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Aaboud, M.; ATLAS Collaboration

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

M. Aaboud et al.*
(ATLAS Collaboration)

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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 \( H \rightarrow \text{invisible} \) decays where \( H \) is produced according to the standard model via vector boson fusion, \( Z(\ell\ell)/H \), and \( W/Z(\text{had})H \), 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 \( 0.26(0.17^{+0.07}_{-0.05}) \) 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 \( \chi \) 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 [29] \( E_T^{\text{miss}} \) 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 \( (Z(\text{lep})H) \) [34], and Higgsstrahlung from a W or Z boson decaying into hadrons \((V(\text{had})H)\) [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 \( \mathcal{B}_{H \rightarrow \text{inv}} = 0.25(0.27^{+0.10}_{-0.08}) \) [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], \( Z(\text{lep})H \) [38], and \( V(\text{had})H \) [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 + 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 ($1 < m_{jj}/\text{TeV} < 1.5$, $1.5 < m_{jj}/\text{TeV} < 2$, and $m_{jj}/\text{TeV} > 2$) 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 ($t\bar{t}$) 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 $Z +$ 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 ($70 \lesssim m_j$, $m_{jj}/\text{GeV} \lesssim 100$) targets the hadronic $W/Z$ boson decays of the associated production, whereas the high mass region ($100 \lesssim m_j, m_{jj}/\text{GeV} < 250$) 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 $\Lambda(B_{H^{\text{inv}}}; \theta)$ [50]. This is done following the implementation described in Ref. [51,52], with $B_{H^{\text{inv}}}$ 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].
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 $B_{H\rightarrow\text{inv}}$ limit of the order of 0.01. The systematic uncertainties on the total $H\rightarrow\text{inv}$ 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 $Z(\text{lep})H$ and $V(\text{had})H$ 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 $V(\text{had})H$ 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 $-2\Delta \ln(\Lambda) (B_{H\rightarrow\text{inv}}; \theta)$ as a function of $B_{H\rightarrow\text{inv}}$ of the individual analyses and of the combined Run 2 result are shown in Fig. 1, corresponding to a best-fit combined value of $B_{H\rightarrow\text{inv}} = 0.20 \pm 0.10$. The dominant uncertainty sources are finite event yields in data and MC simulations, reconstruction of jets and leptons, and modeling of diboson and $W/Z + \text{jets}$ production. In absence of a significant excess, an upper limit at 95% C.L. of $B_{H\rightarrow\text{inv}} < 0.38(0.21^{+0.08}_{-0.06})$ 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 $p_{\text{SM}}$ value of 3% under the SM hypothesis of $B_{H\rightarrow\text{inv}} \approx 10^{-3}$, 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 $H\rightarrow\text{inv}$ 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 $B_{H\rightarrow\text{inv}}$ 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 $V(\text{had})H$ channel, the uncertainty from missing higher order corrections in the $Z(\text{lep})H$ 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 $E_T^{\text{miss}}$ observable in the dominant background from diboson production in the $Z(\text{lep})H$ search is treated as correlated. All other background modeling uncertainties are considered uncorrelated. The impact of these correlation assumptions on the combined $B_{H\rightarrow\text{inv}}$ limit is found to be at most 0.005. In addition, the impact on $B_{H\rightarrow\text{inv}}$ 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 $V + \text{jets}$ background, and diboson production that are nominally not correlated due to different parametrizations in Run 1 and 2. The resulting absolute effect on the $B_{H\rightarrow\text{inv}}$ limit is at most 0.01.

The observed $-2\Delta \ln(\Lambda) (B_{H\rightarrow\text{inv}}; \theta)$ 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 $B_{H\rightarrow\text{inv}} = 0.13 \pm 0.08$ is obtained, corresponding to an observed (expected) upper limit of $B_{H\rightarrow\text{inv}} < 0.26(0.17^{+0.07}_{-0.05})$ at 95% C.L. The $p_{\text{SM}}$ 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 $B_{H\rightarrow\text{inv}}$ are graphically represented in Fig. 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 $B_{H \rightarrow \text{inv}} < 0.24$ 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 $2 \times 10^{-44}$ 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 $10^{-46}$ cm$^2$. While the ATLAS exclusion limits extend to $m_{\text{WIMP}} < 1$ 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 $\sqrt{s} = 13$ TeV recorded in 2015 and 2016 in the VBF, Z(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 $B_{H \rightarrow \text{inv}} < 0.38(0.21^{+0.08}_{-0.06})$ 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 $\sqrt{s} = 7$ 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 $B_{H \rightarrow \text{inv}} < 0.26(0.17^{+0.07}_{-0.05})$ 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 $2 \times 10^{-45}$ 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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(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 Fisica d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
14Institut d'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
17Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
17aAlbert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
19Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
20Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
21School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
22Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogota, Colombia
23aINFN Bologna and Universita’ di Bologna, Dipartimento di Fisica, Italy
23bINFN 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
27aTransilvania University of Brasov, Brasov, Romania
27bHoria Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
27cDepartment of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
27dNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
27eUniversity Politehnica Bucharest, Bucharest, Romania
27fWest University in Timisoara, Timisoara, Romania
28aFaculty 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
29aPhysics Department, Brookhaven National Laboratory, Upton, New York, USA
30aDepartamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
31aCalifornia 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
33cSchool of Physics, University of the Witwatersrand, Johannesburg, South Africa
33dDepartment of Physics, Carleton University, Ottawa, Ontario, Canada
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco
Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des sciences, Université Mohammed V, Rabat, Morocco
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece
Department of Physics, Stockholm University, Sweden
Oskar Klein Centre, Stockholm, Sweden
Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dortmund, Dortmund, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN e Laboratori Nazionali di Frascati, Frascati, Italy
Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
Dipartimento di Fisica, Università di Genova, Genova, Italy
INFN Sezione di Genova, Genova, Italy
Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
School of Physics and Astronomy, Shanghai Jiao Tong University, KLPAC-MoE, SKLPPC, Shanghai, China
Tsung-Dao Lee Institute, Shanghai, China
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
Department of Physics, University of Hong Kong, Hong Kong, China
Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
Department of Physics, Indiana University, Bloomington, Indiana, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
INFN Sezione di Lecce, Lecce, Italy
Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
INFN Sezione di Lecce, Lecce, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
INFN Sezione di Napoli, Napoli, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
INFN Sezione di Pavia, Pavia, Italy
INFN Sezione di Pisa, Pisa, Italy
Also at Department of Physics, King’s College London, London, United Kingdom.

Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.

Also at Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain.

Also at TRIUMF, Vancouver, British Columbia, Canada.

Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

Also at Department of Physics, California State University, Fresno, California, USA.

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at Departament de Física de la Universitat Autonoma de Barcelona, Barcelona, Spain.

Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

Also at Department of Physics, California State University, East Bay, Hayward, California, USA.

Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.

Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Department of Physics, Stanford University, Stanford, California, USA.

Also at Manhattan College, New York, New York, USA.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

Also at Hellenic Open University, Patras, Greece.

Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.

Also at The City College of New York, New York, New York, USA.

Also at Department of Physics, California State University, Sacramento, California, USA.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

Also at Louisiana Tech University, Ruston, Louisiana, USA.

Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
II. Also at National Research Nuclear University MEPhI, Moscow, Russia.

III. Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

IV. Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

V. Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.