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


DOI
10.1103/PhysRevLett.112.201802

Publication date
2014

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):
https://doi.org/10.1103/PhysRevLett.112.201802

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
Search for Invisible Decays of a Higgs Boson Produced in Association with a Z Boson in ATLAS

G. Aad et al.*

(ATLAS Collaboration)

(Received 13 February 2014; revised manuscript received 11 April 2014; published 20 May 2014)

A search for evidence of invisible-particle decay modes of a Higgs boson produced in association with a Z boson at the Large Hadron Collider is presented. No deviation from the standard model expectation is observed in 4.5 fb⁻¹ (20.3 fb⁻¹) of 7 (8) TeV pp collision data collected by the ATLAS experiment. Assuming the standard model rate for ZH production, an upper limit of 75%, at the 95% confidence level is set on the branching ratio to invisible-particle decay modes of the Higgs boson at a mass of 125.5 GeV. The limit on the branching ratio is also interpreted in terms of an upper limit on the allowed dark matter-nucleon scattering cross section within a Higgs-portal dark matter scenario. Within the constraints of such a scenario, the results presented in this Letter provide the strongest available limits for low-mass dark matter candidates. Limits are also set on an additional neutral Higgs boson, in the mass range 110 < m_H < 400 GeV, produced in association with a Z boson and decaying to invisible particles.

DOI: 10.1103/PhysRevLett.112.201802

PACS numbers: 14.80.Bn, 12.60.Fr, 14.80.Ec, 95.35.+d

Some extensions of the standard model (SM) allow a Higgs boson [1–3] to decay to a pair of stable or long-lived particles [4–18] that are not observed by the ATLAS detector. For instance the Higgs boson can decay into two particles with very small interaction cross sections with SM particles, such as dark matter (DM) candidates. Collider data can be used to directly constrain the branching ratio of the Higgs boson to invisible particles. Similarly, limits can be placed on the cross section times branching ratio of any additional Higgs bosons decaying predominantly to invisible particles. LEP results [19] put limits on an invisibly decaying Higgs boson, produced in association with a Z boson, for Higgs masses below 120 GeV.

This Letter presents a search for invisible decays of a Higgs boson produced in association with a Z boson. A Higgs boson in the mass range 110 < m_H < 400 GeV is considered. The distribution of the missing transverse momentum (E_{T}^{miss}) in events with an electron or a muon pair consistent with a Z boson decay is used to constrain the ZH production cross section times the branching ratio of the Higgs boson decaying to invisible particles, over the full mass range. For the newly discovered Higgs boson, a constraint could be placed on the branching ratio to invisible particles. In this case the mass of the Higgs boson is taken to be m_H = 125.5 GeV, the best-fit value from the ATLAS experiment [20], and the ZH production cross section is assumed to be that predicted for the SM Higgs boson. This assumption implies that the hypothesized unobserved particles that couple to the Higgs boson have sufficiently weak couplings to other SM particles to not affect the Higgs boson production cross sections. The total cross section for the associated production of a SM Higgs boson, with m_H = 125.5 GeV, and a Z boson, calculated to next-to-next-to-leading order in QCD [21] and including next-to-leading-order (NLO) electroweak corrections [22,23], is 331 fb at √s = 7 TeV and 410 fb at √s = 8 TeV [24]. The SM branching ratio of the Higgs boson decaying to invisible particles is 1.2 × 10⁻³, arising from the H → ZZ(ν) → 4ν decay. The present search is not sensitive to the low branching ratio for this decay, but instead searches for enhancements in the decay fraction to invisible particles due to physics beyond the standard model (BSM).

The search uses 4.5 fb⁻¹ of data recorded with the ATLAS detector in 2011 at √s = 7 TeV and 20.3 fb⁻¹ of data recorded in 2012 at √s = 8 TeV. The ATLAS detector has been described elsewhere [25]. Simulated signal and background event samples are produced with Monte Carlo (MC) event generators, passed through a full GEANT4 [26] simulation of the ATLAS detector [27] and reconstructed with the same software as the data.

The signal samples are generated with HERWIG++ [28] and its internal POWHEG method [29,30]. The SM ZZ and WZ backgrounds are taken from simulation, since they have limited statistics in the control regions that would allow us to estimate these backgrounds with data. All other background processes to this search are determined from data. In these cases, simulated samples are only used as cross-checks for the obtained background estimates. POWHEG [29–31] interfaced with PYTHIA8 [32] is used to model SM ZZ and WZ production [33]. The production of WW is modeled using HERWIG [34] and SHERPA [35].
Electron candidates are reconstructed from isolated energy deposits in the electromagnetic calorimeter with a shower shape consistent with electrons or photons, matched to inner detector tracks. The electrons used to form a shower shape consistent with electrons or photons, matched energy deposits in the electromagnetic calorimeter with a and found to be negligible.

The uncertainty band of the expected background is widest in the region dominated by the steeply falling Z boson background. To reject the majority of this background, $E^\text{miss}$ is required to be greater than 90 GeV. In events where a significant $E^\text{miss}_T$ arises from misreconstructed energy in the calorimeter, the vectors of $E^\text{miss}_T$ and $p^\text{miss}_T$ are likely to have different azimuthal angles. Thus the azimuthal difference of these two vectors, $\Delta\phi(E^\text{miss}_T, p^\text{miss}_T)$, is required to be less than 0.2.

![Figure 1](color online). Distribution of $E^\text{miss}_T$ for events with the invariant mass of the two leptons $76 < m_{ll} < 106$ GeV in the 8 TeV data (dots). The stacked histograms represent the background predictions from simulation. The signal hypothesis is shown by a dotted line and assumes the SM $ZH$ production rate for a $m_H = 125.5$ GeV Higgs boson with $BR(H \rightarrow inv.) = 1$. The inset at the bottom of the figure shows the ratio of the data to the combined background expectations as well as a band corresponding to the combined systematic uncertainties.
For the signal, the momentum of the reconstructed Z boson is expected to be balanced by the momentum of the invisibly decaying Higgs boson. Therefore the azimuthal separation between the dilepton system, where the magnitude of its transverse momentum is defined as $p_T^{ll}$, and the $E_T^{miss}$, $\Delta \phi(p_T^{ll}, E_T^{miss})$, is required to be greater than 2.6. The boost of the Z boson causes the decay leptons to be produced with a small opening angle. The azimuthal opening angle of produced, as shown in Table I. These backgrounds are ground is SM $ZZ$. The background from inclusive $Z \rightarrow \nu \nu$ production in the signal region is estimated from the background in three sideband regions [51]. These sideband regions are formed by considering events failing one or both of the nominal selection requirements applied to $\Delta \phi(E_T^{miss}, p_T^{ll})$ and the fractional $p_T$ difference. Contributions from non-Z backgrounds in the sideband regions are subtracted. The impact from a correlation between the above two variables is determined from the simulation and a correction, of at most 7%, is applied to account for it. The main uncertainties are due to variations in this correction and differences in the shape of the $E_T^{miss}$ distribution in the control regions. The overall systematic uncertainty is 52% in the 7 TeV data and 59% in the 8 TeV data.

The background from events with only one genuine isolated lepton (inclusive $W$, single-lepton top pairs and single top production) or from multijet events is estimated from data using control samples, selected by requiring two lepton candidates of which at least one fails the full lepton selection criteria. These samples are scaled with a measured $p_T$-dependent factor, determined from data as described in Ref. [52]. Systematic uncertainties are determined following the procedures used in Ref. [52], yielding an uncertainty of 40% in the 7 TeV data and 21% in the 8 TeV data.

Systematic uncertainties on the signal and the SM $ZZ$ and $WZ$ backgrounds are derived from the luminosity uncertainty, the propagation of reconstructed object uncertainties, and from theoretical uncertainties on the production cross sections. The luminosity uncertainty is 1.8% for the 7 TeV data-taking period and 2.8% for the 8 TeV data-taking period [53].

Lepton trigger and identification efficiencies as well as the energy scale and resolution are determined from data using large samples of $Z$ events. After appropriate corrections to the simulation, uncertainties are propagated to the

<table>
<thead>
<tr>
<th>Data period</th>
<th>2011 (7 TeV)</th>
<th>2012 (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ \rightarrow \ell\ell\nu\nu$</td>
<td>20.0 ± 0.7 ± 1.6</td>
<td>91 ± 1 ± 7</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell\ell\ell$</td>
<td>4.8 ± 0.3 ± 0.5</td>
<td>26 ± 1 ± 3</td>
</tr>
<tr>
<td>Dileptonic $\ell\ell$, $Wt$, $WW$, $Z \rightarrow \tau\tau$</td>
<td>0.5 ± 0.4 ± 0.1</td>
<td>20 ± 3 ± 5</td>
</tr>
<tr>
<td>$Z \rightarrow ee, Z \rightarrow \mu\mu$</td>
<td>0.13 ± 0.12 ± 0.07</td>
<td>0.9 ± 0.3 ± 0.5</td>
</tr>
<tr>
<td>$W +$ jets, multijet, semileptonic top</td>
<td>0.020 ± 0.005 ± 0.005</td>
<td>0.29 ± 0.02 ± 0.06</td>
</tr>
<tr>
<td>Total background</td>
<td>25.4 ± 0.8 ± 1.7</td>
<td>138 ± 4 ± 9</td>
</tr>
<tr>
<td>Signal ($m_H = 125.5$ GeV, $\sigma_{ZH,SM}$, $BR(H \rightarrow inv.) = 1$)</td>
<td>8.9 ± 0.1 ± 0.5</td>
<td>44 ± 1 ± 3</td>
</tr>
</tbody>
</table>

Observe the expected number of events in the second column.
event selection. These uncertainties contribute typically 1.0%–1.5% to the overall selection uncertainty. Jet energy scale and resolution uncertainties are derived using a combination of techniques that use dijet, photon + jet, and Z + jet events \([54,55]\). These contribute an uncertainty of between 3% and 6% on the final event selection. The uncertainties on the energy scale and resolution of leptons and jets are also propagated to the \(E_T^{\text{miss}}\) calculation, and the resulting uncertainty in the latter is included in uncertainties given above. Uncertainties in the pile-up simulation, affecting in particular \(E_T^{\text{miss}}\), contribute a further 1%–2% uncertainty.

Theoretical uncertainties on the \(ZH\) production cross section are derived from variations of the renormalization and factorization scale, \(\alpha_s\), and the parton distribution functions (PDFs) \([24]\). These are combined to give an uncertainty of 3.6%–5.7% on the cross section. This analysis is sensitive to the distribution of the Higgs boson \(p_T\) through the \(E_T^{\text{miss}}\), 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 \([22,23,56]\), and uncertainties as a function of the Higgs boson \(p_T\) are considered as a systematic shape uncertainty.

The cross-section uncertainty on the ZZ background is 5% from varying the PDFs, \(\alpha_s\), and QCD scale. The uncertainty on the jet veto for the ZZ background due to the parton showering is estimated to be 6.4% (5.5%) for the 7 (8) TeV data. Because the \(E_T^{\text{miss}}\) distribution of the final selected sample is used in the limit-setting procedure, the impact of PDFs, \(\alpha_s\), and QCD scale uncertainties on the shape of this distribution is also considered. The theoretical uncertainty of the WZ background is considered similarly. The total systematic uncertainty on the SM ZZ background is 8% for both the 7 and 8 TeV data-taking periods, whereas for the WZ background it is 10% (13%) for the 7 (8) TeV data-taking periods.

Event reconstruction and theoretical uncertainties are considered as correlated between the 7 and 8 TeV data, and between the signals and backgrounds estimated from simulation. The systematic uncertainties in methods that determine backgrounds from data using control regions are also assumed to be correlated between the two data sets. The luminosity uncertainty is considered as uncorrelated between the 7 and 8 TeV data.

The numbers of observed and expected events for the 7 and 8 TeV data-taking periods are shown in Table I. Figure 2 shows the \(E_T^{\text{miss}}\) distribution after the full event selection for the 8 TeV data and the expected backgrounds. The normalization of the backgrounds is extracted from a binned profile maximum likelihood fit in the signal region. Systematic uncertainties are considered as nuisance parameters, and are assumed to be constrained by Gaussian distributions. The signal expectation shown corresponds to a Higgs boson with \(m_H = 125.5\) GeV, a SM \(ZH\) production rate, and \(\text{BR}(H \rightarrow \text{inv.}) = 1\). No significant excess is observed over the SM expectation.

Limits are set on the cross section times branching ratio for a Higgs boson decaying to invisible particles anywhere in the mass range 110 < \(m_H\) < 400 GeV. The limits are computed using a maximum likelihood fit to the \(E_T^{\text{miss}}\) distribution following the \(\mathcal{CL}_s\) (signal confidence level) modified frequentist formalism \([57]\) with a profile likelihood test statistic \([58]\). Figure 3 shows the 95% C.L. upper limits on \(\sigma_{ZH} \times \text{BR}(H \rightarrow \text{inv.})\) in the mass range 110 < \(m_H\) < 400 GeV for the combined 7 and 8 TeV data. The expectation for a Higgs boson with a production cross section equal to that expected for a SM Higgs boson and \(\text{BR}(H \rightarrow \text{inv.}) = 1\) is also shown.
For the discovered Higgs boson an upper limit of 75% at 95% C.L. (63% at 90% C.L.) is set on the branching ratio to invisible particles. For this the predicted SM $ZH$ production rate with $m_H = 125.5$ GeV, is assumed. The expected limit in the absence of BSM decays to invisible particles is 62% at 95% C.L. (52% at 90% C.L.).

Within the context of a Higgs-portal DM scenario [59], in which the Higgs boson acts as the mediator particle between DM and SM particles, the Higgs boson can decay to a pair of DM particles. In this case the limit on $\text{BR}(H \rightarrow \text{inv.})$ for the 125.5 GeV Higgs boson can be interpreted in terms of an upper limit on the DM–nucleon scattering cross section [60]. The formalism used to interpret the $\text{BR}(H \rightarrow \text{inv.})$ limit in terms of the spin-independent DM–nucleon scattering cross section is described in Refs. [61,62]. Figure 4 shows 90% C.L. upper limits on the DM–nucleon scattering cross section for three model variants in which a single DM candidate is considered and is either a scalar, a vector, or a Majorana fermion. The Higgs–nucleon coupling is taken as $0.33^{+0.30}_{-0.07}$ [62], the uncertainty of which is expressed by the bands in the figure. Spin-independent results from direct-search experiments are also shown [63–70]. These results do not depend on the assumptions of the Higgs-portal scenario. Within the constraints of such a scenario, however, the results presented in this Letter provide the strongest available limits for low-mass DM candidates. There is no sensitivity to these models once the mass of the DM candidate exceeds $m_H/2$. A search by the ATLAS experiment for DM in more generic models, also using the $\ell\ell + \text{miss } E_T$ final state, is presented in Ref. [71].

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSTM CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINEVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN–CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

![FIG. 4 (color online). Limits on the DM-nucleon scattering cross section at 90% C.L., extracted from the BR($H \rightarrow \text{inv.}$) limit in a Higgs-portal scenario, compared to results from direct-search experiments [63–70]. Cross-section limits and favored regions correspond to a 90% C.L., unless stated otherwise in the legend. Favored regions for DAMA and CoGeNT are based on Ref. [68]. The results from the direct-search experiments do not depend on the assumptions of the Higgs-portal scenario.](image-url)
PRL 112, 201802 (2014) PHYSICAL REVIEW LETTERS

23 MAY 2014

[45] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z axis along the beam pipe. Polar coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ as η = − ln tan(θ/2), and ΔR = √(Δη)² + (Δφ)².