Electron and Photon Reconstruction in CMS

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Compact Muon Solenoid

Photons and Electrons leave a distinctive signal in the electromagnetic calorimeter (ECAL) in the form of energy deposits that are also associated with a trace in the silicon tracker. Due to its incredible energy resolution, the ECAL enables scientists to measure quantities with great precision, as well as helps them with searches for physics beyond the standard model. [2]

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The CMS Detector

The CMS detector features a superconducting solenoid of 6 m internal diameter, capable of generating a magnetic field of 3.8 T.
The solenoid volume houses a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each comprising a barrel and two endcap sections.
Forward calorimeters (HF) supplement the pseudorapidity coverage offered by the barrel and endcap detectors.
Muon detection is facilitated by gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid [2].

The CMS Detector

The CMS detector provides a track resolution of approximately 1.5% for charged particles with a transverse momentum (p_T) between 1 and 10 GeV, and a pseudorapidity ($|\eta|$) less than 1.4 [2].
The Electromagnetic Calorimeter (ECAL) comprises 75,848 crystals, covering pseudorapidity ranges of $|\eta| < 1.48$ in the barrel region (EB) and $1.48 < |\eta| < 3.00$ in the two endcap regions (EE) [2][1].
Energy deposition is detected as scintillation light by avalanche photodiodes (APDs) in the EB and vacuum phototriodes (VPTs) in the EE. The electrical signal is amplified and shaped by a multigain preamplifier (MGPA), yielding three simultaneous analogue outputs with a rise time of approximately 50 ns and a decay to 10% of the peak value within 400 ns [2].

CMS Particle-Flow Event Reconstruction

The CMS particle-flow (PF) event reconstruction optimally combines information from all subdetectors to identify each individual particle in an event. The particle type identification (photon, electron, muon, charged or neutral hadron) is crucial for determining the particle's direction and energy [2].

Photons are identified as ECAL energy clusters not linked to any extrapolated track. Electrons are identified as primary charged-particle tracks and potentially as ECAL energy clusters. Muons are identified as tracks in the central tracker consistent with either tracks or several hits in the muon system. Charged and neutral hadrons may initiate a hadronic shower in the ECAL and are subsequently fully absorbed in the HCAL. [2][1]

Primary Interaction Vertex

The reconstructed vertex with the largest value of summed physics-objects p_T^2 is considered the primary pp interaction vertex. The physics objects are the jets, clustered using the anti-k_T algorithm with a distance parameter of $R = 0.4$, and the associated missing transverse momentum.[2]

Event Selection and Trigger System

Events of interest are selected using a two-tiered trigger system. The first level (L1) uses information from the calorimeters and muon detectors to select events at a rate of about 100 kHz. The high-level trigger (HLT) reduces the event rate to around 1 kHz before data storage. Dedicated techniques are used to reject signals from electronic noise, pileup, or particles not originating from *pp* collisions in the bunch crossing of interest. [2]

Online vs Offline Reconstruction

- **Online Reconstruction:**
  - Also known as *real-time* reconstruction.
  - Performed during data acquisition phase.
  - Aimed at quickly filtering and reducing the amount of data to be stored for further analysis.
  - Uses simplified algorithms due to time constraints.
  - Example: Trigger systems in particle physics experiments.
- **Offline Reconstruction:**
  - Performed after data acquisition phase.
  - Aimed at detailed analysis of the stored data.
  - Uses more complex and precise algorithms as time is not a critical factor.
  - Example: Detailed analysis of collision events in particle physics experiments.

[2]

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Offline Electron and Photon Detection: Overview

Electrons and photons deposit most of their energy in the ECAL, while hadrons primarily deposit energy in the HCAL. The ECAL signals are reconstructed by fitting the signal pulse with multiple template functions to subtract the contribution from out-of-time pileup. As an electron or photon propagates through the material in front of the ECAL, it may interact with the material, leading to a shower of multiple electrons and photons via Bremsstrahlung. [2]

Reconstruction Algorithm

A dedicated algorithm combines the clusters from the individual particles into a single object to recover the energy of the primary electron or photon. A dedicated tracking algorithm, based on the Gaussian sum filter (GSF), is used for electrons to estimate the track parameters. Electron and photon reconstruction in CMS is fully integrated into the PF framework and is based on the same basic building blocks as other particles. [2]

Reconstruction Steps

The energy reconstruction algorithm starts with the formation of clusters by grouping together crystals with energies exceeding a predefined threshold. These clusters are combined into superclusters (SC) to include photon conversions and bremsstrahlung losses. Trajectory seeds in the pixel detector compatible with the SC position and the trajectory of an electron are used to seed the GSF tracking step. All tracks reconstructed in the event are tested for compatibility with an electron trajectory hypothesis. [2]

Particle Flow Algorithm

ECAL clusters, SCs, GSF tracks, and generic tracks associated with electrons, as well as conversion tracks and associated clusters, are all imported into the PF algorithm that links the elements together into blocks of particles. These blocks are resolved into electron and photon objects, starting from either a GSF track or a SC, respectively. Electron or photon objects are built from the refined SCs based on loose selection requirements.[2]

Superclustering in CMS: Overview

In the CMS detector, energy deposits in several ECAL channels are clustered under the assumption that each local maximum above a certain energy threshold (1 GeV) corresponds to a single particle incident on the detector. A Gaussian shower profile is used to determine the fraction of the energy deposit to be assigned to each of the clusters. The multiple ECAL clusters need to be combined into a single Supercluster (SC) that captures the energy of the original electron/photon. This step is known as superclustering. [1][2]

Superclustering Algorithms: Mustache Algorithm

The first superclustering algorithm is the "mustache" algorithm. It uses information only from the ECAL and the preshower detector. The algorithm starts from a seed cluster and additional clusters are added if falling into a zone, whose shape is similar to a mustache in the transverse plane. The size of the mustache region depends on E_T, since the tracks of particles with larger transverse momenta get less bent by the magnetic field. The mustache SCs are used to seed electrons, photons, and conversion-finding algorithms. [2]

Superclustering Algorithms: Refined Algorithm

The second superclustering algorithm is known as the "refined" algorithm. It utilizes tracking information to extrapolate bremsstrahlung tangents and conversion tracks to decide whether a cluster should belong to a SC. It uses mustache SCs as a starting point, but is also capable of creating its own SCs. The refined SCs are used for the determination of all ECAL-based quantities of electron and photon objects. [2]

Electron Track Reconstruction and Association: Overview

Electrons use the Gaussian Sum Filter (GSF) tracking algorithm to account for radiative losses from bremsstrahlung. The reconstruction of electron tracks begins with the identification of a hit pattern that might lie on an electron trajectory, known as "seeding". The electron trajectory seed can be either "ECAL-driven" or "tracker-driven".[2]

Electron Seeding

The ECAL-driven seeding selects mustache Superclusters (SCs) with transverse energy $E_{SC,T} > 4$ GeV and $H/E_{SC} < 0.15$. Each mustache SC is then compared in ϕ and z with a collection of track seeds formed by combining multiple hits in the inner tracker detector. The tracker-driven approach iterates over all generic tracks. If any of these Kalman Filter (KF) tracks is compatible with an ECAL cluster, its track seed is used to seed a GSF track. The ECAL-driven approach performs better for $high - E_T$ isolated electrons with a larger than 95% seeding efficiency for $ET > 10GeV$ for electrons from Z boson decay, whereas the tracker-driven approach is designed to recover efficiency for $low - p_T$ or nonisolated electrons with a seeding efficiency higher than 50% for electrons with $p_T > 3GeV$.
E_{SC} and H are the SC energy and the sum of the energy deposits in the HCAL towers within a cone of $\Delta R = 0.15$.[2]

GSF Tracking Algorithm

The GSF tracking algorithm is run on all ECAL- and tracker-driven seeds. If an ECAL-driven seed shares all but one of its hits with a tracker-driven seed, the resulting track candidate is considered as both ECAL and tracker-seeded. The final collection of selected electron seeds is used to initiate the reconstruction of electron tracks. For a given seed, the track parameters evaluated at each successive tracker layer are used by the KF algorithm to iteratively build the electron trajectory. [2]

Track-Cluster Association

The electron candidates are constructed by associating the GSF tracks with the SCs, where the position of the SC is defined as the energy-weighted average of the constituent ECAL cluster positions. A Boosted Decision Tree (BDT) is used to decide whether to associate a GSF track to an ECAL cluster. The BDT combines track information, supercluster observables, and track-cluster matching variables.
Once the track candidates are reconstructed by the KF algorithm, their parameters are estimated at each layer with a GSF fit in which the energy loss is approximated by an admixture of Gaussian distributions [4]. The GSF tracks obtained from this procedure are extrapolated toward the ECAL under the assumption of a homogeneous magnetic field to perform trackcluster associations.[2]

Bremsstrahlung Recovery

To collect the energy of photons emitted by bremsstrahlung, tangents to the Gaussian Sum Filter (GSF) tracks are extrapolated to the ECAL surface from the track positions. A cluster linked to the track is considered as a potential bremsstrahlung photon if the extrapolated tangent position is within the boundaries of the cluster and the distance between the cluster and the GSF track extrapolation in η is smaller than 0.05.
The fraction of the momentum lost by bremsstrahlung, as measured by the tracker, is defined as:

$$f_{brem} = 1 - \frac{|p_{trk-out}|}{|p_{trk-in}|} \tag{1}$$

where p_{trk-in} is the momentum at the point of closest approach to the primary vertex, and $p_{trk-out}$ is the momentum extrapolated to the surface of the ECAL from the outermost tracker layer. [2]

Photon Conversion Recovery

Bremsstrahlung photons, as well as prompt photons, have a significant probability to further convert into an e^+e^- pair in the tracker material. A conversion-finder was developed to create links between any two tracks compatible with a photon conversion. To recover converted bremsstrahlung photons, the vector sum of any possible bremsstrahlung pair conversion candidate track momenta is checked for compatibility with the aforementioned electron track tangents.[2]

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Online Reconstruction - Overview

- **Online Reconstruction:** Also known as *real-time* reconstruction.
- **Purpose:** To quickly filter and reduce the amount of data during the data acquisition phase.
- **Method:** Uses simplified algorithms due to time constraints.
- **Example:** Trigger systems in particle physics experiments.

[2]

Online Reconstruction - Performance

- **Speed:** Fast enough to keep up with the data acquisition rate.
- **Efficiency:** High, due to the use of simplified algorithms.
- **Precision:** Lower compared to offline reconstruction due to the use of simplified models.

[2]

Offline vs Online Reconstruction - Results

- **Precision:** Offline reconstruction provides more precise results due to the use of complex models.
- **Time:** Offline reconstruction takes more time compared to online reconstruction.
- **Data Volume:** Online reconstruction reduces the volume of data to be stored and analyzed offline.

[2]

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Energy Corrections - Overview

- Energy deposited by electrons and photons in the ECAL is subject to losses.
- Losses occur due to lateral and longitudinal shower leakage, intermodule gaps, dead crystals, and energy lost in the tracker.
- These losses lead to systematic variations in the energy measured in the ECAL.
- A multivariate technique is used to correct the energy estimation for these effects.

[2]

Regression Technique

- Regression fits based on Boosted Decision Trees (BDTs) are applied to correct the energy of e/γ.
- The regression prediction for the target is the correction factor to be applied to the measured energy.
- The regression input variables include the object and event parameters most strongly correlated with the target.

[2]

Double-Sided Crystal Ball (DSCB) Function

- The probability density function used in this regression algorithm is a DSCB function.
- DSCB has a Gaussian core with power law tails on both sides.
- The parameters of the DSCB function are estimated as a function of the input vector of the object and event characteristics.

[2]

Electron Energy Correction - Three Regressions

- The electron energy is corrected via the sequential application of three regressions.
- Step 1: Provides the correction to the SuperCluster (SC) energy.
- Step 2: Provides an estimate of the SC energy resolution.
- Step 3: Yields the final energy value, correcting the combined energy estimate from the SC and the electron track information.

[2]

Photon Energy Correction and Energy Resolution

- The photon energy is corrected using the same method as electrons, except that step 3 is omitted.
- The regressions are trained on samples of simulated events with two electrons or photons in each event.
- Step 2 is performed to obtain an estimate of the per-object resolution.
- It uses the same inputs as in step 1, but the SC energy is scaled by the correction factor obtained from the step 1 regression.

[2]

Final Energy Value Correction

- For electrons, an additional step combining the ECAL energy and momentum estimate from the tracker is performed.
- This improves the predicted electron energy at low E_T, especially where the momentum measurement from the tracker has a better resolution than the corresponding ECAL measurement.

[2]

Energy Corrections - Results

- These regressions lead to significantly improved measurements of electron and photon energies and energy resolutions.
- The primary improvement occurs in the regressions applied to the energy of the SC.
- Correcting the E-p combination, which already uses the improved SC energy, has a smaller impact.

[2]

Residual Differences and Corrections

- After applying the corrections, small differences remain between data and simulation in both the electron and photon energy scales and resolutions.
- An additional spreading needs to be applied to the photon and electron energy resolutions in simulation to match that observed in data.
- The electron and photon energy scales are corrected by varying the scale in the data to match that observed in simulated events.

[2]

Impact of Residual Corrections in H $\rightarrow \gamma\gamma$ Channel

The mass of the Higgs boson in the diphoton channel has been measured exploiting *pp* collision data collected at a center-of-mass energy of 13 TeV by the CMS experiment during 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. This result benefits from a refined calibration of the ECAL, while exploiting new analysis techniques to constrain the uncertainty in the Higgs boson mass to $m_H = 125.78 \pm 0.26$ GeV. A key requirement for this measurement was to measure and correct for nonlinear discrepancies between data and simulation in the energy scale, as a function of E_T, using electrons from Z boson decays. Additional energy scale corrections were derived in bins of $|\eta|$ and E_T to account for any nonlinear response of the ECAL with energy for the purpose of this high-precision measurement. The accuracy of the energy scale correction extrapolation in the energy range of interest of the $H \rightarrow \gamma\gamma$ search (between 45 and 65 GeV in E_T) is 0.05–0.1 (0.1–0.3)% for photons in the EB (EE). The quality of the energy resolution achieved provides a significant improvement in the sensitivity of the $H \rightarrow \gamma\gamma$ search.[2]

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Electron and Photon Identification Variables

Different strategies are used to identify prompt (produced at the primary vertex) and isolated electrons and photons, and separate them from background sources. Background sources can originate from photon conversions, hadrons misidentified as electrons, and secondary electrons from semileptonic decays of b or c quarks. The most important background to prompt photons arises from jets fragmenting mainly into light neutral mesons π^0 or η, which subsequently decay promptly to two photons. Different working points are defined to identify either electrons or photons, corresponding to identification efficiencies of approximately 70, 80, and 90%, respectively. In all cases, data and simulation efficiencies are compatible within 1–5% over the full η and E_T ranges for electrons and photons. [2]

Isolation Energy Sums

One of the most efficient ways to reject electron and photon backgrounds is the use of isolation energy sums, a generic class of discriminating variables that are constructed from the sum of the reconstructed energy in a cone around electrons or photons in different subdetectors. For this purpose, it is convenient to define cones in terms of an η–ϕ metric; the distance with respect to the reconstructed electron or photon direction is defined by ΔR. To ensure that the energy from the electron or photon itself is not included in this sum, it is necessary to define a veto region inside the isolation cone, which is excluded from the isolation sum. [2]

Shower Shape Criteria

Another method to reject jets with high electromagnetic content exploits the shape of the electromagnetic shower in the ECAL. Even if the two photons from neutral hadron decays inside a jet cannot be fully resolved, a wider shower profile is expected, on average, compared with a single incident electron or photon. This is particularly true along the η axis of the cluster, since the presence of the material combined with the effect of the magnetic field reduce the discriminating power resulting from the ϕ profile of the shower. Several shower-shape variables are constructed to parameterize the differences between the geometrical shape of energy deposits from prompt photons or electrons compared with those caused by hadrons from jets. [2] [1]

Hadronic Over Electromagnetic Energy Ratio (H/E)

The H/E ratio is defined as the ratio between the energy deposited in the HCAL in a cone of radius $\Delta R = 0.15$ around the SC direction and the energy of the photon or electron candidate. There are three sources that significantly contribute to the measured hadronic energy (H) of a genuine electromagnetic object: HCAL noise, pileup, and leakage of electrons or photons through the inter-module gaps. For low-energy electrons and photons, the first two sources are the primary contributors, whereas for high-energy electrons, the last contribution dominates. Therefore, to cover both low- and high-energy regions, the H/E selection requirement is of the form $H < X + Y\rho + JE$, where X and Y represent the noise and pileup terms, respectively, and J is a scaling term for high-energy electrons and photons.[2]

$\sigma_{i\eta i\eta}$ and R9

The second moment of the log-weighted distribution of crystal energies in η, calculated in the 5$\times$5 matrix around the most energetic crystal in the SC and rescaled to units of crystal size, is represented by $\sigma_{i\eta i\eta}$. Another important variable is $R9$. Showers of photons that convert before reaching the calorimeter have wider transverse profiles and lower values of $R9$ than those of unconverted photons. The energy weighted η-width and ϕ-width of the SC provide further information of the lateral spread of the shower. [2]

Additional Electron Identification Variables

Additional tracker-related variables are used for the identification of electrons. One such discriminating variable is $|1/E - 1/p|$, where E is the SC energy and p is the track momentum at the point of closest approach to the vertex. Another important variable for the electron identification is $|\Delta\eta^{\mathrm{in}}_{\mathrm{seed}}|$ defined as $|\eta_{\mathrm{seed}} - \eta_{\mathrm{track}}|$, where η_{seed} is the position of the seed cluster in η, and η_{track} is the track η extrapolated from the innermost track position. Similarly, $|\Delta\phi_{\mathrm{in}}| = |\phi_{\mathrm{SC}} - \phi_{\mathrm{track}}|$ is another discriminating variable that uses the SC energy-weighted position in ϕ instead of the seed cluster ϕ. [2]

Photon Identification

Requirements are made on $\sigma_{i\eta i\eta}$, H/E, and the isolation sums after correcting for pileup. The selection requirements were tuned using a MC sample with 2017 data-taking conditions, but these identification criteria are suitable for use in all three years of Run 2. The "loose" working point has an average signal efficiency of about 90%, and is generally used when backgrounds are low. The "medium" and "tight" working points have an average efficiency of about 80% and 70%, respectively, and are used in situations where the background is expected to be larger.[2]

Cut-based Photon Identification

Variable	Barrel (tight WP)	Endcap (tight WP)
H/E	<0.021	<0.032
$\sigma_{i\eta i\eta}$	<0.0099	<0.027
I_{ch}	<0.65 GeV	<0.52 GeV
I_{n}	<0.32 GeV $+ 0.015E_T + 2.26 \times 10^{-5}E_T^2$/GeV	<2.72 GeV $+ 0.012E_T + 2.3 \times 10^{-5}E_T^2$/GeV
I_{γ}	<2.04 GeV $+ 0.0040E_T$	<3.03 GeV $+ 0.0037E_T$

Table: Cut-based photon identification requirements for the tight working point in the EB and EE.

[2]

Electron Rejection

Along with the cut-based photon identification criteria, a prescription is required to reject electrons in the photon identification scheme. The most commonly used method is the conversion-safe electron veto. This veto requires the absence of charged particle tracks, with a hit in the innermost layer of the pixel detector not matched to a reconstructed conversion vertex, pointing to the photon cluster in the ECAL. More efficient rejection of electrons can be achieved by rejecting any photon for which a pixel detector seed consisting of at least two hits in the pixel detector points to the ECAL within some window defined around the photon SC position. The conversion-safe electron veto is appropriate in the cases where electrons do not constitute a major background, whereas the pixel detector seed veto is used when electrons misidentified as photons are expected to be an important background. [2]

Photon Identification Using Multivariate Techniques

A more sophisticated photon identification strategy is based on a multivariate technique, employing a BDT implemented in the TMVA framework. Here, a single discriminant variable is built based on multiple input variables, and provides excellent separation between signal (prompt photons) and background from misidentified jets. The signal is defined as reconstructed photons from a γ + jets simulated sample that are matched at generator level with prompt photons within a cone of size $\Delta R = 0.1$, whereas the background is defined by reconstructed photons in the same sample that do not match with a generated photon within a cone of size $\Delta R = 0.1$. Photon candidates with $E_T > 15$ GeV, $|\eta| < 2.5$, and satisfying very loose preselection requirements are used for the training of the BDT.[2]

Electron Identification Strategies

Electron identification strategies in CMS include both cut-based and multivariate techniques. The cut-based identification uses seven identification variables, with thresholds listed for the tight working point. The combined PF isolation is used, combining information from I_{ch}, I_{γ} and I_{n}. The isolation-related variables are sensitive to the extra energy from pileup interactions, affecting the isolation efficiency when there are many interactions per bunch crossing. The contribution from pileup in the isolation cone is computed assuming $I_{\text{PU}} = \rho A_{\text{eff}}$, where ρ and A_{eff} are defined before. The variable I_{combined} is divided by the electron E_T, and is called the relative combined PF isolation [2].

Electron Identification: Cut-based Identification

- The sequential electron identification selection includes requirements for seven identification variables.
- The combined PF isolation is used, combining information from I_{ch}, I_γ and I_{n}.
- Four working points are generally used in CMS: veto, loose, medium, and tight.

Variable	Barrel (tight WP)	Endcaps (tight WP)
$\sigma_{i\eta i\eta}$	<0.010	<0.035
$\lvert\Delta\eta^{\text{in}}_{\text{seed}}\rvert$	<0.0025	<0.005
$\lvert\Delta\phi^{\text{in}}\rvert$	<0.022 rad	<0.024 rad
H/E	$<0.026 + 1.15\ \text{GeV}/E_{\text{SC}} + 0.032\rho/E_{\text{SC}}$	$<0.019 + 2.06\ \text{GeV}/E_{\text{SC}} + 0.183\rho/E_{\text{SC}}$
I_{combined}/E_T	$<0.029 + 0.51\ \text{GeV}/E_T$	$<0.0445 + 0.963\ \text{GeV}/E_T$
$\lvert 1/E - 1/p\rvert$	$<0.16\ \text{GeV}^{-1}$	$<0.0197\ \text{GeV}^{-1}$
Number of missing hits	≤ 1	≤ 1
Pass conversion veto	Yes	Yes

Table: Cut-based electron identification requirements for the tight working point in the barrel and in the endcaps.

[2]

Electron Identification Using Multivariate Techniques

To further improve the performance of the electron identification, especially at E_T less than 40 GeV, several variables are combined using a BDT. The set of observables is extended relative to the simpler sequential selection: the track-cluster matching observables are computed both at the ECAL surface and at the vertex. More cluster-shape and track-quality variables are also used. The fractional difference between the track momentum at the innermost tracker layer and at the outermost tracker layer, f_{brem}, is also included [2].

High-energy Electron Identification

The CMS experiment employs a dedicated cut-based identification method for the selection of high-E_T electrons, known as high-energy electron pairs (HEEP). Variables similar to those used for the cut-based general electron identification are used to select high-E_T electrons, starting at 35 GeV and extending up to about 2 TeV or more. This selection requires that the lateral spread of energy deposits in the ECAL is consistent with that of a single electron and that the track is matched to the ECAL deposits and is consistent with a particle originating from the nominal interaction point [2].

HEEP Identification Requirements

Variable	Barrel	Endcap
E_T	$>$35 GeV	$>$35 GeV
η range	$\eta_{SC} < 1.44$	$1.57 < \eta_{SC} < 2.50$
$\lvert\Delta\eta^{in}_{seed}\rvert$	$<$0.004	$<$0.006
$\lvert\Delta\phi^{in}\rvert$	$<$0.06 rad	$<$0.06 rad
H/E	<1 GeV$/E_{SC} + 0.05$	<5 GeV$/E_{SC} + 0.05$
$\sigma_{i\eta i\eta}$	—	$<$0.03
$E_{2\times5}/E_{5\times5}$	$>$0.94 OR $E_{1\times5}/E_{5\times5} > 0.83$	—
$IE_{CAL} + I_{HCAL}$	$<$2.0 GeV $+ 0.03E_T + 0.28\rho$	$<$2.5 GeV $+ 0.28\rho$ for $E_T < 50$ GeV else $<$2.5 GeV $+ 0.03(E_T$ - 50 GeV$) + 0.28\rho$
$I_{tracker}$	$<$5 GeV	$<$5 GeV
Number of missing hits	$\leq$1	$\leq$1
d_{xy}	$<$0.02 cm	$<$0.05 cm

Table: Identification requirements for high-E_T electrons in the barrel and in the endcaps [2].

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