Combination of searches for invisible Higgs boson Decays with the ATLAS experiment

Aaboud, M.; ATLAS Collaboration

DOI
10.1103/PhysRevLett.122.231801

Publication date
2019

Document Version
Final published version

Published in
Physical Review Letters

License
CC BY

Citation for published version (APA):
Aaboud, M., & ATLAS Collaboration (2019). Combination of searches for invisible Higgs boson Decays with the ATLAS experiment. Physical Review Letters, 122(23), [231801]. https://doi.org/10.1103/PhysRevLett.122.231801
Combination of Searches for Invisible Higgs Boson Decays with the ATLAS Experiment

M. Aaboud et al.*
(ATLAS Collaboration)

(Received 11 April 2019; published 13 June 2019)

Dark matter particles, if sufficiently light, may be produced in decays of the Higgs boson. This Letter presents a statistical combination of searches for $H \rightarrow \text{invisible}$ decays where $H$ is produced according to the standard model via vector boson fusion, $Z(\ell\ell)H$, and $W/Z$(had)H, all performed with the ATLAS detector using 36.1 fb$^{-1}$ of pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV at the LHC. In combination with the results at $\sqrt{s} = 7$ and 8 TeV, an exclusion limit on the $H \rightarrow \text{invisible}$ branching ratio of $0.26(0.17^{+0.07}_{-0.08})$ at 95% confidence level is observed (expected).

DOI: 10.1103/PhysRevLett.122.231801

One of the central open questions in physics today is the nature of dark matter (DM) that is found to comprise most of the matter in the Universe [1–4]. A compelling candidate for DM is a stable electrically neutral particle $\chi$ whose nongravitational interactions with Standard Model (SM) particles are weak. Such a particle with a mass comparable to the mass scale of the electroweak sector particles could be detectable [5–7] and accommodate the observed DM relic density [8,9]. Numerous models predict detectable production rates of such DM particles at the Large Hadron Collider (LHC) [10–12]. In a wide class of those models, the 125 GeV Higgs boson $H$ [13,14] acts as a portal between a dark sector and the SM sector, either through Yukawa-type couplings to fermionic dark matter, or other mechanisms [15–28]. If kinematically allowed, decays of the Higgs boson to DM particles represent a distinct signature in such models. Higgs boson decays to DM particles can only be indirectly inferred through missing transverse momentum $E_T^{\text{miss}}$ due to DM particles escaping detection, and are therefore termed “invisible” (inv).

Direct searches for invisible Higgs boson decays have been carried out with the ATLAS detector [30–32] in Run 1 of the LHC, using up to 4.7 fb$^{-1}$ of pp collision data at a center-of-mass energy of $\sqrt{s} = 7$ TeV and up to 20.3 fb$^{-1}$ at 8 TeV. Different event topologies were considered, assuming SM production rates: vector boson fusion (VBF) [33], Higgsstrahlung from a $Z$ boson decaying into a pair of electrons or muons ($Z$(lep)$H$) [34], and Higgsstrahlung from a $W$ or Z boson decaying into hadrons ($V$(had)$H$) [35]. These searches for invisible Higgs boson decays have been statistically combined, and an upper limit at 95% confidence level (C.L.) on the invisible Higgs boson branching ratio of $B_{H \rightarrow \text{inv}} < 0.25(0.27^{+0.10}_{-0.08})$ [36] was observed (expected). In combination with visible decay modes of the Higgs boson, the upper observed (expected) limit improved to 0.23 (0.24) [36]. Direct searches for invisible Higgs decays were performed using up to 36.1 fb$^{-1}$ of pp collision data at $\sqrt{s} = 13$ TeV recorded in 2015 and 2016 in the VBF [37], $Z$(lep)$H$ [38], and $V$(had)$H$ [39] topologies at ATLAS. The aforementioned results at $\sqrt{s} = 13$ TeV will be referred to as “Run 2 results” in the following. Similar searches were performed by the CMS Collaboration [40–44].

This Letter presents the statistical combination of the Run 2 searches with 36.1 fb$^{-1}$ of data for invisible decays of the Higgs boson using the ATLAS detector. Subsequently, a statistical combination with the combined Run 1 result [36] from ATLAS is performed. An overview of all results used as inputs in this combination is given in Table I. The analysis is performed under the assumption of SM Higgs boson production. Visible decay modes of the Higgs boson are not considered.

A brief overview of the Run 2 searches for $H \rightarrow \text{inv}$ is given below.

**VBF topology [37].**—The analysis of the VBF production mode employs an $E_T^{\text{miss}}$ trigger that is 98% efficient or better in the considered region of phase space. The event selection requires $E_T^{\text{miss}} > 180$ GeV. Jets ($j$) are reconstructed up to $|\eta(j)| < 4.5$ from energy clusters in the calorimeter using the anti-$k_T$ algorithm [45] with a radius parameter $R = 0.4$. The two jets leading in $p_T$ are required to be separated by $|\Delta\eta_{jj}| > 4.8$. There should be no additional jets with $p_T > 25$ GeV and no isolated electron or muon candidate with $p_T > 7$ GeV. These requirements serve to reduce the contribution from $W/Z$ production in association with jets ($V \pm \text{jets}$). In the search signal region
(SR) the $m_{jj}$ distribution of the background falls more rapidly than the signal, where $m_{jj}$ represents the invariant mass of the two selected leading jets. Thus the SR is divided into three $m_{jj}$ regions ($1 < m_{jj}$/TeV $< 1.5$, $1.5 < m_{jj}$/TeV $< 2$, and $m_{jj}$/TeV $> 2$) to improve the search sensitivity. The dominant background sources are $Z(\nu\nu) +$ jets and $W(\ell\nu) +$ jets production, where the charged lepton $\ell$ is not detected. Control regions (CR) enriched in $Z(\ell\ell) +$ jets and $W(\ell\nu) +$ jets processes with $\ell = e, \mu$ are defined to determine the respective normalization factors in the SR. The main contributions to uncertainties are from the finite number of simulated Monte Carlo (MC) events, the modeling of $V +$ jets production, and accuracy of the jet energy scale (JES). The final discriminant is the number of events in the three $m_{jj}$ regions.

$Z(\text{lep})H$ topology [38].—This search is conducted in the Higgsstrahlung channel where the $Z$ boson decays into a pair of electrons or muons. A selected candidate event must pass at least one of the various single-lepton triggers, fulfill $E_T^{\text{miss}} > 90$ GeV and $E_T^{\text{miss}}/H_T > 0.6$, where $H_T$ is calculated as the scalar sum of the $p_T$ of the selected leptons and jets, and have exactly one pair of isolated electrons or muons with an invariant mass that is consistent with that of the $Z$ boson. The transverse momentum requirement on the leading (subleading) charged lepton is $p_T > 30$ (20) GeV. To reduce the $Z +$ jets background, the dilepton system must be aligned back to back relative to the $E_T^{\text{miss}}$ vector in the transverse plane. Events with jets originating from $b$-quarks ($b$-jets) are vetoed to suppress backgrounds from top quark pair ($tt$) production and $W$ boson production in association with a single top quark ($Wt$). The irreducible $Z(\nu\nu)Z(\ell\ell)$ background is estimated from MC simulations and its production yield is normalized to the theoretical prediction of Refs. [46,47]. The $W(\ell\nu)Z(\ell\ell)$ background contribution is also predicted with MC simulations and is normalized by a scale factor that is obtained from a CR enriched in $WZ$ events. The $Z +$ jets background is estimated with a data-driven method that uses $Z$-enriched CRs. The final discriminant is $E_T^{\text{miss}}$.

$V(\text{had})H$ topology [39].—This analysis considers the Higgsstrahlung channel where the associated $W$ or $Z$ boson decays into hadrons. The final state signature of large $E_T^{\text{miss}}$ and jets also receives contributions from Higgs boson production via gluon fusion with jets originating from initial state radiation, and production via the VBF process. Selected events must pass a $E_T^{\text{miss}}$ trigger and must not contain an isolated electron or muon with $p_T > 7$ GeV. As a $V$ is boosted, the two jets from its decay become increasingly collimated and are eventually merged into one single reconstructed jet. Thus, this search is conducted in two topological channels. In the “merged” topology, the SR is defined with $E_T^{\text{miss}} > 250$ GeV and has at least one trimmed [48,49] large-$R$ jet ($J$) that is reconstructed using the anti-$k_T$ algorithm with $R = 1.0$. The signal large-$R$ jet is the one with the highest $p_T$. For the “resolved” topology, the selected event should have $E_T^{\text{miss}} > 150$ GeV and at least two small-$R$ jets ($j$) with $R = 0.4$. Each event is first passed through the merged topology selection and, if it fails, it is passed through the resolved topology selection. To improve the search sensitivity, the selected events are further split into categories with zero, one, and two identified $b$-jets, and into two mass regions of the invariant mass of the signal large-$R$ jet (two signal small-$R$ jets) for the merged (resolved) topology. The low mass region ($70 < m_J < 100$ GeV) targets the hadronic $W/Z$ boson decays of the associated production, whereas the high mass region ($100 < m_J < 250$ GeV) is sensitive to gluon fusion and VBF production. The main background contributions are from the $V +$ jets and $t\bar{t}$ processes. The predictions from MC simulations are constrained with CRs that contained one or two leptons, and are kinematically similar to the SR. The final discriminant is $E_T^{\text{miss}}$.

The SRs and CRs of the individual input analyses are either orthogonal by construction, or were shown to have an overlap below 1%, which is neglected in the following.

The statistical combination of the analyses is performed by constructing the product of their likelihoods and maximizing the resulting likelihood ratio $\Lambda(B_{H \rightarrow \text{inv}}; \theta)$ [50]. This is done following the implementation described in Ref. [51,52], with $B_{H \rightarrow \text{inv}}$ as the parameter of interest. Systematic uncertainties are modeled in the likelihood function as nuisance parameters $\theta$ constrained by Gaussian or log-normal probability density functions [36].

### TABLE I. Observed and expected upper limits on $B_{H \rightarrow \text{inv}}$ at 95% C.L. from direct searches for invisible decays of the 125 GeV Higgs boson and statistical combinations. Also given are the observed $\sigma$ values under the SM hypothesis.

| Analysis       | $\sqrt{s}$ (TeV) | Int. luminosity (fb$^{-1}$) | Observed $\sigma$ | Expected $\sigma$ | $p_{SM}$ value | Reference |
|----------------|------------------|-----------------------------|-------------------|-------------------|----------------|-----------|
| Run 2 VBF      | 13               | 36.1                        | 0.37              | $0.28^{+0.11}_{-0.08}$ | 0.19           | [37]      |
| Run 2 Z(lep)H  | 13               | 36.1                        | 0.67              | $0.39^{+0.17}_{-0.11}$ | 0.06           | [38]      |
| Run 2 V(had)H  | 13               | 36.1                        | 0.83              | $0.58^{+0.23}_{-0.16}$ | 0.12           | [39]      |
| Run 2 Comb.    | 13               | 36.1                        | 0.38              | $0.21^{+0.08}_{-0.06}$ | 0.03           | this Letter |
| Run 1 Comb.    | 7.8,13           | 4.7, 20.3                   | 0.25              | $0.27^{+0.10}_{-0.08}$ | 0.06           | [36]      |
| Run 1 + 2 Comb.| 7.8,13           | 4.7, 20.3                   | 0.26              | $0.17^{+0.07}_{-0.05}$ | 0.10           | this Letter |
Expected results are obtained using the Asimov dataset technique [50].

In the combination of Run 2 results, most experimental systematic uncertainties as well as the uncertainty on the integrated luminosity and the modeling of additional $pp$ collisions in the same and neighboring bunch crossings (pileup) are correlated across all search channels. Some experimental uncertainties related to flavor tagging and the JES are represented through different parametrizations in the input analyses and are therefore treated as uncorrelated. The impact of this assumption on the combined result is estimated using alternative correlation models where the leading sources of systematic uncertainty in the respective parametrizations are treated as correlated, and found to have an absolute effect on the $B_{H\rightarrow inv}$ limit of the order of 0.01. The systematic uncertainties on the total $H\rightarrow inv$ signal cross section due to the choice of parton distribution functions (PDF) are considered correlated among all channels. By contrast, uncertainties due to missing higher order corrections are estimated through variations of factorization and renormalization scales and treated as correlated between the $Z(lep)H$ and $V(had)H$ processes. This is not done for VBF, which represents a distinct topology. The impact of the corresponding uncertainties on the acceptance rather than the total cross section of $V(had)H$ production is evaluated and found negligible. Few systematic uncertainties that are tightly constrained in a given analysis are left uncorrelated in order not to introduce any potential phase space specific biases.

The negative logarithmic profile likelihood ratios $-2\Delta \ln(\Lambda)/(B_{H\rightarrow inv};\theta)$ as a function of $B_{H\rightarrow inv}$ of the individual analyses and of the combined Run 2 result are shown in Fig. 1, corresponding to a best-fit combined value of $B_{H\rightarrow inv} = 0.20 \pm 0.10$. The dominant uncertainty sources are finite event yields in data and MC simulations, reconstruction of jets and leptons, and modeling of diboson and $W/Z + jets$ production. In absence of a significant excess, an upper limit at 95% C.L. of $B_{H\rightarrow inv} < 0.38(0.21^{+0.08}_{-0.06})$ is observed (expected) with the $CL_s$ formalism [53] using the profile likelihood ratio as a test statistic. The excess in data corresponds to a $p_{SM}$ value of 3% under the SM hypothesis of $B_{H\rightarrow inv} \approx 10^{-3}$, and is a direct consequence of the excesses that are present in each of the three input analyses, see Table I. Each of the individual analyses has been scrutinized and these excesses have been found nonsignificant and independent.

Subsequently, the above Run 2 result is combined with the Run 1 searches for $H \rightarrow inv$ decays [36]. Because of the differences between the detector layouts and data-taking conditions, reconstruction algorithms and their calibrations, and treatment of systematic uncertainties, the correlations between the runs are not clearly identifiable. Hence, no correlations between Run 1 and 2 are assumed for most instrumental uncertainties. The uncertainties related to the modeling of the calorimeter response dependence on jet flavor and pileup are taken as either correlated or uncorrelated between the runs, and the choice which results in a weaker expected exclusion limit on $B_{H\rightarrow inv}$ is adopted. The uncertainty on the JES of b-quark jets was estimated using MC simulations [54,55] and is therefore considered correlated. For the signal modeling, the parton shower uncertainty in the $V(had)H$ channel, the uncertainty from missing higher order corrections in the $Z(lep)H$ analysis, and the uncertainty on the jet multiplicity in the VBF channel [56] are each taken as correlated between the runs since the estimated uncertainties stem from the same source. For the same reason, the uncertainty from missing higher order corrections on the $E_{T}^{miss}$ observable in the dominant background from diboson production in the $Z(lep)H$ search is treated as correlated. All other background modeling uncertainties are considered uncorrelated. The impact of these correlation assumptions on the combined $B_{H\rightarrow inv}$ limit is found to be at most 0.005. In addition, the impact on $B_{H\rightarrow inv}$ in scenarios ranging from full anti-correlation to full correlation is studied using the best linear unbiased estimator (BLUE) [57] for the components of the JES uncertainty, the $V + jets$ background, and diboson production that are nominally not correlated due to different parametrizations in Run 1 and 2. The resulting absolute effect on the $B_{H\rightarrow inv}$ limit is at most 0.01.

The observed $-2\Delta \ln(\Lambda)/(B_{H\rightarrow inv};\theta)$ ratio of the combined Run 1 + 2 result is represented in Fig. 1, alongside the individual Run 1 and Run 2 combinations. A best-fit value of $B_{H\rightarrow inv} = 0.13 \pm 0.08$ is obtained, corresponding to an observed (expected) upper limit of $B_{H\rightarrow inv} < 0.26(0.17^{+0.07}_{-0.05})$ at 95% C.L. The $p_{SM}$ value under the SM hypothesis is 10%, and the compatibility between the Run 1 and Run 2 results is 1.5 standard deviations. The final result, together with the results in the individual Run 2 analyses as well as the Run 2-only and the Run 1-only combinations, are summarized in Table I, and the upper limits on $B_{H\rightarrow inv}$ are graphically represented in Fig. 2.
or a fermion [23,64,65], using the nuclear form factor assumption that invisible Higgs decays to a pair of WIMPs. In the fermion WIMP case, the effective coupling is

\[ \tau \rightarrow \sigma \text{WIMP-N} [cm^2] \]

range down to \( 10^{-46} \text{ cm}^2 \). While the ATLAS exclusion limits extend to \( m_{\text{WIMP}} < 1 \text{ GeV} \), that region is subject to uncertainties in modelling of the nuclear recoil and is therefore not included in Fig. 3.

In summary, direct searches for invisible Higgs boson decays using 36.1 fb\(^{-1}\) of \( pp \) collision data at \( \sqrt{s} = 13 \text{ TeV} \) recorded in 2015 and 2016 in the VBF, \( Z(\text{lep})H \), and \( V(\text{had})H \) topologies are statistically combined assuming SM-like Higgs boson production. An upper limit on the invisible Higgs branching ratio of \( B_{\text{H-inv}} < 0.38(0.21^{+0.08}_{-0.06}) \) is observed (expected) at 95% C.L. A statistical combination of this result with the combination of direct \( H \rightarrow \text{inv} \) searches using up to 4.7 fb\(^{-1}\) of \( pp \) collision data at \( \sqrt{s} = 7 \text{ TeV} \) and up to 20.3 fb\(^{-1}\) at 8 TeV collected in Run 1 of the LHC yields an observed (expected) upper limit of \( B_{\text{H-inv}} < 0.26(0.17^{+0.07}_{-0.05}) \) at 95% C.L. The combined Run 1 + 2 result is translated into upper limits on the WIMP-nucleon scattering cross section for Higgs portal models. The derived limits range down to \( 2 \times 10^{-45} \text{ cm}^2 \) in the scalar and \( 10^{-46} \text{ cm}^2 \) in the fermion WIMP scenarios, highlighting the complementarity of DM searches at the LHC and direct detection experiments.

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 and DNSRC, Denmark; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MINE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’ Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF.

![FIG. 2. The observed and expected upper limits on \( B_{\text{H-inv}} \) at 95% C.L. from direct searches for invisible decays of the 125 GeV Higgs boson and their statistical combinations in Run 1 and 2.](image1)

The results are consistent with a similar statistical combination in Ref. [40].

The constraint from the combined observed Run 1 + 2 exclusion limit of \( B_{\text{H-inv}} < 0.24 \) at 90% C.L. is compared to the results from representative direct DM detection experiments [58–62] in Fig. 3. This comparison is performed in the context of Higgs portal models [63]. The translation of the \( H \rightarrow \text{inv} \) result into a weak interacting massive particle–nucleon scattering cross section \( \sigma_{\text{WIMP-N}} \) relies on an effective field theory approach [33] under the assumption that invisible Higgs decays to a pair of WIMPs are kinematically possible and that the WIMP is a scalar or a fermion [23,64,65], using the nuclear form factor \( f_N = 0.308 \pm 0.018 \) [66]. The excluded \( \sigma_{\text{WIMP-N}} \) values range down to \( 2 \times 10^{-45} \text{ cm}^2 \) in the scalar WIMP scenario. In the fermion WIMP case, the effective coupling is reduced by \( m_{H}^2 \) [33], excluding \( \sigma_{\text{WIMP-N}} \) values down to \( 10^{-46} \text{ cm}^2 \).
and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, Spain; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, 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), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [67].

[1] Planck Collaboration, Planck 2018 results. I. Overview and the cosmological legacy of Planck, arXiv:1807.06205.

[2] WMAP Collaboration, Nine-year Wilkinson microwave anisotropy probe (WMAP) observations: Cosmological parameter results, Astrophys. J. Suppl. Ser. 208, 19 (2013).

[3] G. Bertone, D. Hooper, and J. Silk, Particle dark matter: Evidence, candidates and constraints, Phys. Rep. 405, 279 (2005).

[4] V. Trimble, Existence and nature of dark matter in the universe, Annu. Rev. Astron. Astrophys. 25, 425 (1987).

[5] R. Scherrer and M. S. Turner, On the relic, cosmic abundance of stable, weakly interacting massive particles, Phys. Rev. Lett. 110, 075004 (2013).

[6] R. E. Shrock and M. Suzuki, Invisible decays of Higgs bosons, Phys. Lett. B 108, 250 (1982).

[7] D. Choudhury and D. P. Roy, Signatures of an invisibly decaying Higgs particle at LHC, Phys. Lett. B 322, 368 (1994).

[8] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive, and M. Srednicki, Supersymmetric relics from the big bang, Phys. Rev. D 33, 3263 (1986).

[9] D. Choudhury and D. P. Roy, Signatures of an invisibly decaying Higgs particle at hadron colliders, Phys. Rev. D 71, 115007 (2005).

[10] G. Jungman, M. Kamionkowski, and K. Griest, Super-symmetric dark matter, Phys. Rep. 267, 195 (1996).

[11] J. L. Feng, Dark matter candidates from particle physics and methods of detection, Annu. Rev. Astron. Astrophys. 48, 495 (2010).

[12] A. Boveia and C. Doglioni, Dark matter searches at colliders, Annu. Rev. Nucl. Part. Sci. 68, 429 (2018).

[13] ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716, 1 (2012).

[14] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716, 30 (2012).

[15] I. Antoniadis, M. Tuckmantel, and F. Zwirner, Phenomenology of a leptonic goldstino and invisible Higgs boson decays, Nucl. Phys. B 707, 215 (2005).

[16] N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali, and J. March-Russell, Neutrino masses from large extra dimensions, Phys. Rev. D 65, 024032 (2001).

[17] A. Datta, K. Huitu, J. Laamanen, and B. Mukhopadhyaya, Linear collider signals of an invisible Higgs boson in theories of large extra dimensions, Phys. Rev. D 70, 075003 (2004).

[18] S. Kanemura, S. Matsumoto, T. Nabeshima, and N. Okada, Can WIMP dark matter overcome the nightmare scenario?, Phys. Rev. D 82, 055026 (2010).

[19] A. Djouadi, O. Lebedev, Y. Mambrini, and J. Quevillon, Implications of LHC searches for Higgs-portal dark matter, Phys. Lett. B 708, 757 (2015).

[20] A. Djouadi, A. Falkowski, Y. Mambrini, and J. Quevillon, Direct detection of Higgs-portal dark matter at the LHC, Eur. Phys. J. C 73, 2455 (2013).

[21] D. Choudhury and D. P. Roy, Signatures of an invisibly decaying Higgs particle at LHC, Phys. Lett. B 322, 368 (1994).

[22] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive, and M. Srednicki, Supersymmetric relics from the big bang, Phys. Rev. D 33, 3263 (1986).

[23] H. Davoudiasl, T. Han, and H. E. Logan, Discovering an invisibly decaying Higgs at hadron colliders, Phys. Rev. D 71, 115007 (2005).

[24] R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti, and D. P. Roy, Search for ‘invisible’ Higgs signals at LHC via associated production with gauge bosons, Phys. Lett. B 571, 184 (2003).

[25] D. Ghosh, R. Godbole, M. Guchait, K. Mohan, and D. Sengupta, Looking for an invisible Higgs signal at the LHC, Phys. Lett. B 725, 344 (2013).

[26] G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion, and S. Kraml, Status of invisible Higgs decays, Phys. Lett. B 723, 340 (2013).

[27] G. Jungman, M. Kamionkowski, and K. Griest, Supersymmetric dark matter, Phys. Rep. 267, 195 (1996).

[28] G. Steigman and M. S. Turner, Cosmological constraints on dark matter from WMAP observations: Dark matter from WMAP, Astrophys. J. Suppl. Ser. 100, 141 (1995).

[29] G. Jungman, M. Kamionkowski, and K. Griest, Super-symmetric dark matter, Phys. Rep. 267, 195 (1996).

[30] G. Steigman and M. S. Turner, Cosmological constraints on the properties of weakly interacting massive particles, Nucl. Phys. B253, 375 (1985).

[31] R. J. Scherrer and M. S. Turner, On the relic, cosmic abundance of stable, weakly interacting massive particles, Phys. Rev. D 33, 1585 (1986).
[35] ATLAS Collaboration, Search for invisible decays of the Higgs boson produced in association with a hadronically decaying vector boson in pp collisions at √s = 8 TeV with the ATLAS detector, Eur. Phys. J. C 75, 337 (2015).

[36] ATLAS Collaboration, Constraints on new phenomena via Higgs boson couplings and invisible decays with the ATLAS detector, J. High Energy Phys. 11 (2015) 206.

[37] ATLAS Collaboration, Search for invisible Higgs boson decays in vector boson fusion at √s = 13 TeV with the ATLAS detector, arXiv:1809.06682.

[38] ATLAS Collaboration, Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson in pp collisions at √s = 13 TeV with the ATLAS detector, Phys. Lett. B 776, 318 (2018).

[39] ATLAS Collaboration, Search for dark matter in events with a hadronically decaying vector boson and missing transverse momentum in pp collisions at √s = 13 TeV with the ATLAS detector, J. High Energy Phys. 10 (2018) 180.

[40] CMS Collaboration, Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at √s = 13 TeV, Phys. Rev. D 97, 092005 (2018).

[41] CMS Collaboration, Search for new physics in events with a leptonically decaying Z boson and a large transverse momentum imbalance in proton-proton collisions at √s = 13 TeV, Eur. Phys. J. C 78, 291 (2018).

[42] CMS Collaboration, Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson and transverse momentum imbalance at √s = 13 TeV, Phys. Rev. D 97, 092005 (2018).

[43] CMS Collaboration, Searches for invisible decays of the Higgs boson in pp collisions at √s = 7, 8, and 13 TeV, J. High Energy Phys. 02 (2017) 135.

[44] CMS Collaboration, Search for invisible decays of Higgs bosons in the vector boson fusion and associated ZH production modes, Eur. Phys. J. C 74, 2980 (2014).

[45] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.

[46] M. Grazzini, S. Kallweit, and D. Rathlev, ZZ production at the LHC: Fiducial cross sections and distributions in NNLO QCD, Phys. Lett. B 750, 407 (2015).

[47] F. Caola, K. Melnikov, R. Rontsch, and L. Tancredi, QCD corrections to ZZ production in gluon fusion at the LHC, Phys. Rev. D 92, 094028 (2015).

[48] D. Krohn, J. Thaler, and L.-T. Wang, Jet trimming, J. High Energy Phys. 02 (2010) 084.

[49] ATLAS Collaboration, Jet mass reconstruction with the ATLAS Detector in early Run 2 data, CERN Report No. ATLAS-CONF-2016-035, 2016, https://cds.cern.ch/record/2200211.

[50] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C 71, 1554 (2011); Erratum, Eur. Phys. J. C 73, 2501(E) (2013).

[51] W. Verkerke and D.P. Kirkby, The RooFit toolkit for data modeling, eConf C0303241, MOL7007 (2003).

[52] L. Moneta et al., The RooStats project, Proc. Sci., ACAT2010 (2010) 057.

[53] A.L. Read, Presentation of search results: The CL_, technique, J. Phys. G 28, 2693 (2002).

[54] ATLAS Collaboration, Jet energy measurement and its systematic uncertainty in proton-proton collisions at √s = 7 TeV with the ATLAS detector, Eur. Phys. J. C 75, 17 (2015).

[55] ATLAS Collaboration, Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at √s = 13 TeV with the ATLAS detector, Phys. Rev. D 96, 072002 (2017).

[56] J. W. Stewart and F. J. Tackmann, Theory uncertainties for Higgs and other searches using jet bins, Phys. Rev. D 85, 034011 (2012).

[57] L. Lyons, D. Gibaut, and P. Clifford, How to combine correlated estimates of a single physical quantity, Nucl. Instrum. Methods Phys. Res., Sect. A 270, 110 (1988).

[58] E. Aprile et al., First results on low-mass dark matter from the CRESST-III experiment, in 15th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2017) Sudbury, Ontario, Canada, arXiv:1711.07692.

[59] D.S. Akerib et al., Results from a Search for Dark Matter in the Complete LUX Exposure, Phys. Rev. Lett. 118, 021303 (2017).

[60] X. Cui et al., Dark Matter Results From 54-Ton-Day Exposure of PandaX-II Experiment, Phys. Rev. Lett. 119, 181302 (2017).

[61] E. Aprile et al., Dark Matter Search Results from a One Ton-Year Exposure of XENON1T, Phys. Rev. Lett. 121, 111302 (2018).

[62] P. Agnes et al., Low-Mass Dark Matter Search with the DarkSide-50 Experiment, Phys. Rev. Lett. 121, 081307 (2018).

[63] B. Patt and F. Wilczek, Higgs-field portal into hidden sectors, arXiv:hep-ph/0605188.

[64] P.J. Fox, R. Harnik, J. Kopp, and Y. Tsai, Missing energy signatures of dark matter at the LHC, Phys. Rev. D 85, 056011 (2012).

[65] A. De Simone, G. F. Giudice, and A. Strumia, Benchmarks for dark matter searches at the LHC, J. High Energy Phys. 06 (2014) 081.

[66] M. Hoferichter, P. Klos, J. Menéndez, and A. Schwenk, Improved Limits for Higgs-Portal Dark Matter from LHC Searches, Phys. Rev. Lett. 119, 181803 (2017).

[67] ATLAS Collaboration, ATLAS computing acknowledgements, CERN Report No. ATL-GEN-PUB-2016-002, https://cds.cern.ch/record/2202407.
(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bIstanbul Aydin University, Istanbul, Turkey
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7Department of Physics, University of Arizona, Tucson, Arizona, USA
8Department of Physics, University of Texas at Arlington, Arlington, Texas, USA
9Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10Physics Department, National Technical University of Athens, Zografou, Greece
11Department of Physics, University of Texas at Austin, Austin, Texas, USA
12Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
12bIstanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
12cDepartment of Physics, Bogazici University, Istanbul, Turkey
12dDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
13Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
14Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
15aPhysics Department, Tsinghua University, Beijing, China
15bDepartment of Physics, Nanjing University, Nanjing, China
15cUniversity of Chinese Academy of Science (UCAS), Beijing, China
15dInstitute of Physics, University of Belgrade, Belgrade, Serbia
16Department for Physics and Technology, University of Bergen, Bergen, Norway
17Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
18Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
19Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
20Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
21School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
22INFN Bologna and Universita’ di Bologna, Dipartimento di Fisica, Italy
23INFN Sezione di Bologna, Bologna, Italy
24Physikalisches Institut, Universität Bonn, Bonn, Germany
25Department of Physics, Boston University, Boston, Massachusetts, USA
26Department of Physics, Brandeis University, Waltham, Massachusetts, USA
27Transilvania University of Brasov, Brasov, Romania
27aHoria Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
27bDepartment of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
27cNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
27dUniversity Politehnica Bucharest, Bucharest, Romania
27eWest University in Timisoara, Timisoara, Romania
28Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
28bDepartment of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
29Physics Department, Brookhaven National Laboratory, Upton, New York, USA
30Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
31California State University, California, USA
32Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
33aDepartment of Physics, University of Cape Town, Cape Town, South Africa
33bDepartment of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
34School of Physics, University of the Witwatersrand, Johannesburg, South Africa
34Department of Physics, Carleton University, Ottawa, Ontario, Canada
128 Konstantinov Nuclear Physics Institute of National Research Centre
129 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
130 Department of Physics, New York University, New York, New York, USA
131 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
132 The Ohio State University, Columbus, Ohio, USA
133 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
134 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
135 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
136 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
137 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
138 Graduate School of Science, Osaka University, Osaka, Japan
139 Department of Physics, University of Oslo, Oslo, Norway
140 Department of Physics, Oxford University, Oxford, United Kingdom
141 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
142 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
143 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
144 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
145 Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Portugal
146 Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
147 Departamento de Física da Universidade de Coimbra, Coimbra, Portugal
148 Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
149 Departamento de Física, Universidade do Minho, Braga, Portugal
150 Universidade de Granada, Granada (Spain), Spain
151 Dep Física e CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
152 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
153 Czech Technical University in Prague, Prague, Czech Republic
154 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
155 Department of Physics, University of Washington, Seattle, Washington, USA
156 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
157 Department of Physics, Shinsu University, Nagano, Japan
158 Department Physik, Universität Siegen, Siegen, Germany
159 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
160 SLAC National Accelerator Laboratory, Stanford, California, USA
161 Physics Department, Royal Institute of Technology, Stockholm, Sweden
162 Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
163 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
164 School of Physics, University of Sydney, Sydney, Australia
165 Institute of Physics, Academia Sinica, Taipei, Taiwan
166 E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
167 High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
168 Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
169 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
170 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
171 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
172 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
173 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
174 Tomsk State University, Tomsk, Russia
175 Department of Physics, University of Toronto, Toronto, Ontario, Canada
176 TRIUMF, Vancouver, British Columbia, Canada
177 Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
178 Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
179 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
\textsuperscript{171}Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
\textsuperscript{172}Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
\textsuperscript{173}Department of Physics, University of Illinois, Urbana, Illinois, USA
\textsuperscript{174}Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain
\textsuperscript{175}Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
\textsuperscript{176}Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
\textsuperscript{177}Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
\textsuperscript{178}Department of Physics, University of Warwick, Coventry, United Kingdom
\textsuperscript{179}Waseda University, Tokyo, Japan
\textsuperscript{180}Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
\textsuperscript{181}Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

\textsuperscript{182}Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
\textsuperscript{183}Department of Physics, Yale University, New Haven, Connecticut, USA
\textsuperscript{184}Yerevan Physics Institute, Yerevan, Armenia

\textsuperscript{a}Deceased.
\textsuperscript{b}Also at Department of Physics, King’s College London, London, United Kingdom.
\textsuperscript{c}Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
\textsuperscript{d}Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain.
\textsuperscript{e}Also at TRIUMF, Vancouver, British Columbia, Canada.
\textsuperscript{f}Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
\textsuperscript{g}Also at Department of Physics, California State University, Fresno, California, USA.
\textsuperscript{h}Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
\textsuperscript{i}Also at Departamento de Física de la Universidad Autónoma de Barcelona, Barcelona, Spain.
\textsuperscript{j}Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\textsuperscript{k}Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
\textsuperscript{l}Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.
\textsuperscript{m}Also at Universita di Napoli Parthenope, Napoli, Italy.
\textsuperscript{n}Also at Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain.
\textsuperscript{o}Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
\textsuperscript{p}Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
\textsuperscript{q}Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
\textsuperscript{r}Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
\textsuperscript{s}Also at Department of Physics, California State University, East Bay, Hayward, California, USA.
\textsuperscript{t}Also at Institut Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.
\textsuperscript{u}Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
\textsuperscript{v}Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
\textsuperscript{w}Also at Graduate School of Science, Osaka University, Osaka, Japan.
\textsuperscript{x}Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
\textsuperscript{y}Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
\textsuperscript{z}Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
\textsuperscript{aa}Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
\textsuperscript{ab}Also at CERN, Geneva, Switzerland.
\textsuperscript{ac}Also at Department of Physics, Stanford University, Stanford, California, USA.
\textsuperscript{ad}Also at Manhattan College, New York, New York, USA.
\textsuperscript{ae}Also at Joint Institute for Nuclear Research, Dubna, Russia.
\textsuperscript{af}Also at Hellenic Open University, Patras, Greece.
\textsuperscript{ag}Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.
\textsuperscript{ah}Also at The City College of New York, New York, New York, USA.
\textsuperscript{ai}Also at Department of Physics, California State University, Sacramento, California, USA.
\textsuperscript{aj}Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\textsuperscript{ak}Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
\textsuperscript{al}Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
\textsuperscript{am}Also at Louisiana Tech University, Ruston, Louisiana, USA.
\textsuperscript{an}Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
\textsuperscript{ao}Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
\textsuperscript{ap}Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
\textsuperscript{aq}Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
\textsuperscript{ar}Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
\textsuperscript{as}Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
Also at National Research Nuclear University MEPhI, Moscow, Russia.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.