The CMS/LHC experiment is building a high performance electromagnetic calorimeter. The detailed simulation of the calorimeter, the tracker material in front of it and the high magnetic field, were essential in the design and development phases. Recently, fully simulated events have been used in the evaluation of the DAQ and High Level Trigger design. The current strategy for the reconstruction of electrons and photons is presented as well as indications of its impact on physics performance.

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1. Introduction

The Compact Muon Solenoid (CMS) experiment is a general-purpose detector designed to explore the physics of proton-proton collisions at a centre-of-mass energy of 14 TeV over the full range of luminosities expected at the Large Hadron Collider (LHC).

The CMS detector (Fig. 1a) is designed to measure the energy and momentum of photons, electrons and muons with high precision. The distinctive features of the detector are the 4T axial magnetic field [1], a multi-layer muon system in the return yoke [2], a sampling hadron calorimeter (HCAL) [3], a scintillating crystal electromagnetic calorimeter (ECAL) [4] and a silicon inner tracking system [5] based on fine-grained micro-strip and pixel detectors. The calorimeters and the tracker are located inside the solenoid.

The electromagnetic calorimeter will play an essential role in the study of the electroweak symmetry breaking, particularly through the exploration of the Higgs sector. It is designed to provide very precise energy measurement of electrons and photons and it will consist of about 76000 Lead Tungstate (PbWO₄) crystals arranged in a barrel part and two endcaps, with an additional preshower detector in front of the endcaps (Fig. 1b). The crystals have a short radiation length (X₀ = 8.9 mm) and Molière radius (Rₐ = 2.19 mm), which allows the construction of a compact and highly granular detector.
2. The need of an accurate electron and photon reconstruction

One of the primary goals of the LHC experimental programme is to elucidate the origin of the mass by discovering the Higgs boson predicted by the Standard Model, whatever its mass in the theoretical allowed range up to around 1 TeV/c². If the Higgs boson is light (M_H < 150 GeV/c²) the golden discovery channel is its decay into two photons [6]. For larger masses, processes like H→WW/ZZ become important (the W and Z bosons are identified via their leptonic decays). Especially for a light Higgs boson, its mass resolution is a key issue. The irreducible di-jet background (Fig. 2) is quite large and the mass resolution is completely dominated by the detector resolution. In order to increase the signal significance and make the discovery with lower integrated luminosity the reconstructed Higgs boson mass peak should be as narrow as possible. Therefore an excellent energy and position resolution in the electron and photon reconstruction is mandatory.

3. The full simulation chain

Standard Monte Carlo generators, such as PYTHIA [7] and ISAJET [8], were used to simulate the collisions between the two protons at a centre-of-mass energy of 14 TeV. The CMS simulation package, OSCAR [9], is an application of GEANT4 [10]. It simulates the particles propagation and their interactions with the detector materials. This package is also used for the detector (geometry and material) description. It also includes, and uses, information about the magnetic field.
The CMS reconstruction software, ORCA [11], is based on object-oriented programming technology. The ORCA project handles all the reconstruction tasks as well as the simulation of the detector response, the Level-1 [12] and the High-Level Trigger (HLT). It is used for detector optimisations, trigger studies and global detector performance evaluations. The ECAL detector response simulated in ORCA consists of the simulation of the digitisation procedure by the readout electronics and the addition of Gaussian random smearing to the crystal energy to account for electronic noise, intercalibration uncertainties, deviations from the nominal longitudinal light collection curve, and photostatistics.

4. Main Reconstruction issues

Before reaching the ECAL, electrons radiate in the tracker material (Fig. 3a). For example, for electrons with $P_T = 35 \text{ GeV/c}$ and $|\eta|<1.5$, the mean energy loss is 43.6% before exiting the tracker volume. Most of the energy is radiated as quasi-collinear low energy photons. Their energy spectrum is presented in Fig. 3b. The electron bending in the 4T magnetic field results in a spray of energy reaching the ECAL. The distribution of this energy is, to a good approximation, only in the $\phi$ direction [13].

The photon conversions in the tracker material can degrade the Higgs boson mass resolution and can lead to event losses. The studies of the $H\rightarrow\gamma\gamma$ channel showed that about 24% (35%) of photons convert in the tracker volume before reaching the barrel (endcap) ECAL. A matrix of 5x5 crystals is used to measure the energy of non-converted photons entering the ECAL. Dedicated algorithms are under development to identify and reconstruct the converted photons.
Figure 3. (a) Material budget as a function of $\eta$ for the different tracker subcomponents in units of radiation length. (b) Energy spectrum of bremsstrahlung photons emitted in the tracker material by $P_T = 35$ GeV/c, $|\eta|<1.5$ electrons.

5. Reconstruction techniques

5.1. Energy and position reconstruction

The first step in the reconstruction of an electron or photon is to cluster the energy deposits in the ECAL and estimate the particle’s energy and position from this information. Bremsstrahlung radiation lies to a good approximation, only in the $\phi$ direction. Therefore the electron energy can be recovered by making a cluster of clusters (super-cluster) along a $\phi$ road. In the ECAL Barrel the Hybrid algorithm [13] uses the $\eta$-$\phi$ geometry of the crystals to exploit the knowledge of the lateral shower shape in the $\eta$ direction, while searching dynamically for separated (radiated) energy in the $\phi$ direction (Fig. 4a). In the ECAL Endcaps the energy deposited in the preshower detector needs to be added to the crystal clusters. In Fig. 4b the transverse energy collected in a super-cluster is compared with the transverse energy collected in a single cluster for electrons with $P_T = 30$ GeV/c. The achieved energy resolution for electrons is shown in Table 1. The symbol $\sigma$ stands for the r.m.s. deviation of a Gaussian fit to the peak (not taking into account possible tails of distribution) while the $\sigma_{\text{eff}}$ stands for the half width containing 68.3% of the distribution.

Table 1. Energy resolution performance for barrel and endcap ECAL using electron samples simulated with different pileup conditions.

<table>
<thead>
<tr>
<th>electron sample</th>
<th>$\sigma/E$</th>
<th>$\sigma_{\text{eff}}/E$</th>
<th>$\sigma/E$</th>
<th>$\sigma_{\text{eff}}/E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T = 35$ GeV/c (no pileup)</td>
<td>1.1%</td>
<td>2.2%</td>
<td>1.2%</td>
<td>2.1%</td>
</tr>
<tr>
<td>$P_T = 35$ GeV/c ($2\times10^{33} \text{ cm}^{-2}\text{s}^{-1}$)</td>
<td>1.2%</td>
<td>2.3%</td>
<td>1.6%</td>
<td>2.4%</td>
</tr>
<tr>
<td>$P_T = 35$ GeV/c ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)</td>
<td>1.5%</td>
<td>2.7%</td>
<td>2.7%</td>
<td>3.4%</td>
</tr>
<tr>
<td>$10&lt;P_T&lt;50$ GeV/c ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)</td>
<td>1.5%</td>
<td>3.4%</td>
<td>2.9%</td>
<td>4.2%</td>
</tr>
</tbody>
</table>

The impact point of the electron or photon can be obtained by calculating a
weighted mean position of the crystals in the cluster:

\[ x = \frac{\sum x_i \cdot W_i}{\sum W_i} \]

As crystal position is regarded a point at a certain depth which represents approximately the longitudinal centre of gravity of the shower. Its optimal mean value varies logarithmically with the shower energy and the particle type (electron showers have a maximum about one radiation length less deep than photon showers). The energy dependence of the shower maximum is parameterised as: \( 0.89 \log(E) + 5.7 \). The determination of the parameters is described in reference [13]. In order to take into account the exponential fall of the energy density of the lateral shower shape the following weight is given to each crystal position: \( W_i = W_0 + \log(E_i / \sum E_i) \). The weight is constrained to be positive. It depends on the logarithm of the fraction of the cluster energy contained in the crystal. The parameter \( W_0 \) controls the smallest fractional energy that a crystal can have and still contribute to the position measurement. From optimisation studies, \( W_0 \) is set to 4.2 and corresponds to a fractional energy limit of 1.5%. The achieved position resolution for electrons is shown in Table 2.

### 5.2. Electron – photon separation

The energy-weighted average impact point of the super-cluster is propagated back through the magnetic field to obtain an estimate of the direction of the electron candidate at the vertex, and the hit positions expected in the pixel detector. If at least two pixel hits are associated with the predicted electron track, then the super-cluster is classified as coming from an electron, otherwise
Table 2. Position resolution performance for barrel and endcap ECAL using electron samples simulated with different pileup conditions.

<table>
<thead>
<tr>
<th>electron sample</th>
<th>$P_T$ in GeV/c</th>
<th>$\sigma(\eta) \times 10^3$ mrad</th>
<th>$\sigma(\phi)$ mrad</th>
<th>$\sigma_{\text{eff}}(\phi)$ mrad</th>
<th>$\sigma(\eta) \times 10^3$ mrad</th>
<th>$\sigma(\phi)$ mrad</th>
<th>$\sigma_{\text{eff}}(\phi)$ mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T = 35$ (no pileup)</td>
<td>1.1</td>
<td>1.7</td>
<td>2.5</td>
<td>1.8</td>
<td>2.2</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>$P_T = 35$ (2$\times 10^{33}$ cm$^{-2}$s$^{-1}$)</td>
<td>1.1</td>
<td>1.7</td>
<td>2.5</td>
<td>1.8</td>
<td>2.3</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>$P_T = 35$ (1$\times 10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>1.1</td>
<td>1.9</td>
<td>2.7</td>
<td>2.0</td>
<td>2.9</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>10$&lt;P_T&lt;$50 (1$\times 10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>1.2</td>
<td>2.1</td>
<td>3.4</td>
<td>2.2</td>
<td>2.7</td>
<td>5.1</td>
<td></td>
</tr>
</tbody>
</table>

it is classified as coming from a photon. The matching of super-clusters to pixel hits is a powerful tool to reject di-jet background [14]. As an example, for an electron efficiency of 95% a di-jet rejection factor of 17 can be obtained at low luminosity ($2 \times 10^{33}$ cm$^{-2}$sec$^{-1}$). For high luminosity ($10^{34}$ cm$^{-2}$sec$^{-1}$) the rejection factor is reduced to 14 due to pileup hits.

5.3. Full electron reconstruction

The pixel hits matched to supercluster can be used as seeds to initiate a full electron reconstruction in the Tracker. After the track reconstruction, the parameters of the electron track are combined with those of the supercluster to increase the di-jet background suppression. An effective variable for the background suppression is the ratio of E/P, where E is the supercluster energy and P the reconstructed momentum of the track [15].

5.4. Energy reconstruction and primary vertex finding for photons

For the energy reconstruction of unconverted photons the sum of energies in a matrix of 5×5 crystals around the maximum response crystal is used. For converted photons, the energy is reconstructed by using the same algorithms as for the electrons. The photon conversion affects the energy resolution. Using photons in the ECAL barrel from $H \rightarrow \gamma\gamma$ ($M_{\gamma\gamma} = 100$ GeV/c$^2$) decays a resolution of 0.86% was achieved for unconverted photons and 1.15% for converted [4].

If a photon converts in the tracker and the lateral distance of conversion from the beam axis is between 20 and 65 cm, then the conversion tracks can be reconstructed successfully. Using a sample of photons with $P_T=35$ GeV/c without pileup it was shown that the z coordinate of the primary vertex of the photon can be reconstructed with an accuracy of 1.2 cm. For late conversions (conversion distance beyond 65 cm) the tracks are poorly reconstructed and do not offer any useful information on the primary vertex. For early conversions (conversion distance below 20 cm), the strong magnetic field separates the tracks resulting practically in two distinct super-clusters in the ECAL.
6. Selection efficiencies and rates - Performance

Detailed performance numbers of the online reconstruction and selection in terms of the electron and photon rates output by the HLT at both low and high luminosity can be found in [15]. As an example, the efficiency to select $H\to\gamma\gamma$ events ($M_H^2=115$ GeV/c$^2$) in the HLT was 77% at low luminosity, with a total expected rate output of 43Hz. The $W\to e\nu$ channel occupies 10Hz, the $Z\to e^-e^+$ decay around 1 Hz, the $\gamma$-jet production approximately 2Hz and the remainder comes from the background.

7. Summary and conclusions

Precise electron and photon reconstruction is required for the discovery of the Higgs boson or other new particles. Object-Oriented technology is used for the detailed description of the CMS detector and simulation of the particles interaction with detector materials. A stable reconstruction framework (ORCA) is used for multipurpose analyses. The recovery of the energy losses due to Bremsstrahlung in the tracker material for the electrons and the conversion of photons are two of the most important reconstruction issues. The online reconstruction applied in the evaluation of the High-Level Trigger gave satisfactory results. The offline reconstruction is being based on this foundation.

Acknowledgments

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References

10. S. Agostinelli et al., NIM A 506, (2003), 250-303
11. http://cmsdoc.cern.ch/orca/