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Combination of Searches for Invisible Higgs Boson Decays with the ATLAS Experiment

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Dark matter particles, if sufficiently light, may be produced in decays of the Higgs boson. This Letter presents a statistical combination of searches for $H \to$ invisible decays where H is produced according to the standard model via vector boson fusion, $Z(\ell\ell)H$, and $W/Z(\mathrm{had})H$, 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 $H \to$ invisible branching ratio of $0.26(0.17^{+0.07}_{-0.05})$ at 95% confidence level is observed (expected).

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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 χ 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 [29] $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 ($Z(\mathrm{lep})H$) [34], and Higgsstrahlung from a W or Z boson decaying into hadrons ($V(\mathrm{had})H$) [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 $\mathcal{B}_{H\to\mathrm{inv}} < 0.25(0.27^{+0.10}_{-0.08})$ [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], $Z(\mathrm{lep})H$ [38], and $V(\mathrm{had})H$ [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 $H \to$ inv is given below.

VBF topology [37].—The analysis of the VBF production mode employs an $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger that is 98% efficient or better in the considered region of phase space. The event selection requires $E_{\mathrm{T}}^{\mathrm{miss}} > 180$ 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 $p_{\mathrm{T}} > 25$ GeV and no isolated electron or muon candidate with $p_{\mathrm{T}} > 7$ GeV. These requirements serve to reduce the contribution from W/Z production in association with jets ($V +$ jets). In the search signal region

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TABLE I. Observed and expected upper limits on $\mathcal{B}_{H\to\mathrm{inv}}$ at 95% C.L. from direct searches for invisible decays of the 125 GeV Higgs boson and statistical combinations. Also given are the observed p values under the SM hypothesis.

Analysis	$\sqrt{s}$	Int. luminosity	Observed	Expected	p_{SM} value	Reference
Run 2 VBF	13 TeV	36.1 fb^{-1}	0.37	$0.28^{+0.11}_{-0.08}$	0.19	[37]
Run 2 $Z(\mathrm{lep})H$	13 TeV	36.1 fb^{-1}	0.67	$0.39^{+0.17}_{-0.11}$	0.06	[38]
Run 2 $V(\mathrm{had})H$	13 TeV	36.1 fb^{-1}	0.83	$0.58^{+0.23}_{-0.16}$	0.12	[39]
Run 2 Comb.	13 TeV	36.1 fb^{-1}	0.38	$0.21^{+0.08}_{-0.06}$	0.03	this Letter
Run 1 Comb.	7,8 TeV	4.7, 20.3 fb^{-1}	0.25	$0.27^{+0.10}_{-0.08}$	$\cdots$	[36]
Run $1+2$ Comb.	7,8,13 TeV	4.7, 20.3, 36.1 fb^{-1}	0.26	$0.17^{+0.07}_{-0.05}$	0.10	this Letter

(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 ($1 < m_{jj}/\mathrm{TeV} < 1.5$, $1.5 < m_{jj}/\mathrm{TeV} < 2$, and $m_{jj}/\mathrm{TeV} > 2$) to improve the search sensitivity. The dominant background sources are $Z(\nu\nu) + \mathrm{jets}$ and $W(\ell\nu) + \mathrm{jets}$ production, where the charged lepton ℓ is not detected. Control regions (CR) enriched in $Z(\ell\ell) + \mathrm{jets}$ and $W(\ell\nu) + \mathrm{jets}$ 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 $V + \mathrm{jets}$ production, and accuracy of the jet energy scale (JES). The final discriminant is the number of events in the three m_{jj} regions.

Z*(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 $E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}}/H_T > 0.6$, 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 $p_{\mathrm{T}} > 30\,(20)$ GeV. To reduce the $Z + \mathrm{jets}$ background, the dilepton system must be aligned back to back relative to the $E_{\mathrm{T}}^{\mathrm{miss}}$ vector in the transverse plane. Events with jets originating from b-quarks (b-jets) are vetoed to suppress backgrounds from top quark pair ($t\bar{t}$) 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 $Z + \mathrm{jets}$ background is estimated with a data-driven method that uses Z-enriched CRs. The final discriminant is $E_{\mathrm{T}}^{\mathrm{miss}}$.

V*(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 $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and must not contain an isolated electron or muon with $p_{\mathrm{T}} > 7$ 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 $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ 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 $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ 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 ($70 \lesssim m_J,\ m_{jj}/\mathrm{GeV} \lesssim 100$) targets the hadronic W/Z boson decays of the associated production, whereas the high mass region ($100 \lesssim m_J, m_{jj}/\mathrm{GeV} < 250$) is sensitive to gluon fusion and VBF production. The main background contributions are from the $V + \mathrm{jets}$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$.

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 $\Lambda(\mathcal{B}_{H\to\mathrm{inv}};\theta)$ [50]. This is done following the implementation described in Ref. [51,52], with $\mathcal{B}_{H\to\mathrm{inv}}$ as the parameter of interest. Systematic uncertainties are modeled in the likelihood function as nuisance parameters θ constrained by Gaussian or log-normal probability density functions [36].

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 $\mathcal{B}_{H\to\mathrm{inv}}$ limit of the order of 0.01. The systematic uncertainties on the total $H \to \mathrm{inv}$ 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 $Z(\mathrm{lep})H$ and $V(\mathrm{had})H$ 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 $V(\mathrm{had})H$ 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 $-2\Delta\ln(\Lambda)(\mathcal{B}_{H\to\mathrm{inv}};\theta)$ as a function of $\mathcal{B}_{H\to\mathrm{inv}}$ of the individual analyses and of the combined Run 2 result are shown in Fig. 1, corresponding to a best-fit combined value of $\mathcal{B}_{H\to\mathrm{inv}} = 0.20 \pm 0.10$. The dominant uncertainty sources are finite event yields in data and MC simulations, reconstruction of jets and leptons, and modeling of diboson and $W/Z+\mathrm{jets}$ production. In absence of a significant excess, an upper limit at 95% C.L. of $\mathcal{B}_{H\to\mathrm{inv}} < 0.38(0.21^{+0.08}_{-0.06})$ 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 $\mathcal{B}_{H\to\mathrm{inv}} \simeq 10^{-3}$, 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 $H \to \mathrm{inv}$ 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 $\mathcal{B}_{H\to\mathrm{inv}}$ 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 $V(\mathrm{had})H$ channel, the uncertainty from missing higher order corrections in the $Z(\mathrm{lep})H$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ observable in the dominant background from diboson production in the $Z(\mathrm{lep})H$ search is treated as correlated. All other background modeling uncertainties are considered uncorrelated. The impact of these correlation assumptions on the combined $\mathcal{B}_{H\to\mathrm{inv}}$ limit is found to be at most 0.005. In addition, the impact on $\mathcal{B}_{H\to\mathrm{inv}}$ in scenarios ranging from full anticorrelation to full correlation is studied using the best linear unbiased estimator (BLUE) [57] for the components of the JES uncertainty, the $V+\mathrm{jets}$ background, and diboson production that are nominally not correlated due to different parametrizations in Run 1 and 2. The resulting absolute effect on the $\mathcal{B}_{H\to\mathrm{inv}}$ limit is at most 0.01.

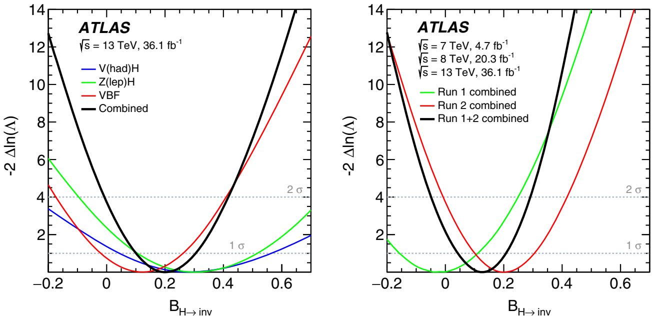

FIG. 1. The observed negative logarithmic profile likelihood ratios $-2\Delta\ln(\Lambda)$ as a function of $\mathcal{B}_{H\to\mathrm{inv}}$ of the $V(\mathrm{had})H$, $Z(\mathrm{lep})H$, and VBF topologies using Run 2 data only and their statistical combination (left). The $-2\Delta\ln(\Lambda)$ functions for the Run 2 combination together with the Run 1 combination and the total Run $1+2$ combination (right).

The observed $-2\Delta\ln(\Lambda)(\mathcal{B}_{H\to\mathrm{inv}};\theta)$ 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 $\mathcal{B}_{H\to\mathrm{inv}} = 0.13 \pm 0.08$ is obtained, corresponding to an observed (expected) upper limit of $\mathcal{B}_{H\to\mathrm{inv}} < 0.26(0.17^{+0.07}_{-0.05})$ 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 $\mathcal{B}_{H\to\mathrm{inv}}$ are graphically represented in Fig. 2.

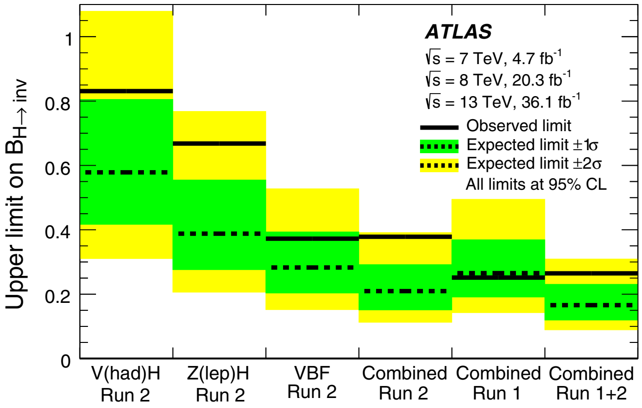

FIG. 2. The observed and expected upper limits on $\mathcal{B}_{H\to\mathrm{inv}}$ at 95% C.L. from direct searches for invisible decays of the 125 GeV Higgs boson and their statistical combinations in Run 1 and 2.

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

The constraint from the combined observed Run $1+2$ exclusion limit of $\mathcal{B}_{H\to\mathrm{inv}} < 0.24$ 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 $H \to \mathrm{inv}$ result into a weak interacting massive particle–nucleon scattering cross section $\sigma_{\mathrm{WIMP}\text{-}N}$ 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 $\sigma_{\mathrm{WIMP}\text{-}N}$ values range down to 2×10^{-45} cm^2 in the scalar WIMP scenario. In the fermion WIMP case, the effective coupling is reduced by m_H^2 [33], excluding $\sigma_{\mathrm{WIMP}\text{-}N}$ values down to 10^{-46} cm^2. While the ATLAS exclusion limits extend to $m_{\mathrm{WIMP}} < 1$ GeV, that region is subject to uncertainties in modelling of the nuclear recoil and is therefore not included in Fig. 3.

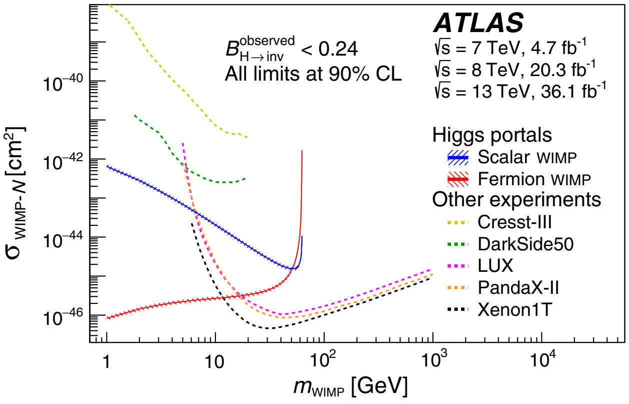

FIG. 3. Comparison of the upper limits at 90% C.L. from direct detection experiments [58–62] on the spin-independent WIMP-nucleon scattering cross section to the observed exclusion limits from this analysis, assuming Higgs portal scenarios where the 125 GeV Higgs boson decays to a pair of DM particles [33,63]. The regions above the limit contours are excluded in the range shown in the plot.

In summary, direct searches for invisible Higgs boson decays using 36.1 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV recorded in 2015 and 2016 in the VBF, $Z(\mathrm{lep})H$, and $V(\mathrm{had})H$ topologies are statistically combined assuming SM-like Higgs boson production. An upper limit on the invisible Higgs branching ratio of $\mathcal{B}_{H\to\mathrm{inv}} < 0.38(0.21^{+0.08}_{-0.06})$ is observed (expected) at 95% C.L. A statistical combination of this result with the combination of direct $H \to \mathrm{inv}$ searches using up to 4.7 fb^{-1} of pp collision data at $\sqrt{s} = 7$ 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 $\mathcal{B}_{H\to\mathrm{inv}} < 0.26(0.17^{+0.07}_{-0.05})$ 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 2×10^{-45} cm^2 in the scalar and 10^{-46} cm^2 in the fermion WIMP scenarios, highlighting the complementarity of DM searches at the LHC and direct detection experiments.

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