CMS Physics Analysis Summary

Search for invisible decays of a Higgs produced in association with a Z boson

The CMS Collaboration

Abstract

A direct search for a standard-model-like Higgs boson produced in association with a Z boson and decaying to invisible particles is reported. A non-zero partial decay width to invisible particles could provide evidence for physics beyond the standard model. The search is performed in data samples corresponding to integrated luminosities of 5.1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 19.6 fb$^{-1}$ at $\sqrt{s} = 8$ TeV, recorded by the CMS experiment at the Large Hadron Collider. No deviation from the background expectation is observed and limits are set on the branching fraction of the standard model Higgs boson decaying to invisible particles assuming the standard model production rate. For a Higgs boson with $m_H = 125$ GeV, the observed (expected) 95% confidence level upper limit on the branching fraction of the Higgs boson to invisible particles is 75% (91%).
1 Introduction

A primary focus of the LHC physics programme after the recent discovery of a Higgs boson [1, 2] by the ATLAS and CMS collaborations is the study of the properties of the new particle. The observation of a sizable branching fraction of the Higgs boson to invisible states [3–5] would be a strong sign of physics beyond the standard model (BSM). Supersymmetric theories (SUSY) tend to contain a stable neutral Lightest SUSY Particle (LSP), and this can open up decays of the Higgs boson into pairs of LSP’s, for example neutralinos [6]. Some theories of large extra dimensions predict graviscalars that could mix with the Higgs boson [7]. As a consequence, the Higgs boson can oscillate to a graviscalar and disappear from our brane. The signature would be equivalent to an invisible decay of the Higgs boson. There can also be contributions from Higgs boson decays into graviscalars [8].

Studies of the new boson at \(m_H \sim 125\) GeV show no significant deviation from the SM Higgs boson hypothesis. Measurements of its couplings are used to constrain the partial decay width to undetected decay modes. The current CMS indirect limit [9] to invisible particles using visible Higgs decay modes with \(m_H = 125\) GeV is 64%, while the current ATLAS indirect limit [10] is 60%.

A direct search for an invisible decay of the new boson has been reported by the ATLAS collaboration excluding at 95% confidence level branching fractions greater than 65% of the total SM Higgs boson decay width; the expected limit is at 84% [11]. The limits derived from the combined LEP data [12] assuming that the Higgs boson decays only into undetected particles exclude, at 95% confidence level, masses below 114.4 GeV.

This analysis summary presents a search for decays to invisible particles for a scalar boson produced in association with a Z boson with the same cross section as the SM Higgs boson and having a mass between 115 GeV and 145 GeV. The analysis strategy is to select events with two oppositely charged leptons (electrons or muons only) compatible with a Z boson decay, large missing transverse energy (\(E_T^{\text{miss}}\)) recoiling against the two leptons and small hadronic activity. The data sample corresponds to an integrated luminosity of 5.1 fb\(^{-1}\) at \(\sqrt{s} = 7\) TeV and 19.6 fb\(^{-1}\) at \(\sqrt{s} = 8\) TeV.

2 CMS detector

The CMS detector, described in detail in Reference [13], is a multipurpose apparatus designed to study high transverse momentum (\(p_T\)) physics processes in proton-proton collisions. A superconducting solenoid occupies the central region of the CMS detector, providing a magnetic field of 3.8 T parallel to the beam direction. Charged particle trajectories are measured by the silicon pixel and strip trackers, which cover a pseudorapidity region of \(|\eta| < 2.5\), where \(\eta = -\ln(\tan(\theta/2))\), and \(\theta\) is the polar angle of the trajectory of the particle with respect to the direction of the counterclockwise beam. The crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL) surround the tracking volume and cover \(|\eta| < 3\). The steel/quartz-fiber Cherenkov calorimeter (HF) extends the coverage to \(|\eta| < 5\). The muon system consists of gas detectors embedded in the iron return yoke outside the solenoid, with a coverage of \(|\eta| < 2.4\). The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than 3 \(\mu\)s, using coarse information from the calorimeters and muon detectors. The High Level Trigger processor farm further reduces the event rate to a few hundred Hertz having the full event information at its disposal before the data go to storage for full event reconstruction.
3 Background overview

This analysis searches for an excess of events over the SM contribution in the dilepton + $E_T^{\text{miss}}$ final states. A careful understanding of the backgrounds is necessary since no mass peak is expected in this final state. We have considered the following SM background processes:

- Continuum $ZZ \rightarrow 2\ell 2\nu$ is almost irreducible because it gives the same final state as the signal and contributes approximately 70% of the total background.

- $WZ \rightarrow \ell \nu \ell \ell$, where the lepton from the $W$ decay is not identified either by failing lepton identification or by being outside the kinematical selections. The $WZ$ background contributes approximately 25% of the total background and the kinematic distributions are rather similar to the $ZZ \rightarrow 2\ell 2\nu$ background.

- Rest of backgrounds:
  - Continuum $WW \rightarrow \ell \nu \ell \nu$ events, where the leptons fall into the dilepton $Z$ boson mass window constitute approximately 2% of the background.
  - Top quark events ($t\bar{t}$ and $tW$), where the leptons fall into the dilepton $Z$ boson mass window and no jets are reconstructed contribute about 1% of the background.
  - Inclusive $W + \text{jets}$ events, where one jet is reconstructed as a lepton. This background is approximately 1% of the total background.
  - The inclusive $Z/\gamma^{*} \rightarrow \ell^{+}\ell^{-}$ production is the most dangerous background since it is hard to model and it has a final state similar to the signal. It is largely reduced by requiring large $E_T^{\text{miss}}$ together with additional topological requirements to approximately 0.5% to the total background.
  - SM Higgs boson with $m_H = 125$ GeV. While the invisible Higgs decays shows a characteristic very large $E_T^{\text{miss}}$ and low jet multiplicity behavior, most of the SM Higgs processes show just either a moderate $E_T^{\text{miss}}$ or large jet multiplicity behavior. The only channel which has the same topology is $Z(\rightarrow \ell\ell)H(ZZ \rightarrow 4\nu)$, but the cross section times branching ratio value is too low to give any noticeable yield.

4 Simulation

Several Monte Carlo event generators are used to simulate the signal and background processes. The POWHEG 2.0 program [14] provides event samples for the signal and the $t\bar{t}$, and $tW$ processes. Drell-Yan, and diboson processes are generated using the MADGRAPH 5.1.3 [15] event generator. For leading-order generators, the default set of parton distribution functions (PDF) CTEQ6L[16] is used, and CT10 [17] is used for next-to-leading order (NLO) generators.

Cross section calculations are performed at next-to-next-to-leading order (NNLO) for the Higgs processes [18, 19], while NLO calculations are used for background cross sections. For all Monte Carlo simulations, the detector response is simulated using a detailed description of the CMS detector, based on the GEANT4 package [20]. Minimum bias events are superimposed on the simulated events to emulate the additional pp interactions per bunch crossing (pile-up). All Monte Carlo samples are reweighted to be consistent with the pile-up distribution as measured in the data. The average number of pile-up events per beam crossing is about 10 and 20 respectively in the 2011 and 2012 data sample.
5 Object selection

Events with electrons are collected by using dielectron triggers with thresholds of $p_T > 17$ GeV and $p_T > 8$ GeV for the leading and the other electron. The muon channel relies mostly on double muon triggers while single-muon triggers are added in order to recover residual trigger inefficiencies. As the instantaneous luminosity increased the rates needed to be adjusted. Therefore, the thresholds on the double-muon triggers changed from $p_T > 7$ GeV for each of the two muons to $p_T > 17$ GeV on the leading muon and to $p_T > 8$ GeV on the other muon. The threshold for the single-muon trigger increased from $p_T > 17$ GeV to $p_T > 24$ GeV.

Prior the lepton selection, a primary vertex has to be selected as the event vertex. The vertex with largest value of $\sum p_T^2$ for the associated tracks is selected. According to simulation, this requirement provides the correct assignment for the primary vertex in more than 99% of both signal and background events. The tracks of both lepton candidates are required to be compatible with the primary vertex origin hypothesis.

Muon candidate reconstruction is based on two main algorithms: in the first, tracks in the silicon tracker are matched to energy deposits in the muon detectors and in the second algorithm a combined fit is performed to signals in both the silicon tracker and the muon system [21]. The muon candidates in this analysis are required to be reconstructed as particle flow muons [22, 23] by at least one of these two algorithms. To reduce the muon misidentification rate further identification criteria are applied based on the number of measurements in the tracker and in the muon system, the fit quality of the muon track, and its consistency with the selected primary vertex location.

Electron candidates are also reconstructed using two algorithms [24]: in the first energy clusters in the ECAL are matched to signals in the silicon tracker and in the second one tracks in the silicon tracker are matched to ECAL clusters. The electron candidates used in the analysis can be reconstructed by either algorithm. To reduce the electron misidentification rate the candidates are subjected to additional identification criteria which are based on the distribution of the electromagnetic shower in the ECAL, a matching of the trajectory of an electron track with the cluster in the ECAL and its consistency with originating from the selected primary vertex. Electron candidates with an ECAL cluster in the transition region between ECAL barrel and endcap ($1.4442 < |\eta| < 1.566$) are rejected. Candidates that are identified to come from photon conversions in the detector material are explicitly removed.

Leptons produced in the decay of Z bosons are expected to be isolated from hadronic activity in the event. Isolation is defined from the sum of the flux of the momenta of the particle flow based objects found in a cone of radius $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$ built around each lepton, where $\phi$ is the azimuthal angle, and $\eta$ is the pseudo-rapidity. The isolation sum is required to be smaller than 15% (20%) of the electrons’ (muons’) $p_T$. To correct for the contribution to the isolation sum from pile-up interactions and underlying event, a median energy density ($\rho$) is determined on an event-by-event basis using the method described in [25]. For electron candidates an effective-area is derived to re-normalise the $\rho$-estimate to the number of pile-up interactions. After the re-normalisation, the contribution is subtracted from the isolation sum. For muon candidates the correction is performed instead by subtracting half the sum of the $p_T$ of the charged particles in the cone of interest which are not associated with the primary vertex.

Jets are reconstructed from particle-flow candidates [26] by using the anti-$k_T$ clustering algorithm [27] with a distance parameter $R$ of 0.5, as implemented in the FASTJET package [28, 29]. The jet momentum is defined as the vectorial sum of all particle momenta assigned to the jet, and is found in the simulation to be within 5% to 10% of the true momentum over the whole $p_T$. 
range and detector acceptance. An overall energy subtraction is applied to correct for the extra energy clustered in jets due to additional proton-proton interactions within the same bunch crossing following the procedure described in [25, 30]. In the subtraction the charged particle candidates associated to secondary vertices reconstructed in the event are also included. Other jet energy-scale corrections applied are derived from the simulation, and are confirmed with in situ measurements of the energy balance of dijet and γ+jets events.

The particle-flow based missing transverse energy [22], $E_{\text{T,PF}}^{\text{miss}}$, is calculated as the opposite-sign vectorial sum of the transverse momenta of all particle flow candidates reconstructed in the event. In addition, the magnitude of the reduced-$E_{\text{T}}^{\text{miss}}$ (red-$E_{\text{T}}^{\text{miss}}$) observable, defined in Section 6.1, is used to suppress $Z + \text{jets}$ background.

Top-quark decays that almost always involve $b$-quarks are identified by the presence of jets containing $b$-quarks ($b$-jets). To suppress such background, a top tagging technique based on soft-muon and $b$-jet tagging [31] is applied. The first method rejects events with soft-muons which are likely to come from semileptonic $b$-decays. The $b$-jet tagging algorithm looks for a group of tracks within a jet forming a secondary vertex.

6 Search strategy

The leptonic final state in the $ZH$ channel consists of two opposite charged same-flavor high $p_T$ isolated leptons compatible with a $Z$ boson decay, large $E_{\text{T}}^{\text{miss}}$ from the undetectable particles recoiling against the two leptons and small jet activity. The signal cross section is several orders of magnitude lower than the major reducible background processes like Drell-Yan and $W + \text{jets}$, and therefore tight requirements are needed to isolate the possible signal.

Two analyses are carried out, both lead to similar performance. It was decided to consider one of them as the principal analysis and the other as a cross-check before looking at the final selected events in data. The selection has been optimized to obtain the best expected limit for $m_H = 125$ GeV, although very similar results are obtained if the best expected significance is used instead. A mass independent event selection followed by a fit to the shape of the transverse mass distribution is used to discriminate between the signal and the backgrounds.

6.1 Event selection

Events are selected to have two well-identified, isolated leptons of same flavour ($e^+e^-$ or $\mu^+\mu^-$) with $p_T > 20$ GeV that have an invariant mass within $\pm 15$ GeV of an on-shell $Z$ boson.

The red-$E_{\text{T}}^{\text{miss}}$, previously used in similar analyses conducted by the D0 [32] and OPAL [33] experiments, is used to suppress the $Z$+jets background. The red-$E_{\text{T}}^{\text{miss}}$ has been developed, in an event-by-event basis, to suppress the contribution from misconstruction to the $E_{\text{T,PF}}^{\text{miss}}$. In each event, $E_{\text{T,PF}}^{\text{miss}}$ and jets are decomposed along an orthogonal set of axes. One of the axes is defined by the $p_T$ of the dilepton system, the other perpendicular to it. The recoil of the dilepton is defined in two different ways:

- clustered recoil ($\vec{R}_{\text{clus}}$), vectorial sum of the particle-flow jets reconstructed in the event;
- unclustered recoil ($\vec{R}_{\text{uncl}}$), sum of all particle-flow candidates in the event, with the exception of the two leptons; it is constructed as the vectorial sum of the $E_{\text{T,PF}}^{\text{miss}}$ and the dilepton $p_T$, with opposite sign.

On each axis ($i = \text{parallel/orthogonal to the dilepton}$), the red-$E_{\text{T}}^{\text{miss}}$ projection is defined as
6.1 Event selection

\[ \text{red-}E_{T}^{\text{miss}} = p_{T}^{\ell\ell} - \min(R_{\text{clus}}, R_{\text{uncl}}). \] (1)

Presence of real \( E_{T}^{\text{miss}} \) in the recoil of the dilepton is expected to be significant in the parallel projection, while the component perpendicular to the dilepton is dominated by jet and \( E_{T}^{\text{miss}} \) resolution. The absolute red-\( E_{T}^{\text{miss}} \) variable is the sum in quadrature of the two components. The red-\( E_{T}^{\text{miss}} \) shows a better performance than the \( E_{T}^{\text{miss}} \) in terms of signal efficiency and Drell-Yan background suppression. It is also found to be more stable than the \( E_{T}^{\text{miss}} \) under variations of pile-up conditions and jet energy scale. Please note that red-\( E_{T}^{\text{miss}} \) is used only in defining the missing transverse energy requirement, while \( E_{T}^{\text{miss}} \) is used in constructing all other observables.

Since little hadronic activity is expected in this final state, any event having at least one jet with \( E_{T} > 30 \) GeV is rejected. The top-quark background is suppressed by applying soft-muon and b-jet tagging. The tagged b-jet is required to have \( p_{T} > 20 \) GeV and to be reconstructed within the tracker acceptance volume (i.e. \( |\eta| < 2.5 \)). The soft-muon is required to have \( p_{T} > 3 \) GeV.

To reduce the WZ background in which both bosons decay leptonically, events containing additional leptons with \( p_{T} > 10 \) GeV are rejected.

The event selection is optimized using three variables: red-\( E_{T}^{\text{miss}} \), \( \Delta \phi_{\ell\ell - E_{T}^{\text{miss}}_{\text{PF}}} \) and \( |E_{T}^{\text{miss}}_{\text{PF}} - p_{T}^{\ell\ell}| / p_{T}^{\ell\ell} \). The latter two variables are powerful in suppressing reducible background processes like Drell-Yan and top. The selection criteria applied to these variables is optimized in order to obtain the best expected exclusion limits at 95% CL. For each possible set of selections the full analysis, including the estimation of data-driven backgrounds and the systematic uncertainties, is repeated. The final selection criteria obtained after optimization are: red-\( E_{T}^{\text{miss}} > 110 \) GeV, \( \Delta \phi_{\ell\ell - E_{T}^{\text{miss}}_{\text{PF}}} > 2.6 \) and \( |E_{T}^{\text{miss}}_{\text{PF}} - p_{T}^{\ell\ell}| / p_{T}^{\ell\ell} < 0.2 \).

The results from this search are obtained by analysing the shape of the reconstructed transverse mass \( m_{T} \) of the dilepton and the \( E_{T}^{\text{miss}}_{\text{PF}} \) system, which is defined as follows:

\[ m_{T}^{2} = \left[ \sqrt{(p_{T}^{\ell\ell})^{2} + (m_{\ell\ell})^{2}} + \sqrt{(E_{T}^{\text{miss}}_{\text{PF}})^{2} + (m_{\ell\ell})^{2}} \right]^{2} - \left[ p_{T}^{\ell\ell} + E_{T}^{\text{miss}}_{\text{PF}} \right]^{2} \] (2)

where \( p_{T}^{\ell\ell} \) and \( m_{\ell\ell} \) are the transverse momentum and invariant mass of the dilepton system, respectively.

The cross-check analysis is carried out with different object definition and final event selection. In particular, it uses the particle-flow based missing transverse energy \( E_{T}^{\text{miss}}_{\text{PF}} \) rather than the red-\( E_{T}^{\text{miss}} \). The lepton selection is slightly tighter using more sophisticated multivariate techniques, as described in [1, 34, 35]. The b-jet tagging algorithm looks for tracks with large impact parameter within jets, in addition to the rejection of events with soft-muons. The event selection is optimized using the same three variables. \( E_{T}^{\text{miss}}_{\text{PF}} \) is required to be larger than 120 GeV, \( \Delta \phi_{\ell\ell - E_{T}^{\text{miss}}_{\text{PF}}} \) is required to be larger than 160 degrees, and \( |E_{T}^{\text{miss}}_{\text{PF}} - p_{T}^{\ell\ell}| / p_{T}^{\ell\ell} \) is required to be smaller than 0.25. After the selection, the chosen variable to discriminate signal and the remaining background is \( m_{T}^{\ell\ell E_{T}^{\text{miss}}_{\text{PF}}} = \sqrt{2 p_{T}^{\ell\ell} E_{T}^{\text{miss}}_{\text{PF}} (1 - \cos \Delta \phi_{\ell\ell - E_{T}^{\text{miss}}_{\text{PF}}})} \).
7 Background predictions

The ZZ and WZ backgrounds are modeled using Monte Carlo simulation, and are normalised to their respective NLO cross sections computed with MCFM [36].

The Z+jets background is modeled from an orthogonal control sample of events with a single photon produced in association with jets (γ + jets). This choice has the advantage of using a large statistics sample, which resembles the Z production in all important aspects: production mechanism, underlying event conditions, pile-up scenario, and hadronic recoil. The kinematics and overall normalisation of γ + jets events are matched to Z + jets in data through reweighing factors determined as a function of the Z boson $p_T$ measured from data. This procedure takes into account the dependence of the red-$E_T^{\text{miss}}$ on the associated hadronic activity. Residual discrepancies can arise due to differences in the effective pile-up of the γ + jets sample due to the photon trigger pre-scale and event selection. These are taken into account by reweighing events according to the number of reconstructed vertices. The electroweak processes involving photon and neutrino are subtracted using simulated predictions. This procedure yields an accurate model of the red-$E_T^{\text{miss}}$ distribution in Z+jets events, as shown in Figure 1 (left), which compares the red-$E_T^{\text{miss}}$ distribution of the reweighed γ+jets events along with other backgrounds to the red-$E_T^{\text{miss}}$ distribution of the dilepton events in data. Figure 1 (right) shows the comparison of the $\Delta\phi_{l\ell , -E_T^{\text{miss}}}$ distribution obtained from the γ+jets events along with other backgrounds to the same distribution in the dilepton sample. A good agreement is found between data and background predictions. Due to the lack of statistics in high red-$E_T^{\text{miss}}$ tail, a 100% uncertainty is assumed on this method. Given that the Z+jets background remaining after all selections is very small, the large uncertainty assigned has negligible impact on the final results.

Figure 1: The left (right) plot shows the red-$E_T^{\text{miss}}$ ($\Delta\phi_{l\ell , -E_T^{\text{miss}}}$) distribution in data compared to the estimated background from data or simulation. The expected distributions from different background processes are stacked on top of each other. Electron events and muon events are combined. The small plots below both distributions show the ratio of observed data to expected background events.

The background processes that do not involve a Z resonance are referred to as non-resonant backgrounds (NRB). The contribution of the non-resonant flavor symmetric backgrounds is estimated by using a control sample of events with dileptons of different flavour ($e^+e^-$ and $\mu^+\mu^-$) that pass all analysis selections. Non-resonant backgrounds consists mainly of leptonic W decays in $t\bar{t}$, $tW$ decays and WW events. Small contributions from single top-quark events produced from s-channel and t-channel processes, and $Z \rightarrow \tau\tau$ events in which $\tau$ leptons produce light leptons and $E_T^{\text{miss}}$ are included in the estimate of non-resonant backgrounds.
The non-resonant background in the $e^+e^-$ and $\mu^+\mu^-$ final states is estimated by applying a scale factor ($\alpha$) to the selected $e^{\pm}\mu^{\mp}$ events. The scale factor is defined as:

\[ N_{\mu\mu} = \alpha_{\mu\mu} \times N_{e\mu}, \quad N_{ee} = \alpha_{ee} \times N_{e\mu}, \]

and it is computed from the sidebands (SB) of the Z peak ($40 < m_{\ell\ell} < 70$ GeV and $110 < m_{\ell\ell} < 200$ GeV) by using the following relations:

\[ \alpha_{\mu\mu} = \frac{N_{SB\mu\mu}}{N_{SB\mu}}, \quad \alpha_{ee} = \frac{N_{SBee}}{N_{SB\mu}}, \]

where $N_{SB\mu\mu}$, $N_{SBee}$, and $N_{SB\mu}$ are the number of events in the Z sidebands counted in a top-enriched sample of $e^+e^-$, $\mu^+\mu^-$, and $e^{\pm}\mu^{\mp}$ final states, respectively. In order to reduce the uncertainties of scale factors, the samples are selected in a looser region ($E_T^{miss} > 65$ GeV, $p_T^{\ell\ell} > 50$ GeV, $0.4 < E_T^{miss}/p_T^{\ell\ell} < 1.8$ and a b-tagged jet). The measured values of $\alpha$ with the corresponding statistical uncertainties are $\alpha_{7 \text{ TeV}}^{\mu\mu} = 0.64 \pm 0.06$, $\alpha_{7 \text{ TeV}}^{ee} = 0.42 \pm 0.04$ and $\alpha_{8 \text{ TeV}}^{\mu\mu} = 0.69 \pm 0.03$, $\alpha_{8 \text{ TeV}}^{ee} = 0.43 \pm 0.02$. The validity of the procedure for computing the scale factor was checked by closure tests on simulated samples. By comparing the scale factors calculated with and without applying a b-tagging veto, a conservative 25% uncertainty is assigned to the prediction of the method.

8 Efficiencies and systematic uncertainties

Systematic uncertainties on the data driven background estimates are described in Section 7.

The signal efficiency and ZZ, WZ backgrounds are estimated using simulation. The ZH production cross section is taken from [18, 19]. Uncertainties on ZH signal efficiency, ZZ and WZ background processes are derived from variations of the QCD scale, $\alpha_s$ and parton distribution functions (PDFs) variations [36–41]. The uncertainty related to the QCD scale is 6-11% for ZH, ZZ and WZ processes. The effect of variations in $\alpha_s$ and PDFs is 5-6%.

Residual discrepancies between data and simulation are corrected by determining data-to-simulation scale factors. The lepton reconstruction and identification scale factors are measured using a control sample of $Z/\gamma \rightarrow \ell^+\ell^-$ events in the Z peak region [42]. The associated uncertainty is about 2% per lepton. The impact of the jet energy scale and $E_T^{miss}$ uncertainties on the analysis is also considered. The uncertainty assigned to the luminosity measurement is 2.2% at $\sqrt{s} = 7$ TeV and 4.4% at $\sqrt{s} = 8$ TeV [43].

The changes in the shape of the final discriminant variable, $m_T$, are also considered. The following uncertainties are considered for the shape variation:

- Lepton momentum scale.
- Unclustered energy.
- Jet energy scale, resolution.
- b-tagging Efficiency.
- Limited number of events to predict the signal efficiency and the background yields.
- Pile up.

All these sources of uncertainty are summarized in Table 1. The combined signal efficiency uncertainty is estimated to be about 12% and is dominated by the theoretical uncertainty due
to missing higher-order corrections and PDF uncertainties. The total uncertainty in the background estimations in the signal region is about 15%, which is dominated by the theoretical uncertainties on the ZZ and WZ processes.

<table>
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<th>Type</th>
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<td>Rate</td>
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<td></td>
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<td></td>
<td>QCD scale variation (VV)</td>
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<td></td>
<td>(Z/\gamma^* \rightarrow \ell^+\ell^-) normalization</td>
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</tr>
<tr>
<td></td>
<td>Top, WW &amp; W + jets normalisation</td>
<td>25-100</td>
</tr>
<tr>
<td></td>
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Table 1: Summary of all systematic uncertainties. The ones assigned as shape uncertainties are propagated to both event rates and to the \(m_T\) distributions in the limit calculation.

9 Results

The numbers of observed and expected events for both the 2011 and 2012 data taking periods are shown in Table 2. The signal model assumes a SM ZH production rate for a Higgs boson with \(m_H = 125\) GeV and a 100% branching fraction to invisible particles. Good agreement between the data and the background prediction is observed.

<table>
<thead>
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<th>(\sqrt{s} = 8) TeV</th>
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<td></td>
<td>(ee)</td>
<td>(\mu\mu)</td>
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<tr>
<td>ZH(125)</td>
<td>2.2 ± 0.3</td>
<td>3.3 ± 0.5</td>
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<tr>
<td>(Z/\gamma^* \rightarrow \ell^+\ell^-)</td>
<td>0.3 ± 0.3</td>
<td>0.7 ± 0.7</td>
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<tr>
<td>WZ (\rightarrow 3\ell\nu)</td>
<td>2.0 ± 0.3</td>
<td>2.3 ± 0.3</td>
</tr>
<tr>
<td>ZZ (\rightarrow 2\ell2\nu)</td>
<td>5.1 ± 0.6</td>
<td>7.3 ± 0.8</td>
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<tr>
<td>(Top/WW/W + Jets)</td>
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<tr>
<td>total bkg.</td>
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<td>11.0 ± 1.3</td>
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<tr>
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</table>

Table 2: Observed number of events, background estimates and signal predictions at \(\sqrt{s} = 7\) TeV and 8 TeV. Statistical and systematic uncertainties are reported.

Since no excess is observed over the SM expectation, upper limits are derived for two quantities: the product of the Higgs boson production cross section and BR\((H \rightarrow \text{invisible})\); and the ratio of this product over the SM Higgs production cross section [18, 19]. The latter can be interpreted as the upper limit on BR\((H \rightarrow \text{invisible})\) assuming the SM production rate. To compute the upper limits the modified frequentist construction \(CL_s\) [44–46] is used. The number
of events are modeled as a Poisson random variable, where the mean value is the sum of the contributions from signal and background processes. The $m_T$ distributions used in the analysis are shown in Figure 2.

![Figure 2](image_url)

Figure 2: Transverse mass distributions used in the analysis. The expected distributions from different background processes are stacked on top of each other while a signal corresponding to $m_H = 125$ GeV is superimposed. The grey bands are total statistical and systematic uncertainties of backgrounds. 7 TeV (8 TeV) events are shown on the left (right). Electron events and muon events are combined.

The 95% observed and median expected confidence level upper limits computed with the CL$_s$ method are shown in Figure 3. For a Higgs boson with $m_H = 125$ GeV, assuming the SM production rate, the observed (expected) upper limit on the branching fraction to invisible particles is 75% (91%) at 95% CL, comparable with indirect limits from fits of coupling deviations by ATLAS [10] and CMS [9]. The performance of the cross-check analysis is comparable with respect to the principal analysis, as summarized in Appendix A.

![Figure 3](image_url)

Figure 3: (left) Expected and observed 95% CL upper limits on the cross section times branching fraction, $\sigma_{ZH} \times \text{BR}(ZH \rightarrow \ell \ell + \text{invisible})$. The blue dash line is SM ZH production cross section multiplied by BR($Z \rightarrow \ell \ell$) with theoretical uncertainties, assuming BR($H \rightarrow \text{invisible}$) is 100%. BR($Z \rightarrow \ell \ell$) is the branching fraction of a Z boson decaying to all three types of charged leptons [47]. (right) Expected and observed 95% CL upper limits on $\sigma_{ZH} \times \text{BR}(H \rightarrow \text{invisible})$ relative to the SM Higgs production cross section.
10 Summary

A search for decays to invisible particles of a Higgs boson at the Large Hadron Collider using the CMS experiment is presented. The study uses the full 2011 and 2012 data samples at 7 TeV and 8 TeV, respectively. This search is performed for a SM-like Higgs boson produced in association with a Z boson. The Higgs boson mass range between 115 GeV and 145 GeV is studied. The results are interpreted to place limits on the branching fraction to invisible particles of the SM Higgs boson. For a Higgs boson with \( m_H = 125 \text{ GeV} \), assuming the SM production rate, the observed (expected) 95% CL upper limit on the branching fraction of the Higgs boson to invisible particles is 75% (91%).

References


Appendix A: results from the cross-check analysis

The number of observed and expected events for both $\sqrt{s} = \text{7 TeV}$ and $\sqrt{s} = \text{8 TeV}$ for the cross-check analysis are shown in Table 3. Good agreement between the background expectation and the data is also found. For a Higgs boson with $m_{H} = 125 \text{ GeV}$, assuming the SM production rate, the observed (expected) 95% CL branching fraction limit of 73% (87%), which is consistent, within uncertainties, with the principal analysis.

![Table 3: Observed number of events, background estimates and signal predictions at $\sqrt{s} = \text{7 TeV}$ and 8 TeV for the cross-check analysis. Statistical and systematic uncertainties are reported. The reported yields combine the muon and electron final states in a single channel.](image-url)