Higgs boson to four electrons in CMS – full simulation

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Abstract

Many decay channels will be exploited to search for the Higgs boson at the LHC. One of the most important channels is \( H \to ZZ \to 4e \), where below the \( 2M_Z \) threshold one or both Zs could be off mass shell. In this paper the signal and the main background processes are evaluated using recent theoretical predictions. Electron reconstruction is then presented, with dedicated algorithms developed for specific problems expected at the CMS experiment. Finally these algorithms are used to reconstruct the Higgs boson and thus to estimate its observability in CMS through this decay channel.

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1 Introduction

The existence and properties of the Higgs boson are the main unresolved questions of the Standard Model. Direct searches at LEP give a lower mass limit of 114.4 GeV/c² at the 95% confidence level [1], and electroweak precision measurements results are $m_H = 96^{+70}_{-38}$ GeV/c² with $m_H < 219$ GeV/c² at the 95% confidence level [2]. Future LHC experiments, CMS and ATLAS, will be able to search efficiently for the Higgs boson in the mass region from the lower LEP limit up to about 1 TeV [3]. In this paper the region of the Higgs boson mass below the $2M_Z$ threshold is studied.

2 Study of the signal characteristics

Cross sections for the Higgs boson production and branching ratios for its decay have been calculated using computer programs given in the Ref. [4], implementing recent theoretical calculations. For all relevant processes next to leading order (NLO) cross sections are included. The cross sections for four electrons final states are 1.40, 2.56 and 0.57 fb for the Higgs boson masses of 130, 150 and 170 GeV/c² respectively.

Monte Carlo event generators, such as PYTHIA [5] used in this study, allow cross section evaluations at the leading order (LO). In order to account for higher order corrections, (for instance, NLO gluon fusion production cross section is about 70% higher than the LO one) simulated events are normalized to the NLO cross sections given above. This procedure is justified only if the events kinematics is unchanged, which is verified by comparing a prediction of the Higgs boson transverse momentum ($p_T$) distribution from PYTHIA with the same one obtained with the soft gluon resummation techniques [6], implemented in ResBos [7].

3 Study of the backgrounds

For the physics channel studied here, the background consists of all the processes with four electrons in the final state. The main background processes are the irreducible $ZZ^*/\gamma^* \rightarrow 4e$ and the two reducible backgrounds, $Zb\bar{b} \rightarrow 4e$ and $t\bar{t} \rightarrow 4e$.

The $ZZ^*/\gamma^*$ background. At hadron colliders there are two production processes for this background, quark annihilation $q\bar{q} \rightarrow ZZ^*/\gamma^*$ and gluon fusion $gg \rightarrow ZZ^*/\gamma^*$. Only the first process is implemented in PYTHIA, with a cross section calculated at the leading order, $\sigma(pp \rightarrow ZZ^*/\gamma^*) = 7.95$ pb. The NLO calculations for the production of pairs of real vector bosons are given in the Ref. [8], and the K factor is estimated at about 1.44. For the gluon fusion contribution, NLO corrections are still unknown. Therefore, $\sigma(gg)/\sigma(q\bar{q}) = 0.35$ is taken [9], neglecting the kinematical differences between these two production processes.

The $t\bar{t}$ background. The NLO cross section has been calculated in [10] and the result at the LHC center of mass energy is given in Ref. [11], $\sigma_{NLO}(pp \rightarrow t\bar{t} = 758.8 \pm 75$ pb). Useful characteristics to suppress this background are: soft electrons $p_T$ spectrum, presence of two non-isolated electrons (on average) with sizeable impact parameter, flattish invariant mass distribution of the two hardest electrons and low mass peak in the invariant mass distribution of the two softest electrons.

The $Zb\bar{b}$ background. At the LO, there are two processes for production at hadron colliders, quark annihilation $q\bar{q} \rightarrow Zb\bar{b}$ and gluon fusion $gg \rightarrow Zb\bar{b}$. Using CompHEP [12] program, the LO cross sections for all initial states is computed. The total cross section is 929.58 pb with a total qq initial state contribution of about 16%. The partonic events generated by CompHEP are then passed through PYTHIA for hadronization as well as initial and final state radiation, and through PHOTOS [13] for the generation of internal bremsstrahlung in the Z decay. The presence of a real Z boson makes this background insensitive to a Z mass cut (besides the internal radiation effects), contrary to the t\bar{t} background case. As in the case of the t\bar{t} background, this background is characterized by the presence of two non-isolated electrons with sizeable impact parameter and soft $p_T$ spectrum, since they are coming from semi-leptonic b decays.

4 Electron reconstruction

The small number of events in the signal process together with the multielectron final state, demand an excellent reconstruction efficiency and low cuts on the electrons transverse momentum. In addition, the significance of the signal is inversely proportional to the square root of the four electrons invariant mass width, requiring the best possible precision of the reconstructed electron momentum. In CMS, the electron reconstruction quality relies on the performance of both the tracker (consisting of layers of pixel detectors and silicon microstrip detectors)
and the electromagnetic calorimeter (consisting of PbWO$_4$ crystal towers). A previously foreseen silicon-MSGC (Microstrip Gas Chambers) version of the CMS tracker is used in this study, giving however comparable results to the final version of the tracker design [14].

For the reconstruction studies, a detailed simulation of the CMS detector implemented in the CMSIM program is used [15]. The reconstruction algorithms have been used or developed within the CMS Reconstruction and Analysis (ORCA) framework [16], with nominal ECAL [17] and tracker [14] resolutions.

The biggest problem comes from the bremsstrahlung radiation in the tracker cavity. The material budget in front of the electromagnetic calorimeter varies between $0.3 - 0.4 \times \eta$ for $\eta \approx 0$ and grows to about $1.5 \times \eta$ in the region $\eta \approx 1.6$. The bremsstrahlung radiation affects both ECAL and tracker measurements. Photons are radiated along the tangent to the electron trajectory, while electrons curve in the magnetic field. This simple kinematics can be used to search for photon energy depositions in the ECAL to improve electron reconstruction algorithms.

### 4.1 Track reconstruction

For electron track finding and fitting the forward kalman filter (FKF) algorithm available in the reconstruction program is used. This algorithm starts with searching for compatible hits in the two pixel layers, assuming a vertex at the nominal interaction point, and successively propagates the track by extrapolating it to the next layer and searching for compatible hits. A minimum of eight hits is required to build a track candidate. After that, the track parameters are reevaluated by refitting backward all the hits found. The average track finding efficiencies are 84.3% (88.3%) for electrons with $p_T = 10$ (30) GeV/c in the barrel. It is important to note that tracker reconstruction is still not fully optimized for electron energy loss and the latest developments show that improvements may be expected.

### 4.2 Cluster reconstruction

Several clustering algorithms have been proposed in CMS. In this work the so called dynamic clustering algorithm [18] is used. It starts with a cluster seed defined as a local maximum, and constructs the cluster by attaching crystals being adjacent by side and having smaller energy than at least one crystal already belonging to the cluster. In this way the cluster stops when it encounters a crystal with higher energy deposit, which happens either in case of noise fluctuations or in a case of a physical neighboring cluster. For electrons with $p_T = 10$ (30) GeV/c the average number of crystals in the electron cluster is about 25 (35).

The kinematics of the bremsstrahlung process allows to predict where to search for radiated energy deposition in the ECAL, starting from an electron cluster. If a photon is separated enough and has enough energy to create a separate cluster, it is then possible to associate this photon cluster with the electron cluster. The recovery algorithm firstly estimates the maximum azimuthal distance between the electron and the radiated photon using the reconstructed transverse energy of the electron cluster. Then it searches for secondary cluster having its reconstructed position in the area between central cluster and maximum azimuthal distance.

In order to match electron clusters and tracks better, a procedure is developed which considers all clusters around the extrapolated track point as electron candidate, performs bremsstrahlung clusters recovery for each candidate, and chooses as the final candidate the one giving the best matching of electron cluster plus bremsstrahlung clusters to the extrapolated track.

### 4.3 Electron momentum estimation

Electron momentum is estimated from both tracker and ECAL measurements. For the ECAL energy estimation a so called 'single weight method' is developed, based on the prediction of deposited electron energy using a shower model [19]. This method is used for energy estimation for events with small amount of bremsstrahlung radiation, while for other events a simple cluster energy sum is used. The criterium for deciding which estimator to use is based on the effective $\chi^2$ between the predicted and the measured energy in the considered set of crystals. The acceptance for using the single weight estimator for a typical value $\chi^2 < 15$ is about 50%, for electrons with $p_T = 10$ GeV/c and can be relaxed as the electron energy increases.

Events with reconstructed calorimetric energy over track momentum ($E/p$) estimation significantly greater than 1 arise from overestimated track curvature due to the bremsstrahlung. On the other hand, events with $E/p$ significantly lower than 1 originate from incomplete bremsstrahlung recovery in the ECAL. In both these extreme cases
the energy estimation is taken from the less biased estimator, while for the intermediate cases the two measurements are combined. As a result, a combined estimator is defined as:

\[
\tilde{p} = \begin{cases} 
  w_E \cdot E + w_p \cdot p, & \text{if } \frac{E}{p} - 1 \leq 2\sigma_{E/p} \\
  E, & \text{if } \frac{E}{p} > 1 + 2\sigma_{E/p} \\
  p, & \text{if } \frac{E}{p} < 1 - 2\sigma_{E/p}.
\end{cases}
\]

The results for electrons with \(p_T = 10\) GeV/c in the barrel, comparing ECAL, tracker and the combined estimator are shown in Fig. 1. The effective RMS and efficiencies are improved with respect to either ECAL or tracker alone estimators. Event acceptance in the \(\pm 2\sigma (\pm 3\sigma)\) resolution window are 78% (87%) for \(p_T = 10\) GeV/c and 66% (76%) for \(p_T = 30\) GeV/c electrons.

![Figure 1: Comparison of the ECAL, tracker and combined momentum estimators, normalized to the generated electron momentum, for \(p_T = 10\) GeV/c electrons in the barrel.](image)

### 5 Analysis cuts

The developed electron reconstruction algorithms are applied to the reconstruction of the signal and background events. Optimized kinematical cuts and event acceptance are shown in Table 1, for events with all four electrons in the barrel. The most important contribution (apart from preselection and trigger) comes from the initial electron reconstruction efficiency. As has been said, electron track reconstruction is still not completely optimized, opening the possibility to increase the signal acceptance. The reconstructed two electrons and four electrons invariant mass for 150 GeV/c² Higgs boson are shown in Fig. 2. A left tail in both distributions is present, as a consequence of the bremsstrahlung effect. Despite the developed electron reconstruction algorithms, the presence of four electrons in the signal final state makes this effect still the dominating one. The overall event acceptance in the mass window \(\pm 2\sigma_m\) are 11%, 15% and 18% for Higgs boson masses of 130, 150 and 170 GeV/c² respectively.

![Table 1: Summary of the results on the Higgs boson reconstruction. For the total acceptance the \(2\sigma_m\) is taken. Isolation efficiencies are obtained with parton level analysis.](table)

### 6 Observability in CMS

To estimate the signal visibility the endcap part of the detector is included by using the assumptions that the overall electron finding efficiency remains at the same level, i.e. about 66%, and that the Higgs boson mass resolution is degraded by about 15%, with the \(\pm 2\sigma_m\) acceptance remaining the same. These assumptions are...
Figure 2: Two electrons reconstructed invariant mass closest to the nominal Z boson mass (left) and four electrons reconstructed mass (right), for 150 GeV/c² Higgs boson mass.

Based on combining the reconstruction results with the particle level analysis. A detailed study and optimization of reconstruction algorithms in the endcaps is, however, needed, especially for electron tracking due to the high level of material budget. For the ZZ* background the results obtained with full detector simulations are used. For other backgrounds, as for the Higgs boson masses other than 130, 150 and 170 GeV/c², the full reconstruction results have been combined with results from the particle level analysis. The final number of signal events and that of background events expected in this channel are given in Fig. 3 (left) for one year of LHC running at high luminosity. As can be seen, the expected number of signal events are about 15, 30 and 10 for the Higgs boson mass of 130, 150 and 170 GeV/c² respectively, while the total number of background events remains below 8.

Figure 3: Number of expected signal and background events in the mass window ±2σ_{m_H}, after one year of LHC running at high luminosity (left). The signal significance for one year of LHC running at high luminosity and two years of LHC running at low luminosity (right).

The Poissonian significance of the signal is shown in Fig. 3 (right) as a function of the four electrons reconstructed mass. As expected, it follows the shape of the Higgs boson to ZZ* branching ratio. Further optimization of the tracker electron finding algorithms is expected to improve the significance. Another possible improvement could be expected by developing a recovery algorithm for internal bremsstrahlung.

7 Conclusion

In CMS the Higgs boson can be discovered through the H → ZZ* →4e decay channel in one year of LHC running at high luminosity if its mass is in the region between 131 GeV/c² and 164 GeV/c², and above 174 GeV/c² up to the kinematically allowed limit 2M_Z. In the vicinity of 150 GeV/c² the Higgs boson can be found after two years of LHC running at low luminosity. By combining this channel with the Z muonic decay, the signal and
background number of events increase by a factor four (which is of course a naive extrapolation and requires detailed reconstruction study of muons in CMS), while the signal significance increase by a factor of about two. It means that the Higgs boson can be discovered through the $H \rightarrow ZZ^* \rightarrow 4l (l=\mu, e)$ channel from about 120 GeV/c$^2$ all the way up to $2M_Z$, for the integrated luminosity of $10^5$ pb$^{-1}$.

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References


[16] See http://cmsdoc.cern.ch/orca/

