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Search for type-III Seesaw heavy leptons in $pp$ collisions at $\sqrt{s} = 8 \text{ TeV}$ with the ATLAS Detector

The ATLAS Collaboration

Abstract

A search for the pair-production of heavy leptons ($N^0, L^\pm$) predicted by the type-III seesaw theory formulated to explain the origin of small neutrino masses is presented. The decay channels $N^0 \to W^\pm \ell^\mp (\ell = e, \mu, \tau)$ and $L^\pm \to W^\pm \nu (\nu = \nu_e, \nu_\mu, \nu_\tau)$ are considered. The analysis is performed using the final state that contains two leptons (electrons or muons), two jets from a hadronically decaying $W$ boson, and large missing transverse momentum. The data used in the measurement correspond to an integrated luminosity of 20.3 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV collected by the ATLAS detector at the LHC. No evidence of heavy lepton pair-production is observed. Heavy leptons with masses below 325–540 GeV are excluded at the 95% confidence level, depending on the theoretical scenario considered.
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INTRODUCTION

Experiments show that neutrinos have much smaller masses than charged leptons (see Ref. [1], and references therein). While in the Standard Model (SM) the charged fermions acquire masses by coupling to the Higgs \((H)\) boson, the neutrinos may become massive via new physics beyond the SM, e.g. via the introduction of Majorana mass terms [2]. These masses could be small due to the seesaw mechanism [3, 4], which relies on new massive states that couple to a charged lepton and the Higgs field. Among different models for the seesaw mechanism, the type-III model [2, 5] introduces at least two extra triplets of fermionic fields with zero hypercharge in the adjoint representation of \( \text{SU}(2)_L \) that generate neutrino masses and couple to gauge bosons. This model predicts new charged and neutral heavy leptons that could be produced in proton-proton collisions at the Large Hadron Collider (LHC).

A search by the CMS experiment [6] excluded the type-III seesaw heavy leptons with masses in the range of 100-210 GeV, depending on theoretical assumptions. A recent search by ATLAS [7] also sets complementary limits on heavy leptons using the three-lepton final state. Similar searches have also been done by L3 experiment [8] ruling out charged heavy leptons with masses below 100 GeV.

In this paper, a search for heavy leptons predicted by the type-III seesaw mechanism is presented. The search exploits the mass region above 100 GeV. A minimal type-III seesaw model [9] is used to optimize the analysis strategy and interpret the search results. The model introduces a triplet with one neutral and two oppositely-charged leptons denoted by \( N^0 \) and \( L^\pm \), respectively. The heavy leptons decay into a SM lepton and a \( W, Z \) or Higgs boson. The heavy leptons are assumed to be degenerate in mass. This assumption does not affect the result because in the case of a small mass splitting due to radiative corrections, the decays within the heavy leptons are highly suppressed [10]. The dominant production mechanism for type-III seesaw heavy leptons in \( pp \) collisions is pair-production through the weak coupling to the \( W \) boson propagator: \( pp \to W^* \to N^0L^\pm \), and the largest branching fraction is the one with two \( W \) bosons in the final state: \( N^0 \to W^\pm l^\mp (l = e, \mu, \tau) \) and \( L^\pm \to W^\pm \nu (\nu = \nu_e, \nu_\mu, \nu_\tau) \). The production cross-section does not depend on the branching fraction between the SM leptons and the new heavy lepton states \( V_\alpha, (\alpha = e, \mu, \tau) \), which enter only in the expressions for the \( L \) and \( N \) decay widths.

The fraction of \( L \) and \( N \) decays to lepton flavor \( \alpha \) is proportional to \( b_\alpha = |V_\alpha|^2/(|V_e|^2 + |V_\mu|^2 + |V_\tau|^2) \). The limits obtained may be interpreted in terms of a range of mixing angles and Yukawa couplings [9], allowing tests of a range of models with different couplings to gauge bosons and cross-section predictions [11, 12]. In the type-III seesaw model considered here, a benchmark point is defined by setting \( V_\tau \) to zero, so that \( b_e = 0.53 \), \( b_\mu = 0.43 \) and \( b_\tau = 0 \). The search is performed for the process \( pp \to N^0L^\pm \to W^\pm l^\mp W^\pm \nu \), where one \( W \) boson decays leptonically and the other \( W \) boson decays hadronically, resulting in a lepton pair in the final state with either the same charge (same-sign, SS) or with the opposite charge (opposite-sign, OS).

DATA SAMPLE AND MONTE CARLO SIMULATION

The analysis uses data from \( \sqrt{s} = 8 \) TeV \( pp \) collisions at the LHC that were recorded by the ATLAS detector using single-electron and single-muon triggers. A detailed description of the ATLAS detector can be found elsewhere [10]. The data sample corresponds to 20.3 ± 0.6 fb\(^{-1}\) of integrated luminosity. Data quality criteria are applied to ensure that events were recorded with stable beam conditions and with all relevant sub-
detector systems operational. The triggers are fully efficient for leptons with $p_T > 25$ GeV, where transverse momentum $p_T$ is defined as the magnitude of the momentum component orthogonal to the beam axis. Events are required to have a reconstructed collision vertex with at least three associated tracks, each with $p_T > 400$ MeV. In events with multiple vertices, the vertex with the largest $\sum p_T^2$ of associated tracks is taken as the primary event vertex.

Monte Carlo (MC) samples are used to optimize the event selection and to model the kinematics and normalization of most background processes. Signal samples are generated for heavy lepton masses in the range 100–600 GeV. MadGraph 5 is used to calculate the matrix elements for each process, while MadEvent with the MSTW2008 parton distribution functions (PDF) set simulates the initial hard scattering and the N and L decay. Pythia 8.153 is used to simulate the decays of $W$ bosons and the underlying physics by providing parton showers and hadronization, as well as adding initial- and final-state radiation (ISR and FSR) to the events simulated in MadEvent. The main background sources arise from the production of a $Z$ boson in association with jets ($Z$+jets), single and pair-production of top quarks, and diboson production ($WW, WZ, ZZ$). The $Z$+jets and diboson processes are simulated with SHERPA 1.4.1, a generator based on a multileg matrix element calculation matched to the parton shower using the CKKW prescription, and using the CT10 PDF set. For diboson production, both the electroweak and strong production processes are simulated. Top-quark pair events and single-top-quark events in the $Wt$-channel are simulated using MadGraph with the CTEQ6L1 PDF set, interfaced to Pythia 6.520 and using MC@NLO 4.03, which is interfaced to Herwig 6.520 and Jimmy 4.31 with the CT10 PDF set. Top pair production in association with a vector boson, $t\bar{t} + W/Z$, is simulated using MadGraph with the CTEQ6L1 PDF set, interfaced to Pythia 8.153 for parton showering and hadronization. Single top quark production in the $t$-channel is simulated using AcerMC v3.8 with Pythia 6.426 and the CTEQ6L1 PDF set.

All samples of simulated events include the effect of multiple $pp$ interactions in the same and neighboring bunch crossings (pileup) by overlaying simulated minimum-bias events on each generated signal and background event. The number of overlaid events is chosen to match the average number of interactions per $pp$ bunch crossing observed in the data as it evolved throughout the data-taking period (giving an average of 21 interactions per crossing for the whole data-taking period). The generated samples are processed through the GEANT4-based detector simulation or a fast simulation using a parameterization of the performance of the calorimetry and GEANT4 for the other parts of the detector. The standard ATLAS reconstruction software is used for both simulated and collision data.

**OBJECT DEFINITIONS**

The reconstructed objects used in this analysis are electrons, muons, jets, and missing transverse momentum. Electrons are reconstructed from clusters of energy depositions in the calorimeter that match a track reconstructed in the inner detector (ID) and satisfy the “tight” criteria defined in Ref. The electrons are required to have $p_T > 25$ GeV and pseudorapidity $|\eta| < 2.47$, excluding the transition region between the barrel and endcaps in the liquid argon calorimeter ($1.37 < |\eta| < 1.52$). Muons are reconstructed by combining ID and and muon spectrometer tracks that are spatially matched and have consistent curvatures. The muon tracks are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. In addition, leptons are required to be isolated from other tracks and calorimetric activity. To ensure that leptons originate from the interaction point, requirements of $|d_0|/\sigma_{d_0} < 3$ and $|z_0\sin\theta| < 0.5$ mm are imposed on the electrons and muons, where $d_0$ is the transverse (longitudinal) impact parameter of the lepton, and $\sigma_{d_0}$ is the uncertainty on the measured $d_0$. The lepton impact parameters are measured with respect to the event primary vertex.

Jets are reconstructed from three-dimensional topological clusters of energy depositions in the calorimeter using the anti-$k_T$ algorithm with a radius parameter of $R = 0.4$. The energies of jets are calibrated to the hadronic energy scale by correcting for energy losses in passive material, the non-compensating response of the calorimeter, and extra energy due to multiple $pp$ interactions. The jets are required to have $p_T > 30$ GeV and $|\eta| < 2.8$. For jets with $p_T < 50$ GeV and $|\eta| < 2.4$, the summed scalar $p_T$ of associated tracks from the reconstructed primary vertex is required to be at least 25% of the summed scalar $p_T$ of all tracks associated with the jet. In the pseudorapidity range $|\eta| < 2.5$, jets containing $b$-hadrons are identified using a $b$-tagging algorithm with an efficiency of 70% and with a misidentification rate for selecting light-quark or gluon jets of less than 1%. The identification efficiency of the algorithm for jets containing $c$-hadrons is 20%. The efficiencies and misidentification rates are determined from $t\bar{t}$ MC events.

The missing transverse momentum vector (with its magnitude $E_{T\text{miss}}$) is derived using the calorimeter cell energies within $|\eta| < 4.9$ and corrected on the basis of dedicated calibrations of the associated physics objects including muons. Calorimeter cells containing energy depositions above noise and not associated with high-$p_T$ physics objects are also included.
EVENT SELECTION

Events that contain exactly two reconstructed leptons (electrons or muons), at least two jets, and no b-tagged jets are selected. One of these leptons is required to match the object upon which the event was triggered. Different sets of optimized selection criteria are used for the events in the OS and SS final states. The optimization is done using simulated heavy lepton pair-production events at a benchmark mass of 300 GeV. For the OS (SS) final state, the leading and next-to-leading lepton candidates are required to have $p_T$ greater than 100 (70) GeV and 25 (40) GeV, respectively. The invariant mass of the two lepton candidates is required to be larger than 130 (90) GeV in order to suppress background from the production of $Z$+jets. The hadronically decaying $W$ candidate is formed by combining the two jets with highest $p_T$, and the $p_T$ of the first and second leading jets are respectively required to be larger than 60 (40) and 30 (25) GeV, for the OS (SS) final state. The invariant mass of the $W$ candidate, $m_{jj}$, is required to be between 60 and 100 GeV. Events selected in the OS (SS) final state are required to have a $E_T^{miss}$ of at least 110 (100) GeV and, for OS events, an angular separation $\Delta R_{jj} = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 2$ between the two jets with highest $p_T$, where $\Delta \eta$ and $\Delta \phi$ are defined as the differences in pseudorapidity and azimuthal angle between the jets.

BACKGROUND ESTIMATE

The background in this search can be classified into two categories based on the origin of the charged lepton candidates. The first category of backgrounds consists of events in which two leptons are produced via the decays of $W$ or $Z$ bosons and are correctly reconstructed. This category of backgrounds includes the production of $Z$+jets, $t\bar{t}$, $Wt$ single-top-quark and diboson events. Smaller contributions originate from $tt + W/Z$ events. Contributions from triboson events, such as $WWW$, and events containing a Higgs boson, are negligible. The number of events from this background category is estimated using the simulated samples described previously.

The second category corresponds to all other sources, such as events containing at least one particle that is incorrectly identified as a lepton, or a lepton which originates from secondary interactions and decays, which are together denoted as fakes, and events with a lepton whose charge is incorrectly determined. Fake electrons originate primarily from jets that have a large electromagnetic energy fraction passing the electron selection requirements, photon conversions, and electrons from semileptonic decays of charm or bottom hadrons. Fake muons include muons arising from semileptonic decays of charm or bottom hadrons, in-flight decays of pions or kaons, or energetic particles that reach the muon spectrometer.

For the OS final state, the background contribution is dominated by events from the first category. For the SS final state, the expected background is very small and is also primarily from the first category. Events from $Z$+jets production can mimic the SS signal if the charge of one of the electrons is incorrectly determined. The background events from this contribution are modeled by simulation, with correction factors derived using $Z \rightarrow ee$ events in data. The probability of misidentifying the muon charge is negligible.

The background contribution in the second category (i.e. fake leptons) is estimated using an in situ technique [38] that relies minimally on simulation. This is done by reweighting a complementary set of events, selected by changing the electron identification criterion from “tight” to “loose” [33] and by loosening the muon $|d_{xy}|/\sigma_{xy}$ and the electron and muon isolation requirements, while keeping the event selection otherwise identical. The reweighting factors are defined as the ratio of the number of events containing a lepton that satisfies the nominal criteria to the number of events containing a lepton that only fulfill the relaxed criteria. These factors are measured as a function of the candidate $p_T$ and $\eta$ in data samples that are enriched in fake leptons [38]. Corrections to the factors due to true leptons from vector boson decay in the background-enriched samples are taken from MC simulation.

Figure 1 shows a comparison of the missing transverse momentum distribution of data, expected backgrounds and signal predictions when all the selection requirements, except for the missing transverse momentum requirement, are applied. The shape and the rate of the background estimate is in good agreement with the data.

The background estimates are validated by comparing the predicted numbers of events in simulation to those observed in data in several control regions that have event selection criteria similar to those for the signal region.

The control region for top quark pairs is defined by

<table>
<thead>
<tr>
<th>Event Type</th>
<th>OS</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake Leptons</td>
<td>1.4 ± 0.9</td>
<td>0.67 ± 0.42</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>2.4 ± 1.2</td>
<td>0.06 ± 0.23</td>
</tr>
<tr>
<td>$WW/WZ/ZZ$</td>
<td>9.2 ± 2.9</td>
<td>1.95 ± 0.58</td>
</tr>
<tr>
<td>$t\bar{t}$ (+$W/Z$) and single top</td>
<td>17.9 ± 6.9</td>
<td>0.47 ± 0.25</td>
</tr>
<tr>
<td>Total</td>
<td>31.0 ± 7.7</td>
<td>3.15 ± 0.80</td>
</tr>
<tr>
<td>Data</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>Signal $m_{L/N} = 150$ GeV</td>
<td>9.5 ± 1.6</td>
<td>20.3 ± 2.3</td>
</tr>
<tr>
<td>Signal $m_{L/N} = 300$ GeV</td>
<td>12.2 ± 0.6</td>
<td>5.7 ± 0.5</td>
</tr>
</tbody>
</table>

TABLE I. Event yields for opposite-sign (OS) and same-sign (SS) selection for predicted backgrounds, data, and type-III seesaw lepton pair-production with masses of 150 and 300 GeV. The reported errors include both the statistical and systematic uncertainties.
selecting events with two $b$-tagged jets. In this region, according to MC simulation, all the events are from top quark pair and single top quark production with a negligible contribution from other sources. MC simulation predicts $26 \pm 3$ (stat.) events and in data 32 events are observed. The scale factor, the ratio of the observed and predicted event yields, is found to be consistent with unity.

The diboson control region is obtained using a $WZ$-enriched sample of events containing three leptons without a requirement on the missing transverse momentum. In this control region, according to MC simulation all the events are from diboson production with a negligible contribution from other sources. MC simulation predicts $11 \pm 1$ events and in data 9 events are observed. The scale factor is found to be consistent with unity.

**SYSTEMATIC UNCERTAINTIES**

The uncertainties on the rate of top quark and diboson backgrounds due to potential differences between data and MC simulation are evaluated using the statistical uncertainties of the measured scale factors in the control samples. They are the dominant systematic uncertainties ($\sim 35\%$) on the background estimates. For top quark production, an additional systematic uncertainty is considered to account for a potential difference between scale factors in the control region and the signal region. This is done by comparing the nominal $t\bar{t}$ sample to alterna-
tive $t\bar{t}$ MC samples. These samples include events that are generated using Powheg-Box 1.0 (patch 4) [44] [45] and the leading-order, multileg generator Alpgen v2.13 [46]. The Powheg-Box generator is interfaced to the Pythia 6.426 showering routines with either CT10 or HeraPDF [45] PDF sets and with the Powheg $h_{\text{amp}}$ parameter set to either the mass of the top quark or infinity [47]. Alpgen is interfaced to Herwig 6.520, and used to simulate top pair events with up to four additional partons in the matrix element. The uncertainties due to QCD ISR and FSR modeling are estimated with samples generated with AcerMC v3.8 interfaced to Pythia 6.426 in which the parton shower parameters are varied in a range consistent with a measurement of additional hadronic activity in $t\bar{t}$ events [50]. The differences observed in the signal region by using different MC simulations are about 35%.

For the $Z+n$-jets ($n\geq 2$) background estimate, the dominant systematic uncertainty in the OS final state is from the uncertainty on its production cross-section ($\sim 50\%$) [51]. For the SS final state, the systematic uncertainty is dominated by the statistical uncertainty on the measured electron charge misidentification rate. Uncertainties on the background estimate due to fake...
leptons are determined in dedicated studies using a combination of simulation and data. They account for potential biases in the method used to extract the reweighting factors, and for the dependency of the reweighting factors on the event topology.

For both the predicted signal and background event yields, uncertainties resulting from detector effects from jet energy scale and resolution [40], lepton reconstruction and identification efficiencies [50, 52], lepton momentum scales and resolutions [52, 53], and missing transverse momentum [52] are considered. They are typically small (1–5%). The theoretical uncertainties on the signal production cross-section and acceptance, such as PDF choice and ISR and FSR modeling, are found to be negligible.

The background estimates and their uncertainties are tested in two other regions: a Z+jets control region and the hadronic W sidebands. The Z+jets control region is selected by requiring the invariant mass of the oppositely-charged lepton pair to be consistent with the Z boson mass. In this region, approximately 70% of the events are from a Z boson produced in association with jets. The predicted number of events is 34 ± 4, where the error includes both the statistical and systematic uncertainties, and 32 events are observed in data. For the hadronic W sidebands, the analysis was repeated using the same event selection, but requiring the invariant mass of the hadronically decaying W candidate to be 35 < m_{WZ} < 60 GeV or 100 < m_{WZ} < 125 GeV. This selection provides samples dominated by background events with kinematic properties similar to those of the signal candidates. In this region the predicted number of events is 34 ± 7 events, where the error includes both the statistical and systematic uncertainties, and in data 18 events are observed. The data are in agreement with the predictions within 1.9 standard deviations.

RESULTS AND INTERPRETATION

Table I shows the predicted numbers of signal and background events and the observed data events in the signal region. The data agree with the background-only hypothesis. Figure 2 shows the flavor composition of the simulated signal and background events, and of the observed events in data. In the absence of any significant data excess, upper limits on the production rate of pp → N^0L^± → W^±l^±W^±ν at the 95% confidence level (C.L.) are derived as a function of the heavy lepton mass. The background estimates and their uncertainties are calculated for different theoretical assumptions, such as exclusive coupling between the heavy leptons and muons (b_e = 0, b_μ = 1) or electrons (b_e = 1, b_μ = 0 ). In the limit calculations for exclusive couplings, events in the two-muon (two-electron) final state are excluded for exclusive electron (muon) coupling. Heavy leptons with a mass below 400 (325) GeV can be ruled out by the data in the case of exclusive coupling to muons (electrons). Masses less than 540 (470) GeV are excluded in the scenario in which heavy leptons can only decay to the Wℓ or Wν final state.

CONCLUSIONS

A search for the pair-production of heavy leptons predicted by the type-III seesaw model is presented. The analysis is performed using a final state that contains two leptons, two jets from a hadronically decaying W boson, and large missing transverse momentum. The data used in the search correspond to an integrated luminosity of 20.3 fb^{-1} of pp collisions at √s = 8 TeV collected by the ATLAS detector at the LHC. No evidence of heavy lepton production is observed. Heavy leptons with masses below 325–540 GeV are excluded at the 95% confidence level, depending on the considered theoretical scenarios.

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References:

[26] Production mechanisms involving weak interactions at Born level (of order \( \alpha^2_{EW} \)) are referred to as electroweak production. Production mechanisms involving both the strong and electroweak interactions at Born level (of order \( \alpha^3_{EW} \)) are referred to as strong production.
[37] 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 upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \(\phi\) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \(\theta = -\ln \tan(\theta/2)\).
Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 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 Fisica La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
(a) INFN Sezione di Lecce; (b) 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 LA, United States of America
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 Fisica 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 MA, United States of America
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
(a) INFN Sezione di Milano; (b) 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 MA, United States of America
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University 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
(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
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 IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCP TM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
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
Also at Department of Physics, Stanford University, Stanford CA, United States of America

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

Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

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

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

* Deceased