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DOI
10.1103/PhysRevLett.112.201802

Publication date
2014

Document Version
Final published version

Published in
Physical Review Letters

Link to publication

Citation for published version (APA):

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Search for Invisible Decays of a Higgs Boson Produced in Association with a Z Boson in ATLAS

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(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.

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 \(\sqrt{s} = 7 \text{ TeV}\) and 410 fb at \(\sqrt{s} = 8 \text{ TeV}\) [24]. The SM branching ratio of the Higgs boson decaying to invisible particles is \(1.2 \times 10^{-3}\), arising from the \(H \rightarrow ZZ^{(*)} \rightarrow 4\ell\) 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 \(\sqrt{s} = 7 \text{ TeV}\) and 20.3 fb⁻¹ of data recorded in 2012 at \(\sqrt{s} = 8 \text{ TeV}\). 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 the 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].

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for the 7 and 8 TeV data, respectively. A separate sample simulated with gg2VV [36] interfaced with JIMMY [37] accounts for WW/ZZ production through quark-box diagrams, which are not included in the above mentioned samples. The MC@NLO [38] generator interfaced with JIMMY is used to model __H__ decay, with small variations in the applied __p_T__ threshold in different data-taking periods. Events must also have at least one reconstructed vertex with at least three associated tracks with __p_T__ > 500 MeV. Data quality criteria are applied to reject events from non-collision backgrounds or events with degraded detector performance [48].

The invariant mass of the selected dilepton system, __m_μμ__, is required to satisfy 76 < __m_μμ__ < 106 GeV to be consistent with leptons originating from a Z boson decay.

Figure 1 shows the __E^miss_T__ distribution in the 8 TeV data sample after the dilepton mass requirement. In this figure the data are consistent with the expected background based on simulated samples for all but the multijet background. 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^miss_T__ is required to be greater than 90 GeV. In events where a significant __E^miss_T__ arises from misreconstructed energy in the calorimeter, the vectors of __E^miss_T__ and __p_T^miss__ are likely to have different azimuthal angles. Thus the azimuthal difference of these two vectors, __Δφ(E^miss_T, p_T^miss)__, is required to be less than 0.2.

![FIG. 1 (color online). Distribution of __E^miss_T__ for events with the invariant mass of the two leptons 76 < __m_μμ__ < 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 → 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.](image-url)
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 $p_T^{\ell\ell}$, and the $E_T^{miss}$, $\Delta \phi(p_T^{\ell\ell}, E_T^{miss})$, 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 the two leptons, $\Delta \phi(\ell, \ell')$, is thus required to be less than 1.7. Furthermore $p_T^{\ell\ell}$ and $E_T^{miss}$ are expected to be similar. Therefore the fractional $p_T$ difference, defined as $|E_T^{miss} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, is required to be less than 0.2. Finally, for the majority of the signal no additional high-$p_T$ jets are expected to be observed in the events, while for the background from boosted $Z$ bosons and from $W + jets$ pairs one or more jets are expected. Thus, events are required to have no reconstructed jets with $p_T > 25$ GeV and $|\eta| < 2.5$.

After the selection requirements, the dominant background is SM $ZZ$ production followed by SM $WZ$ production, as shown in Table I. These backgrounds are simulated using MC samples normalized to NLO cross sections. The simulation of $WZ$ events is validated by comparing them to data events in which the third-lepton veto is replaced by an explicit third-lepton requirement. The theoretical prediction of the $ZZ$ production is in agreement with the ATLAS cross-section measurement at $\sqrt{s} = 7$ TeV [50].

Background contributions from events with a genuine isolated lepton pair, not originating from a $Z \to ee$ or $Z \to \mu\mu$ decay ($WW$, $t\bar{t}$, $Wt$, and $Z \to \tau\tau$), are estimated by exploiting the flavor symmetry in the dilepton final state of these processes. Distributions for events with an $e\mu$ pair, appropriately scaled to account for differences in electron and muon reconstruction efficiencies, can be used to estimate this background in the electron and muon channels. The difference between the efficiencies for electrons and muons is estimated using the square root of the ratio of the numbers of dimuon and dielectron events in data within the $m_{\ell\ell}$ window. Events in the $e\mu$ control region not originating from $WW$, $t\bar{t}$, $Wt$, or $Z \to \tau\tau$ backgrounds are subtracted using simulated samples. Important sources of systematic uncertainty are variations in the correction factor for the efficiencies for electrons and muons and uncertainties in the simulated samples used for the subtraction. The combined systematic uncertainty is 23% for both the 7 and 8 TeV data. The estimated background from these sources is consistent with the expectation from the simulation.

The background from inclusive $Z \to ee$ and $Z \to \mu\mu$ 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 $\Delta \phi(E_T^{miss}, p_T^{\ell\ell})$ 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 small background from events with only one genuine isolated lepton (inclusive $W$, single-lepton top pairs and single top production) or from multijet 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>$ZZ \to \ell\ell\nu\nu$</td>
<td>$20.0 \pm 0.7 \pm 1.6$</td>
<td>$91 \pm 1 \pm 7$</td>
</tr>
<tr>
<td>$WZ \to \ell\ell\ell\ell$</td>
<td>$4.8 \pm 0.3 \pm 0.5$</td>
<td>$26 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>Dileptonic $t\bar{t}$, $Wt$, $WW$, $Z \to \tau\tau$</td>
<td>$0.5 \pm 0.4 \pm 0.1$</td>
<td>$20 \pm 3 \pm 5$</td>
</tr>
<tr>
<td>$Z \to ee$, $Z \to \mu\mu$</td>
<td>$0.13 \pm 0.12 \pm 0.07$</td>
<td>$0.9 \pm 0.3 \pm 0.5$</td>
</tr>
<tr>
<td>$W + jets$, multijet, semileptonic top</td>
<td>$0.020 \pm 0.005 \pm 0.008$</td>
<td>$0.29 \pm 0.02 \pm 0.06$</td>
</tr>
<tr>
<td>Total background</td>
<td>$25.4 \pm 0.8 \pm 1.7$</td>
<td>$138 \pm 4 \pm 9$</td>
</tr>
<tr>
<td>Signal ($m_H = 125.5$ GeV, $\sigma_{ZH,SM}$, BR($H \to \text{inv.}$) = 1)</td>
<td>$8.9 \pm 0.1 \pm 0.5$</td>
<td>$44 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>Observed</td>
<td>$28$</td>
<td>$152$</td>
</tr>
</tbody>
</table>
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 CLs (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 $BR(H \rightarrow \text{inv.})$ 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 $BR(H \rightarrow \text{inv.})$ 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 dilepton + large $E_T^{\text{miss}}$ 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; MSMT 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, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, 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), as well as the Tier-2 facilities worldwide.

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