Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS


DOI
10.1103/PhysRevLett.112.201802

Publication date
2014

Document Version
Final published version

Published in
Physical Review Letters

Link to publication

Citation for published version (APA):
https://doi.org/10.1103/PhysRevLett.112.201802

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
Search for Invisible Decays of a Higgs Boson Produced in Association with a $Z$ Boson in ATLAS

G. Aad et al.*

(ATLAS Collaboration)

(Received 13 February 2014; revised manuscript received 11 April 2014; published 20 May 2014)

A search for evidence of invisible-particle decay modes of a Higgs boson produced in association with a $Z$ boson at the Large Hadron Collider is presented. No deviation from the standard model expectation is observed in 4.5 fb$^{-1}$ (20.3 fb$^{-1}$) of 7 (8) TeV $pp$ collision data collected by the ATLAS experiment. Assuming the standard model rate for $ZH$ production, an upper limit of 75%, at the 95% confidence level is set on the branching ratio to invisible-particle decay modes of the Higgs boson at a mass of 125.5 GeV. The limit on the branching ratio is also interpreted in terms of an upper limit on the allowed dark matter-nucleon scattering cross section within a Higgs-portal dark matter scenario. Within the constraints of such a scenario, the results presented in this Letter provide the strongest available limits for low-mass dark matter candidates. Limits are also set on an additional neutral Higgs boson, in the mass range $110 < m_H < 400$ GeV, produced in association with a $Z$ boson and decaying to invisible particles.

DOI: 10.1103/PhysRevLett.112.201802 PACS numbers: 14.80.Bn, 12.60.Fr, 14.80.Ec, 95.35.+d

Some extensions of the standard model (SM) allow a Higgs boson [1–3] to decay to a pair of stable or long-lived particles [4–18] that are not observed by the ATLAS detector. For instance the Higgs boson can decay into two particles with very small interaction cross sections with SM particles, such as dark matter (DM) candidates. Collider data can be used to directly constrain the branching ratio of the Higgs boson to invisible particles. Similarly, limits can be placed on the cross section times branching ratio of any additional Higgs bosons decaying predominantly to invisible particles. LEP results [19] put limits on an invisibly decaying Higgs boson, produced in association with a $Z$ boson, for Higgs masses below 120 GeV.

This Letter presents a search for invisible decays of a Higgs boson produced in association with a $Z$ boson. A Higgs boson in the mass range $110 < m_H < 400$ GeV is considered. The distribution of the missing transverse momentum ($E_T^{miss}$) in events with an electron or a muon pair consistent with a $Z$ boson decay is used to constrain the $ZH$ production cross section times the branching ratio of the Higgs boson decaying to invisible particles, over the full mass range. For the newly discovered Higgs boson, a constraint could be placed on the branching ratio to invisible particles. In this case the mass of the Higgs boson is taken to be $m_H = 125.5$ GeV, the best-fit value from the ATLAS experiment [20], and the $ZH$ production cross section is assumed to be that predicted for the SM Higgs boson. This assumption implies that the hypothesized unobserved particles that couple to the Higgs boson have sufficiently weak couplings to other SM particles to not affect the Higgs boson production cross sections. The total cross section for the associated production of a SM Higgs boson, with $m_H = 125.5$ GeV, and a $Z$ boson, calculated to next-to-next-to-leading order in QCD [21] and including next-to-leading-order (NLO) electroweak corrections [22,23], is 331 fb at $\sqrt{s} = 7$ TeV and 410 fb at $\sqrt{s} = 8$ TeV [24]. The SM branching ratio of the Higgs boson decaying to invisible particles is $1.2 \times 10^{-3}$, arising from the $H \rightarrow ZZ^{(*)} \rightarrow 4\nu$ decay. The present search is not sensitive to the low branching ratio for this decay, but instead searches for enhancements in the decay fraction to invisible particles due to physics beyond the standard model (BSM).

The search uses 4.5 fb$^{-1}$ of data recorded with the ATLAS detector in 2011 at $\sqrt{s} = 7$ TeV and 20.3 fb$^{-1}$ of data recorded in 2012 at $\sqrt{s} = 8$ TeV. The ATLAS detector has been described elsewhere [25]. Simulated signal and background event samples are produced with Monte Carlo (MC) event generators, passed through a full GEANT4 [26] simulation of the ATLAS detector [27] and reconstructed with the same software as the data.

The signal samples are generated with HERWIG++ [28] and its internal POWHEG method [29,30]. The SM $ZZ$ and $WZ$ backgrounds are taken from simulation, since they have limited statistics in the control regions that would allow us to estimate these backgrounds with data. All the other background processes to this search are determined from data. In these cases, simulated samples are only used as cross-checks for the obtained background estimates. POWHEG [29–31] interfaced with PYTHIA8 [32] is used to model SM $ZZ$ and $WZ$ production [33]. The production of $WW$ is modeled using HERWIG [34] and SHERPA [35].

* Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article title, journal citation, and DOI.
for the 7 and 8 TeV data, respectively. A separate sample simulated with gg2VV [36] interfaced with JIMMY [37] accounts for WW/ZZ production through quark-box diagrams, which are not included in the above mentioned samples. The MC@NLO [38] generator interfaced with JIMMY is used to model $t\bar{t}$, $Wt$, and $s$-channel single top-quark production. AcerMC [39] interfaced with PYTHIA [40] models $t$-channel single top-quark production. Inclusive $Z/\gamma^{\ast}$ production is simulated with ALPGEN [41] interfaced with JIMMY or PYTHIA for the 7 or 8 TeV data, respectively. Inclusive $W$ production is simulated with ALPGEN interfaced with JIMMY. Contributions to this search from the $H \rightarrow WW^{(*)} \rightarrow \ell^{+}\ell^{-}\ell^{+}\ell^{-}$ and $H \rightarrow ZZ^{(*)} \rightarrow \ell^{+}\ell^{-}\ell^{+}\ell^{-}$ decays of a 125.5 GeV SM Higgs boson are studied using POWHEG [29–31,42,43] interfaced with PYTHIA8 and found to be negligible.

Electron candidates are reconstructed from isolated energy deposits in the electromagnetic calorimeter with a shower shape consistent with electrons or photons, matched to inner detector tracks [44]. The electrons used to form a $Z$ boson candidate are required to have transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.47$ [45]. Electrons with $p_T > 7$ GeV that satisfy less stringent identification criteria on the calorimeter cluster shape, track quality, and track-cluster matching [44] are used to veto events with more than two charged leptons.

Muons are reconstructed combining tracks independently found in the muon spectrometer and inner tracking detector [46]. Muons forming a $Z$ boson candidate are required to have $p_T > 20$ GeV and $|\eta| < 2.4$. Muons with $p_T > 7$ GeV are used to veto events with more than two charged leptons.

Jets are reconstructed using the anti-$k_T$ algorithm [47] with a radius parameter $R = 0.4$. They must have $p_T > 20$ GeV and $|\eta| < 4.5$. To discriminate against jets from additional minimum bias interactions, selection criteria are applied to ensure that most of the jet momentum, for jets with $|\eta| < 2.5$, is associated with tracks originating from the primary vertex, which is taken to be the vertex with the highest summed $p_T$ of associated tracks.

To ensure good separation between electrons, muons, and jets, electrons are removed if they are within $\Delta R \leq 0.2$ of an identified muon, and jets are removed if they are within $\Delta R \leq 0.2$ of an identified electron. Remaining electrons and muons are removed if they are within $\Delta R \leq 0.4$ of a remaining jet or if the scalar sum of track momenta, not associated with the lepton, in a cone of $\Delta R < 0.2$ around the lepton direction is greater than 10% of the lepton $p_T$.

The $E_T^{\text{miss}}$ is the magnitude of the negative vectorial sum of the transverse momenta from calibrated objects, such as identified electrons, muons, photons, hadronic decays of tau leptons, and jets [48]. Clusters of calorimeter cells not matched to any object are also included. The analysis also uses a track-based missing transverse momentum ($p_T^{\text{miss}}$) computed from all inner detector tracks with $p_T > 500$ MeV and $|\eta| < 2.5$, that satisfy stringent quality criteria [49] and are consistent with originating from the primary vertex. For the $p_T^{\text{miss}}$ calculation, tracks matched to electrons are discarded and replaced by the transverse energy $E_T$ of the matched cluster measured in the calorimeter to include any photon radiation in the calculation.

Event selection criteria are determined in an optimization procedure, using simulated samples, to maximize the signal significance of the search. Events are required to pass a single-lepton or lepton-pair trigger, with small variations in the applied $p_T$ threshold in different data-taking periods. Events must also have at least one reconstructed vertex with at least three associated tracks with $p_T > 500$ MeV. Data quality criteria are applied to reject events from non-collision backgrounds or events with degraded detector performance [48].

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

Figure 1 shows the $E_T^{\text{miss}}$ distribution in the 8 TeV data sample after the dilepton mass requirement. In this figure the data are consistent with the expected background based on simulated samples for all but the multijet background. The uncertainty band of the expected background is widest in the region dominated by the steeply falling $Z$ boson background. To reject the majority of this background, $E_T^{\text{miss}}$ is required to be greater than 90 GeV. In events where a significant $E_T^{\text{miss}}$ arises from misreconstructed energy in the calorimeter, the vectors of $E_T^{\text{miss}}$ and $p_T^{\text{miss}}$ are likely to have different azimuthal angles. Thus the azimuthal difference of these two vectors, $\Delta \phi(E_T^{\text{miss}}, p_T^{\text{miss}})$, is required to be less than 0.2.

![FIG. 1 (color online). Distribution of $E_T^{\text{miss}}$ for events with the invariant mass of the two leptons $76 < m_{\ell\ell} < 106$ GeV in the 8 TeV data (dots). The stacked histograms represent the background predictions from simulation. The signal hypothesis is shown by a dotted line and assumes the SM $ZH$ production rate for a $m_H = 125.5$ GeV Higgs boson with BR($H \rightarrow \text{inv.}$) = 1. The inset at the bottom of the figure shows the ratio of the data to the combined background expectations as well as a band corresponding to the combined systematic uncertainties.](image-url)
For the signal, the momentum of the reconstructed Z boson is expected to be balanced by the momentum of the invisibly decaying Higgs boson. Therefore the azimuthal separation between the dilepton system, where the magnitude of its transverse momentum is defined as $p_T^{\ell\ell}$, and the $E_T^{\text{miss}}$, $\Delta \phi (p_T^{\ell\ell}, E_T^{\text{miss}})$, is required to be greater than 2.6. The boost of the Z boson causes the decay leptons to be produced with a small opening angle. The azimuthal opening angle of production, as shown in Table I. These backgrounds are invisibly decaying Higgs boson. Therefore the azimuthal $p_T$ difference, defined as $|E_T^{\text{miss}} - p_T^{\ell\ell}| / p_T^{\ell\ell}$, is required to be less than 0.2. Finally, for the majority of the signal no additional high-$p_T$ jets are expected to be observed in the events, while for the background from boosted $Z$ bosons and from $t\bar{t}$ pairs one or more jets are expected. Thus, events are required to have no reconstructed jets with $p_T > 25$ GeV and $|\eta| < 2.5$.

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

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

The background from inclusive $Z \rightarrow \ell\ell$ and $Z \rightarrow \mu\mu$ production in the signal region is estimated from the background in three sideband regions [51]. These sideband regions are formed by considering events failing one or both of the nominal selection requirements applied to $\Delta \phi (E_T^{\text{miss}}, p_T^{\ell\ell})$ and the fractional $p_T$ difference. Contributions from non-$Z$ backgrounds in the sideband regions are subtracted. The impact from a correlation between the above two variables is determined from the simulation and a correction, of at most 7%, is applied to account for it. The main uncertainties are due to variations in this correction and differences in the shape of the $E_T^{\text{miss}}$ distribution in the control regions. The overall systematic uncertainty is 52% in the 7 TeV data and 59% in the 8 TeV data.

The small background from events with only one genuine isolated lepton (inclusive $W$, single-lepton top pairs and single top production) or from multijet events is estimated from data using control samples, selected by requiring two lepton candidates of which at least one fails the full lepton selection criteria. These samples are scaled with a measured $p_T$-dependent factor, determined from data as described in Ref. [52]. Systematic uncertainties are determined following the procedures used in Ref. [52], yielding an uncertainty of 40% in the 7 TeV data and 21% in the 8 TeV data.

Systematic uncertainties on the signal and the SM $ZZ$ and $WZ$ backgrounds are derived from the luminosity uncertainty, the propagation of reconstructed object uncertainties, and from theoretical uncertainties on the production cross sections. The luminosity uncertainty is 1.8% for the 7 TeV data-taking period and 2.8% for the 8 TeV data-taking period [53].

Lepton trigger and identification efficiencies as well as the energy scale and resolution are determined from data using large samples of Z events. After appropriate corrections to the simulation, uncertainties are propagated to the

---

**Table I.** Number of events observed in data and expected from the signal and from each background source for the 7 and 8 TeV data-taking periods. Uncertainties on the signal and background expectations are presented with statistical uncertainties first and systematic uncertainties second.

<table>
<thead>
<tr>
<th>Data period</th>
<th>2011 (7 TeV)</th>
<th>2012 (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ \rightarrow \ell\ell\nu\nu$</td>
<td>$20.0 \pm 0.7 \pm 1.6$</td>
<td>$91 \pm 1 \pm 7$</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell\ell\ell$</td>
<td>$4.8 \pm 0.3 \pm 0.5$</td>
<td>$26 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>Dileptonic $t\bar{t}$, $Wt$, $WW$, $Z \rightarrow \tau\tau$</td>
<td>$0.5 \pm 0.4 \pm 0.1$</td>
<td>$20 \pm 3 \pm 5$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$, $Z \rightarrow \mu\mu$</td>
<td>$0.13 \pm 0.12 \pm 0.07$</td>
<td>$0.9 \pm 0.3 \pm 0.5$</td>
</tr>
<tr>
<td>$W + \text{jets}$, multijet, semileptonic top</td>
<td>$0.020 \pm 0.005 \pm 0.008$</td>
<td>$0.29 \pm 0.02 \pm 0.06$</td>
</tr>
<tr>
<td>Total background</td>
<td>$25.4 \pm 0.8 \pm 1.7$</td>
<td>$138 \pm 4 \pm 9$</td>
</tr>
<tr>
<td>Signal ($m_H = 125.5$ GeV, $\sigma_{ZH, SM}$, BR($H \rightarrow \text{inv.}$) = 1)</td>
<td>$8.9 \pm 0.1 \pm 0.5$</td>
<td>$44 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>Observed</td>
<td>28</td>
<td>152</td>
</tr>
</tbody>
</table>
event selection. These uncertainties contribute typically 1.0%–1.5% to the overall selection uncertainty. Jet energy scale and resolution uncertainties are derived using a combination of techniques that use dijet, photon + jet, and Z + jet events [54,55]. These contribute an uncertainty of between 3% and 6% on the final event selection. The uncertainties on the energy scale and resolution of leptons and jets are also propagated to the $E_T^{\text{miss}}$ calculation, and the resulting uncertainty in the latter is included in uncertainties given above. Uncertainties in the pile-up simulation, affecting in particular $E_T^{\text{miss}}$, contribute a further 1%–2% uncertainty.

Theoretical uncertainties on the $ZH$ production cross section are derived from variations of the renormalization and factorization scale, $\alpha_s$, and the parton distribution functions (PDFs) [24]. These are combined to give an uncertainty of 3.6%–5.7% on the cross section. This analysis is sensitive to the distribution of the Higgs boson $p_T$ through the $E_T^{\text{miss}}$, and uncertainties in the $p_T$ boost of the Higgs boson can affect the signal yield. An additional systematic uncertainty of 1.9% is applied to the normalization [22,23,56], and uncertainties as a function of the Higgs boson $p_T$ are considered as a systematic shape uncertainty.

The cross-section uncertainty on the $ZZ$ background is 5% from varying the PDFs, $\alpha_s$, and QCD scale. The uncertainty on the jet veto for the $ZZ$ background due to the parton showering is estimated to be 6.4% (5.5%) for the 7 (8) TeV data. Because the $E_T^{\text{miss}}$ distribution of the final selected sample is used in the limit-setting procedure, the impact of PDFs, $\alpha_s$, and QCD scale uncertainties on the shape of this distribution is also considered. The theoretical uncertainty of the $WZ$ background is considered similarly. The total systematic uncertainty on the SM $ZZ$ background is 8% for both the 7 and 8 TeV data-taking periods, whereas for the $WZ$ background it is 10% (13%) for the 7 (8) TeV data-taking periods.

Event reconstruction and theoretical uncertainties are considered as correlated between the 7 and 8 TeV data, and between the signals and backgrounds estimated from simulation. The systematic uncertainties in methods that determine backgrounds from data using control regions are also assumed to be correlated between the two data sets. The luminosity uncertainty is considered as uncorrelated between the 7 and 8 TeV data.

The numbers of observed and expected events for the 7 and 8 TeV data-taking periods are shown in Table I. Figure 2 shows the $E_T^{\text{miss}}$ distribution after the full event selection for the 8 TeV data and the expected backgrounds. The normalization of the backgrounds is extracted from a binned profile maximum likelihood fit in the signal region. Systematic uncertainties are considered as nuisance parameters, and are assumed to be constrained by Gaussian distributions. The signal expectation shown corresponds to a Higgs boson with $m_H = 125.5$ GeV, a SM $ZH$ production rate, and $\text{BR}(H \rightarrow \text{inv.}) = 1$. No significant excess is observed over the SM expectation.

Limits are set on the cross section times branching ratio for a Higgs boson decaying to invisible particles anywhere in the mass range $110 < m_H < 400$ GeV. The limits are computed using a maximum likelihood fit to the $E_T^{\text{miss}}$ distribution following the CL$_s$ (signal confidence level) modified frequentist formalism [57] with a profile likelihood test statistic [58]. Figure 3 shows the 95% C.L. upper limits on $\sigma_{ZH} \times \text{BR}(H \rightarrow \text{inv.})$ in the mass range $110 < m_H < 400$ GeV for the combined 7 and 8 TeV data. The expectation for a Higgs boson with a production cross section equal to that expected for a SM Higgs boson and $\text{BR}(H \rightarrow \text{inv.}) = 1$ is also shown.
For the discovered Higgs boson an upper limit of 75% at 95% C.L. (63% at 90% C.L.) is set on the branching ratio to invisible particles. For this the predicted SM $ZH$ production rate with $m_H = 125.5$ GeV, is assumed. The expected limit in the absence of BSM decays to invisible particles is 62% at 95% C.L. (52% at 90% C.L.).

Within the context of a Higgs-portal DM scenario $[59]$, in which the Higgs boson acts as the mediator particle between DM and SM particles, the Higgs boson can decay to a pair of DM particles. In this case the limit on $BR(H \rightarrow inv.)$ for the 125.5 GeV Higgs boson can be interpreted in terms of an upper limit on the DM–nucleon scattering cross section $[60]$. The formalism used to interpret the $BR(H \rightarrow inv.)$ limit in terms of the spin-independent DM–nucleon scattering cross section is described in Refs. $[61,62]$. Figure 4 shows 90% C.L. upper limits on the DM–nucleon scattering cross section for three model variants in which a single DM candidate is considered and is either a scalar, a vector, or a Majorana fermion. The Higgs–nucleon coupling is taken as $0.33^{+0.30}_{-0.07}$ $[62]$, the uncertainty of which is expressed by the bands in the figure. Spin-independent results from direct-search experiments are also shown $[63–70]$. These results do not depend on the assumptions of the Higgs-portal scenario. Within the constraints of such a scenario, however, the results presented in this Letter provide the strongest available limits for low-mass DM candidates. There is no sensitivity to these models once the mass of the DM candidate exceeds $m_H/2$. A search by the ATLAS experiment for DM in more generic models, also using the dilepton $+$ large $E_T^{miss}$ final state, is presented in Ref. $[71]$. We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; IFI, INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNEIFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTDF, Serbia; MSSS, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

Turkish Atomic Energy Authority, Ankara, Turkey

LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA

Department of Physics, University of Arizona, Tucson, Arizona, USA

Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA

Physics Department, University of Athens, Athens, Greece

Physics Department, National Technical University of Athens, Zografou, Greece

Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

Institutes of Physics, University of Belgrade, Belgrade, Serbia

Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

Department for Physics and Technology, University of Bergen, Bergen, Norway

Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA

Department of Physics, Humbold University, Berlin, Germany

Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

Department of Physics, Bogazici University, Istanbul, Turkey

Department of Physics, Dogus University, Istanbul, Turkey

Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

INFN Sezione di Bologna, Italy

Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

Physikalisches Institut, University of Bonn, Bonn, Germany

Department of Physics, Boston University, Boston, Massachusetts, USA

Department of Physics, Brandeis University, Waltham, Massachusetts, USA

Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio De Janeiro, Brazil

Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil

Federal University of Sao Joao del Rei (UFJD), Sao Joao del Rei, Brazil

Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

Physics Department, Brookhaven National Laboratory, Upton, New York, USA

National Institute of Physics and Nuclear Engineering, Bucharest, Romania

National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania

University Politehnica Bucharest, Bucharest, Romania

West University in Timisoara, Timisoara, Romania

Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa, Ontario, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA

Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Department of Modern Physics, University of Science and Technology of China, Anhui, China

Department of Physics, Nanjing University, Jiangsu, China

School of Physics, Shandong University, Shandong, China

Physics Department, Shanghai Jiao Tong University, Shanghai, China

Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

Nevis Laboratory, Columbia University, Irvington, New York, USA

Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

INFN Gruppo Collegato di Cosenza, Italy

Dipartimento di Fisica, Università della Calabria, Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas, Texas, USA

Physics Department, University of Texas at Dallas, Richardson, Texas, USA

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham, North Carolina, USA

SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

INFN Laboratori Nazionali di Frascati, Frascati, Italy

Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

Section de Physique, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova, Italy

Dipartimento di Fisica, Università di Genova, Genova, Italy

E. Andronikashvili Institute of Physics, Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia

High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France

Department of Physics, Hampton University, Hampton, Virginia, USA

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Physics, Indiana University, Bloomington, Indiana, USA

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City, Iowa, USA

Department of Physics, Iowa State University, Ames, Iowa, USA

Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

Department of Physics, Kyushu University, Fukuoka, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, United Kingdom

INFN Sezione di Lecce, Italy

Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

Louisiana Tech University, Ruston, Louisiana, USA

Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA

Department of Physics, McGill University, Montreal, Quebec, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA

Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

INFN Sezione di Milano, Italy

Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
b Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

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

Also at Institut Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, University of Cape Town, Cape Town, South Africa.

Also at CERN, Geneva, Switzerland.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
Also at Manhattan College, New York, NY, USA.

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

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

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.

Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.

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

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.

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

Also at DESY, Hamburg and Zeuthen, Germany.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.

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

Also at Physics Department, Brookhaven National Laboratory, Upton, NY, USA.

Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

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

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

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

Also at Physics Department, Brookhaven National Laboratory, Upton, NY, USA.

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

Also at DESY, Hamburg and Zeuthen, Germany.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.