Measurement of Dijet Azimuthal Decorrelations in pp Collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

Azimuthal decorrelations between the two central jets with the largest transverse momenta are sensitive to the dynamics of events with multiple jets. We present a measurement of the normalized differential cross section based on the full dataset ($\int L \, dt = 36 \text{ pb}^{-1}$) acquired by the ATLAS detector during the 2010 $\sqrt{s} = 7$ TeV proton-proton run of the LHC. The measured distributions include jets with transverse momenta up to 1.3 TeV, probing perturbative QCD in a high energy regime.

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The production of events containing high transverse-momentum ($p_T$) jets is a key signature of quantum chromodynamic (QCD) interactions between partons in $pp$ collisions at large center-of-mass energies ($\sqrt{s}$). The Large Hadron Collider (LHC) opens a window into the dynamics of interactions with high-$p_T$ jets in a new energy regime of $\sqrt{s} = 7$ TeV. QCD predicts the decorrelation in the azimuthal angle between the two most energetic jets, $\Delta \phi$, as a function of the number of partons produced. Events with only two high-$p_T$ jets have small azimuthal decorrelations, $\Delta \phi \sim \pi$, while $\Delta \phi \ll \pi$ is evidence of events with several high-$p_T$ jets. QCD also describes the evolution of the shape of the $\Delta \phi$ distribution, which narrows with increasing leading jet $p_T$. Distributions in $\Delta \phi$ therefore test perturbative QCD (pQCD) calculations for multiple jet production without requiring the measurement of additional jets. Furthermore, a detailed understanding of events with large azimuthal decorrelations is important to searches for new physical phenomena with dijet signatures, such as supersymmetric extensions to the Standard Model [1].

In this Letter, we present a measurement of dijet azimuthal decorrelations with jet $p_T$ up to 1.3 TeV as measured by the ATLAS detector, beyond the reach of previous colliders. The normalized differential cross section $(1/\sigma) (d\sigma/|d\Delta \phi|)$ is based upon an integrated luminosity $\int L \, dt = (36 \pm 4) \text{ pb}^{-1}$ [2]. The $\Delta \phi$ distribution is normalized by the inclusive dijet cross section, $\sigma$, integrated over the same phase space. This construction minimizes experimental and theoretical uncertainties. Previous measurements of $\Delta \phi$ from the D0 [3] and CMS [4] collaborations are extended here to higher jet $p_T$ values.

Jets are reconstructed using the anti-$k_t$ algorithm [5] (implemented with FASTJET [6]) with radius $R = 0.6$, and the jet four-momenta are constructed from a sum over its constituents, treating each as an $(E, \vec{p})$ four-vector with zero mass. The anti-$k_t$ algorithm is well-motivated since it is infrared-safe to all orders, produces geometrically well-defined cone-like jets, and is used for pQCD calculations (from partons), event generators (from stable particles), and the detector (from energy clusters [7]). The azimuthal decorrelation, $\Delta \phi$, is defined as the absolute value of the difference in azimuthal angle between the jet with the highest $p_T$ in each event, $p_T^{\text{max}}$, and the jet with the second-highest $p_T$ in the event. There are nine analysis regions in $p_T^{\text{max}}$, where the lowest region is bounded by $p_T^{\text{max}} > 110 \text{ GeV}$ and the highest region requires $p_T^{\text{max}} > 800 \text{ GeV}$ [7]. Only jets with $p_T > 100 \text{ GeV}$ and $|y| < 2.8$, where $y$ is the jet rapidity [8], are considered. The two leading jets that define $\Delta \phi$ are required to satisfy $|y| < 0.8$, restricting the measurement to a central $y$ region where the momentum fractions $(x)$ of the interacting partons are roughly equal and the experimental acceptance for multijet production is increased. In this region where $0.02 \lesssim x \lesssim 0.14$, the parton distribution function (PDF) uncertainties are typically $\pm 3\%$ (at fixed factorization scale) [9]. The cross sections, measured over the range $\pi/2 \leq |\Delta \phi| \leq \pi$ and normalized independently for each analysis region, are compared with expectations from a pQCD calculation [10] that is next-to-leading order (NLO) in three-parton production. The perturbative prediction for the cross section is $\mathcal{O}(\alpha_s^4)$, where $\alpha_s$ is the strong coupling constant.

The angular decorrelation is sensitive to multijet configurations such as those produced by event generators like SHERPA [11], which matches higher-order tree-level pQCD diagrams with a dipole parton-shower model [12]. Samples for $2 \rightarrow 2 - 6$ jet production are combined using an improved CKKW matching scheme [13]. The progression of the parton shower is vetoed to avoid double counting of emissions. Event generators such as PYTHIA [14] and HERWIG [15] use $2 \rightarrow 2$ leading order pQCD matrix elements matched with phenomenological parton-cascade models to simulate higher-order QCD effects. Such models have been successful at reproducing other QCD processes measured by the ATLAS collaboration [7, 10].

The ATLAS detector [16] consists of an inner tracking system surrounding a thin superconducting solenoid providing a 2T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer based on large superconducting toroids. Jet measurements depend most heavily on the calorimeters. The electromagnetic calorimeter is a lead liquid-argon (LAr) detector with an accordion geometry. Hadron calorimetry is based on two different detector technologies, with scintillator tiles or LAr as the active medium, and with either steel, copper, or tungsten as the absorber material. The pseudorapidity ($\eta$) [8] and $\phi$ segmentations of
the calorimeters are sufficiently fine to ensure that angular resolution uncertainties are negligible compared to other sources of systematic uncertainty.

A hardware-based calorimeter jet trigger identified events of interest; the decision was further refined in software [17, 18]. Events with at least one jet that satisfied a minimum transverse energy \( E_T \) requirement were recorded for further analysis. The events in each \( p_T^{\text{max}} \) range are selected by a single trigger with a given \( E_T \) threshold, and the lower end of the range is chosen above \( E_T \) for which that trigger is \( 100\% \) efficient. Three sets of triggered events with different integrated luminosity are considered: 2.3 pb\(^{-1}\) for \( 100 < p_T^{\text{max}} \leq 160 \) GeV, 9.6 pb\(^{-1}\) for \( 160 < p_T^{\text{max}} \leq 260 \) GeV, and 36 pb\(^{-1}\) for \( p_T^{\text{max}} > 260 \) GeV [2]. Events are also required to have a reconstructed primary vertex within 15 cm in \( z \) of the center of the detector; each vertex had \( 5 \) associated tracks. The inputs to the anti-\( k_t \) jet algorithm are clusters of calorimeter cells seeded by cells with energy that is significantly above the measured noise [3]. Jets reconstructed in the detector, whether in data or the GEANT4-based simulation [19, 20], are corrected for the effects of hadronic shower response and detector-material distributions using a \( p_T \)- and \( \eta \)-dependent calibration [7] based on the detector simulation and validated with extensive test-beam [17] and collision data [21] studies. Jets likely to have arisen from detector noise or cosmic rays are rejected [22].

The resulting \( \Delta \phi \) distribution is shown in Fig. 1 for jets with \( p_T > 100 \) GeV. There are 146788 events in the data sample, 85 of which have at least five jets with \( p_T > 100 \) GeV. Also shown is the PYTHIA sample with MRST 2007 LO PDF [23] and ATLAS MC09 underlying event tune [24], processed through the full detector simulation and normalized to the number of events in the data sample. Two- and three-jet production primarily populates the region \( 2\pi/3 < \Delta \phi < \pi \) while smaller values of \( \Delta \phi \) require additional activity such as soft radiation or more jets in an event. Fig. 1 illustrates that the decorrelation increases when a third high-\( p_T \) jet is also required. Events with additional high-\( p_T \) jets widen the overall distribution.

The measured differential \( \Delta \phi \) distributions in data are corrected in a single step with a bin-by-bin unfolding method [7] to compensate for trigger and detector inefficiencies and the effects of finite experimental resolutions. These correction factors, evaluated using the PYTHIA sample, lie within \( \pm 9\% \) of unity. The leading sources of systematic uncertainty on the normalized cross sec-

FIG. 1. The \( \Delta \phi \) distribution for \( \geq 2, \geq 3, \geq 4, \) and \( \geq 5 \) jets with \( p_T > 100 \) GeV. Overlaid on the calibrated but otherwise uncorrected data (points) are results from PYTHIA processed through the detector simulation (lines). All uncertainties are statistical only.

FIG. 2. The differential cross section \( (1/\sigma)(d\sigma/d\Delta \phi) \) binned in nine \( p_T^{\text{max}} \) regions. Overlaid on the data (points) are results from the NLO pQCD calculation. The error bars on the data points indicate the statistical (inner error bar) and systematic uncertainties added in quadrature in this and subsequent figures. The theory uncertainties are indicated by the hatched regions. Different bins in \( p_T^{\text{max}} \) are scaled by multiplicative factors of ten for display purposes. The region near the divergence at \( \Delta \phi \to \pi \) is excluded from the calculation.
tion are the jet energy scale calibration ($2 - 17\%$) [7],
the bin-by-bin unfolding method ($1 - 19\%$), and the jet
energy and position resolutions ($0.5 - 5\%$). The ranges
in parentheses represent the magnitude of the uncertainties
near $\pi$ and $\pi/2$, respectively, and correspond to the
analysis region with the smallest statistical uncertainty
($160 < p_T^{\text{max}} < 210$ GeV). Uncertainties due to multiple
$pp$ interactions in the same beam crossing ($< 0.8\%$ on
the cross section for all analysis regions) are included in
the evaluation of the jet energy scale uncertainties.

The normalized differential cross section is shown for
each of the nine $p_T^{\text{max}}$ analysis regions as a function of
$\Delta\phi$ in Fig. 2. As $p_T^{\text{max}}$ increases, and the probability
for the emission of a hard third jet is reduced, the fraction
of events near $\pi$ becomes larger. Overlaid on the
data are the results from a NLO pQCD $[Q(\alpha_s^3)]$ calculation,
NLOJET++ [10] with fastNLO [25] and using the
MSTW 2008 PDF [8]. The factorization and renormalization
scales are set to $p_T^{\text{max}}$ and are varied independently up and down
by a factor of two to determine the scale uncertainties. The scale uncertainties are larger between $\pi/2 < \Delta\phi < 2\pi/3$
where the pQCD calculation is effectively leading order in four-parton
production. The PDF uncertainties are treated as the
envelope of the 68$\%$ CL uncertainties from MSTW 2008 [8],
NNPDF 2.0 [26], and CTEQ 10 [27], and are combined with
the uncertainties resulting from an $\alpha_s$ variation of
$\pm 0.004$; the $\alpha_s$ contributions dominate. The calculation
is corrected for non-perturbative effects due to hadronization
and the underlying event [28, 29]; the correction is
smaller than 3$\%$. The fixed-order calculation fails near
$\Delta\phi \rightarrow \pi$ where soft processes dominate and contributions
from logarithmic terms are enhanced. Figure 3 displays
the ratio of the cross section with respect to the
NLO calculation. In most regions, the theory is consistent
with the data. However, the prediction in the range
$110 < p_T^{\text{max}} < 160$ GeV is relatively low in the central
region of $\Delta\phi$ where the scale uncertainties are small.

The data are also compared with predictions from
SHERPA, PYTHIA, and HERWIG in Fig. 3. The
leading-logarithmic approximations used in these event
generators’ parton-shower models effectively regularize the
divergence at $\Delta\phi \rightarrow \pi$; all three provide a good
description of the data in this region. In the region
$\pi/2 < \Delta\phi < 5\pi/6$, where multijet contributions are
significant, this observable distinguishes between the three
generators. SHERPA, which explicitly includes higher-order
tree-level diagrams, performs well in most $\Delta\phi$ and
$p_T^{\text{max}}$ regions. Having phenomenological parameters that
have been adjusted to previous ATLAS measurements,
PYTHIA [28] and HERWIG [24] also describe the data.

In summary, we present a measurement of dijet azimuthal
decorrelations in events produced in $pp$ collisions at $\sqrt{s} = 7$ TeV. The normalized differential cross sections
are based on the full dataset ($\mathcal{L} dt = 36\,\text{pb}^{-1}$) collected by the ATLAS collaboration during the 2010 run of the LHC. Expectations from NLO pQCD $[O(\alpha_s^4)]$ and those of several event generators successfully describe the general characteristics of our measurements, including the increasing slope of the $\Delta\phi$ distribution with $p_T^\text{max}$ and the shape near $\Delta\phi \sim \pi/2$ where events with multiple jets make a considerable contribution. Our data, which include jets with $p_T$ values that significantly exceed earlier measurements, explore QCD in a new kinematic region.

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[8] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Rapidity is defined as $y = \frac{1}{2} \ln[(E + p_T)/(E - p_T)]$, where $E$ is the energy and $p_T$ is the longitudinal component of the momentum along the beam direction.
7 The University of Texas at Arlington, Department of Physics, Box 19059, Arlington, TX 76019, United States of America
8 University of Athens, Nuclear & Particle Physics, Department of Physics, Panepistimiopolis, Zografou, GR 15771 Athens, Greece
9 National Technical University of Athens, Physics Department, 9-Iroon Polytechniou, GR 15780 Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, H. Javid Avenue 33, AZ 143 Baku, Azerbaijan
11 Instituto de Física de Altas Energías, IFAE, Edifici Cn, Universitat Autònoma de Barcelona, ES - 08193 Bellaterra (Barcelona), Spain
12 University of Belgrade(a), Institute of Physics, P.O. Box 57, 11001 Belgrade; Vinca Institute of Nuclear Sciences(b) M. Petrovica Alasa 12-14, 11000 Belgrade, Serbia, Serbia
13 University of Bergen, Department for Physics and Technology, Allegaten 55, NO - 5007 Bergen, Norway
14 Lawrence Berkeley National Laboratory and University of California, Physics Division, MS50B-6227, 1 Cyclotron Road, Berkeley, CA 94720, United States of America
15 Humboldt University, Institute of Physics, Berlin, Newtonstr. 15, D-12489 Berlin, Germany
16 University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Sidlerstrasse 5, CH - 3012 Bern, Switzerland
17 University of Birmingham, School of Physics and Astronomy, Edgbaston, Birmingham B15 2TT, United Kingdom
18 Bogazici University(a), Faculty of Sciences, Department of Physics, TR - 80815 Bebek-Istanbul; Dogus University(b), Faculty of Arts and Sciences, Department of Physics, 34722, Kadikoy, Istanbul; (c)Gaziantep University, Faculty of Engineering, Department of Physics Engineering, 27310, Sehitkamil, Gaziantep, Turkey; Istanbul Technical University(c), Faculty of Arts and Sciences, Department of Physics, 34469, Maslak, Istanbul, Turkey
19 INFN Sezione di Bologna(a); Università di Bologna, Dipartimento di Fisica(b), viale C. Berti Pichat, 6/2, IT - 40127 Bologna, Italy
20 University of Bonn, Physikalisches Institut, Nussallee 12, D - 53115 Bonn, Germany
21 Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, MA 02215, United States of America
22 Brandeis University, Department of Physics, MS057, 415 South Street, Waltham, MA 02454, United States of America
23 Universidade Federal do Rio de Janeiro, COPPE/EE/IF (a), Caixa Postal 68528, Ilha do Fundao, BR - 21945-970 Rio de Janeiro; (b)Universidade de Sao Paulo, Instituto de Fisica, R.do Matao Trav. R.187, Sao Paulo - SP, 05508 - 900, Brazil
24 Brookhaven National Laboratory, Physics Department, Bldg. 510A, Upton, NY 11973, United States of America
25 National Institute of Physics and Nuclear Engineering(a)Bucharest-Magurele, Str. Atomistilor 407, P.O. Box MG-6, R-077125, Romania; University Politechnica Bucuresti(b), Rectorat - AN 001, 313 Splaiul Independentei, sector 6, 060042 Bucuresti; West University(c) in Timisoara, Bd. Vasile Parvan 4, Timisoara, Romania
26 University of Buenos Aires, FCEyN, Dto. Fisica, Pab I - C. Universitaria, 1428 Buenos Aires, Argentina
27 University of Cambridge, Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, United Kingdom
28 Carleton University, Department of Physics, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada
29 CERN, CH - 1211 Geneva 23, Switzerland
30 University of Chicago, Enrico Fermi Institute, 5640 S. Ellis Avenue, Chicago, IL 60637, United States of America
31 Pontificia Universidad Católica de Chile, Facultad de Física, Departamento de Física(a), Avda. Vicuna Mackenna 4860, San Joaquin, Santiago; Universidad Técnica Federico Santa María, Departamento de Física(b), Avda. España 1680, Casilla 110-V, Valparaíso, Chile
32 Institute of High Energy Physics, Chinese Academy of Sciences(a), P.O. Box 918, 19 Yuquan Road, Shijing Shan District, CN - Beijing 100049; University of Science & Technology of China (USTC), Department of Modern Physics(b) Hefei, CN - Anhui 230026; Nanjing University, Department of Physics(c), Nanjing, CN - Jiangsu 210093; Shandong University, High Energy Physics Group(d), Jinan, CN - Shandong 250100, China
33 Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, FR - 63177 Aubiere Cedex, France
34 Columbia University, Nevis Laboratory, 136 So. Broadway, Irvington, NY 10533, United States of America
35 University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, DK - 2100 København 0, Denmark
36 INFN Gruppo Collegato di Cosenza(a); Università della Calabria, Dipartimento di Fisica(b), IT-87036 Arcavacata di Rende, Italy
37 Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology, (FPACS, AGH-UST), al. Mickiewicz 30, PL-30059 Cracow, Poland
Royal Holloway, University of London, Department of Physics, Egham Hill, Egham, Surrey TW20 0EX, United Kingdom

University College London, Department of Physics and Astronomy, Gower Street, London WC1E 6BT, United Kingdom

Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC, Université Paris Diderot, CNRS/IN2P3, 4 place Jussieu, FR - 75252 Paris Cedex 05, France

Fysiska institutionen, Lunds universitet, Box 118, SE - 221 00 Lund, Sweden

Universidad Autonoma de Madrid, Facultad de Ciencias, Departamento de Fisica Teorica, ES - 28049 Madrid, Spain

Universität Mainz, Institut für Physik, Staudinger Weg 7, DE - 55099 Mainz, Germany

University of Manchester, School of Physics and Astronomy, Manchester M13 9PL, United Kingdom

CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

University of Massachusetts, Department of Physics, 710 North Pleasant Street, Amherst, MA 01003, United States of America

McGill University, High Energy Physics Group, 3600 University Street, Montreal, Quebec H3A 2T8, Canada

University of Melbourne, School of Physics, AU - Parkville, Victoria 3010, Australia

The University of Michigan, Department of Physics, 2477 Randall Laboratory, 500 East University, Ann Arbor, MI 48109-1120, United States of America

Michigan State University, Department of Physics and Astronomy, High Energy Physics Group, East Lansing, MI 48824-2320, United States of America

INFN Sezione di Milano\(^{(a)}\); Università di Milano, Dipartimento di Fisica\(^{(b)}\), via Celoria 16, IT - 20133 Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Independence Avenue 68, Minsk 220072, Republic of Belarus

National Scientific & Educational Centre for Particle & High Energy Physics, NC PHEP BSU, M. Bogdanovich St. 153, Minsk 220040, Republic of Belarus

Massachusetts Institute of Technology, Department of Physics , Room 24-516, Cambridge, MA 02139, United States of America

University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Leninsky pr. 53, RU - 117 924 Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), B. Cheremushkinskaya ul. 25, RU 117 218 Moscow, Russia

Moscow Engineering & Physics Institute (MEPhI), Kashirskoe Shosse 31, RU - 115409 Moscow, Russia

Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP), 12(2), Leninskie gory, GSP-1, Moscow 119991 Russian Federation, Russia

Ludwig-Maximilians-Universität München, Fakultät für Physik, Am Coulombwall 1, DE - 85748 Garching, Germany

Max-Planck-Institut für Physik, (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

Nagasaki Institute of Applied Science, 536 Aba-machi, JP Nagasaki 851-0193, Japan

Nagoya University, Graduate School of Science, Furo-Cho, Chikusa-ku, Nagoya, 464-8602, Japan

INFN Sezione di Napoli\(^{(a)}\); Università di Napoli, Dipartimento di Scienze Fisiche\(^{(b)}\), Complesso Universitario di Monte Sant’Angelo, via Cinthia, IT - 80126 Napoli, Italy

University of New Mexico, Department of Physics and Astronomy, MSC07 4220, Albuquerque, NM 87131 USA, United States of America

Nikhef National Institute for Subatomic Physics, and University of Amsterdam, Science Park 105, 1098 XG Amsterdam, Netherlands

Department of Physics, Northern Illinois University, LaTourette Hall Normal Road, DeKalb, IL 60115, United States of America

Budker Institute of Nuclear Physics (BINP), RU - Novosibirsk 630 090, Russia

New York University, Department of Physics, 4 Washington Place, New York NY 10003, USA, United States of America

Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210-1117, United States of America

Okayama University, Faculty of Science, Tsushimanaka 3-1-1, Okayama 700-8530, Japan
111 University of Oklahoma, Homer L. Dodge Department of Physics and Astronomy, 440 West Brooks, Room 100, Norman, OK 73019-0225, United States of America
112 Oklahoma State University, Department of Physics, 145 Physical Sciences Building, Stillwater, OK 74078-3072, United States of America
113 Palacký University, 17.listopadu 50a, 772 07 Olomouc, Czech Republic
114 University of Oregon, Center for High Energy Physics, Eugene, OR 97403-1274, United States of America
115 LAL, Univ. Paris-Sud, IN2P3/CNRS, Orsay, France
116 Osaka University, Graduate School of Science, Machikaneyama-machi 1-1, Toyonaka, Osaka 560-0043, Japan
117 University of Oslo, Department of Physics, P.O. Box 1048, Blindern, NO - 0316 Oslo 3, Norway
118 Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom
119 INFN Sezione di Pavia(a); Università di Pavia, Dipartimento di Fisica Nucleare e Teorica(b), Via Bassi 6, IT-27100 Pavia, Italy
120 University of Pennsylvania, Department of Physics, High Energy Physics Group, 209 S. 33rd Street, Philadelphia, PA 19104, United States of America
121 Petersburg Nuclear Physics Institute, RU - 188 300 Gatchina, Russia
122 INFN Sezione di Pisa(a); Università di Pisa, Dipartimento di Fisica E. Fermi(b), Largo B. Pontecorvo 3, IT - 56127 Pisa, Italy
123 University of Pittsburgh, Department of Physics and Astronomy, 3941 O’Hara Street, Pittsburgh, PA 15260, United States of America
124 Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP(a), Avenida Elias Garcia 14-1, PT - 1000-149 Lisboa, Portugal; Universidad de Granada, Departamento de Fisica Teorica y del Cosmos and CAFPE(b), E-18071 Granada, Spain
125 Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ - 18221 Praha 8, Czech Republic
126 Charles University in Prague, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, V Holesovickach 2, CZ - 18000 Praha 8, Czech Republic
127 Czech Technical University in Prague, Zikova 4, CZ - 166 35 Praha 6, Czech Republic
128 State Research Center Institute for High Energy Physics, Moscow Region, 142281, Protvino, Pobeda street, 1, Russia
129 Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom
130 University of Regina, Physics Department, Canada
131 Ritsumeikan University, Noji Higashi 1 chome 1-1, JP - Kusatsu, Shiga 525-8577, Japan
132 INFN Sezione di Roma I(a); Università La Sapienza, Dipartimento di Fisica(b), Piazzale A. Moro 2, IT- 00185 Roma, Italy
133 INFN Sezione di Roma Tor Vergata(a); Università di Roma Tor Vergata, Dipartimento di Fisica(b), via della Ricerca Scientifica, IT-00133 Roma, Italy
134 INFN Sezione di Roma Tre(a); Università Roma Tre, Dipartimento di Fisica(b), via della Vasca Navale 84, IT-00146 Roma, Italy
135 Réseau Universitaire de Physique des Hautes Energies (RUPHE): Université Hassan II, Faculté des Sciences Ain Chock(a), B.P. 5366, MA - Casablanca; Centre National de l’Energie des Sciences Techniques Nucleaires (CNESTEN)(b), B.P. 1382 R.P. 10001 Rabat 10001; Université Mohamed Premier(c), LPTPM, Faculté des Sciences, B.P.717. Bd. Mohamed VI, 60000, Oujda ; Université Mohammed V, Faculté des Sciences(d),4 Avenue Ibn Battouta, BP 1014 RP, 10000 Rabat, Morocco
136 CEA, DSM/IRFU, Centre d’Etudes de Saclay, FR - 91919 Gif-sur-Yvette, France
137 University of California Santa Cruz, Santa Cruz Institute for Particle Physics (SCIPP), Santa Cruz, CA 95064, United States of America
138 University of Washington, Seattle, Department of Physics, Box 351560, Seattle, WA 98195-1560, United States of America
139 University of Sheffield, Department of Physics & Astronomy, Hounsfield Road, Sheffield S3 7RH, United Kingdom
140 Shinshu University, Department of Physics, Faculty of Science, 3-1-1 Asahi, Matsumoto-shi, JP - Nagano 390-8621, Japan
141 Universität Siegen, Fuchbereich Physik, D 57068 Siegen, Germany
142 Simon Fraser University, Department of Physics, 8888 University Drive, CA - Burnaby, BC V5A 1S6, Canada
143 SLAC National Accelerator Laboratory, Stanford, California 94309, United States of America
144 Comenius University, Faculty of Mathematics, Physics & Informatics\(^{(a)}\), Mlynska dolina F2, SK - 84248
Bratislava; Institute of Experimental Physics of the Slovak Academy of Sciences, Dept. of Subnuclear Physics\(^{(b)}\), Watsonova 47, SK - 04353 Kosice, Slovak Republic
145 \(^{(a)}\)University of Johannesburg, Department of Physics, PO Box 524, Auckland Park, Johannesburg 2006;
\(^{(b)}\)School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, Johannesburg, South Africa, South Africa
146 Stockholm University: Department of Physics\(^{(a)}\); The Oskar Klein Centre\(^{(b)}\), AlbaNova, SE - 106 91 Stockholm, Sweden
147 Royal Institute of Technology (KTH), Physics Department, SE - 106 91 Stockholm, Sweden
148 Stony Brook University, Department of Physics and Astronomy, Nicolls Road, Stony Brook, NY 11794-3800,
United States of America
149 University of Sussex, Department of Physics and Astronomy Pevensey 2 Building, Falmer, Brighton BN1 9QH,
United Kingdom
150 University of Sydney, School of Physics, AU - Sydney NSW 2006, Australia
151 Institute of Physics, Academia Sinica, TW - Taipei 11529, Taiwan
152 Technion, Israel Inst. of Technology, Department of Physics, Technion City, IL - Haifa 32000, Israel
153 Tel Aviv University, Raymond and Beverly Sackler School of Physics and Astronomy, Ramat Aviv, IL - Tel Aviv
69978, Israel
154 Aristotle University of Thessaloniki, Faculty of Science, Department of Physics, Division of Nuclear & Particle
Physics, University Campus, GR - 54124, Thessaloniki, Greece
155 The University of Tokyo, International Center for Elementary Particle Physics and Department of Physics, 7-3-1
Hongo, Bunkyo-ku, JP - Tokyo 113-0033, Japan
156 Tokyo Metropolitan University, Graduate School of Science and Technology, 1-1 Minami-Osawa, Hachioji, Tokyo
192-0397, Japan
157 Tokyo Institute of Technology, Department of Physics, 2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan
158 University of Toronto, Department of Physics, 60 Saint George Street, Toronto M5S 1A7, Ontario, Canada
159 TRIUMF\(^{(a)}\), 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3; \(^{(b)}\)York University, Department of Physics and
Astronomy, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada
160 University of Tsukuba, Institute of Pure and Applied Sciences, 1-1-1 Tennoudai, Tsukuba-shi, JP - Ibaraki
305-8571, Japan
161 Tufts University, Science & Technology Center, 4 Colby Street, Medford, MA 02155, United States of America
162 Universidad Antonio Narino, Centro de Investigaciones, Cra 3 Este No.47A-15, Bogota, Colombia
163 University of California, Irvine, Department of Physics & Astronomy, CA 92697-4575, United States of America
164 INFN Gruppo Collegato di Udine\(^{(a)}\); ICTP\(^{(b)}\), Strada Costiera 11, IT-34014, Trieste; Università di Udine,
Dipartimento di Fisica\(^{(c)}\), via delle Scienze 208, IT - 33100 Udine, Italy
165 University of Illinois, Department of Physics, 1110 West Green Street, Urbana, Illinois 61801, United States of
America
166 University of Uppsala, Department of Physics and Astronomy, P.O. Box 516, SE -751 20 Uppsala, Sweden
167 Instituto de Física Corpuscular (IFIC) Centro Mixto UVEG-CSIC, Apdo. 22085 ES-46071 Valencia, Dept.
Física At. y Nuclear; Dept. Ing. Electrónica; Univ. of Valencia, and Inst. de Microelectrónica de Barcelona
(IMB-CNMC-CSIC) 08193 Bellaterra, Spain
168 University of British Columbia, Department of Physics, 6224 Agricultural Road, CA - Vancouver, B.C. V6T 1Z1,
Canada
169 University of Victoria, Department of Physics and Astronomy, P.O. Box 3055, Victoria B.C., V8W 3P6, Canada
170 Waseda University, WISE, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan
171 The Weizmann Institute of Science, Department of Particle Physics, P.O. Box 26, IL - 76100 Rehovot, Israel
172 University of Wisconsin, Department of Physics, 1150 University Avenue, WI 53706 Madison, Wisconsin, United
States of America
173 Julius-Maximilians-University of Würzburg, Physikalisches Institute, Am Hubland, 97074 Würzburg, Germany
174 Bergische Universität, Fachbereich C, Physik, Postfach 100127, Gauss-Strasse 20, D- 42097 Wuppertal, Germany
175 Yale University, Department of Physics, PO Box 208121, New Haven CT, 06520-8121, United States of America
176 Yerevan Physics Institute, Alikhanian Brothers Street 2, AM - 375036 Yerevan, Armenia
177 Centre de Calcul CNRS/IN2P3, Domaine scientifique de la Doua, 27 bd du 11 Novembre 1918, 69622
Villeurbanne Cedex, France
\(^{a}\) Also at LIP, Portugal
\textsuperscript{b} Also at Faculdade de Ciencias, Universidade de Lisboa, Lisboa, Portugal
\textsuperscript{c} Also at CPPM, Marseille, France.
\textsuperscript{d} Also at TRIUMF, Vancouver, Canada
\textsuperscript{e} Also at FPACS, AGH-UST, Cracow, Poland
\textsuperscript{f} Also at Department of Physics, University of Coimbra, Coimbra, Portugal
\textsuperscript{g} Also at Università di Napoli Parthenope, Napoli, Italy
\textsuperscript{h} Also at Institute of Particle Physics (IPP), Canada
\textsuperscript{i} Also at Louisiana Tech University, Ruston, USA
\textsuperscript{j} Also at Universidade de Lisboa, Lisboa, Portugal
\textsuperscript{k} At California State University, Fresno, USA
\textsuperscript{l} Also at Faculdade de Ciencias, Universidade de Lisboa and at Centro de Fisica Nuclear da Universidade de Lisboa, Lisboa, Portugal
\textsuperscript{m} Also at California Institute of Technology, Pasadena, USA
\textsuperscript{n} Also at University of Montreal, Montreal, Canada
\textsuperscript{o} Also at Baku Institute of Physics, Baku, Azerbaijan
\textsuperscript{p} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
\textsuperscript{q} Also at Manhattan College, New York, USA
\textsuperscript{r} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
\textsuperscript{s} Also at Taiwan Tier-1, ASGC, Academia Sinica, Taipei, Taiwan
\textsuperscript{t} Also at School of Physics, Shandong University, Jinan, China
\textsuperscript{u} Also at Rutherford Appleton Laboratory, Didcot, UK
\textsuperscript{v} Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
\textsuperscript{w} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, USA
\textsuperscript{x} Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
\textsuperscript{y} Also at Institute of Physics, Jagiellonian University, Cracow, Poland
\textsuperscript{z} Also at Centro de Fisica Nuclear da Universidade de Lisboa, Lisboa, Portugal
\textsuperscript{aa} Also at Department of Physics, Oxford University, Oxford, UK
\textsuperscript{ab} Also at CEA, Gif sur Yvette, France
\textsuperscript{ac} Also at LPNHE, Paris, France
\textsuperscript{ad} Also at Nanjing University, Nanjing Jiangsu, China
\textsuperscript{*} Deceased