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Measurement of the Azimuthal Angle Dependence of Inclusive Jet Yields in Pb + Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector

G. Aad et al.*

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Measurements of the variation of inclusive jet suppression as a function of relative azimuthal angle, $\Delta \phi$, with respect to the elliptic event plane provide insight into the path-length dependence of jet quenching. ATLAS has measured the $\Delta \phi$ dependence of jet yields in 0.14 nb$^{-1}$ of $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb collisions at the LHC for jet transverse momenta $p_T > 45$ GeV in different collision centrality bins using an underlying event subtraction procedure that accounts for elliptic flow. The variation of the jet yield with $\Delta \phi$ was characterized by the parameter, $v_2^{\text{jet}}$, and the ratio of out-of-plane ($\Delta \phi \sim \pi/2$) to in-plane ($\Delta \phi \sim 0$) yields. Nonzero $v_2^{\text{jet}}$ values were measured in all centrality bins for $p_T < 160$ GeV. The jet yields are observed to vary by as much as 20% between in-plane and out-of-plane directions.

$dN/d\phi \propto 1 + 2v_2\cos(\phi - \Psi_2), \tag{1}$

where the elliptic event plane angle, $\Psi_2$, specifies the orientation of the initial density profile in the transverse plane, and the parameter $v_2$ quantifies the magnitude of the modulation. Jets measured at different azimuthal angles relative to the event plane, $\Delta \phi = \phi_{\text{jet}} - \Psi_2$, result from partons that traverse, on average, different path lengths and density profiles in the medium. Thus, a measurement of the variation of the jet yield as a function of $\Delta \phi$ should provide a direct constraint on theoretical models of the path-length dependence of the energy loss. This measurement is not directly sensitive to potential variations in the jet yield with respect to higher-order event plane angles. Such variations may result from fluctuations in the initial geometry that also give rise to higher-order flow harmonics [11–13].

Variations in jet yield as a function of $\Delta \phi$ have been observed indirectly through measurements of single hadrons with large transverse momentum ($p_T$) at the RHIC [14–16] and the LHC [17–19]. The utility of such measurements is limited by the weak relationship between hadron $p_T$ and the transverse momentum of the parent parton shower. This Letter presents the results of measurements using fully reconstructed jets, which have kinematic properties that are more closely related to those of the parent partons. The $\Delta \phi$ dependence of the inclusive jet yield was measured in $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb collisions as a function of jet $p_T$ and Pb + Pb collision centrality. The measurement was performed with the anti-$k_t$ algorithm [20] with distance parameter $R = 0.2$, chosen to limit the contribution of the underlying event (UE) to the measurement. The $\Delta \phi$ dependence was characterized by the jet $v_2$, $v_2^{\text{jet}}$, and the ratio of out-of-plane ($3\pi/8 \leq \Delta \phi \leq \pi/2$) to in-plane ($0 \leq \Delta \phi < \pi/8$) jet yields at

*Full author list given at the end of the article.

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fixed $p_T$ and centrality. Such dependence is expected to be small in either the most central or most peripheral collisions, due to the lack of initial-state anisotropy and the lack of quenching, respectively. For intermediate centralities, measurement of the $\Delta \phi$ dependence of the jet yields probes the interplay between dependence of quenching on the overall system size and energy density, as well as on the initial-state anisotropy.

The measurements presented here were performed with the ATLAS detector [21] using its calorimeter, inner detector, trigger, and data acquisition systems. The calorimeter system consists of a liquid-argon electromagnetic (EM) calorimeter covering $|\eta| < 3.2$, a steel-scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, a liquid-argon hadronic calorimeter covering $1.5 < |\eta| < 3.2$, and a forward calorimeter (FCal) covering $3.2 < |\eta| < 4.9$. Charged-particle tracks were measured over the range $|\eta| < 2.5$ using the inner detector [22], 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 $z = \pm 140$ m and cover $|\eta| > 8.3$. In $\text{Pb} + \text{Pb}$ collisions the ZDCs primarily measure noninteracting “spectator” neutrons from the incident nuclei. A ZDC coincidence trigger was defined by requiring a signal consistent with one or more neutrons in each of the calorimeters.

$\text{Pb} + \text{Pb}$ collisions corresponding to a total integrated luminosity of 0.14 nb$^{-1}$ were analyzed. The events were recorded using either a minimum-bias trigger, formed from the logical OR of triggers based on a ZDC coincidence or total transverse energy in the event, or a jet trigger implemented using the $\text{Pb} + \text{Pb}$ jet reconstruction algorithm. The jet trigger selected events having at least one jet with transverse energy $E_T > 20$ GeV. Event selection and background rejection criteria were applied [17] yielding $52 \times 10^6$ and $14 \times 10^6$ events in the minimum-bias and jet-triggered samples, respectively. For each event, $\Psi_2$ was computed from the azimuthal distribution of the transverse energy measured in the FCal [17,23], and angles with respect to $\Psi_2$ were defined over $0 \leq \Delta \phi \leq \pi/2$. The centrality of $\text{Pb} + \text{Pb}$ collisions was characterized by the $\Sigma E_T^{\text{FCal}}$, the total transverse energy measured in the FCal [17]. The results reported here were obtained using the following centrality intervals defined according to successive percentiles of the $\Sigma E_T^{\text{FCal}}$ distribution ordered from the most central (highest $\Sigma E_T^{\text{FCal}}$) to the most peripheral collisions: $5\%$–$10\%$, $10\%$–$20\%$, $20\%$–$30\%$, $30\%$–$40\%$, $40\%$–$50\%$, and $50\%$–$60\%$. The centrality interval $5\%$–$60\%$ coincides to the range over which the $\Psi_2$ resolution is adequate for the measurement. A Glauber model analysis [24,25] of the $\Sigma E_T^{\text{FCal}}$ distribution [17] was used to evaluate the average number of nucleons participating in the collision, $\langle N_{\text{part}} \rangle$, in each centrality interval.

The jet reconstruction and underlying event subtraction procedures are the same as those used in Ref. [3], which is summarized in the following. The anti-$k_t$ algorithm was applied to calorimeter towers with segmentation $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$. A two-step 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. This subtraction accounts for elliptic flow by modulating the average background density by the magnitude of the elliptic flow measured by the calorimeter, $v_2^{\text{calo}}$, over the interval $|\eta| < 3.2$ and excluding $\eta$ regions containing jets. Following reconstruction, the jet energies were corrected to account for the calorimeter energy response using an $\eta$- and $E_T$-dependent multiplicative factor that was derived from Monte Carlo (MC) simulations [26].

Separate from the calorimeter jets, “track jets” were reconstructed by applying the anti-$k_t$ algorithm with $R = 0.4$ to charged particles having $p_T > 4$ GeV. The $p_T$ of the track jets, $p_T^{\text{track}}$, is largely unaffected by the UE due to the $p_T > 4$ GeV requirement. To exclude the contribution to the jet yield from UE fluctuations of soft particles falsely identified as calorimeter jets, the jets used in this analysis were required to be within $|\Delta R| = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.2$ of a track jet with $p_T^{\text{track}} > 10$ GeV or an EM cluster [27] with $p_T > 9$ GeV.

The performance of the jet reconstruction was evaluated using the GEANT4-simulated detector response [28,29] in a MC sample of $pp$ hard scattering events at $\sqrt{s_{NN}} = 2.76$ TeV. The events were produced with the PYTHIA event generator [30] version 6.423 using the AUET2B tune [31] and overlaid on minimum-bias $\text{Pb} + \text{Pb}$ collisions recorded by ATLAS. Through this embedding procedure, the MC sample contains a UE contribution that is identical in all respects to the data, including azimuthal modulation to the jet yield from UE fluctuations of soft particles falsely identified as calorimeter jets, the jets reconstructed in this analysis were required to be within $|\Delta R| = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.2$ of a track jet with $p_T^{\text{track}} > 10$ GeV or an EM cluster [27] with $p_T > 9$ GeV.

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60–80 GeV, 80–110 GeV, 110–160 GeV, and 160–210 GeV. The measurement in each \( p_T \) range was performed using events selected by the jet trigger except for the 45–60 GeV \( p_T \) range, in which minimum-bias events were used. The \( \Delta \phi \) dependence of the jet yields in the 60–80 GeV \( p_T \) interval is shown for each centrality range in Fig. 1. A significant \( \Delta \phi \) variation that is consistent with a \( \cos^2 \Delta \phi \) modulation is seen for all centrality intervals.

The measured yields and the resulting \( \nu^{\text{jet}}_2 \) values are distorted by the finite resolutions in \( \Psi_2 \) and the jet \( p_T \). The \( \Psi_2 \) resolution was evaluated using a subevent technique [17,23] in which \( \Psi_2 \) was measured separately in the positive and negative \( \eta \) halves of the FCal yielding values \( \Psi_2^+ \) and \( \Psi_2^- \), respectively. The width of the \( \Psi_2^+ - \Psi_2^- \) distribution was used [23] to estimate a factor, \( \kappa \), that was used to correct each measured \( \nu_2 \) value for the finite \( \Psi_2 \) resolution according to

\[
\nu_2 = \nu_2|\text{meas}| / \kappa. \tag{2}
\]

This factor was evaluated for events containing jets to account for the relevant distribution of events within each centrality interval.

The \( p_T \) dependence, and possibly also the \( \Delta \phi \) dependence, of the measured yields are affected by the JER, which arises from both fluctuations in the UE and the detector response. The MC study shows that for the \( R = 0.2 \) jets used in this analysis, the JER-induced migration between jet \( p_T \) intervals is sufficiently small that a “bin-by-bin” unfolding method, utilizing multiplicative corrections to the jet yields, is appropriate. The bin-by-bin correction factors are defined to be the number of generator-level jets divided by the number of reconstructed jets in each \( p_T \), \( \Delta \phi \), and centrality interval. The MC studies show no significant \( \Delta \phi \) variation of the JER, JES, and the correction factors, and so these correction factors were taken to be \( \Delta \phi \) independent. Since the measurements presented here depend only on the ratios of jet yields between different \( \Delta \phi \) intervals for the same \( p_T \) range, the correction factors do not affect any of the final results; the potential for a \( \Delta \phi \) dependence of the correction factors is included in the estimates of the systematic uncertainty.

Systematic uncertainties on the corrected \( \nu_2 \) values arise due to uncertainties on the two correction procedures described above. Uncertainties on \( \kappa \) were estimated by using the values obtained in previous studies [17]. The uncertainties were found to vary between 1% and 4% from central to peripheral collisions. Potential distortions in the measurement of \( \Psi_2 \) due to the production of jets in the FCal pseudorapidity range were studied in the MC sample and found to be negligible for the centrality intervals included in this analysis.

Uncertainties on the measurements arising from \( \Delta \phi \)-dependent systematic uncertainties on the bin-by-bin correction factors were estimated by determining the sensitivity of these correction factors to each systematic variation and then parametrizing that sensitivity with a \( \cos^2 \Delta \phi \) dependence. The sensitivity to the \( \Delta \phi \) dependence of the spectrum was evaluated by varying the \( p_T \) spectrum of the generator-level jets in each \( \Delta \phi \) interval within a range consistent with the measured \( \nu_2^{\text{jet}} \) values. The JES and JER contributions to the uncertainty were obtained by varying the relationship between generator-level and reconstructed jet \( p_T \) in the determination of the correction factors. These procedures utilized the JES constraints obtained from track jets and direct measurements of the UE contribution to the JER [3]. Parametrizations of the measured \( \nu_2^{\text{calo}} \) and the average background \( E_T \) underlying a typical jet measured in the data were used to provide the dependence of variations on centrality.

The azimuthal dependence of jet suppression can be characterized by \( \nu_2^{\text{jet}} \), which was obtained by correcting the \( \nu_2|\text{meas} | \) values using Eq. (2). Figure 2 shows the resulting \( \nu_2^{\text{jet}} \) values as a function of jet \( p_T \) for all centrality intervals. Significant, nonzero values are observed over the range \( 45 < p_T < 160 \) GeV for all centrality intervals. A direct comparison between the \( \nu_2 \) of single high-\( p_T \) charged particles and \( \nu_2^{\text{jet}} \) is generally not possible; however, the fact that both quantities exhibit only a weak \( p_T \) dependence leads to the expectation that they should be of similar magnitude. In the charged-particle measurements,

![FIG. 1 (color online). \( \Delta \phi \) dependence of measured \( d^2N_{\text{jet}}/dp_Td\Delta \phi \) in the 60 < \( p_T < 80 \) GeV interval for six ranges of collision centrality. The yields are normalized by the total number of jets in the \( p_T \) interval. The solid curves indicate the results of fitting the data to the functional form of Eq. (1), with the resulting \( \nu_2 \) values, \( \nu^{\text{jet}}_2 |\text{meas}| \), listed in each panel. The error bars and errors on \( \nu^{\text{jet}}_2 |\text{meas}| \) indicate statistical uncertainties.](image-url)
the \( v_2 \) values of charged particles with \( 28 < p_T < 48 \text{ GeV} \) were found to vary between 0.02 and 0.05 for the 10\%–50\% centrality range \[18\], which are generally in agreement with \( v_2^{\text{jet}} \) values reported here indicating no obvious inconsistencies between the two results.

The centrality dependence of \( v_2^{\text{jet}} \) is shown in Fig. 3 as a function of \( \langle N_{\text{part}} \rangle \) for different ranges in \( p_T \). The variation of jet yields with \( \Delta \phi \) can also be characterized by the ratio of jet yields between the most out-of-plane and most in-plane bins,

\[
R_{\Delta \phi}^{\text{max}} = \frac{d^2N_{\text{jet}}}{dp_T d\Delta \phi}|_{\text{out}}/\frac{d^2N_{\text{jet}}}{dp_T d\Delta \phi}|_{\text{in}}. \tag{3}
\]

This quantity is more general than \( v_2^{\text{jet}} \) as it does not assume a functional form for the \( \Delta \phi \) dependence of the jet yields. The nuclear modification factor, \( R_{AA} \), is a measure of the effect of quenching on hard scattering rates, and \( R_{\Delta \phi}^{\text{max}} \) can be interpreted as the ratio of \( \Delta \phi \)-dependent \( R_{AA} \) factors,

\[
R_{\Delta \phi}^{\text{max}} = R_{AA}|_{\text{out}}/R_{AA}|_{\text{in}} \tag{16}.
\]

The yields were corrected for \( \Psi_2 \) resolution assuming that the \( \Delta \phi \) variation is dominated by the cos2 \( \Delta \phi \) modulation,

\[
\frac{d^2N_{\text{corr}}}{dp_T d\Delta \phi} = \frac{d^2N_{\text{meas}}}{dp_T d\Delta \phi} \left( \frac{1 + 2v_2^{\text{jet}} \cos 2 \Delta \phi}{1 + 2v_2^{\text{jet meas}} \cos 2 \Delta \phi} \right). \tag{4}
\]

The results, expressed in terms of the quantity \( f_2 = 1 - R_{\Delta \phi}^{\text{max}} \), show as much as a 20\% variation between the out-of-plane and in-plane jet yields, but they are reduced slightly from the maximal difference, evaluated at \( \Delta \phi = \pi/2 \) and \( \Delta \phi = 0 \), by the finite bin size used in the measurement. That reduction was corrected by assuming a \( 1 + 2v_2^{\text{jet}} \cos 2 \Delta \phi \) variation of the jet yields within the \( \Delta \phi \) bins containing \( \Delta \phi = 0 \) and \( \pi/2 \), and calculating the corresponding yields at those \( \Delta \phi \) values. From these yields, \( f_2^{\text{corr}} \) was calculated analogously to \( f_2 \). The magnitude of the correction is typically a few percent. The \( f_2^{\text{corr}} \) values are shown in Fig. 3. For a pure cos2 \( \Delta \phi \) modulation of the jet yields, \( f_2^{\text{corr}} \) would be given by \( 4v_2^{\text{jet}}/(1 + 2v_2^{\text{jet}}) \). To test for deviations of the \( \Delta \phi \) dependence of the jet yields from a pure cos2 \( \Delta \phi \) variation, \( 4v_2^{\text{jet}}/(1 + 2v_2^{\text{jet}}) \) was calculated using the measured \( v_2^{\text{jet}} \) values and is shown for each \( p_T \) and centrality interval in Fig. 3.

Similar variations of \( v_2^{\text{jet}} \), \( f_2^{\text{corr}} \), and \( 4v_2^{\text{jet}}/(1 + 2v_2^{\text{jet}}) \) with \( \langle N_{\text{part}} \rangle \) are seen in the 60–80 GeV range, which has the best statistical precision. A reduction in \( f_2^{\text{corr}} \) and \( v_2^{\text{jet}} \) in both the most central and peripheral collisions is not surprising; for very central collisions, the anisotropy of the initial state is small and the possible \( \Delta \phi \) variation of path lengths in the medium is limited. Although the anisotropy is greater in peripheral collisions, there is little suppression in the jet yields \[3\]. Therefore large variations in jet yield as a function of \( \Delta \phi \) would be unexpected. The \( f_2^{\text{corr}} \) and \( 4v_2^{\text{jet}}/(1 + 2v_2^{\text{jet}}) \) values are generally in agreement within uncertainties, indicating an azimuthal
dependence of relative suppression when measured with respect to the elliptic event plane that is dominated by second-harmonic modulation.

This Letter has presented results of ATLAS measurements of the variation of $R = 0.2$ anti-$k_T$ jet yields in $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb collisions as a function of $\Delta \phi$, the relative azimuthal angle of the jet with respect to the elliptic event plane. A significant $\Delta \phi$ variation in the jet yield is observed for all centrality intervals and in all $p_T$ ranges except for the 160–210 GeV $p_T$ interval where the statistical uncertainties are large. The observed azimuthal variation of jet yields amounts to a reduction of 10%–20% in the jet yields between in-plane and out-of-plane directions. These results establish a relationship between jet suppression and the initial nuclear geometry that should constrain models of the path-length dependence of the quenching mechanism.

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(ATLAS Collaboration)

1 School of Chemistry and 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
4a Department of Physics, Ankara University, Ankara, Turkey
4b Department of Physics, Gazi University, Ankara, Turkey
4c Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4d Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Universite´ 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 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
12 Instituto de Física e Química, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
13b 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 Physics Department, 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, Dogus University, Istanbul, Turkey
19c Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
19d INFN Sezione di Bologna, Bologna, Italy
20a Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
20b Physikalisch Institut, University of Bonn, Bonn, Germany
21 Department of Physics, Boston University, Boston, Massachusetts, USA
22 Department of Physics, Brandeis University, Waltham, Massachusetts, USA
23 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 (UFJJFR), Sao Joao del Rei, Brazil
24c Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, New York, USA
26a National Institute of Physics and Nuclear Engineering, Bucharest, Romania
26b National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
26c University Politehnica Bucharest, Bucharest, Romania
26d 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
32a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
32b Departamento de Física, Universidad Técnica Federico Santa Maria, Valparaíso, Chile
33a Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

PRL 111, 152301 (2013) PHYSICAL REVIEW LETTERS week ending 11 OCTOBER 2013

152301-14
33b Department of Modern Physics, University of Science and Technology of China, Anhui, China
33c Department of Physics, Nanjing University, Jiangsu, China
33d School of Physics, Shandong University, Shandong, China
33e Physics Department, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université et Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington, New York, USA
36 Niels Bohr Institute, University of Copenhagen, København, Denmark
37b INFN Gruppo Collegato di Cosenza, Cosenza, Italy
37b Dipartimento di Fisica, Università della Calabria, Rende, Italy
38a AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
38b 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, Texas, USA
41 Physics Department, University of Texas at Dallas, Richardson, Texas, USA
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, North Carolina, USA
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 INFN Sezione di Genova, Genova, Italy
50b Dipartimento di Fisica, Università di Genova, Genova, Italy
51a E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
51b 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 Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton, Virginia, USA
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
58 Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
59 II Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
59b Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
59c ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59d Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 Department of Physics, Indiana University, Bloomington, Indiana, USA
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City, Iowa, USA
63 Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
64 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
65 Graduate School of Science, Kobe University, Kobe, Japan
66 Faculty of Science, Kyoto University, Kyoto, Japan
67 Kyoto University of Education, Kyoto, Japan
68 Department of Physics, Kyushu University, Fukuoka, Japan
69 Instituto de Fisica La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
70 Physics Department, Lancaster University, Lancaster, United Kingdom
71 INFN Sezione di Lecce, Lecce, Italy
72b Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
72c Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Louisiana Tech University, Ruston, Louisiana, USA
79 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
80 Fysiska institutionen, Lunds universitet, Lund, Sweden
81 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
aDeceased.
bAlso at Department of Physics, King’s College London, London, United Kingdom.
cAlso at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal.
dAlso at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
eAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
fAlso at TRIUMF, Vancouver, BC, Canada.
gAlso at Department of Physics, California State University, Fresno, CA, USA.
hAlso at Novosibirsk State University, Novosibirsk, Russia.
iAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.
jAlso at Universitá di Napoli Parthenope, Napoli, Italy.
kAlso at Institute of Particle Physics (IPP), Canada.
lAlso at Department of Physics, Middle East Technical University, Ankara, Turkey.
mAlso at Louisiana Tech University, Ruston, LA, USA.
nAlso at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
oAlso at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
qAlso at Institució Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.
rAlso at Department of Physics, University of Cape Town, Cape Town, South Africa.
sAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
tAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
uAlso at Manhattan College, New York, NY, USA.
vAlso at Institute of Physics, Academia Sinica, Taipei, Taiwan.
wAlso at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
xAlso at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
yAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
zAlso at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
aaAlso at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
bbAlso at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
ccAlso at 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.
ddAlso at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
eeAlso at Section de Physique, Université de Genève, Geneva, Switzerland.
ffAlso at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
ggAlso at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
hhAlso at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
iiAlso at DESY, Hamburg and Zeuthen, Germany.
jjAlso at International School for Advanced Studies (SISSA), Trieste, Italy.
kkAlso at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
llAlso at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
mnAlso at Nevis Laboratory, Columbia University, Irvington, NY, USA.
noAlso at Physics Department, Brookhaven National Laboratory, Upton, NY, USA.
opAlso at Department of Physics, Oxford University, Oxford, United Kingdom.
ppAlso at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
qqAlso at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.