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Aaboud, M.; ATLAS Collaboration

DOI
10.1103/PhysRevLett.122.231801

Publication date
2019

Document Version
Final published version

Published in
Physical Review Letters

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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 \( W/Z(\text{had})H \), all performed with the ATLAS detector using 36.1 \( \text{fb}^{-1} \) 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 kinetically 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” \( (\text{inv}) \).

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 \( \text{fb}^{-1} \) of \( pp \) collision data at a center-of-mass energy of \( \sqrt{s} = 7 \) TeV and up to 20.3 \( \text{fb}^{-1} \) 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 \( B_{H \rightarrow \text{inv}} \) \( < 0.25(0.27^{+0.10}_{-0.08}) \) \([36]\) 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 \( \text{fb}^{-1} \) 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 \( \text{fb}^{-1} \) 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 \( \left| \eta(j) \right| < 4.5 \) 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 \( \left| \Delta \eta (j) \right| > 4.8 \). 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 \( (V + \text{jets}) \). 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 ($1 < m_{jj}/\text{TeV} < 1.5$, $1.5 < m_{jj}/\text{TeV} < 2$, and $m_{jj}/\text{TeV} > 2$) to improve the search sensitivity. The dominant background sources are $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ production, where the charged lepton $\ell$ is not detected. Control regions (CR) enriched in $Z(\ell\ell) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ 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 $V + \text{jets}$ 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 $E_T^{\text{miss}} > 90 \text{ GeV}$ 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 $p_T > 30 \text{ (20) GeV}$. To reduce the $Z + \text{jets}$ 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 background 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 $Z + \text{jets}$ 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 $p_T > 7 \text{ GeV}$. 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 $E_T^{\text{miss}} > 250 \text{ GeV}$ 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 $E_T^{\text{miss}} > 150 \text{ GeV}$ 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 $V + \text{jets}$ 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].

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\sqrt{s}$</th>
<th>Int. luminosity</th>
<th>Observed</th>
<th>Expected</th>
<th>$p_{SM}$ value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2 VBF</td>
<td>13 TeV</td>
<td>36.1 fb$^{-1}$</td>
<td>0.37</td>
<td>0.28$^{+0.11}_{-0.08}$</td>
<td>0.19</td>
<td>[37]</td>
</tr>
<tr>
<td>Run 2 Z(lep)H</td>
<td>13 TeV</td>
<td>36.1 fb$^{-1}$</td>
<td>0.67</td>
<td>0.39$^{+0.17}_{-0.11}$</td>
<td>0.06</td>
<td>[38]</td>
</tr>
<tr>
<td>Run 2 V(had)H</td>
<td>13 TeV</td>
<td>36.1 fb$^{-1}$</td>
<td>0.83</td>
<td>0.58$^{+0.23}_{-0.16}$</td>
<td>0.12</td>
<td>[39]</td>
</tr>
<tr>
<td>Run 2 Comb.</td>
<td>13 TeV</td>
<td>36.1 fb$^{-1}$</td>
<td>0.38</td>
<td>0.21$^{+0.08}_{-0.06}$</td>
<td>0.03</td>
<td>this Letter</td>
</tr>
<tr>
<td>Run 1 Comb.</td>
<td>7.8 TeV</td>
<td>4.7, 20.3 fb$^{-1}$</td>
<td>0.25</td>
<td>0.27$^{+0.10}_{-0.08}$</td>
<td>···</td>
<td>[36]</td>
</tr>
<tr>
<td>Run 1 + 2 Comb.</td>
<td>7.8, 13 TeV</td>
<td>4.7, 20.3, 36.1 fb$^{-1}$</td>
<td>0.26</td>
<td>0.17$^{+0.07}_{-0.05}$</td>
<td>0.10</td>
<td>this Letter</td>
</tr>
</tbody>
</table>

TABLE I. Observed and expected upper limits on $B_{H^{\text{inv}}}$ at 95% C.L. from direct searches for invisible decays of the 125 GeV Higgs boson and statistical combinations. Also given are the observed $p$ values under the SM hypothesis.
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 $E_{\text{T}}^{\text{miss}}$ 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.
or a fermion [23,64,65], using the nuclear form factor
are kinematically possible and that the WIMP is a scalar
In the fermion WIMP case, the effective coupling is
range down to
125 GeV Higgs boson decays to a pair of DM particles[33,63].
the nucleon scattering cross section to the observed exclusion limits
experiments [58–62] in Fig. 3. This comparison is performed in the context of Higgs portal models [63]. The translation of the $H \to \text{inv}$ 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 $2 \times 10^{-45}$ cm$^2$ in the scalar $V(\text{had})H$ 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, $Z(\text{lep})H$, 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 $B_{H \to \text{inv}} < 0.38(0.21^{+0.08}_{-0.06})$ is observed (expected) at 95% C.L. A statistical combination of this result with the combination of direct $H \to \text{inv}$ 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 $B_{H \to \text{inv}} < 0.26(0.17^{+0.07}_{-0.05})$ 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.

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; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/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.
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), INFIN-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].


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120 Konstantinov Nuclear Physics Institute of National Research Centre Kurchatov Institute, Protvino, Russia
120 Novosibirsk State University Novosibirsk, Russia
121 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
122 Department of Physics, New York University, New York, New York, USA
123 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
124 The Ohio State University, Columbus, Ohio, USA
125 Faculty of Science, Okayama University, Okayama, Japan
126 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
127 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
128 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
129 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
130 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
131 Graduate School of Science, Osaka University, Osaka, Japan
132 Department of Physics, University of Oslo, Oslo, Norway
133 Department of Physics, Oxford University, Oxford, United Kingdom
134 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
135 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
136 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, St. Petersburg, Russia
137 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
138 Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
139 Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
140 Departamento de Física, Universidade do Minho, Braga, Portugal
141 Universidade de Granada, Granada (Spain), Spain
142 Dep Física and CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
143 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
144 Czech Technical University in Prague, Prague, Czech Republic
145 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
146 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
147b Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
148 Department of Physics, University of Washington, Seattle, Washington, USA
149 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
150 Department of Physics, Shinshu University, Nagano, Japan
151 Department Physik, Universität Siegen, Siegen, Germany
152 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
153 SLAC National Accelerator Laboratory, Stanford, California, USA
154 Physics Department, Royal Institute of Technology, Stockholm, Sweden
155 Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
156 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
157 School of Physics, University of Sydney, Sydney, Australia
158 Institute of Physics, Academia Sinica, Taipei, Taiwan
159 E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
160 High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
161 Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
162 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
163 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
164 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
165 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
166 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
167 Department of Physics, Tomsk State University, Tomsk, Russia
168 Department of Physics, University of Toronto, Toronto, Ontario, Canada
169 TRIUMF, Vancouver, British Columbia, Canada
170 Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences,
University of Tsukuba, Tsukuba, Japan
171 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Department of Physics, University of Illinois, Urbana, Illinois, USA

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

Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, Connecticut, USA

Yerevan Physics Institute, Yerevan, Armenia

a Deceased.
b Also at Department of Physics, King’s College London, London, United Kingdom.

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

c Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain.

d 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 Departamento de Física de la Universidad Autónoma 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, Freiberg, 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 of 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.