Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

G. Aad et al. (The ATLAS Collaboration)*

Collisions of heavy ions at ultra-relativistic energies are expected to produce an evanescent hot, dense state, with temperatures exceeding two trillion kelvins, in which the relevant degrees of freedom are not hadrons, but quarks and gluons. In this medium, high-energy quarks and gluons are expected to transfer energy to the medium by multiple interactions with the ambient plasma. There is a rich theoretical literature on in-medium QCD energy loss extending back to Bjorken, who proposed to look for “jet quenching” in proton-proton collisions [1]. This work also suggested the observation of highly unbalanced dijets when one jet is produced at the periphery of the collision. For comprehensive reviews of recent theoretical work in this area, see Refs. [2, 3].

Single particle measurements made by RHIC experiments established that high transverse momentum ($p_T$) hadrons are produced at rates a factor of five or more lower than expected by assuming QCD factorization holds in every binary collision of nucleons in the oncoming nuclei [4, 5]. This observation is characterized by measurements of $R_{AA}$, the ratio of yields in heavy ion collisions to proton-proton collisions, divided by the number of binary collisions. Di-hadron measurements also showed a clear absence of back-to-back hadron production in more central heavy ion collisions [5], strongly suggestive of jet suppression. The limited rapidity coverage of the experiment, and jet energies comparable to the underlying event energy, prevented a stronger conclusion being drawn from these data.

The LHC heavy ion program was foreseen to provide an opportunity to study jet quenching at much higher jet energies than achieved at RHIC. This letter provides the first measurements of jet production in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV per nucleon-nucleon collision, the highest center of mass energy ever achieved for nuclear collisions. At this energy, next-to-leading-order QCD calculations [6] predict abundant rates of jets above 100 GeV produced in the pseudorapidity region $|\eta| < 4.5$ [7], which can be reconstructed by ATLAS.

The data in this paper were obtained by ATLAS during the 2010 lead-lead run at the LHC and correspond to an integrated luminosity of approximately 1.7 $\mu$b$^{-1}$.

For this study, the focus is on the balance between the highest transverse energy pair of jets in events where those jets have an azimuthal angle separation, $\Delta\phi = |\phi_1 - \phi_2| > \pi/2$ to reduce contributions from multi-jet final states. In this letter, jets with $\Delta\phi > \pi/2$ are labeled as being in opposite hemispheres. The jet energy imbalance is expressed in terms of the asymmetry $A_J$,

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

where the first jet is required to have a transverse energy $E_{T1} > 100$ GeV, and the second jet is the highest transverse energy jet in the opposite hemisphere with $E_{T2} > 25$ GeV. The average contribution of the underlying event energy is subtracted when deriving the individual jet transverse energies. The event selection is chosen such that the first jet has high reconstruction efficiency and the second jet is above the distribution of background fluctuations and the intrinsic soft jets associated with the collision. Dijet events are expected to have $A_J$ near zero, with deviations expected from gluon radiation falling outside the jet cone, as well as from instrumental effects. Energy loss in the medium could lead to much stronger deviations in the reconstructed energy balance.

The ATLAS detector [8] is well-suited for measuring jets due to its large acceptance, highly segmented electromagnetic (EM) and hadronic calorimeters. These allow efficient reconstruction of jets over a wide range in the region $|\eta| < 4.5$. The detector also provides precise charged particle and muon tracking. An event display showing the Inner Detector and calorimeter systems is shown in Fig. 1.

Liquid argon (LAr) technology providing excellent energy and position resolution is used in the electromagnetic calorimeter that covers the pseudorapidity range

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FIG. 1: Event display of a highly asymmetric dijet event, with one jet with $E_T > 100$ GeV and no evident recoiling jet, and with high energy calorimeter cell deposits distributed over a wide azimuthal region. By selecting tracks with $p_T > 2.6$ GeV and applying cell thresholds in the calorimeters ($E_T > 700$ MeV in the electromagnetic calorimeter, and $E > 1$ GeV in the hadronic calorimeter) the recoil can be seen dispersed widely over azimuth.

$|\eta| < 3.2$. The hadronic calorimetry in the range $|\eta| < 1.7$ is provided by a sampling calorimeter made of steel and scintillating tiles. In the end-caps ($1.5 < |\eta| < 3.2$), LAr technology is also used for the hadronic calorimeters, matching the outer $|\eta|$ limits of the electromagnetic calorimeters. To complete the $\eta$ coverage, the LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, extending the coverage up to $|\eta| = 4.9$. The calorimeter ($\eta, \phi$) granularities are $0.1 \times 0.1$ for the hadronic calorimeters up to $|\eta| = 2.5$ (except for the third layer of the Tile calorimeter, which has a segmentation of $0.2 \times 0.1$ up to $|\eta| = 1.7$), and then $0.2 \times 0.2$ up to $|\eta| = 4.9$. The EM calorimeters are longitudinally segmented into three compartments and feature a much finer readout granularity varying by layer, with cells as small as $0.025 \times 0.025$ extending to $|\eta| = 2.5$ in the middle layer. In the data taking period considered, approximately 187,000 calorimeter cells (98% of the total) were usable for event reconstruction.

The bulk of the data reported here were triggered using coincidence signals from two sets of Minimum Bias Trigger Scintillator (MBTS) detectors, positioned at $z = \pm 3.56$ m, covering the full azimuth between $2.09 < |\eta| < 3.84$ and divided into eight $\phi$ sectors and two $\eta$ sectors. Coincidences in the Zero Degree Calorimeter and LUCID luminosity detectors were also used as primary triggers, since these detectors were far less susceptible to LHC beam backgrounds. These triggers have a large overlap and are close to fully efficient for the events studied here.

In the offline analysis, events are required to have a time difference between the two sets of MBTS counters of $\Delta t < 3$ ns and a reconstructed vertex to efficiently reject beam-halo backgrounds. The primary vertex is derived from the reconstructed tracks in the Inner Detector (ID), which covers $|\eta| < 2.5$ using silicon pixel and strip detectors surrounded by straw tubes. These event selection criteria have been estimated to accept over 98% of the total lead-lead inelastic cross section.

The level of event activity or “centrality” is characterized using the total transverse energy ($\Sigma E_T$) deposited in the Forward Calorimeters (FCal), which cover $3.2 < |\eta| < 4.9$, shown in Fig. 2. Bins are defined in centrality according to fractions of the total lead-lead cross section selected by the trigger and are expressed in terms of percentiles (0-10%, 10-20%, 20-40% and 40-100%) with 0% representing the upper end of the $\Sigma E_T$ distribution. Previous heavy ion experiments have shown a clear correlation of the $\Sigma E_T$ with the geometry of the overlap region of the colliding nuclei and, correspondingly, the total event multiplicity. This is verified in the bottom panel of Fig. 2 which shows a tight correlation between the energy flow near mid-rapidity and the forward $\Sigma E_T$. The forward $\Sigma E_T$ is used for this analysis to avoid biasing the centrality measurement with jets.

Jets have been reconstructed using the infrared-safe anti-$k_t$ jet clustering algorithm [9] with the radius parameter $R = 0.4$. The inputs to this algorithm are “towers” of calorimeter cells of size $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ with the input cells weighted using energy-density dependent factors to correct for calorimeter non-compensation and other energy losses. Jet four-momenta are constructed by the vectorial addition of cells, treating each cell as an $(E, \vec{p})$ four-vector with zero mass.

The jets reconstructed using the anti-$k_t$ algorithm contain a mix of genuine jets and jet-sized patches of the underlying event. For each event, we estimate the average transverse energy density in each calorimeter layer in bins of width $\Delta \eta = 0.1$, and averaged over azimuth. In the averaging, we exclude jets with $D = E_T(\text{max})/(E_T)$, the ratio of the maximum tower energy over the mean tower energy, greater than 5. The value $D_{\text{cut}} = 5$ is chosen
FIG. 2: (top) Distribution of uncorrected $\Sigma E_T$ in the Forward Calorimeter (FCal). Bins in event activity or "centrality" are indicated by the alternating bands (see text for details) and labeled according to increasing fraction of lead-lead total cross section starting from the largest measured $\Sigma E_T$.

(bottom) Correlation of uncorrected $\Sigma E_T$ in $|\eta| < 3.2$ with that measured in the FCal ($3.2 < |\eta| < 4.9$).

based upon simulation studies, and the results have been tested to be stable against variations in this parameter. These average energies are subtracted layer-by-layer from the cells that make up each jet, scaling appropriately for the cell area. The final reported four-momentum for each jet is then recalculated from the remaining energy in the cells.

The efficiency of the jet reconstruction algorithm, and other event properties, have been studied using PYTHIA [10] events superimposed on HIJING events [11]. There is no parton-level interference between the PYTHIA and HIJING generated events. A GEANIT4 [12] simulation models the detector response [13] to all the final state particles from the two generated events. The HIJING parameters used do not include jet quenching, but variations in flow as a function of centrality are added. It is found that jets with $E_T > 100$ GeV are reconstructed with nearly 100% efficiency at all centralities.

Simulations have been used to check the overall linearity and resolution of the reconstruction with respect to the primary jet energy, assuming jet shapes similar to those found in proton-proton collisions [14]. However, the efficiency, linearity, and resolution for reconstructing jets may be poorer if the jets are substantially modified by the medium. To check the sensitivity to such effects, the jet shape, characterized here as the ratio of the "core" energy (integrated over $\sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.2$) to the total energy, has been studied. This ratio shows only a weak dependence on centrality, providing evidence that the high-energy jets do look approximately like jets measured in proton-proton collisions, and that the energy subtraction procedure does not introduce significant biases.

After event selection, the requirement of a leading jet with $E_T > 100$ GeV and $|\eta| < 2.8$ yields a sample of 1693 events. These are called the "jet selected events". The lead-lead data are also compared with a sample of 17 nb$^{-1}$ of proton-proton collision data [14], which yields 6732 events.

A striking feature of this sample is the appearance of events with only one high ET jet clearly visible in the calorimeter, and no high ET jet opposite to it in azimuth. Such an event is shown in Fig. 1. The calorimeter $E_T$ and charged particle $E_T$ are shown in regions of $\eta \times \Delta \phi = 0.1 \times 0.1$. Inspection of this event shows a highly asymmetric pair of jets with the particles recoiling against the leading jet being widely distributed in azimuth.

To quantify the transverse energy balance between jets in these events, we calculate the dijet asymmetry, $A_J$, in different centrality bins between the highest $E_T$ (leading) jet and the highest $E_T$ jet in the opposite hemisphere (second jet). The second jet is required to have $E_T > 25$ GeV in order to discriminate against background from the underlying event. This excludes around 5% of the jet selected events in the most central 40% of the cross section, and accepts nearly all of the more peripheral events.

The dijet asymmetry and $\Delta \phi$ distributions are shown in four centrality bins in Fig. 3, where they are compared with proton-proton data and with fully-reconstructed HI-JING+PYTHIA simulated events. The simulated events are intended to illustrate the effect of the heavy ion background on jet reconstruction, not any underlying physics process. The dijet asymmetry in peripheral lead-lead events is similar to that in both proton-proton and simulated events; however, as the events become more central, the lead-lead data distributions develop different characteristics, indicating an increased rate of highly asymmetric dijet events. The asymmetry distribution broadens; the mean shifts to higher values; the peak at zero asymmetry is no longer visible; and for the most central events a peak is visible at higher asymmetry values.
FIG. 3: (top) Dijet asymmetry distributions for data (points) and unquenched HIJING with superimposed PYTHIA dijets (solid yellow histograms), as a function of collision centrality (left to right from peripheral to central events). Proton-proton data from √s = 7 TeV, analyzed with the same jet selection, is shown as open circles. (bottom) Distribution of Δφ, the azimuthal angle between the two jets, for data and HIJING+PYTHIA, also as a function of centrality.

Numerous studies have been performed to verify that the events with large asymmetry are not produced by backgrounds or detector effects. Detector effects primarily include readout errors and local acceptance loss due to dead channels and detector cracks. All of the jet events in this sample were checked, and no events were flagged as problematic. The analysis was repeated first requiring both jets to be within |η| < 1 and |η| < 2, to see if there is any effect related to boundaries between the calorimeter sections, and no change to the distribution was observed. Furthermore, the highly-asymmetric dijets were not found to populate any specific region of the calorimeter, indicating that no substantial fraction of produced energy was lost in an inefficient or uncovered region.

To investigate the effect of the underlying event, the jet radius parameter R was varied from 0.4 to 0.2 and 0.6 with the result that the large asymmetry was not reduced. In fact, the asymmetry increased for the smaller radius, which would not be expected if detector effects are dominant. The analysis was independently corroborated by a study of “track jets”, reconstructed with ID tracks of pT > 4 GeV using the same jet algorithms. The ID has an estimated efficiency for reconstructing charged hadrons above pT > 1 GeV of approximately 80% in the most peripheral events (the same as that found in 7 TeV proton-proton operation) and 70% in the most central events, due to the approximately 10% occupancy reached in the silicon strips. A similar asymmetry effect is also observed with track jets. The jet energy scale and underlying event subtraction were also validated by correlating calorimeter and track-based jet measurements.

The missing ET distribution was measured for minimum bias heavy ion events as a function of the total ET deposited in the calorimeters up to about ΣET = 10 TeV. The resolution as a function of total ET shows the same behavior as in proton-proton collisions. None of the events in the jet selected sample was found to have an anomalously large missing ET.

The events containing high-pT jets were studied for the presence of high-pT muons that could carry a large fraction of the recoil energy. Fewer than 2% of the events have a muon with pT > 10 GeV, potentially recoiling against the leading jet, so this can not explain the prevalence of highly asymmetric dijet topologies in more central events.

None of these investigations indicate that the highly-asymmetric dijet events arise from backgrounds or detector-related effects.

In summary, first results are presented on jet reconstruction in lead-lead collisions, with the ATLAS detector at the LHC. In a sample of events with a reconstructed jet with transverse energy of 100 GeV or more, an asymmetry is observed between the transverse energies of the
leading and second jets that increases with the centrality of the collisions. This has a natural interpretation in terms of QCD energy loss, where the second jet is attenuated, in some cases leading to striking highly-asymmetric dijet events. This observation is the first of an enhancement of such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

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

[7] The ATLAS reference system is a Cartesian right-handed coordinate system, with the nominal collision point at the origin. The anticlockwise beam direction defines the positive z-axis, while the positive x-axis is defined as pointing from the collision point to the center of the LHC ring and the positive y-axis points upwards. The azimuthal angle $\phi$ is measured around the beam axis, and the polar angle $\theta$ is measured with respect to the z-axis. Pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$.

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, PL - 31342 Krakow, Poland
Southern Methodist University, Physics Department, 106 Fondren Science Building, Dallas, TX 75275-0175, United States of America
University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080-3021, United States of America
DESY, Notkestr. 85, D-22603 Hamburg and Platanenallee 6, D-15738 Zeuthen, Germany
TU Dortmund, Experimentelle Physik IV, DE - 44221 Dortmund, Germany
Technical University Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, D-01069 Dresden, Germany
Universität Dortmund, Experimentelle Physik IV, DE - 44221 Dortmund, Germany
Duke University, Department of Physics, Durham, NC 27708, United States of America
University of Edinburgh, School of Physics & Astronomy, James Clerk Maxwell Building, The Kings Buildings, Mayfield Road, Edinburgh EH9 3JZ, United Kingdom
INFN Sezione di Genova(a); Università di Genova, Dipartimento di Fisica(b), via Dodecaneso 33, IT - 16146 Genova, Italy
Institute of Physics of the Georgian Academy of Sciences, 6 Tamarashvili St., GE - 380077 Tbilisi; Tbilisi State University, HEP Institute, University St. 9, GE - 380086 Tbilisi, Georgia
Justus-Liebig-Universität Giessen, II Physikalisches Institut, Heinrich-Buff Ring 16, D-35392 Giessen, Germany
University of Glasgow, Department of Physics and Astronomy, Glasgow G12 SQX, United Kingdom
Georg-August-Universität, II. Physikalisches Institut, Friedrich-Hund Platz 1, D-37077 Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, 53 avenue des Martyrs, FR - 38026 Grenoble Cedex, France
Hampton University, Department of Physics, Hampton, VA 23668, United States of America
Harvard University, Laboratory for Particle Physics and Cosmology, 18 Hammond Street, Cambridge, MA 02138, United States of America
Ruprecht-Karls-Universität Heidelberg: Kirchhoff-Institut für Physik(a), Im Neuenheimer Feld 227, D-69120 Heidelberg; Physikalisches Institut(b), Philosophenweg 12, D-69120 Heidelberg; ZITI Ruprecht-Karls-University Heidelberg(c), Lehrstuhl für Informatik V, B6, 23-29, DE - 68131 Mannheim, Germany
Hiroshima University, Faculty of Science, 1-3-1 Kagamiyama, Higashihiroshima-shi, JP - Hiroshima 739-8526, Japan
Hiroshima Institute of Technology, Faculty of Applied Information Science, 2-1-1 Miyake Saeki-ku, Hiroshima-shi, JP - Hiroshima 731-5193, Japan
Indiana University, Department of Physics, Swain Hall West 117, Bloomington, IN 47405-7105, United States of America
Institut für Astro- und Teilchenphysik, Technikerstrasse 25, A - 6020 Innsbruck, Austria
University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242-1479, United States of America
Iowa State University, Department of Physics and Astronomy, Ames High Energy Physics Group, Ames, IA 50011-3160, United States of America
Joint Institute for Nuclear Research, JINR Dubna, RU-141980 Moscow Region, Russia
KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305-0801, Japan
Kobe University, Graduate School of Science, 1-1 Rokkodai-cho, Nada-ku, JP Kobe 657-8501, Japan
Kyoto University, Faculty of Science, Oiwake-cho, Kitashirakawa, Sakyou-ku, Kyoto-shi, JP - Kyoto 606-8502, Japan
Kyoto University of Education, 1 Fukakusa, Fujimori, fushimi-ku, Kyoto-shi, JP - Kyoto 612-8522, Japan
Universidad Nacional de La Plata, FCE, Departamento de Física, IFLP (CONICET-UNLP), C.C. 67, 1900 La Plata, Argentina
Lancaster University, Physics Department, Lancaster LA1 4YB, United Kingdom
INFN Sezione di Lecce(a); Università del Salento, Dipartimento di Fisica(b)Via Arneseo IT - 73100 Lecce, Italy
University of Liverpool, Oliver Lodge Laboratory, P.O. Box 147, Oxford Street, Liverpool L69 3BX, United Kingdom
Jožef Stefan Institute and University of Ljubljana, Department of Physics, SI-1000 Ljubljana, Slovenia
Queen Mary University of London, Department of Physics, Mile End Road, London E1 4NS, United Kingdom
16

76 Royal Holloway, University of London, Department of Physics, Egham Hill, Egham, Surrey TW20 0EX, United Kingdom
77 University College London, Department of Physics and Astronomy, Gower Street, London WC1E 6BT, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, Université Pierre et Marie Curie (Paris 6), Université Denis Diderot (Paris-7), CNRS/IN2P3, Tour 33, 4 place Jussieu, FR - 75252 Paris Cedex 05, France
79 Fysiska institutionen, Lunds universitet, Box 118, SE - 221 00 Lund, Sweden
80 Universidad Autonoma de Madrid, Facultad de Ciencias, Departamento de Fisica Teorica, ES - 28049 Madrid, Spain
81 Universität Mainz, Institut für Physik, Staudinger Weg 7, DE - 55099 Mainz, Germany
82 University of Manchester, School of Physics and Astronomy, Manchester M13 9PL, United Kingdom
83 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
84 University of Massachusetts, Department of Physics, 710 North Pleasant Street, Amherst, MA 01003, United States of America
85 McGill University, High Energy Physics Group, 3600 University Street, Montreal, Quebec H3A 2T8, Canada
86 University of Melbourne, School of Physics, AU - Parkville, Victoria 3010, Australia
87 The University of Michigan, Department of Physics, 2477 Randall Laboratory, 500 East University, Ann Arbor, MI 48109-1120, United States of America
88 Michigan State University, Department of Physics and Astronomy, High Energy Physics Group, East Lansing, MI 48824-2320, United States of America
89 INFN Sezione di Milano(a); Università di Milano, Dipartimento di Fisica(b), via Celoria 16, IT - 20133 Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Independence Avenue 68, Minsk 220072, Republic of Belarus
91 National Scientific & Educational Centre for Particle & High Energy Physics, NC PHEP BSU, M. Bogdanovich St. 153, Minsk 220040, Republic of Belarus
92 Massachusetts Institute of Technology, Department of Physics, Room 24-516, Cambridge, MA 02139, United States of America
93 University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada
94 P.N. Lebedev Institute of Physics, Academy of Sciences, Leninsky pr. 53, RU - 117 924 Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), B. Cheremushkinskaya ul. 25, RU 117 218 Moscow, Russia
96 Moscow Engineering & Physics Institute (MEPhI), Kashirskoe Shose 31, RU - 115409 Moscow, Russia
97 Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP), 1/2, Leninskie gory, GSP-1, Moscow 119991 Russian Federation, Russia
98 Ludwig-Maximilians-Universität München, Fakultät für Physik, Am Coulombwall 1, DE - 85743 Garching, Germany
99 Max-Planck-Institut für Physik, (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
100 Nagasaki Institute of Applied Science, 536 Aba-machi, JP Nagasaki 851-0193, Japan
101 Nagoya University, Graduate School of Science, Furo-Cho, Chikusa-ku, Nagoya, 464-8602, Japan
102 INFN Sezione di Napoli(a); Università di Napoli, Dipartimento di Scienze Fisiche(b), Complesso Universitario di Monte Sant’Angelo, via Cintia, IT - 80126 Napoli, Italy
103 University of New Mexico, Department of Physics and Astronomy, MSC07 4220, Albuquerque, NM 87131 USA, United States of America
104 Radboud University Nijmegen/NIKHEF, Department of Experimental High Energy Physics, Heyendaalseweg 135, NL-6525 AJ, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics, and University of Amsterdam, Science Park 105, 1098 XG Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, LaTourette Hall Normal Road, DeKalb, IL 60115, United States of America
107 Budker Institute of Nuclear Physics (BINP), RU - Novosibirsk 630 090, Russia
108 New York University, Department of Physics, 4 Washington Place, New York NY 10003, USA, United States of America
109 Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210-1117, United States of America
110 Okayama University, Faculty of Science, Tsushimanaka 3-1-1, Okayama 700-8530, Japan
SLAC National Accelerator Laboratory, Stanford, California 94309, United States of America
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
Uniersity of Johannesburg, Department of Physics, PO Box 524, Auckland Park, Johannesburg 2006;
School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, Johannesburg, South Africa, South Africa
Stockholm University: Department of Physics(a); The Oskar Klein Centre(b), AlbaNova, SE - 106 91 Stockholm, Sweden
Royal Institute of Technology (KTH), Physics Department, SE - 106 91 Stockholm, Sweden
Stony Brook University, Department of Physics and Astronomy, Nicolls Road, Stony Brook, NY 11794-3800, United States of America
University of Sussex, Department of Physics and Astronomy Pevensey 2 Building, Falmer, Brighton BN1 9QH, United Kingdom
University of Sydney, School of Physics, AU - Sydney NSW 2006, Australia
Institute of Physics, Academia Sinica, TW - Taipei 11529, Taiwan
Technion, Inst. of Technology, Department of Physics, Technion City, IL - Haifa 32000, Israel
Tel Aviv University, Raymond and Beverly Sackler School of Physics and Astronomy, Ramat Aviv, IL - Tel Aviv 69978, Israel
Aristotle University of Thessaloniki, Faculty of Science, Department of Physics, Division of Nuclear & Particle Physics, University Campus, GR - 54212, Thessaloniki, Greece
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
Tokyo Metropolitan University, Graduate School of Science and Technology, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan
Tokyo Institute of Technology, Department of Physics, 2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan
University of Toronto, Department of Physics, 60 Saint George Street, Toronto M5S 1A7, Ontario, Canada
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
University of Tsukuba, Institute of Pure and Applied Sciences, 1-1-1 Tennoudai, Tsukuba-shi, JP - Ibaraki 305-8571, Japan
Tufts University, Science & Technology Center, 4 Colby Street, Medford, MA 02155, United States of America
Universidad Antonio Narino, Centro de Investigaciones, Cra 3 Este No.47A-15, Bogota, Colombia
University of California, Irvine, Department of Physics & Astronomy, CA 92697-4575, United States of America
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
University of Illinois, Department of Physics, 1110 West Green Street, Urbana, Illinois 61801, United States of America
University of Uppsala, Department of Physics and Astronomy, P.O. Box 516, SE -751 20 Uppsala, Sweden
Instituto de Física Corpuscular (IFIC) Centro Mixto UVEG-CSIC, Apdo. 22085 ES-46071 Valencia, Dept. Física At. Mol. y Nuclear; Dept. Ing. Electrónica; Univ. of Valencia, and Inst. de Microelectrónica de Barcelona (IMB-CNM-CSIC) 08193 Bellaterra, Spain
University of British Columbia, Department of Physics, 6224 Agricultural Road, CA - Vancouver, B.C. V6T 1Z1, Canada
University of Victoria, Department of Physics and Astronomy, P.O. Box 3055, Victoria B.C., V8W 3P6, Canada
Waseda University, WISE, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan
The Weizmann Institute of Science, Department of Particle Physics, P.O. Box 26, IL - 76100 Rehovot, Israel
University of Wisconsin, Department of Physics, 1150 University Avenue, WI 53706 Madison, Wisconsin, United States of America
Julius-Maximilians-University of Würzburg, Physikalisches Institute, Am Hubland, 97074 Würzburg, Germany
Bergische Universität, Fachbereich C, Physik, Postfach 100127, Gauss-Strasse 20, D- 42097 Wuppertal, Germany
Yale University, Department of Physics, PO Box 208121, New Haven CT, 06520-8121, United States of America
Yerevan Physics Institute, Ali Khanian Brothers 2, AM - 375036 Yerevan, Armenia
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