Search for invisible anomalous Higgs boson decay with the ATLAS detector at the LHC

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Abstract. A direct search for evidence of decays to invisible particles of a Higgs boson at the Large Hadron Collider (LHC) is presented. This search is performed for a Standard Model-like Higgs boson produced in association with a Z boson and having a mass between $m_H = 115$ GeV and $m_H = 300$ GeV. The results are interpreted to place limits on the branching fraction to invisible particles of the newly discovered boson with mass near 125 GeV. Assuming that this is the Standard Model Higgs boson, its decay to invisible particles is not measurable, but could have a large contribution from the decay to the dark matter particles, for example. In addition, limits are set on any neutral Higgs-like particle, produced in association with a Z boson and decaying predominantly to invisible particles.

No deviation from the Standard Model expectation is observed in the search, which uses 4.7 fb^{-1} of 7 TeV pp collision data and 13.0 fb^{-1} of 8 TeV pp collision data collected by the ATLAS experiment at the LHC. Assuming the ZH production rate for a 125 GeV Standard Model Higgs boson, limits are set on the invisible branching fraction at 95% condence level. The observed exclusion is for branching fractions greater than 65%, and the expected limit is 84%.

1. Introduction

Some extensions to the Standard Model (SM) allow a Higgs boson [1-3] to decay to stable or longlived particles that interact with the Higgs boson, but have only weak interactions with other elementary particles. The results obtained so far in the search for the SM Higgs boson do not exclude the possibility of a sizable branching ratio to invisible particles for the SM Higgs boson candidate at $m_H \sim 125$ GeV [4,5]. Combined LEP results [6] have excluded an invisibly decaying Higgs boson for $m_H < 114.4$ GeV under the assumption that such a Higgs boson is produced in association with a Z boson at the rate expected for a SM Higgs boson and that it decays predominantly to invisible particles. A further Higgs-like boson decaying predominantly to invisible particles is not excluded for $m_H > 115$ GeV. This note presents a search for decays to invisible particles for a narrow 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 and 300 GeV. The results are also interpreted in terms of the 125 GeV Higgs boson candidate, where the ZH production cross section is taken to be that predicted for a SM Higgs boson.

2. Signal Analysis and Analysis Overview

The signal process searched for is the associated production of ZH. The Higgs boson is assumed to decay to invisible particles. The Z boson decaying into electrons or muons is considered for this analysis. The SM ZH cross section for $m_H = 125$ GeV is 316 fb at $\sqrt{s} = 7$ TeV and 394 fb at $\sqrt{s} = 8$ TeV [7,8]. It is calculated at NLO [9] and at NNLO [10] in QCD, and NLO EW radiative corrections [11] are applied. Including the requirement that the Z boson decays to e, μ, or τ reduces these cross sections to 31.9 fb and 39.8 fb respectively. A very small SM contribution to the $ZH \rightarrow ll+$ inv. nal state arises when the Higgs boson decays to four neutrinos via two Z bosons. The predicted cross section of this process for $m_H = 125$ GeV is 3.4×10^2 fb at $\sqrt{s} = 7$ TeV and 4.2×10^2 fb at $\sqrt{s} = 8$ TeV. The present search is not sensitive to this particular process although it is part of the signal, but instead searches for enhancements of the invisible decay fraction due to physics beyond the Standard Model (BSM).

The POWHEG [12] interfaced with HERWIG++ [13] Monte Carlo (MC) generator is used to simulate the signal. In the simulation the associatively produced Z boson is forced to decay to e, μ, or τ. The invisible decay of the Higgs boson is simulated by forcing the Higgs boson to decay to two Z bosons, which are then forced to decay to neutrinos. For most distributions shown in this note the signal simulation is normalized assuming the SM ZH production rate and a 100% branching fraction of the Higgs boson to invisible particles. Signal samples are generated at Higgs boson masses of 115, 120, 125, 130, 150, 200, and 300 GeV.

This analysis searches for an excess of events over the SM contribution in the dilepton + large missing transverse energy (E_T^{miss}) final states. The processes that contribute to the SM expectation are as follows. The $ZZ \rightarrow ll\nu\nu$; this is an irreducible background and contributes approximately 70% of the total background. The $WZ \rightarrow l\nu ll$, where the W decay lepton is not identied either by failing lepton identication or by being outside the kinematical selections. The WZ background contributes approximately 20% of the total background. The $WW \rightarrow l\nu l\nu$ events, where the leptons mimic a Z boson. This background constitute approximately 5% of the total background. The top quark events ($t\bar{t}$ and Wt) where the leptons mimic a Z boson are considerably reduced by applying a jet veto. These contribute approximately 2% of the background. The $Z \rightarrow ll$ events are largely reduced by requiring large E_T^{miss}. Additional cuts are also applied to further suppress this background. The remaining background contributes approximately 1% to the total background. The $W \rightarrow l\nu$ and dijet events can fake the signal if one or two jets are reconstructed as leptons. These backgrounds are approximately 1% of the total. The $H \rightarrow ZZ^{(*)} \rightarrow ll\nu\nu$, for a 125 GeV SM Higgs boson, would produce a E_T^{miss} that falls below the cut. Thus, this process is considered negligible. And finally the $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$, for a 125 GeV SM Higgs boson, would have a dilepton mass that falls outside the Z peak and is thus also considered to be negligible.

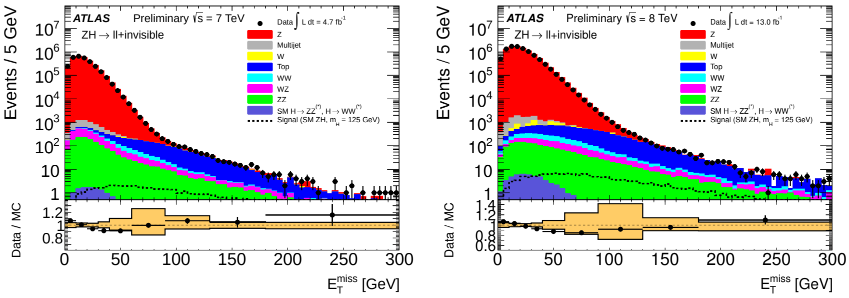
3. Data and Monte Carlo Samples

This search uses 4.7 fb^{-1} of data recorded in 2011 at a center of mass energy of 7 TeV and 13.0 fb^{-1} of data recorded in 2012 at a center of mass energy of 8 TeV. Events are selected using a combination of triggers that select single electrons or muons or a pair of electrons or muons. The trigger eciency, for signal events passing the full selection cuts described below, is nearly 100% in both data periods in the electron channel, and approximately 95% and 94% in the 2011 and 2012 periods respectively in the muon channel. The data are required to have been recorded during stable beam conditions and during nominal detector performance and data readout conditions.

Background processes are modeled using tree level and NLO MC generators. Table 1 above summarises the Monte Carlo (MC) simulation used to estimate the backgrounds.

Background	Generator	Cross Section	MC Statistics
ZZ	HERWIG	6.49 pb (7 TeV)	50k
$Z \to ll$	SHERPA	0.38 pd (8 TeV, m_{ll}-filtered)	400k
$WZ \to l\nu ll$	HERWIG	17.9 pb (7 TeV)	100k
WZ	SHERPA	2.51 pb (8 TeV, m_{ll}-filtered)	590k
$H \to ZZ^{(*)} \to ll\nu\nu$	POWHEG	16.3 fb (7 TeV)	50k
	POWHEG	20.8 fb (8 TeV)	50k
$H \to WW^{(*)} \to l\nu l\nu$	POWHEG	374.7 fb (7 TeV)	50k, 30k
	POWHEG	478.5 fb (8 TeV)	500k, 500k

Table 1: The MC simulation samples used to estimate the ZZ, WZ background, and yields of the Standard Model Higgs boson processes sharing the same nal state. For the MC statistics of the $H \to WW^{(*)} \to l\nu l\nu$ boson samples, the rst number indicates the statistics of the gluon-gluon fusion samples, whereas the second indicates the statistics of vector-boson fusion samples.



(a) (b)

Figure 1: E_T^{miss} distributions after the dilepton mass requirement from the 2011 (a) and 2012 (b) data. The observed data are represented by the black dots and the histograms represent the background predictions from the MC samples listed in Section 3. The signal hypothesis is shown by the dotted line and assumes the SM ZH production rate for a Higgs boson with $m_H = 125$ GeV and a 100% invisible branching fraction. The insets at the bottom of the gures show the ratio of the data to the combined background expectations as well as a band corresponding to the combined systematic uncertainties.

4. Event Selection

Events are selected using a combination of triggers that select single electrons or muons or a pair of electrons or muons as mentioned in Section 3. Only well identified leptons are selected to ensure that leptons from non-collision events like cosmic rays are rejected. As a result, muon are required to be picked up in the Inner-Detector and the Muon-Spectrometer whle electrons must have tight electromagnetic shower-shape requirements. Lepton pairs are required to be of the same flavour and must be oppositely charged. These leptons must further be compatable with decay from a Z boson. One of these compatability requirements, for example, is that the events must have $E_T^{miss} > 90$ GeV. Events with three leptons need to be vetoed. A full jet veto is also required to sort out events with fake a missing transverse energy. There is also a series of requirements to ensure that the E_T^{miss} is genuine. That is, it is not produced by leptons or jets that are missmeasured.

Figure 2 shows the E_T^{miss} distributions after the dilepton mass requirement. The data agree with the MC within the uncertainty error bands.

Process	Estimation method	Uncertainty (%)	
		2011	2012
ZH Signal	MC	7	6
ZZ	MC	11	10
WZ	MC	12	14
WW	MC	14	not used
Top quark	MC	90	not used
Top quark, WW and $Z \to \tau\tau$	$e\mu$ CR	not used	4
Z	ABCD method	56	51
W + jets, multijet	Matrix method	15	22

Table 2: Summary of the systematic uncertainties on each background and on the signal yield. The method used to estimate the backgrounds and the associated sources of systematic uncertainties are given and the total systematic uncertainties for each data taking period are given.

5. Systematic Uncertainties

Systematic uncertainties on the signal mode, the ZZ and WZ backgrounds as well as the WW and top quark backgrounds (for the 2011 data taking period) are estimated from MC samples. Uncertainties in the backgrounds are either measured from data or based on normalization to data in control regions. The luminosity uncertainty (1.8% for 2011 and 3.6% for 2012) is derived using the same method as source [14].Lepton trigger and identification efficiencies as well as energy scale and resolution uncertainties are derived from high statistics Z samples. These contribute typically 1.0-1.5% to the overall selection uncertainty. Jet energy scale and resolution uncertainties (which contribute 3-6% uncertainty to the final event selection) are derived using a combination of techniques that use dijet, photon + jet, and Z+ jet events [15]. Both the uncertainties on the leptons and the jets are propogated to the E_T^{miss} calculation and an additional uncertainty on E_T^{miss}, related to the pile-up simulation, contribute a 1-2% uncertainty on the final even selection in signal and backgrounds estimated from the MC simulation.

Uncertainties on the ZH production cross section are derived from the variations of the QCD scale, α_s and PDF variations [7,8]. These combine to give an uncertainty of 4.9-5.1% on the cross section for the SM Higgs boson having a mass between 115 and 300 GeV. This analysis is sensitive to the transverse momentum of the Higgs boson the the E_T^{miss} and uncertainties in the p_T boost of the Higgs boson can affect the signal yield. An additional systematic uncertainty of 1.9% is applied to the normalization and differentioal uncertainties as a function of the transverse momentum of the Higgs boson is considered as shape systematics [16,17].

The object and theoretical uncertainties are considered as correlated between the 2011 and 2012 data and between the signals and all the backgrounds estimated from the MC simulation. The systematic uncertainties in the data-driven methods are also assumed to be correlated between the two datasets while the luminosity uncertainty is considered to be uncorrelated. Since different methods are used for the background estimation between the 2011 and 2012 datasets, the uncertainties for the WW and the top quark backgrounds are considered to be uncorrelated between the two datasets.

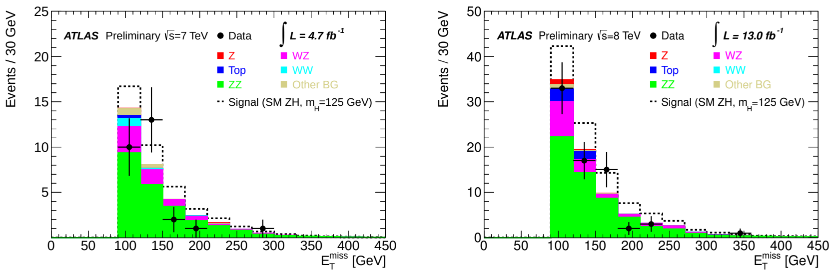
The systematic uncertainties are summarised in Table 2.

6. Results

Table 3 summarizes the expected contributions from each background source and observed number of data events. Figure 3 shows the final E_T^{miss} distributions with the observed data and expected backgrounds for both the 2011 and 2012 data taking periods. No excess is observed

Data Period	2011 (7 TeV)	2012 (8 TeV)
ZZ	$23.5 \pm 0.8 \pm 2.5$	$56.5 \pm 1.2 \pm 5.7$
WZ	$6.2 \pm 0.4 \pm 0.7$	$13.9 \pm 1.2 \pm 2.1$
WW	$1.1 \pm 0.2 \pm 0.2$	used $e\mu$ data-driven
Top quark	$0.4 \pm 0.1 \pm 0.4$	used $e\mu$ data-driven
$e\mu$ data-driven	used MC	$4.9 \pm 0.9 \pm 0.2$
Z	$0.16 \pm 0.13 \pm 0.09$	$1.4 \pm 0.4 \pm 0.7$
W + jets, multijet	$1.3 \pm 0.3 \pm 0.2$	$1.4 \pm 0.4 \pm 0.3$
Total BG	$32.7 \pm 1.0 \pm 2.6$	$78.0 \pm 2.0 \pm 6.5$
Observed	27	71

Table 3: Observed number of events and expected contributions from each background source seperated into the 2011 and 2012 data taking periods. Associated uncertainties with the background predictions are presented with statistical uncertainties first followed by the systematic errors.



(a) (b)

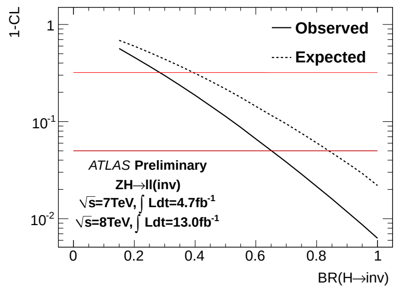
Figure 2: Distribution of E_T^{miss} for signal events in the 2011 (a) and 2012 (b) data taking periods. The observed data is indicated by the black points and the histograms represent the background predictions. The dashed line indicates the prediction from the signal model and is stacked on the background prediction. The signal model assumes a SM Higgs boson with a mass of 125 GeV and a 100% branching fraction to invisible particles.

over the SM expectation and limits are set for two scenarios. The first scenario explores the possibiitye that the recently discovered Higgs boson with $m_H \sim 125$ GeV has a non-neglible branching ratio to invisible particles while the second considers the possibility of a Higgs-like boson in a range of masses from 115 GeV to 300 GeV with a significant branching fraction to invisible particles.

The limits are computed from a maximum likelihood fit to the E_T^{miss} distribution following the CL_S modified frequntist formalism with profilelikelihood test statistics [18,19].

Figure 4 shows the interpretation of the first scenario. Assuming a ZH production rate for a 125 GeV SM Higgs boson, limits are set on the invisible branching fraction at 95% CL. The observed exclusion is for branching fractions greater that 65% and the expected limit is 84%.

For the second scenario limits are set considering only the hypothesis of a single invisibly decaying Higgs-like boson. The limits do not consider possible multiple Higgs boson candidates all having non-negligible invisible branching fractions. Figure 5 shows 95% CL limits on the ZH production cross section multiplied by the invisible branching fraction of such a Higgs boson in the mass range 115-300 GeV for the considered data taking periods, as well as the limit achieved from the combination of both periods. Again, no excess is observed over the mass range.



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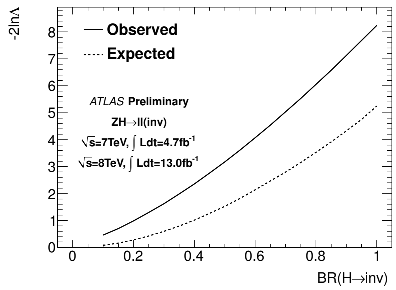
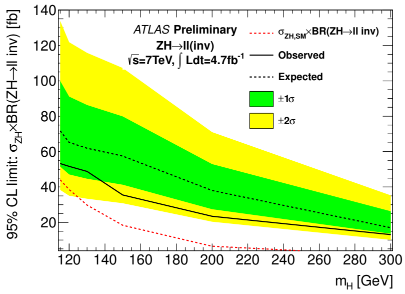
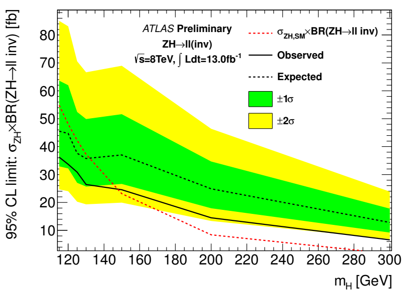


(b)

Figure 3: Confidene level (CL) (a) and profile likelihood (b) scanned against BR($H \to$ invisible) forthe SM Higgs boson with $m_H \sim 125$ GeV. The dashed line shows the expected values and the solid line indicates the observed values. The red lines in (a) indicate the 68% and 95% CL.



(a)



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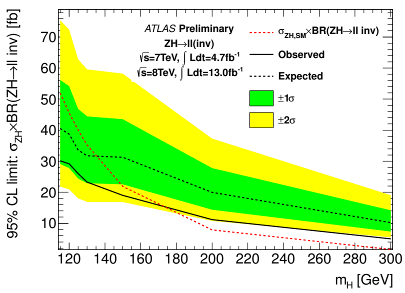

(c)

Figure 4: 95% CL limits on the cross section times branching fraction of a Higgs-like boson decaying to invisible particles for the 2011 (a) and 2012 (b) data taking periods and a combination of both periods (c). Dashed lines show the background only expected limits and solid lines show the observed limit.

7. Conclusion

A direct search for evidence of the invisible decays of a Higgs boson at the LHC has been performed. While the invisible branching fraction for a SM Higgs boson is too small to be accessible, this measurement is sentitive to enhancements of the invisible branching fraction such as from decays to dark matter particles. After the full selection, 27 events are observed compared to a SM expectation of 32.7 ± 1.0 (stat.) ± 2.76 (syst.) background events in 4.7 fb^{-1} of data taken at $\sqrt{s} = 7$ TeV during the 2011 run and 71 events are observed compared to an expected 78.0 ± 2.0 (stat.) ± 6.5 (syst.) background events in 13.0 fb^{-1} of data taken at

$\sqrt{s} = 8$ TeV during part of the 2012 run. No significant excess over the expected background is observed and limits are set on the allowed invisible branching fraction of the recently observed 125 GeV Higgs boson candidate. Assuming the ZH production rate for a 125 GeV SM Higgs boson, limits are set on the invisible branching fraction at 95% CL. The observed exclusion is for branching fractions greater than 65% and the expected limit is 84%. Limits are also set on the cross section times invisible branching fraction of a possible additional Higgs-like boson over the mass range 115-300 GeV. No excess is observed over the mass range.

8. References

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