transverse energy sums of the trigger towers and information to

identify τ leptons and muons via their minimum ionizing particle (MIP) signature and isolation are passed to the Global Calorimeter Trigger (GCT). The GCT performs a simple jet clustering algorithm and is able to calculate per event observables such as the number of jets, the total and missing transverse energy and sum of the transverse energy of all jets above a certain threshold (H_T). These information are delivered to the global trigger

In the muon trigger all three detector components (DT,CSC, and RPC) contribute. In the local trigger, the DT chambers deliver track segments in the ϕ -projection and hit patterns in the η -projection, while the CSCs produce three-dimensional track segments. Both use timing information to associate this information with the bunch crossing. In the regional trigger, DT and CSC information are processed in separate track finders, which produce muon candidates. These are ordered as a function of p_T and track quality and up to four candidates are delivered to the global muon trigger from each track finder. The RPCs also deliver muon candidates. With their excellent timing resolution of about 1 ns they deliver an unambiguous association of the muon candidates to the correct bunch crossing. The global muon trigger receives up to four muon candidates each from the DTs, the CSCs and the barrel and endcap RPCs. The information consists of p_T , η , ϕ and information on the quality of the muon reconstruction. Candidates from the RPCs are matched with the ones from DT and CSC and, if matches are found, merged into single candidates. Unmatched candidates with low quality are suppressed. The track of the candidates is extrapolated back into the calorimeters to add the MIP and isolation information from the regional calorimeter trigger. The four best muon candidates are forwarded to the global trigger.

The global trigger collects the information from the global muon and global calorimeter trigger. Up to 128 trigger algorithms can be performed on the trigger objects at the same time, the most basic being simple p_T thresholds. If the criteria of one of the algorithms is met by the event, it is accepted by the L1 trigger and a signal is sent to the DAQ to read out the event.

Data acquisition system (DAQ)

Following an L1 accept the DAQ receives the information from the different subdetectors split in about 650 data sources, each delivering about 2 kB of data. These event fragments are assembled into whole events by the event builder. The event is then sent to one Filter Unit in the Event Filter, where the HLT software is running. The DAQ has to deal with input rates of up to 100 kHz and consists of 8 nearly independent slices, each able to take input at a rate of 12.5 kHz. The DAQ includes a back-pressure system, which automatically throttles the L1 trigger in the case where the input rate exceeds what can be processed by the DAQ. This introduces dead times in the detector readout but prevents data corruption and buffer overflows. To fully utilize the capacities of the trigger system and the DAQ, trigger thresholds can be adapted during data taking. The shortest time scale on which the thresholds are kept constant is called lumi section and is defined as 2^{20} LHC orbits, corresponding to about 93 s. The structure of the DAQ is shown in Figure 3.10.

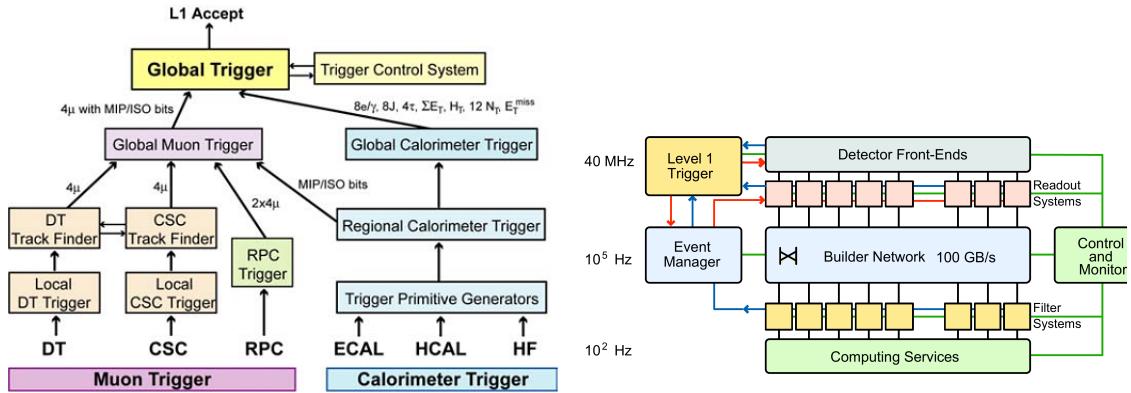


Figure 3.10: Structure of the CMS Level-1 trigger (left) and data acquisition system (DAQ) (right)

High level trigger (HLT)

The HLT software is run on a dedicated computing element, the Event Filter Farm, located in the CMS service caverns. During the data taking in 2012 it consisted of about 13200 processor cores [11], allowing for a processing time of about 150 ms at a input rate of 100 kHz. The HLT system reduces input data rates of up to 100 GB/s to several hundred MB/s, which are sent to the CERN computer centre for storage. As a full event reconstruction can be performed at HLT level, even if it is often restricted to small regions of the detector for timing reasons, much more complex quantities can be used to separate potentially interesting signatures from the large backgrounds. However, approximate methods have to be used sometimes to maintain an acceptable processing time per event. Also, some calibration and alignment methods can only be performed after the data taking, making the HLT less precise compared to the offline reconstruction. While a large variety of triggers is used by CMS to select different kinds of events, this description will focus on the ones most relevant to this analysis.

The most important signal and control samples are collected with dilepton triggers. In general, they select events that contain two leptons (electrons or muons), of which one is required to have a reconstructed transverse momentum p_T of at least 17 GeV, while for the second this is relaxed to 8 GeV. In general, the lepton with the higher (lower) p_T is referred to as the leading (trailing) lepton. While the algorithms employed to reconstruct muons and electrons are the same among all possible combinations of leptons, the triggers used for preselection at L1 level differ in their thresholds [12]. The dielectron HLT is based on the so called L1 seed L1_DoubleEG_13_7 and the dimuon on a logical OR of L1_DoubleMu_10_Open and L1_DoubleMu_10_3p5. To select events with an electron and a muon, two HLTs are employed, one with the electron and one with the muon as the leading lepton. The L1 seeds are a logical OR of L1_Mu3p5_EG12 and L1_MuOpen_EG12, and L1_Mu12_EG7, respectively. The numbers refer to the p_T or E_T thresholds of the muon and e/γ candidates in GeV, while Open indicates a threshold of 0 GeV. As the algorithms to reconstruct physics objects at HLT level are so similar to those used offline, no dedicated description is given here.

4 Data analysis and event selection

4.1 Trigger and event processing

4.2 Object reconstruction

The physics objects relevant to this analysis are electrons, muons, jets and the missing transverse energy E_T^{miss} . Here the reconstruction of these objects from the information provided by the CMS detector is described. While the electron and muon candidates used here are reconstructed independent of each other with dedicated algorithms, jets and E_T^{miss} are provided by the particle flow (PF) algorithm. It combines information from all subdetectors to achieve a consistent description of the full event.

4.2.1 Muon reconstruction and selection

The track of a muon is reconstructed separately in the inner tracker and the muon system, resulting in a *tracker track* and a *standalone muon*.

Tracks in the inner tracker are reconstructed using a method called Combinatorial Track Finder (CTF) [13], which performs pattern recognition and track fitting employing a Kalman filter technique [14]. The track is described by a five-dimensional state vector, whose initial parameters are taken from track seeds, determined from three hits or two hits and a vertex constraint in the pixel detector or the innermost layers of the strip detector. The state vector is extrapolated to the next tracker layer taking into account uncertainties and energy losses due to interactions with the tracker. If tracker hits are found in the modules where they are expected from the extrapolation, they are added to the track candidate. If no hits are found, a ghost hit is added to the track to account for inefficiencies in the hit reconstruction. A track fit is then performed to all hits associated with the track candidate, using again Kalman filtering and smoothing. This procedure is performed iteratively, each time removing the hits already associated to a track candidate and relaxing the requirements on the track seeds to allow for reconstruction of track with low p_T or not originating from the primary interaction. In the reconstruction of the data taken in 2012, seven iterations were performed [15].

For the reconstruction of *standalone muons* in the muon system, the hits inside the individual muon chambers are fitted to generate track segments, providing first estimates of the track parameters under the hypothesis that the muon was created in the interaction region and was travelling through the muon system from the inside out. These segments are used as starting points for a track reconstruction using all hits from the DTs, CSCs and RPCs, again using the Kalman filtering technique [16].

Criterion	Selection
Acceptance	
p_T	$> 10 \text{ GeV}$
$ \eta $	< 2.4
Muon ID	
Required to be a	<i>tracker muon</i> <i>global muon</i> <i>particle flow muon</i>
Track quality	
χ^2/N_{dof}	< 10
valid muon hits	> 0
matched stations	> 1
valid pixel hits	> 0
tracker layers with hits	> 6
Impact parameter	
$d_0 = \sqrt{dx^2 + dy^2}$	$< 0.02 \text{ cm}$
dz	$< 0.1 \text{ cm}$

Table 4.1: Summary of requirements of the muon selection.

Tracker tracks are promoted to *tracker muons* when they can be matched to a track segment in the muon detector. *Standalone muons* are matched to tracks from the inner tracker. If a compatible track is found a combined fit to all hits of the track and the *standalone muon* is performed, resulting in a *global muon*. The PF algorithm applies further selection requirements to the reconstructed *global* and *track muons*, introducing a fourth category, the *particle flow muon* [17].

Muons selected in this analysis are required to be reconstructed as *tracker*, *global* and *particle flow* muons. The χ^2 per degrees of freedom of the track fit must not exceed 10. Several requirements on the information available for the different track fits are made: At least one muon chamber hit must be included in the track fit of the *global muon*. For the fit of the *tracker muon* at least one hit in the pixel detector and six layers with hits in the strip detector have to be available. Also the track from the inner tracker has to be matched to at least two track segments in the muon chambers. To ensure that the muon originates from the primary interaction and to suppress backgrounds from cosmic muons the impact parameter of the track with respect to the primary vertex must not exceed 0.02 cm in the x - y plane and 0.1 cm in z direction. Selected are muons with a p_T larger than 10 GeV and $|\eta|$ less than 2.4. The muon selection is summarized in Table 4.1.

4.2.2 Electron reconstruction and selection

The signature of an electron in the CMS detector is a track reconstructed by the tracking detectors that leads to a matching cluster of energy reconstructed in the ECAL. In practice this is complicated by the large material budget of the tracking detectors, resulting in a high

probability of an electron to loose energy in form of bremsstrahlung. About 35% of all electrons loose more than 70% of their energy and for 10% the energy loss exceeds 95% [18]. The reconstruction is further complicated by the large solenoidal magnetic field, which bends the electron's trajectory away from the radiated photons, leading to a spread of the energy in ϕ direction. This has to be taken into account both in the tracking algorithms and the clustering of the energy deposits in the ECAL.

In the ECAL two different algorithms are used to group the energy deposits into clusters and clusters of clusters, called super clusters (SCs), in the barrel and endcap regions of the detector. Both are designed to group together the energy deposits of the electron itself and those of the bremsstrahlung photons. In the range of $1.6 < |\eta| < 2.6$ the preshower is located in front of the ECAL and electrons will deposit a fraction of their energy there. The energy deposited in the strips of the preshower between an SC in the ECAL and the primary vertex is summed and added to the energy of this SC [19]. ADD SC position calculation and electron charge!
CHANGE ALL REFS TO EGM-13-001 once submitted to journal!

In the track reconstruction with Kalman filters as discussed above energy losses due to interactions of the particles with the tracker material are considered to be Gaussian. For electrons, however, this is not sufficient because the dominant energy loss due to bremsstrahlung is a non-gaussian contribution. Electron candidate tracks are therefore fitted with a Gaussian Sum Filtern (GSF) algorithm [20], which models the non-Gaussian components as a sum of Gaussian distributions. GSF tracking is initiated in two ways. *ECAL driven seeding* requires the presence of a track seed that matches the position of an SC when extrapolating backwards from the ECAL to track [18]. Alternatively, *tracker driven seeding* is started by tracks that either match the position of ECAL clusters when extrapolated to the ECAL surface, covering the case of no bremsstrahlung, or are of poor quality with only few associated hits [13]. The GSF track and the energy measurement in the ECAL are combined into the final electron candidate.

Electrons are selected requiring p_T larger than 10 GeV and $|\eta| < 2.5$. The gap region between ECAL barrel and endcaps of $1.442 < |\eta| < 1.566$ is excluded. To suppress background from muons that radiate photons electrons with a distance of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ to the nearest *global or tracker muon* less than 0.1 are rejected. Backgrounds from photon conversion, decays of heavy flavour quarks or charged hadrons are suppressed by a set of selection criteria. The matching of track and supercluster is quantified by the differences between the supercluster position and the parameters of the track extrapolated from the vertex to the ECAL surface in $\Delta\phi$ and $\Delta\eta$. As the energy of the electron is contained in the ECAL, the ratio of hadronic energy deposited in the HCAL behind the electron candidate must be small. The energy spread in the ECAL due to bremsstrahlung occurs in ϕ direction. Therefore no significant spread of the energy in η , parametrized as

$$\sigma_{i\eta i\eta} = \frac{\sum_i^{5\times 5} w_i \cdot (\eta_i - \bar{\eta}_{5\times 5})^2}{\sum_i^{5\times 5} w_i}, \quad (4.1)$$

$$w_i = \max(0, 4.7 + \ln(\frac{E_i}{E_{5\times 5}})), \quad (4.2)$$

is expected, where for 5×5 crystals around the seed crystal the distance in η from the

Criterion	Selection at HLT		Selection at Analysis Level	
	EB	EE	EB	EE
Acceptance				
p_T	trigger dependent		$> 10 \text{ GeV}$	
$ \eta $	< 2.5		$< 2.5, \text{ excluding } 1.442 < \eta < 1.566$	
ID variables				
$ \Delta\eta $	0.01	0.01	0.007	0.009
$ \Delta\phi $	0.15	0.10	0.15	0.10
$\sigma_{inj\eta}$	0.011	0.031	0.01	0.03
H/E	0.10	0.075	0.12	0.10
$ \frac{1}{E} - \frac{1}{p} $	-		0.05	0.05
Conversion rejection				
missing pixel hits	-		≤ 1	≤ 1
vertex fit probability	-		$< 10^{-6}$	$< 10^{-6}$
Impact parameter				
$d0 = \sqrt{dx^2 + dy^2}$	-		$< 0.02 \text{ cm}$	$< 0.02 \text{ cm}$
dz	-		$< 0.1 \text{ cm}$	$< 0.1 \text{ cm}$

Table 4.2: Summary of requirements of the electron selection.

mean η of the cluster is summed, weighted by the energy deposit in each crystal. For a well measured electron there is good agreement between the energy deposited in the ECAL and the track momentum measured at the vertex. Therefore the value of $|\frac{1}{E} - \frac{1}{p}|$ must be small. Requirements on the impact parameter of the track with respect to the vertex are made. Two requirements are applied to reject electrons from converted photons. Only one pixel layer with missing hit is allowed, rejecting most conversions occurring after the first layer of the pixel detectors. To reject also conversion in this first layer and in the beam pipe, vertex fits for the electron track with neighbouring tracks are performed in order to reconstruct the point of conversion. For a prompt electron, the probability of these fits is low. Some of these requirements are already applied on HLT level. In order to select electrons for which the trigger is fully efficient, selections at least as strict are applied at analysis level. The specific requirements are listed in Table 4.2, separately for barrel and endcap when appropriate.

4.2.3 Observables reconstructed with Particle Flow

The algorithm

The particle flow (PF) algorithm is designed to combine information from all subdetectors to reconstruct a consistent description of the event, resulting in a list of reconstructed particles. The basic building blocks are PF elements, which are reconstructed in each subdetector separately: Tracks of charged particles in the tracker, energy clusters in the calorimeters and muon tracks in the muon system. A linking algorithm then combines elements into blocks based on their geometrical distance, for example by extrapolating a track into the ECAL and HCAL

and searching for compatible clusters. Similarly, calorimeter clusters are linked between the preshower, ECAL, and HCAL and tracks from the tracker are associated with those from the muon system. The reconstruction of *particle candidates* is performed on the elements inside a block. Muons are reconstructed first, followed by electrons, for which, similar to the standard algorithm described above, a refit of the track with the GSF algorithm is performed and bremsstrahlung photons are collected in the ECAL. Lastly, calorimeter clusters compatible with a track are identified as charged hadron, while clusters without a matching track are either categorized as neutral hadrons, or, if no or only small energy deposits in the HCAL exist, as photons [21].

Jets

The jets of particles produced in the hadronization of quarks and gluons are grouped together by clustering algorithms. An anti- k_T algorithm [22], performed using a fast implementation [23, 24], is used in this analysis. Input to the clustering are the *particle candidates* reconstructed by the particle flow algorithm.

The anti- k_T algorithm is a sequential clustering algorithm. Two distance measures are introduced, the first between two particles or pseudo-jets i and j and the second between particle or pseudo-jet i and the beam axis:

$$d_{ij} = \min(k_{Ti}^{-2}, k_{Tj}^{-2}) \frac{\Delta_{ij}^2}{R^2}, \quad (4.3)$$

$$d_{iB} = k_{ti}^{-2}, \quad (4.4)$$

with $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and k_{Ti} , y_i , and ϕ_i being the transverse momentum, rapidity and azimuth of a particle. For an entity (particle, pseudo-jet) i all distances are calculated. If the smallest is a d_{ij} , i and j are combined in a new pseudo-jet. If the smallest distance if the distance to the beam d_{iB} , the pseudo-jet is considered a final jet and removed from the list of particles available for clustering. The parameter R governs the size of the resulting jet and is set to 0.5 in this analysis.

The measured jet energy has to be corrected for energy offsets and the non-uniform and non-linear response of the detector. Each component of the jet's four-momentum vector is corrected by a multiplicative factor [25]

$$p_\mu^{cor} = C \cdot p_\mu^{raw}. \quad (4.5)$$

The correction is applied as a sequence of different factors:

$$C = C_{\text{offset}}^{L1}(p_T^{raw}) \cdot C_{MC}^{L2L3}(p'_T, \eta) \cdot C_{rel}^{L2Residual}(\eta) \cdot C_{abs}^{L3Residual}(p''_T). \quad (4.6)$$

The L1 correction, applied to the raw jet, corrects for offsets due to the underlying event and pileup using a jet area approach. The jet area A_j is determined for each jet and the particles in the event are clustered with a k_T jet clustering algorithm with a distance parameter $R = 0.6$, which clusters a large number of soft jets in each event. The median p_T density ρ is then defined as the median of the distribution of p_{Tj}/A_j for all of these jets. Therfore ρ is not influenced

by the presence of hard jets from the primary interaction in the event and is a measure for the pileup activity, the underlying event and electronic noise. Jets are then corrected by the factor $C_{\text{offset}}^{L1}(p_T^{\text{raw}}) = 1 - \frac{(\rho - \langle \rho_{UE} \rangle) \cdot A_j}{p_T^{\text{raw}}}$, where $\langle \rho_{UE} \rangle$ is the mean p_T density due to the underlying event, measured in events with no pileup interactions. The L2L3 corrections, derived from Simulation, corrects for the non-linearities and non-uniformities of the detector response to jets of different p_T and η and is applied to the offset-corrected jet. To correct for the differences between Simulation and real data, jets in data events are further corrected for the residual differences between the two.

In this analysis, the p_T of a jet is required to exceed 40 GeV and jets are required to lie inside the fiducial volume of the ECAL of $|\eta| < 3.0$. A set of loose quality selections is applied to suppress jets reconstructed because of detector noise, ensuring that the jet is reconstructed in more than one subdetector and has more than one constituent. As the jet clustering is performed using all reconstructed *particle candidates*, jets within $\Delta R = 0.4$ to leptons identified with the criteria described above are rejected.

Because of their long lifetime, b-jets decay at a measurable distance from their production vertex, allowing for the reconstruction of a secondary vertex. In this analysis the *combined secondary vertex* (CSV) algorithm is used. Likelihood ratios based on a variety of variables characterizing the secondary vertices and the tracks inside the jet are used to construct a single discriminator. If its value exceeds a given threshold, the jet is tagged as originating from a b-quark [26]. The performance of the b-tagging algorithms have been measured on the $\sqrt{s} = 8$ TeV dataset [27]. The average identification efficiency as a function of the discriminator value is shown on the left side of Figure 4.1. For the medium working point of 0.679, chosen in this analysis, the efficiency is about 70% while the probability to misidentify a jet originating from a light quark as a b-jet is between 1% and 3%, depending on the p_T of the jet, as shown on the right side of Figure 4.1. In this analysis b-jets are considered with a p_T larger than 30 GeV and $|\eta| < 2.4$.

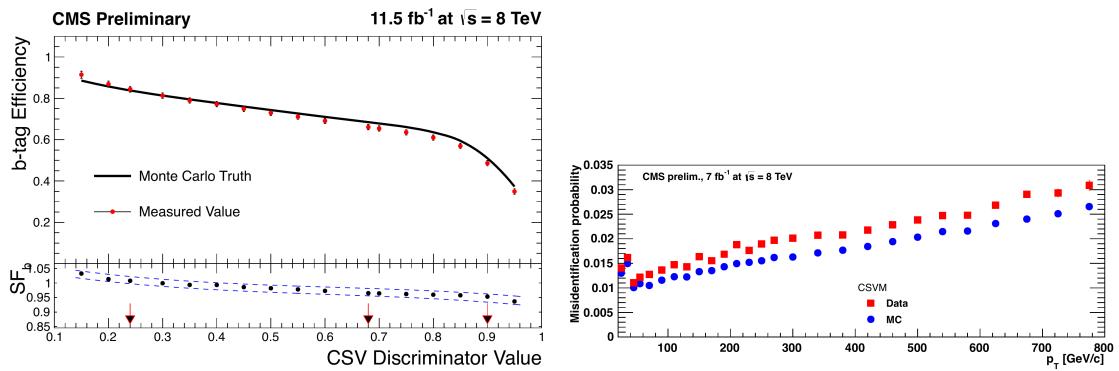


Figure 4.1: Performance of the CSV b-tagging algorithm. Shown is the identification efficiency as a function of the discriminator value (left) and the probability of misidentifying a jet originating from a light quark as a b-jet [27].

Missing transverse energy

As the transverse momenta of the initial partons are negligible compared to their large momenta in beam direction, the sum of the transverse momenta of all particles produced in the interaction is essentially zero because of conservation of momentum. For the reconstructed event this is not necessarily the case, leading to a missing transverse energy (E_T^{miss}) different from zero. The measurements in the detector have a finite resolution and are subject to detector noise and are subject to gaps in the detector acceptance. Also, particles that are only weakly interacting, such as neutrinos, are not detected by CMS and cause an imbalance of the transverse momentum sum. As this imbalance is the only experimental signature of this class of particles, a good E_T^{miss} resolution is a key factor for the discovery of processes that include the production of new weakly interacting particles.

Several algorithms have been developed in CMS to reconstruct E_T^{miss} [28]. Calorimetric (Calo) \vec{E}_T^{miss} is calculated as the negative vector sum of the energy deposits in each calorimeter tower. The small energy deposits from muons are replaced by the p_T measurements of muons. A further correction is introduced in the track-corrected (TC) \vec{E}_T^{miss} . For well reconstructed tracks, the track measurement is more precise than the measurement of a hadron's energy in the HCAL. Therefore, for tracks not associated with an electron or muon, the track measurement is used in the calculation of \vec{E}_T^{miss} . The energy deposit in the calorimeter is excluded, based on a model of the calorimeter response, treating all hadrons as pions. In contrast to these subdetector-based approaches, the event description of the particle flow algorithm can be used to calculate \vec{E}_T^{miss} . It is defined as the negative vector sum over the p_T vectors of all particle flow candidates:

$$\vec{E}_T^{miss} = - \sum_{\text{PF candidates}} \vec{p}_T^i. \quad (4.7)$$

Comparing the resolution for the E_T^{miss} components in x and y direction, as shown in Figure 4.2 for the data collected in 2011, PF E_T^{miss} performs best of the three algorithms and is therefore used in this analysis.

Several corrections can be applied to the calculation of E_T^{miss} . The *type-I* corrections propagate the corrections to the jet energy to the E_T^{miss} calculation for all jets with p_T larger than 10 GeV and with less than 90% of their energy deposited in the ECAL. The effects of pileup on the E_T^{miss} reconstruction can be mitigated by applying *type-0* corrections, which are calculated on minimum bias events to parametrize the effects of such interactions on E_T^{miss} . Further corrections can be applied to correct for modulations of the E_T^{miss} in ϕ [29]. As this analysis searches for events with a large genuine E_T^{miss} and is therefore not very sensitive to E_T^{miss} introduced by resolution effect, none of these corrections are applied. However, *type-I* corrected PF E_T^{miss} is considered as a cross check.

Lepton isolation

While the lepton selection criteria described above are sufficient to reject backgrounds from particles misidentified as leptons, they do not suppress real leptons not originating from the primary interaction. As these are often produced in decay of heavy flavour quarks inside a

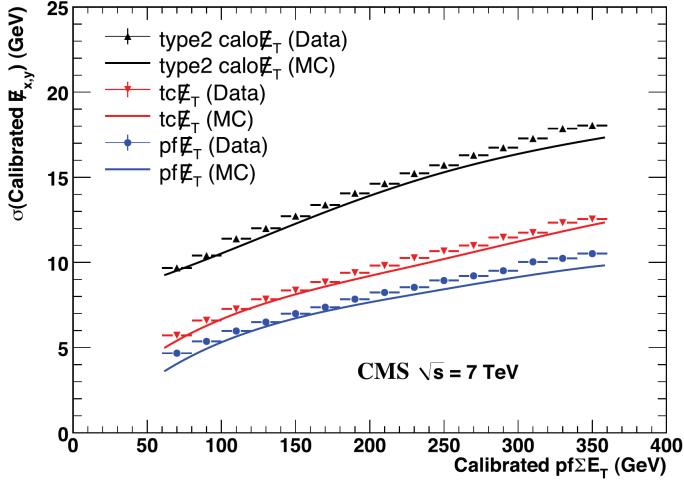


Figure 4.2: Calibrated E_T^{miss} resolution as a function of the sum of the E_T of all particle flow candidates in an event. Shown are Calo E_T^{miss} in black, TC E_T^{miss} in red and PF E_T^{miss} in blue [28].

jet, are more suitable criterion is to consider the amount of activity in the detector close to the lepton candidate, called lepton isolation. In this analysis, particle based isolation is used. For this the energy deposited by charged hadron, neutral hadron, and photon particle flow candidates in a cone of $\Delta R = 0.3$ around the lepton is summed:

$$\text{Iso} = \sum_{\text{charged hadrons}} E_T + \sum_{\text{neutral hadrons}} E_T + \sum_{\text{photons}} E_T. \quad (4.8)$$

The calculation of the isolation is distorted by pileup if PF candidates originating from pileup interactions lie within the cone and are counted in the isolation sum. This is easily remedied for charged hadrons, as those originating from a pileup vertex can be excluded from the calculation. For neutral hadrons and photons there is no track that can be associated to a vertex and a direct identification as pileup particles is not possible. Different approaches are pursued to correct for this contribution for electrons and muons. In both cases an estimate for the contribution of neutral pileup is subtracted from the isolation sum, which changes to:

$$\text{Iso} = \sum_{\text{charged hadrons}} E_T + \max(0, \sum_{\text{neutral hadrons}} E_T + \sum_{\text{photons}} E_T - \sum_{\text{neutral PU}} E_T). \quad (4.9)$$

For electrons the correction is similar to the L1 offset correction for jets described above. As a measure for the pileup contribution in the isolation cone the median p_T density in the event ρ is multiplied by the effective area of the electron in the detector, which is calculated in bins of η . The pileup correction is therefore defined as $\sum_{\text{neutral PU}} E_T = \rho \cdot A_{\text{electron}}^{\text{eff}}$. For muons $\Delta\beta$ corrections are applied. Here it is utilized that on average the contribution of neutral particles from pileup is half that of charged particles, leading to a correction defined as $\sum_{\text{neutral PU}} E_T = 0.5 \cdot \sum_{\text{charged PU}} E_T$. Because of the stochastic nature of these approaches overcorrection is possible. Therefore, no negative contribution from neutral particles is allowed in equation 4.9. ADD PLOTS SHOWING ISO VS NVTX

For both electrons and muons the isolation sum must not exceed $0.15 \cdot p_T$ of the lepton candidate. MAKE FANCY PLOTS SHOWING WHY THIS IS A GOOD CHOICE

4.3 Datasets

4.4 Event selection

5 Estimation of Standard Model backgrounds

5.1 Flavour-symmetric backgrounds

5.2 Backgrounds containing a Z boson

5.3 Investigation of possible further backgrounds

5.4 Search for a kinematic edge with a fit

6 Results

6.1 Result of the counting experiment

6.2 Result of the search for a kinematic edge

7 Interpretation in simplified models

7.1 Simplified Models for Supersymmetric Signatures

7.2 The T6bbledge and T6bbslepton model

7.3 Interpretation of the counting experiment in simplified models

8 Outlook to LHC Run II

9 Conclusion

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