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

The ATLAS Collaboration

Abstract

Measurements of inclusive jet production are performed in $pp$ and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC, corresponding to integrated luminosities of 4.0 pb$^{-1}$ 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 two in central collisions compared to $pp$ collisions. The $R_{AA}$ shows a slight increase with $p_T$ and no significant variation with rapidity.
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Relativistic heavy-ion collisions at the LHC produce a medium of strongly interacting nuclear matter composed of deconfined color charges [1–4]. Hard scattering processes occurring in these collisions produce high transverse momentum ($p_T$) partons that propagate through the medium and lose energy, resulting in the phenomenon of “jet quenching.” The partonic energy loss can be probed through measurements of the suppression of jet production rates. The effects of energy loss have been observed through the suppression of single hadrons [5–11] and jets constructed from charged particles [12]. ATLAS has previously reported measurements with fully reconstructed jets [13] by comparing the jet yields in central collisions, where the colliding nuclei have large overlap, to the yields in peripheral collisions. Those results indicate that the rate of jets in Pb+Pb collisions is suppressed by a factor of approximately two in central collisions relative to $pp$ collisions. A more sensitive probe of energy loss is provided by measurements of the suppression relative to $pp$ collisions, where there are no quenching effects.

The magnitude of the suppression is expected to depend on both the $p_T$ dependence of the energy loss as well as the shape of the initial jet production $p_T$ spectrum [1]. This spectrum becomes increasingly steep at larger values of the jet rapidity [14]. Thus measurements of jet suppression for jets in different intervals of rapidity provide complementary information about the energy loss. Additionally, parton showers initiated by quarks may be quenched differently than gluons [15], and the fraction of quark-initiated jets is expected to increase 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

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \frac{d^2N_{\text{jet}}}{dp_Tdy}_{\text{central}}}{\langle T_{AA} \rangle \frac{d^2N_{\text{jet}}}{dp_Tdy}_{\text{pp}}}.$$ 

This Letter presents measurements of the inclusive jet $R_{AA}$ in Pb+Pb collisions at a nucleon–nucleon center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ 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 (EM) 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 straw-tube transition-radiation tracker ($|\eta| < 2.0$), all immersed in a 2 T axial magnetic field. The zero-degree calorimeters (ZDCs) are located symmetrically at $z = \pm 140$ cm 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 triggers based on a ZDC coincidence or total transverse energy in the event, is fully efficient in the range of centralities presented here. The jet trigger identified jets by applying the anti-$k_t$ algorithm with $R = 0.2$ with a UE subtraction procedure similar to that applied in the offline analysis. The jet trigger selected events having at least one jet with transverse energy $E_T > 20$ GeV at the electromagnetic scale [21].

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.

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 $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ 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 PYQUEN 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 $p_T = 200$ GeV, the relative JER is approximately 10% and is independent of centrality. However at $p_T = 40$ GeV, it varies from 20–40% between

<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>22.4 ± 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>
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</tbody>
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<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>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>
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 pseudo-experiment 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 $p_T > 100$ 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 Pb+Pb collisions.

A centrality-dependent uncertainty on the JES due to differences between $pp$ and Pb+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 Pb+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 Pb+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 Pb+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 per cent, 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 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 2–2.1. These results are consistent with a previous measurement with fewer events [37]. The differential per-event jet yield in Pb+Pb collisions, multiplied by $1/(T_{AA})$, 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 sections for that same rapidity bin; the jet suppression is evidenced by the fact that the jet yields fall below these lines.

The jet $R_{AA}$ as a function of $p_T$ is shown in Fig. 3 for different ranges in collision centrality and jet rapidity. The $R_{AA}$ 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 $R_{AA}$ 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 $R_{AA}$ 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...
exclusive jet production in $pp$, 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.

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(c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) 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 MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and 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) Physics Department, Shanghai Jiao Tong University, Shanghai, 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 The Henryk Niewodniczanski 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
Department of Physics, Indiana University, Bloomington IN, United States of America
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City IA, United States of America
Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Olive 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 Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst 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
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
D.V.Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
(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
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 ON, Canada
160 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
165 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
166 Department of Physics, University of Illinois, Urbana IL, United States of America
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-CNMI), University of Valencia and CSIC, Valencia, Spain
169 Department of Physics, University of British Columbia, Vancouver BC, Canada
170 Department of Physics and Astronomy, University of Victoria, Victoria BC, 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 WI, United States of America
175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
177 Department of Physics, Yale University, New Haven CT, United States of America
178 Yerevan Physics Institute, Yerevan, Armenia
179 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
a Also at Department of Physics, King’s College London, London, United Kingdom
b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
d Also at TRIUMF, Vancouver BC, Canada
e Also at Department of Physics, California State University, Fresno CA, United States of America
f Also at Tomsk State University, Tomsk, Russia
 Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
h Also at Università di Napoli Parthenope, Napoli, Italy
i Also at Institute of Particle Physics (IPP), Canada
j Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
k Also at Chinese University of Hong Kong, China
l Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
m Also at Louisiana Tech University, Ruston LA, United States of America
n Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
o Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
p Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
q Also at CERN, Geneva, Switzerland
r Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
s Also at Manhattan College, New York NY, United States of America
t Also at Novosibirsk State University, Novosibirsk, Russia
u Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
v Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
w Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
x Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
y Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
z Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
aa Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
Also at Section de Physique, Université de Genève, Geneva, Switzerland
Also at International School for Advanced Studies (SISSA), Trieste, Italy
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
Also at Department of Physics, Oxford University, Oxford, United Kingdom
Also at Department of Physics, Nanjing University, Jiangsu, China
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
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