Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment

Aaboud, M.; Aad, G.; Abbott, B.; Abdinov, O.; Abeloos, B; Abidi, S.H.; Abouzeid, Ossama Sherif Alexander; Abraham, NL; Abramowicz, H.; Abreu, H.; Abulaiti, Y.; Acharya, B.S.; Adachi, Sosuke; Adamczyk, L.; Adelman, J.; Adersberger, M.; Adye, T.; Affolder, A. A.; Afik, Y.; Agheorghiesei, C.; Aguilar-Saavedra, J. A.; Ahlen, S. P.; Ahmadov, F.; Aielli, G.; Hansen, Jørn Dines; Hansen, Jørgen Beck; Dam, Mogens; Xella, Stefania; Hansen, Peter Henrik; Petersen, Troels Christian; Alonso Diaz, Alejandro; Monk, James William; Wiglesworth, Graig; Stark, Simon Holm; Besjes, Geert-Jan; Bajic, Milena; Thiele, Fabian Alexander Jürgen; de Almeida Dias, Flavia; Galster, Gorm Aske Gram Krohn

Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.120.211802

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment

M. Aaboud et al.∗ (ATLAS Collaboration)

(Received 14 February 2018; published 22 May 2018)

A direct search for the standard model Higgs boson decaying to a pair of charm quarks is presented. Associated production of the Higgs and Z bosons, in the decay mode ZH → ℓ⁺ ℓ⁻ c ¯c is studied. A data set with an integrated luminosity of 36.1 fb⁻¹ of pp collisions at √s = 13 TeV recorded by the ATLAS experiment at the LHC is used. The H → c ¯c signature is identified using charm-tagging algorithms. The observed (expected) upper limit on σ(pp → ZH) × B(H → c ¯c) is 2.7 (3.9 ± 1.1) pb at the 95% confidence level for a Higgs boson mass of 125 GeV, while the standard model value is 26 fb.

DOI: 10.1103/PhysRevLett.120.211802

In July 2012, the ATLAS and CMS collaborations announced the discovery of a new particle with a mass of approximately 125 GeV [1,2] in searches for the standard model (SM) Higgs boson at the Large Hadron Collider (LHC) [3]. Subsequent measurements indicate that this particle is consistent with the SM Higgs boson [4–10]. Direct evidence for the Yukawa coupling of the Higgs boson to the top [11] and bottom [12,13] quarks was recently obtained. Measurements of the Yukawa coupling of the Higgs boson to quarks in generations other than the third are difficult at hadron colliders, due to small branching fractions, large backgrounds, and challenges in jet flavor identification [14,15]. This Letter presents a direct search by the ATLAS experiment for the decay of the Higgs boson to a pair of charm (c) quarks. This search targets the production of the Higgs boson in association with a Z boson decaying to charged leptons: Z(ℓ⁺ ℓ⁻)H(c ¯c), where ℓ = e, μ.

The SM branching fraction for a Higgs boson with a mass of 125 GeV to decay to a pair of charm quarks is predicted to be 2.9% [16]. The inclusive cross section for σ(pp → ZH) × B(H → c ¯c) is 26 fb at √s = 13 TeV [17]. Rare exclusive decays of the Higgs boson to a light vector meson or quarkonium state and a photon can also probe the couplings of the second-generation quarks to the Higgs boson [18–21]. Previously, the ATLAS Collaboration presented an indirect search for the decay of the Higgs boson to c quarks via the decay to J/ψγ, obtaining a branching fraction limit of 1.5 × 10⁻³ at the 95% confidence level (C.L.), which approximately corresponds to a limit of 540 times the SM branching fraction prediction [14,20]. Bounds on the Higgs boson branching fractions to unobserved final states and fits to global rates constrain B(H → c ¯c) < 20% at the 95% C.L., assuming SM production cross sections [22]. These limits can still accommodate large modifications to the Higgs boson coupling to charm quarks from new physics [22]. In this Letter, a new approach is introduced to investigate the coupling of the Higgs boson to charm quarks.

The search is performed using pp collision data recorded in 2015 and 2016 with the ATLAS detector [23] at √s = 13 TeV. The ATLAS detector at the LHC covers nearly the entire solid angle around the collision point [24]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets. An additional pixel layer was installed for the √s = 13 TeV running period [25]. After the application of beam, detector, and data-quality requirements, the integrated luminosity corresponds to 36.1 ± 0.8 fb⁻¹, measured following Ref. [26]. Events are required to contain exactly two same-flavor leptons with an invariant mass consistent with that of the Z boson, and at least two jets of which one or two are identified as charm jets (c jets). In this Letter, lepton refers to only electrons or muons. The analysis procedure is validated by measuring the yield of ZW and ZZ production, where the sample is enriched in W → cs, cd and Z → c ¯c decays. Further details can be found in Ref. [12].

Monte Carlo (MC) simulated samples were produced for signal and background processes using the full ATLAS detector simulation [27] using GEANT4 [28]. Table I provides details of the event generators used for each signal and background sample. Signal events were produced at next-to-leading order (NLO) for the q ¯q → ZH process and at leading order (LO) for the gg → ZH process with POWHEG-BOX v2 [32]. The dominant Z + jets background and the resonant diboson ZW and ZZ processes were generated using SHERPA 2.2.1 [54]. The H background was

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TABLE I. The configurations used for event generation of the signal and background processes. If two parton distribution functions (PDFs) are shown, the first is for the matrix element calculation and the second for the parton shower, otherwise the same is used for both. Alternative event generators and configurations, used to estimate systematic uncertainties, are in parentheses. Tune refers to the underlying-event tuned parameters of the parton shower event generator. MG5_AMC refers to MadGraph5_AMC@NLO 2.2.2 [29]; PYTHIA 8 refers to version 8.212 [30]. Heavy-flavor hadron decays modeled by EvGen 1.2.0 [31] are used for all samples except those generated using SHERPA. The order of the calculation of the cross sections used to normalize the predictions is indicated. The $q\bar{q} \to ZH$ cross section is estimated by subtracting the $gg \to ZH$ cross section from the $pp \to ZH$ cross section. The asterisk (*) in the last column denotes that the indicated order is for the $pp \to ZH$ cross section. NNLO denotes next-to-next-to-leading order; NLL denotes next-to-leading log and NNLL denotes next-to-next-to-leading log.

<table>
<thead>
<tr>
<th>Process</th>
<th>Event Generator (alternative)</th>
<th>Parton Shower (alternative)</th>
<th>PDF (alternative)</th>
<th>Tune</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \to ZH$</td>
<td>POWHEG-BOX v2 [32] +GoSAM [35] +MiNLO [45,46]</td>
<td>PYTHIA 8</td>
<td>PDF4LHC15NLO [33] /CTEQ6L1 [36,37]</td>
<td>AZNLO [34]</td>
<td>NNLO (QCD)*+NLO (EW) [38–44]</td>
</tr>
<tr>
<td>$gg \to ZH$</td>
<td>POWHEG-BOX v2</td>
<td>PYTHIA 8 (HERWIG 7 [47])</td>
<td>PDF4LHC15NLO /CTEQ6L1</td>
<td>AZNLO (A14 [48])</td>
<td>NLO+NLL (QCD) [17–51]</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>POWHEG-BOX v2</td>
<td>PYTHIA 8 (HERWIG 7)</td>
<td>NNPDF3.0NNLO /NNPDF2.3LO</td>
<td>A14</td>
<td>NNLO + NLL [53]</td>
</tr>
<tr>
<td>$ZW, ZZ$</td>
<td>SHERPA 2.2.1 [54] (POWHEG-BOX)</td>
<td>SHERPA (PYTHIA 8)</td>
<td>NNPDF3.0NNLO /NNPDF2.3LO</td>
<td>SHERPA</td>
<td>NLO</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>SHERPA 2.2.1 (MG5_AMC)</td>
<td>SHERPA (PYTHIA 8)</td>
<td>NNPDF3.0NNLO /NNPDF2.3LO</td>
<td>SHERPA</td>
<td>NNLO [55]</td>
</tr>
</tbody>
</table>

generated using POWHEG-BOX v2. Backgrounds from single top and multijet production and the contribution from Higgs decays other than $b\bar{b}$ and $c\bar{c}$ are assessed to be negligible and not considered further. The Higgs boson mass is set to $m_H = 125$ GeV and the top-quark mass is set to 172.5 GeV.

Events are required to have at least one reconstructed primary vertex. Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter that are associated with charged-particle tracks reconstructed in the inner detector [56,57]. Muon candidates are reconstructed by combining inner detector tracks with muon spectrometer tracks or energy deposits in the calorimeters consistent with the passage of minimum-ionizing particles [58]. For data recorded in 2015, the single-electron (muon) trigger required a candidate with $p_T > 24(20)$ GeV; in 2016 the lepton $p_T$ threshold was raised to 26 GeV. Events are required to contain a pair of same-flavor leptons, both satisfying $p_T > 7$ GeV and $|\eta| < 2.5$. At least one lepton must have $p_T > 27$ GeV and correspond to a lepton that passed the trigger. The two leptons are required to satisfy loose track-isolation criteria with an efficiency greater than 99%. They are required to have opposite charge in dimuon events, but not in dielectron events due to the non-negligible charge misidentification rate of electrons. The invariant mass of the dilepton system is required to be consistent with the mass of the Z boson: 81 GeV $< m_{\ell\ell} < 101$ GeV.

Jets are reconstructed from topological energy clusters in the calorimeters [59,60] using the anti-$k_t$ algorithm [61] with a radius parameter of 0.4 implemented in the FastJet package [62]. The jet energy is corrected using a jet-area-based technique [63,64] and calibrated [65,66] using $p_T$- and $\eta$-dependent correction factors determined from simulation, with residual corrections from internal jet properties. Further corrections from in situ measurements are applied to data. Selected jets must have $p_T > 20$ GeV and $|\eta| < 2.5$. Events are required to contain at least two jets. If a muon is found within a jet, its momentum is added to the selected jet. An overlap removal procedure resolves cases in which the same physical object is reconstructed multiple times, e.g. an electron also reconstructed as a jet.

![ATLAS Simulation](image-url)  

FIG. 1. The $c$-jet-tagging efficiency (colored scale) as a function of the $b$-jet and $l$-jet rejection as obtained from simulated $t\bar{t}$ events. The cross, labeled as working point, WP, denotes the selection criterion used in this analysis. The solid and dotted black lines indicate the contours in rejection space for the fixed $c$-tagging efficiency used in the analysis and two alternatives.
Jets in simulated events are labeled according to the presence of a heavy-flavor hadron with $p_T > 5$ GeV within $\Delta R = 0.3$ from the jet axis. If a $b$ hadron is found the jet is labeled as a $b$ jet. If no $b$ hadron is found, but a $c$ hadron is present, then the jet is labeled as a $c$ jet. Otherwise the jet is labeled as a light-flavor jet ($f$ jet).

Flavor-tagging algorithms exploit the different lifetimes of $b$, $c$, and light-flavor hadrons. A $c$-tagging algorithm is used to identify $c$ jets. Charm jets are particularly challenging to tag because $c$ hadrons have shorter lifetimes and decay to fewer charged particles than $b$ hadrons. Boosted decision trees are trained to obtain two multivariate discriminants: to separate $c$ jets from $f$ jets and $c$ jets from $b$ jets. The same variables used for $b$ tagging [67,68] are used. Figure 1 shows the selection criteria applied in the two-dimensional multivariate discriminant space, to obtain an efficiency of 41% for $c$ jets and rejection factors of 4.0 and 20 for $b$ jets and $f$ jets. The efficiencies are calibrated to data using $b$ quarks from $t \rightarrow Wb$ and $c$ quarks from $W \rightarrow cs$, $cd$ with methods identical to the $b$-tagging algorithms [67]. Statistical uncertainties in the simulation are reduced, by weighting events according to the tagging efficiencies of their jets, parametrized as a function of jet flavor, $p_T$, $\eta$ and the angular separation between jets, rather than imposing a direct requirement on the $c$-tagging discriminants.

Data are analyzed in four categories with different expected signal purities. The dijet invariant mass, $m_{c\bar{c}}$, constructed using the two highest-$p_T$ jets, is the discriminating variable in each category. Categories are defined using the transverse momentum of the reconstructed $Z$ boson, $p_T^Z$ (75 GeV $\leq p_T^Z < 150$ GeV and $p_T^Z \geq 150$ GeV) and the number of $c$ tags amongst the leading jets (either one or two). The $p_T^Z$ requirements exploit the harder $p_T^Z$ distribution in $ZH$ compared to $Z +$ jets production. Background events are rejected by requiring the angular separation between the two jets constituting the dijet system, $\Delta R_{c\bar{c}}$, to be less than 2.2, 1.5, or 1.3 for events satisfying $75 \leq p_T^Z < 150$ GeV, $150 \leq p_T^Z < 200$ GeV, or $p_T^Z \geq 200$ GeV. The signal acceptance ranges from 0.5% to 3.4% depending on the category. A joint binned maximum-profile-likelihood fit to $m_{c\bar{c}}$ in the categories is used to extract the signal yield and the $Z +$ jets background normalization. The fit uses 15 bins in each category within the range of 50 GeV $< m_{c\bar{c}} < 200$ GeV, with a bin width of 10 GeV. The parameter of interest, $\mu$, common to all categories, is the signal strength, defined as the ratio of the measured signal yield to the SM prediction.

Systematic uncertainties affecting the signal and background predictions include theoretical uncertainties in the signal and background modeling and experimental uncertainties. Table II shows their relative impact on the fitted value of $\mu$. Uncertainties in the $m_{c\bar{c}}$ shape of the backgrounds are assessed by comparisons between nominal and alternative event generators as indicated in Table I.

Systematic uncertainties are incorporated within the statistical model through nuisance parameters that modify the shape and/or normalization of the distributions. Statistical uncertainties in the simulation samples are accounted for. The $Z +$ jets background is normalized from the data through the inclusion of an unconstrained normalization parameter for each category. The fitted

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma/\sigma_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical</strong></td>
<td></td>
</tr>
<tr>
<td>Floating $Z +$ jets normalization</td>
<td>49%</td>
</tr>
<tr>
<td><strong>Systematic</strong></td>
<td></td>
</tr>
<tr>
<td>Flavor tagging</td>
<td>73%</td>
</tr>
<tr>
<td>Background modeling</td>
<td>47%</td>
</tr>
<tr>
<td>Lepton, jet and luminosity</td>
<td>28%</td>
</tr>
<tr>
<td>Signal modeling</td>
<td>28%</td>
</tr>
<tr>
<td>MC statistical</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table III. Postfit yields for the signal and background processes in each category from the profile likelihood fit. Uncertainties include statistical and systematic contributions. The prefit SM expected $ZH(c\bar{c})$ signal yields are indicated in parenthesis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$1 \ c \ tag$</th>
<th>$2 \ c \ tags$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$75 \leq p_T^Z &lt; 150$ GeV</td>
<td>$p_T^Z \geq 150$ GeV</td>
</tr>
<tr>
<td>$Z +$ jets</td>
<td>69400 $\pm$ 500</td>
<td>15650 $\pm$ 180</td>
</tr>
<tr>
<td>$ZW$</td>
<td>750 $\pm$ 130</td>
<td>290 $\pm$ 50</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>490 $\pm$ 70</td>
<td>180 $\pm$ 28</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>2020 $\pm$ 280</td>
<td>130 $\pm$ 50</td>
</tr>
<tr>
<td>$ZH(b\bar{b})$</td>
<td>32 $\pm$ 2</td>
<td>19.5 $\pm$ 1.5</td>
</tr>
<tr>
<td>$ZH(c\bar{c})$ (SM)</td>
<td>$-143 \pm 170$ (2.4)</td>
<td>$-84 \pm 100$ (1.4)</td>
</tr>
<tr>
<td>Total</td>
<td>72500 $\pm$ 320</td>
<td>16180 $\pm$ 140</td>
</tr>
<tr>
<td>Data</td>
<td>72504</td>
<td>16181</td>
</tr>
</tbody>
</table>
The ATLAS Collaboration, using a modified frequentist CLs method [69,70] to account for relative variations between categories, has observed and predicted $m_{c\bar{c}}$ distributions in the 2 c-tag analysis categories. The expected signal is scaled by a factor of 100. Backgrounds are corrected to the results of the fit to the data. The predicted background from the simulation is shown as red dashed histograms. The ratios of the data to the fitted background are shown in the lower panels. The error bands indicate the sum in quadrature of the statistical and systematic uncertainties in the background prediction.

Normalization parameters range between 1.13 and 1.30. All other background normalization factors are correlated between categories, with acceptance uncertainties of order 10% to account for relative variations between categories.

The dominant contributions to the uncertainty in $\mu$ are the efficiency of the tagging algorithms, the jet energy scale and resolution, and the background modeling. The largest uncertainty is due to the normalization of the dominant $Z +$ jets background. The typical uncertainty in the tagging efficiency is 25% for $c$ jets, 5% for $b$ jets, and 20% for $l$ jets.

Table III shows the fitted signal and background yields. The $m_{c\bar{c}}$ distributions in the 2 c tag categories are shown in Fig. 2 with the background shapes and normalizations according to the result of the fit. Good agreement is observed between the postfit shapes of the distributions and the data.

The analysis procedure is validated by measuring the yield of $ZV$ production, where $V$ denotes a $W$ or $Z$ boson, with the same event selection. The fraction of the $ZZ$ yield from $Z \to c\bar{c}$ decays is $\sim 55\%$ ($20\%$) in the 2 c tag (1 c tag) category, while the fraction of the $ZW$ yield from $W \to cs$, $cd$ is $\sim 65\%$ for both the 2 and 1 c tag categories. Contributions of Higgs boson decays to $cc$ and $bb$ are treated as background and constrained to the SM predictions within their theoretical uncertainties. The diboson signal strength is measured to be $\mu_{ZV} = 0.6^{+0.3}_{-0.5}$ with an observed (expected) significance of 1.4 (2.2) standard deviations.

The best-fit value for the $ZH(c\bar{c})$ signal strength is $\mu_{ZH} = -69 \pm 101$. By assuming a signal with the kinematics of the SM Higgs boson, model-dependent corrections are made to extrapolate to the inclusive phase space. Hence, an upper limit on $\sigma(pp \to ZH) \times B(H \to c\bar{c})$ is computed using a modified frequentist CLs method [69,70] with the profile likelihood ratio as the test statistic. The observed (expected) upper limit is found to be $2.7 (3.9^{+2.1}_{-1.1})$ pb at the 95% C.L. This corresponds to an observed (expected) upper limit on $\mu$ at the 95% C.L. of $110 (150^{+80}_{-40})$. The uncertainties in the expected limits correspond to the $\pm 1\sigma$ interval of background-only pseudoexperiments. With the current sensitivity, the result depends weakly on the assumption of the SM rate for $H \to bb$. The observed limit remains within 5% of the nominal value when the assumed value for normalization of the $ZH(bb)$ background is varied from zero to twice the SM prediction.

A search for the decay of the Higgs boson to charm quarks has been performed using 36.1 fb$^{-1}$ of data collected with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 13$ TeV at the LHC. No significant excess of $ZH(c\bar{c})$ production is observed over the SM background expectation. The observed upper limit on $\sigma(pp \to ZH) \times B(H \to c\bar{c})$ is 2.7 pb at the 95% C.L. The corresponding expected upper limit is $3.9^{+2.1}_{-1.1}$ pb. This is the most stringent limit to date in direct searches for the inclusive decay of the Higgs boson to charm quarks.

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; BMWFW 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,


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ATLAS Collaboration, Search for Higgs and $Z$ Boson Decays to $\phi\gamma$ with the ATLAS Detector, Phys. Rev. Lett. 117, 111802 (2016).


ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of $\eta$. 

$\eta = \ln \left( \frac{1 + \tan(\theta/2)}{1 - \tan(\theta/2)} \right)$, where $\theta$ is the polar angle.
the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.


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Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
Department of Physics, 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
National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
University Politehnica Bucharest, Bucharest, Romania
University Politehnica Bucharest, Bucharest, Romania
Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China
School of Physics, Shandong University, Shandong, China
Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
Department of Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departmento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Physics, Nanjing University, Jiangsu, China
Physics Department, Tsinghua University, Beijing, China
University of Chinese Academy of Science (UCAS), Beijing, China
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
Department of Physics, Indiana University, Bloomington, Indiana, USA
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Physics, Tsinghua University, Beijing, China
University of Chinese Academy of Science (UCAS), Beijing, China
Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
Department of Physics, The University of Hong Kong, Hong Kong, China
Department of Physics, The University of Hong Kong, Hong Kong, China
Physics Department, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
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
67 Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
68 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
69 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
70 Graduate School of Science, Kobe University, Kobe, Japan
71 Faculty of Science, Kyoto University, Kyoto, Japan
72 Kyoto University of Education, Kyoto, Japan
73 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
74 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
75 Physics Department, Lancaster University, Lancaster, United Kingdom
76 INFN Sezione di Lecce, Lecce, Italy
77 Facoltà di Matematica e Fisica, Università del Salento, Lecce, Italy
78 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
79 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
80 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
81 Department of Physics and Astronomy, University College London, London, United Kingdom
82 Louisiana Tech University, Ruston, Louisiana, USA
83 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
84 Fysiska institutionen, Lunds universitet, Lund, Sweden
85 Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
86 Institut für Physik, Universität Mainz, Mainz, Germany
87 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
88 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
89 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
90 Department of Physics, McGill University, Montreal, Québec, Canada
91 School of Physics, University of Melbourne, Victoria, Australia
92 Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
93 Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
94 INFN Sezione di Milano, Milano, Italy
95 Dipartimento di Fisica, Università di Milano, Milano, Italy
96 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
97 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
98 Group of Particle Physics, University of Montreal, Montreal, Québec, Canada
99 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
100 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
101 National Research Nuclear University MEPhI, Moscow, Russia
102 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
103 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
104 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
105 Nagasaki Institute of Applied Science, Nagasaki, Japan
106 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
107 INFN Sezione di Napoli, Napoli, Italy
108 Dipartimento di Fisica, Università di Napoli, Napoli, Italy
109 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
110 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
111 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
112 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
113 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
114 Department of Physics, New York University, New York, New York, USA
115 The Ohio State University, Columbus, Ohio, USA
116 Faculty of Science, Okayama University, Okayama, Japan
117 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
118 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
119 Palacký University, RCPTM, Olomouc, Czech Republic
120 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
121 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
122 Graduate School of Science, Osaka University, Osaka, Japan
123 Department of Physics, University of Oslo, Oslo, Norway
124 Department of Physics, Oxford University, Oxford, United Kingdom
INFN-TIFPA, Trento, Italy
University of Trento, Trento, Italy

TRIUMF, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy

Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
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, Spain
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan

Department of Particle Physics, The 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
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Department of Physics, Yale University, New Haven, Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

"Deceased.
Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at TRIUMF, Vancouver, British Columbia, Canada.
Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.
Also at Physics Department, An-Najah National University, Nablus, Palestine.
Also at Department of Physics, California State University, Fresno, CA, USA.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.
Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
Also at 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 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Borough of Manhattan Community College, City University of New York, New York City, NY, USA.
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 Louisiana Tech University, Ruston, LA, USA.
Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
Also at Graduate School of Science, Osaka University, Osaka, Japan.
Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.
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 Georgian Technical University (GTU), Tbilisi, Georgia.
Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.