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.

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].
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 pπ production with a radius parameter $R = 0.4$. They must have $p_T > 20$ GeV and $|\eta| < 2.4$ [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 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 $p_T^2$ 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.

![Figure 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($H \to \text{inv.}) = 1$. 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.
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 boost of the ground is SM \( j \)

\[ \text{the fractional } p_T \text{ difference, defined as } |E_T^{\text{miss}} - p_T^{\ell \ell}|/p_T^{\ell \ell}, \text{ is required to be less than 0.2. Finally, for the majority of the signal no additional high-}p_T \text{ jets are expected to be observed in the events, while for the background from boosted Z bosons and from } t \bar{t} \text{ pairs one or more jets are expected. Thus, events are required to have no reconstructed jets with } p_T > 25 \text{ GeV and } |\eta| < 2.5. \]

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 \( \sqrt{s} = 7 \text{ TeV} \) [50].

Background contributions from events with a genuine isolated lepton pair, not originating from a \( Z \to \ell \ell \) or \( Z \to \mu \mu \) decay (\( WW, t \bar{t}, Wt, \) and \( Z \to \tau \tau \)), 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 \( Z \to \tau \tau \) 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 \( Z \to ee \) and \( Z \to \mu \mu \) 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>
<thead>
<tr>
<th>Data period</th>
<th>2011 (7 TeV)</th>
<th>2012 (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ → e\ell\nu</td>
<td>20.0 ± 0.7 ± 1.6</td>
<td>91 ± 1 ± 7</td>
</tr>
<tr>
<td>ZZ → µ\ell\nu</td>
<td>4.8 ± 0.3 ± 0.5</td>
<td>26 ± 1 ± 3</td>
</tr>
<tr>
<td>ZZ → \ell\ell, Wt, WW, Z → ττ</td>
<td>0.5 ± 0.4 ± 0.1</td>
<td>20 ± 3 ± 5</td>
</tr>
<tr>
<td>ZZ → ee, Z → µµ</td>
<td>0.13 ± 0.12 ± 0.07</td>
<td>0.9 ± 0.3 ± 0.5</td>
</tr>
<tr>
<td>W + jets, multijet, semileptonic top</td>
<td>0.020 ± 0.005 ± 0.008</td>
<td>0.29 ± 0.02 ± 0.06</td>
</tr>
<tr>
<td>Total background</td>
<td>25.4 ± 0.8 ± 1.7</td>
<td>138 ± 4 ± 9</td>
</tr>
<tr>
<td>Signal (( m_H = 125.5 \text{ GeV}, \sigma_{ZH,}\text{SM}, \text{BR}(H \to \text{inv.}) = 1)</td>
<td>8.9 ± 0.1 ± 0.5</td>
<td>44 ± 1 ± 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 \( E_T^{miss} \) calculation, and the resulting uncertainty in the latter is included in uncertainties given above. Uncertainties in the pile-up simulation, affecting in particular \( E_T^{miss} \), 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 \( E_T^{miss} \), 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 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 \( E_T^{miss} \) 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 \( E_T^{miss} \) 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 \( BR(H \rightarrow inv.) = 1 \). 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 \( E_T^{miss} \) distribution following the CLs (signal confidence level) modified frequentist formalism [57] with a profile likelihood test statistic [58]. Figure 3 shows the 95% C.L. upper limits on \( \sigma ZH \times BR(H \rightarrow inv.) \) 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 \( BR(H \rightarrow inv.) = 1 \) 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 $BR(H \rightarrow \text{inv.})$ 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 $BR(H \rightarrow \text{inv.})$ 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 $E_T^{\text{miss}}$ 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; DNRF, 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; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, 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; NII, 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), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, 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; NII, 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), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

---

**FIG. 4** (color online). Limits on the DM-nucleon scattering cross section at 90% C.L., extracted from the $BR(H \rightarrow \text{inv.})$ limit in a Higgs-portal scenario, compared to results from direct-search experiments [63–70]. Cross-section limits and favored regions correspond to a 90% C.L., unless stated otherwise in the legend. Favored regions for DAMA and CoGeNT are based on Ref. [68]. The results from the direct-search experiments do not depend on the assumptions of the Higgs-portal scenario.

---

[45] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the $z$ axis along the beam pipe. Polar coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity $\eta$ is defined in terms of the polar angle $\theta$ as $\eta = - \ln(\tan(\theta/2))$, and $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.  

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

Institute 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, Humboldt 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 (UFSJ), 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 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 Maria, 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

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
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York, New York, USA
Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
INFN Sezione di Pavia, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
Departamento de Física, Universidade do Minho, Braga, Portugal
Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Dep Fisica and CEFITEC of Facultad de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina, Saskatchewan, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma I, Italy
Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Italy
Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, 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-Agdal, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
139 Department of Physics, University of Washington, Seattle, Washington, USA
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
144 SLAC National Accelerator Laboratory, Stanford, California, USA
145 Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
146 Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
147 Department of Physics, University of Cape Town, Cape Town, South Africa
148 Department of Physics, University of Johannesburg, Johannesburg, South Africa
149 School of Physics, University of the Witwatersrand, Johannesburg, South Africa
150 The Oskar Klein Centre, Stockholm, Sweden
151 Physics Department, Royal Institute of Technology, Stockholm, Sweden
152 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
153 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
154 School of Physics, University of Sydney, Sydney, Australia
155 Institute of Physics, Academia Sinica, Taipei, Taiwan
156 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
157 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
158 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
159 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
160 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
161 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
162 Department of Physics, University of Toronto, Toronto, Ontario, Canada
163 TRIUMF, Vancouver, British Columbia, Canada
164 Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
165 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
166 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
167 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
168 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
169 INFN Gruppo Collegato di Udine, Italy
170 ICTP, Trieste, Italy
171 Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
172 Department of Physics, University of Illinois, Urbana, Illinois, USA
173 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
174 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMM), University of Valencia and CSIC, Valencia, Spain
175 Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
176 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
177 Department of Physics, University of Warwick, Coventry, United Kingdom
178 Waseda University, Tokyo, Japan
179 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
180 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
181 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
182 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
183 Department of Physics, Yale University, New Haven, Connecticut, USA
184 Yerevan Physics Institute, Yerevan, Armenia
185 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

\textsuperscript{a} Deceased.
\textsuperscript{b} Also at Department of Physics, King’s College London, London, United Kingdom.
\textsuperscript{c} Also at Physics Department, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
\textsuperscript{d} Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
\textsuperscript{e} Also at TRIUMF, Vancouver, British Columbia, Canada.
\textsuperscript{f} Also at Department of Physics, California State University, Fresno, CA, USA.
\textsuperscript{g} Also at Novosibirsk State University, Novosibirsk, Russia.
\textsuperscript{h} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
\textsuperscript{i} Also at Università di Napoli Parthenope, Napoli, Italy.
\textsuperscript{j} Also at Institute of Particle Physics (IPP), Canada.