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DOI
10.1103/PhysRevLett.114.072302

Publication date
2015

Document Version
Final published version

Published in
Physical Review Letters

Link to publication

Citation for published version (APA):

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Measurements of the Nuclear Modification Factor for Jets in Pb + Pb Collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)
(Received 10 November 2014; published 20 February 2015)

Measurements of inclusive jet production are performed in $pp$ and Pb + Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with the ATLAS detector at the LHC, corresponding to integrated luminosities of 4.0 and 0.14 nb$^{-1}$, respectively. The jets are identified with the anti-$k_t$ algorithm with $R = 0.4$, and the spectra are measured over the kinematic range of jet transverse momentum $32 < p_T < 500$ GeV and absolute rapidity $|y| < 2.1$ and as a function of collision centrality. The nuclear modification factor $R_{AA}$ is evaluated, and jets are found to be suppressed by approximately a factor of 2 in central collisions compared to $pp$ collisions. The $R_{AA}$ shows a slight increase with $p_T$ and no significant variation with rapidity.

Hard scattering rates are enhanced in more central collisions; the larger overlap results in a higher integrated luminosity of partons able to participate in hard scattering processes, and these hard scattering rates are expected to be proportional to the nuclear overlap function $T_{AA}$. The suppression is quantified by the nuclear modification factor

$$R_{AA} = \frac{1}{N_{\text{ext}} \, d^2N_{\text{jet}}}{d^2\sigma_{\text{jet}}}{d\eta \, dy}_{\text{central}}.$$ 

This Letter presents measurements of the inclusive jet $R_{AA}$ in Pb + Pb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\text{NN}}} = 2.76$ TeV. It utilizes Pb + Pb data collected during 2011 corresponding to an integrated luminosity of 0.14 nb$^{-1}$ as well as data from $pp$ collisions recorded during 2013 at the same center-of-mass energy corresponding to 4.0 pb$^{-1}$. Results are presented for jets reconstructed in the calorimeter with the anti-$k_t$ jet-finding algorithm [16] with jet radius parameter $R = 0.4$. The contribution of the underlying event (UE) to each jet, assumed to be uncorrelated and additive, was subtracted on a per-jet basis.

The measurements presented here were performed with the ATLAS calorimeter, inner detector, trigger, and data acquisition systems [17,18]. The calorimeter system consists of a liquid argon (LAr) electromagnetic calorimeter ($|\eta| < 3.2$), a steel-scintillator sampling hadronic calorimeter ($|\eta| < 1.7$), a LAr hadronic calorimeter ($1.5 < |\eta| < 3.2$), and a forward calorimeter (FCal) ($3.2 < |\eta| < 4.9$). Charged-particle tracks were measured over the range $|\eta| < 2.5$ using the inner detector [19], which is composed of silicon pixel detectors in the innermost layers, followed by silicon microstrip detectors and a strawtube transition-radiation tracker ($|\eta| < 2.0$), all immersed in a 2 T axial magnetic field. The zero-degree calorimeters

* Full author list given at the end of the article.
(ZDCs) are located symmetrically at $z = \pm 140$ m and cover $|\eta| > 8.3$. A ZDC coincidence trigger was defined by requiring a signal consistent with one or more neutrons in each of the calorimeters.

The $pp$ events used in the analysis were selected using the ATLAS jet trigger [20] with multiple values of the trigger $p_T$ thresholds. During $pp$ data taking, the average number of $pp$ interactions per bunch crossing (pile-up) varied from 0.3 to 0.6. The $pp$ events were required to contain at least one primary vertex, reconstructed from at least two tracks, and jets originating from all such vertices were included in the cross section measurement.

Data from $Pb + Pb$ collisions were recorded using either a minimum-bias trigger or a jet trigger. The minimum-bias trigger, formed from the logical OR of $ZDC$ coincidence criteria were applied [22] yielding 53 x 10$^6$ and 14 x 10$^6$ events in the minimum-bias and jet-triggered samples, respectively.

The centrality of $Pb + Pb$ collisions was characterized by $\Sigma E_T^{FCal}$, the total transverse energy measured in the FCal [22]. The centrality intervals were defined according to successive percentiles of the $\Sigma E_T^{FCal}$ distribution ordered from the most central (highest $\Sigma E_T^{FCal}$) to the most peripheral collisions. A Glauber model analysis of the $\Sigma E_T^{FCal}$ distribution was used to evaluate the $\langle T_{AA} \rangle$ and the number of nucleons participating in the collision, $\langle N_{part} \rangle$, in each centrality interval [22–24]. The centrality intervals used in this measurement are indicated in Table I along with the values of $\langle T_{AA} \rangle$ and $\langle N_{part} \rangle$ for those intervals.

### Table I. The $\langle T_{AA} \rangle$ and $\langle N_{part} \rangle$ values and their uncertainties in each centrality bin.

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>$\langle T_{AA} \rangle$ (mb$^{-1}$)</th>
<th>$\langle N_{part} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>23.45 ± 0.37</td>
<td>356.2 ± 2.5</td>
</tr>
<tr>
<td>10–20</td>
<td>14.43 ± 0.30</td>
<td>260.7 ± 3.6</td>
</tr>
<tr>
<td>20–30</td>
<td>8.73 ± 0.26</td>
<td>186.4 ± 3.9</td>
</tr>
<tr>
<td>30–40</td>
<td>5.04 ± 0.22</td>
<td>129.3 ± 3.8</td>
</tr>
<tr>
<td>40–50</td>
<td>2.7 ± 0.17</td>
<td>85.6 ± 3.6</td>
</tr>
<tr>
<td>50–60</td>
<td>1.33 ± 0.12</td>
<td>53.0 ± 3.1</td>
</tr>
<tr>
<td>60–70</td>
<td>0.59 ± 0.07</td>
<td>30.1 ± 2.5</td>
</tr>
<tr>
<td>70–80</td>
<td>0.24 ± 0.04</td>
<td>15.1 ± 1.7</td>
</tr>
<tr>
<td>0–1</td>
<td>29.04 ± 0.46</td>
<td>400.1 ± 1.3</td>
</tr>
<tr>
<td>1–5</td>
<td>25.62 ± 0.40</td>
<td>377.6 ± 2.2</td>
</tr>
<tr>
<td>5–10</td>
<td>20.59 ± 0.34</td>
<td>330.3 ± 3.0</td>
</tr>
<tr>
<td>60–80</td>
<td>0.41 ± 0.05</td>
<td>22.6 ± 2.1</td>
</tr>
</tbody>
</table>

The jet reconstruction and UE subtraction procedures described in Ref. [13] were applied to both $pp$ and $Pb + Pb$ data. The anti-$k_t$ algorithm was applied to logical towers with segmentation $\Delta R \times \Delta \phi = 0.1 \times 0.1$ formed from energy deposits in the calorimeter. An iterative procedure was used to obtain an event-by-event estimate of the average $\eta$-dependent UE energy density while excluding actual jets from that estimate. The jet kinematics were obtained by subtracting the UE energy from the towers within the jet. Following reconstruction, the jet energies were corrected for the calorimeter energy response using the procedure described in Ref. [25].

In addition to the calorimetric jets, “track jets” were reconstructed by applying the anti-$k_t$ algorithm with $R = 0.4$ to charged particles with $p_T > 4$ GeV. In the $Pb + Pb$ analysis, the track jets were used in conjunction with electromagnetic clusters to exclude the contribution to the jet yield from UE fluctuations of soft particles incorrectly interpreted as calorimetric jets [13]. The jets were required to be within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ of a track jet with $p_T > 7$ GeV or an electromagnetic cluster with $p_T > 8$ GeV.

The performance of the jet reconstruction in $Pb + Pb$ collisions was evaluated using the gEANT4-simulated detector response [26,27] in a Monte Carlo (MC) sample of $pp$ hard scattering events at $\sqrt{s} = 2.76$ TeV. The events were produced with the PYTHIA event generator [28] version 6.423 with parameters chosen according to the so-called AUET2B tune [29] and overlaid with minimum-bias $Pb + Pb$ collisions recorded by ATLAS during the same data-taking period as the data used in the analysis. Thus, the MC sample contains a UE contribution that is identical in all respects to the data. A separate PYTHIA sample was produced for the analysis of the $pp$ data with the detector simulation adjusted to match the conditions during the $pp$ data taking including pile-up. Additional MC samples were used in evaluations of the jet energy scale (JES) uncertainty. The PYQUREN generator [30], which applies medium-induced energy loss to parton showers produced by PYTHIA, was used to generate a sample of jets with fragmentation functions that differ from those in the nominal PYTHIA sample in a fashion consistent with measurements of fragmentation functions in quenched jets [31–33].

The jet spectra, defined to be the average differential yield in a given $p_T$ bin, were constructed from a mixture of minimum-bias ($Pb + Pb$ only) and jet-triggered samples. In each $p_T$ bin, the trigger with the most events and that was more than 99% efficient for that bin was used. The jet spectra were unfolded [13] to account for the $p_T$ bin migration induced by the jet energy resolution (JER) using a method based on the singular value decomposition [34]. The effects of the JER, which receives contributions from both the detector response and UE fluctuations, were evaluated by applying the same procedure to the MC samples as was applied to the data and by matching the
resulting reconstructed jets and “generator jets” that are reconstructed from final-state PYTHIA hadrons. For each pair, the \( p_T \) of the generator and reconstructed jets were used to populate a detector response matrix. Separate response matrices were obtained for each centrality interval.

The response matrix is generally diagonal, indicating that jets are likely to be reconstructed in the same \( p_T \) bin as the generator jets. The average \( p_T \) difference between reconstructed and generator jets is \( \lesssim 1\% \), independent of centrality. However, the response distributions broaden at low \( p_T \) as the relative JER increases due to the larger UE fluctuations. At \( p_T = 200 \text{ GeV} \), the relative JER is approximately 10\% and is independent of centrality. However, at \( p_T = 40 \text{ GeV} \), it varies from 20\% to 40\% between peripheral and central collisions. The unfolding is most sensitive in this region, and the range of jet \( p_T \) used in the unfolding was chosen separately in each centrality interval to be as low as possible while maintaining stability in the unfolding procedure. The statistical covariance of each unfolded spectrum was evaluated using the pseudoeperiment procedure described in Ref. [13]. Systematic uncertainties in the unfolding procedure were evaluated by varying the choice of regularization parameter used in the unfolding.

The effects of any inefficiency in the jet reconstruction, including inefficiency introduced by the UE jet rejection requirement, were corrected for by a multiplicative correction applied after unfolding. This factor, obtained from the MC sample, is unity for \( p_T > 100 \text{ GeV} \) and reaches a maximum of 1.3 in the most central collisions at the lowest \( p_T \). For values larger than unity, an uncertainty of 0.5\% was assigned to this correction based on the comparison of the jet reconstruction efficiency with respect to track jets between the data and MC sample.

Uncertainties on the JER and JES have been evaluated using data-driven techniques in \( pp \) collisions \[21,35\]. A systematic uncertainty of 1.5\% on the JES was assigned to account for potential differences, not described by the MC simulations, between the two data-taking periods. This value was obtained by comparing the calorimetric response with respect to the \( p_T \) of matched track jets in \( pp \) and peripheral \( \text{Pb} + \text{Pb} \) collisions.

A centrality-dependent uncertainty on the JES due to differences between \( pp \) and \( \text{Pb} + \text{Pb} \) in the partonic composition of jets and in their fragmentation was estimated with the PYQUEN sample. The jet response in that sample was found to differ by up to 1\% from that in the PYTHIA sample. The magnitude of this variation was checked with a similar study using track jets to compare central and peripheral \( \text{Pb} + \text{Pb} \) data. The uncertainty was taken to be 1\% in the most central collisions with the uncertainty decreasing in more peripheral collisions.

The impacts of the JER and JES uncertainties on the spectra were assessed by constructing new response matrices with a systematically varied relationship between the reconstructed and generator jet kinematics and repeating the unfolding. Correlations in the JES and JER uncertainties across the \( pp \) and \( \text{Pb} + \text{Pb} \) samples were accounted for in the propagation of the uncertainties to the \( R_{AA} \).

Uncertainties on the \( T_{AA} \) and integrated luminosity affect the overall normalization of the yields and thus are independent of jet \( p_T \) and rapidity. The uncertainties on \( \langle T_{AA} \rangle \) vary between 1\% and 10\% in the most central and peripheral collisions, respectively, with the full set of values given in Table I. The uncertainty on the integrated luminosity is estimated to be 3.1\%. It is determined, following the same methodology as that detailed in Ref. [36], from a calibration of the luminosity scale derived from beam-separation scans performed during the 2.76 TeV operation of the LHC in 2013.

The total systematic uncertainty on the \( pp \) cross sections is dominated by the JES uncertainty, which is as large as 15\%. For the \( \text{Pb} + \text{Pb} \) jet yields, this uncertainty is also dominant and in the most central collisions is 22\%. In the \( R_{AA} \), much of this uncertainty cancels. However, the dominant contribution is due to the JES in most centrality and rapidity intervals and is typically 10\%.

The uncertainties due to the unfolding are generally a few percent, but for some \( p_T \) values near the upper and lower limits included in the measurement the contributions from this source are as large as 15\%. The contributions of the JER to the total uncertainty on \( R_{AA} \) are less than 3\% except in the most central collisions at low \( p_T \), where they are as large as 10\%. In the most peripheral bins, the \( \langle T_{AA} \rangle \) uncertainties are independent of jet \( p_T \) and rapidity.
uncertainties that affect the overall normalization are the dominant contribution.

The $pp$ differential jet cross sections are shown in Fig. 1 for the following absolute rapidity ranges: 0–0.3, 0.3–0.8, 0.8–1.2, 1.2–2.1, and 0–2.1. These results are consistent with a previous measurement with fewer events [37]. The differential per-event jet yield in $\mathrm{Pb+Pb}$ collisions, multiplied by $1/(N_{\mathrm{AA}})$, is shown in Fig. 2, in selected rapidity and centrality bins in the lower and upper panels, respectively. The dashed lines represent the $pp$ jet cross section for the same rapidity bin scaled by the same factor.

The jet $R_{\mathrm{AA}}$ as a function of $p_T$ is shown in Fig. 3 for different ranges in collision centrality and jet rapidity. The $R_{\mathrm{AA}}$ is observed to increase weakly with $p_T$, except in the most peripheral collisions. In the 0%–10% and $|y| < 2.1$ centrality and rapidity intervals, which have the smallest statistical uncertainty, the $R_{\mathrm{AA}}$ is 0.47 at $p_T \sim 55$ GeV and rises to 0.56 at $p_T \sim 350$ GeV. These distributions were fit, accounting for the pointwise correlations in the uncertainties, to the functional form $a \ln(p_T) + b$. The slope parameter was found to be significantly above zero in all but the most peripheral collisions. The magnitude and weak increase of the $R_{\mathrm{AA}}$ in central collisions are described quantitatively by recent theoretical calculations [38,39]. The results of this measurement are consistent with
measurements of the jet central-to-peripheral ratio [13], although in those measurements the uncertainties are too large to infer any significant $p_T$ dependence.

The rapidity dependence of the $R_{AA}$ is shown in the top panel of Fig. 4 for jets with $80 < p_T < 100$ GeV for three centrality bins. The $R_{AA}$ shows no significant rapidity dependence over the $p_T$ and rapidity ranges presented in this measurement. The $\langle N_{\text{part}} \rangle$ dependence is shown in the bottom panel of Fig. 4 for jets in the same $p_T$ interval and with $|y| < 2.1$. The $R_{AA}$ decreases smoothly from the most peripheral collisions (smallest $\langle N_{\text{part}} \rangle$ values) to central collisions, where it reaches a minimal value of approximately 0.4 in the most central 1% of collisions. A similar $\langle N_{\text{part}} \rangle$ dependence is observed for jets in different ranges of $p_T$ and rapidity.

In summary, this Letter presents measurements of inclusive jet production in $pp$ and $Pb + Pb$ collisions over a wide range in $p_T$, rapidity, and centrality. The jet nuclear modification factor $R_{AA}$ obtained from these measurements shows a weak rise with $p_T$, with a slope that varies with collision centrality. No significant slope is observed in the most peripheral collisions. The $R_{AA}$ decreases gradually with increasing $\langle N_{\text{part}} \rangle$. At forward rapidity, the increasing steepness of the jet production spectrum is expected to result in more suppression of the jet yields. In this kinematic region, the production is increasingly dominated by quark jets, which may lose less energy than gluon jets [15]. The observed lack of rapidity dependence in the $R_{AA}$ places constraints on relative energy loss for quark and gluon jets in theoretical descriptions of jet quenching.

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; CPNP and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICyT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society, and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, and Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom), and BNL (USA) and in the Tier-2 facilities worldwide.

[17] 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 $\theta$ as $\eta = -\ln \tan(\theta/2)$.

1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany, New York, USA
3 Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4 Department of Physics, Ankara University, Ankara, Turkey
4a Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4b Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7 Department of Physics, University of Arizona, Tucson, Arizona, USA
8 Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Fisica d’Altes Energies and Departament de Fisica de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
13a Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19a Department of Physics, Bogazici University, Istanbul, Turkey
19b Department of Physics, Bilkent University, Ankara, Turkey
19c Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20a INFN Sezione di Bologna, Italy
20b Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston, Massachusetts, USA
23 Department of Physics, Brandeis University, Waltham, Massachusetts, USA
24 Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
24a Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
24b Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
24c Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, New York, USA
26 National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
26a University Politehnica Bucharest, Bucharest, Romania
26b 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, Ontario, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
32 Department of Física, Pontificia Universidad Católica de Chile, Santiago, Chile
32a Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
33a Institute of Modern Physics, University of Science and Technology of China, Anhui, China
133a INFN Sezione di Roma, Italy
133b Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
134a INFN Sezione di Roma Tor Vergata, Italy
134b Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135a INFN Sezione di Roma Tre, Italy
135b Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136a Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
136b Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
136c Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
136d Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
136e Facultés des sciences, Université Mohammed V-Agdal, Rabat, Morocco
137 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
138 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
145a Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
145b Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
146a Department of Physics, University of Cape Town, Cape Town, South Africa
146b Department of Physics, University of Johannesburg, Johannesburg, South Africa
146c School of Physics, University of the Witwatersrand, Johannesburg, South Africa
147a Department of Physics, Stockholm University, Sweden
147b The Oskar Klein Centre, Stockholm, Sweden
148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto, Ontario, Canada
160a TRIUMF, Vancouver, British Columbia, Canada
160b Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
164 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
165a INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
165b ICTP, Trieste, Italy
165c Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
166 Department of Physics, University of Illinois, Urbana, Illinois, USA
167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
168 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-CNM), University of Valencia and CSIC, Valencia, Spain
169 Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
170 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
171 Department of Physics, University of Warwick, Coventry, United Kingdom
172 Waseda University, Tokyo, Japan
173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
174 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
\textsuperscript{176}Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
\textsuperscript{177}Department of Physics, Yale University, New Haven, Connecticut, USA
\textsuperscript{178}Yerevan Physics Institute, Yerevan, Armenia

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 Institute of Physics, 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, BC, Canada.
\textsuperscript{f}Also at Department of Physics, California State University, Fresno, CA, USA.
\textsuperscript{g}Also at Tomsk State University, Tomsk, 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.
\textsuperscript{k}Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
\textsuperscript{l}Also at Chinese University of Hong Kong, China.
\textsuperscript{m}Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
\textsuperscript{n}Also at Louisiana Tech University, Ruston, LA, USA.
\textsuperscript{o}Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
\textsuperscript{p}Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
\textsuperscript{q}Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
\textsuperscript{r}Also at CERN, Geneva, Switzerland.
\textsuperscript{s}Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
\textsuperscript{t}Also at Manhattan College, New York, NY, USA.
\textsuperscript{u}Also at Novosibirsk State University, Novosibirsk, Russia.
\textsuperscript{v}Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
\textsuperscript{w}Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
\textsuperscript{x}Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
\textsuperscript{y}Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

\textsuperscript{a}Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
\textsuperscript{b}Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.
\textsuperscript{c}Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\textsuperscript{d}Also at Section de Physique, Université de Genève, Geneva, Switzerland.
\textsuperscript{e}Also at International School for Advanced Studies (SISSA), Trieste, Italy.
\textsuperscript{f}Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
\textsuperscript{g}Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
\textsuperscript{h}Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
\textsuperscript{i}Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.
\textsuperscript{j}Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
\textsuperscript{k}Also at Department of Physics, Oxford University, Oxford, United Kingdom.
\textsuperscript{l}Also at Department of Physics, Nanjing University, Jiangsu, China.
\textsuperscript{m}Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
\textsuperscript{n}Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
\textsuperscript{o}Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.