Medium-Induced Modification of Z-Tagged Charged Particle Yields in Pb+Pb Collisions at 5.02 TeV with the ATLAS Detector

Aad, G.; ATLAS Collaboration

DOI
10.1103/PhysRevLett.126.072301

Publication date
2021

Document Version
Final published version

Published in
Physical Review Letters

License
CC BY

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
Medium-Induced Modification of Z-Tagged Charged Particle Yields in Pb + Pb Collisions at 5.02 TeV with the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)

(Received 25 August 2020; revised 3 November 2020; accepted 8 January 2021; published 19 February 2021)

The yield of charged particles opposite to a Z boson with large transverse momentum \( p_T \) is measured in 260 \( \text{pb}^{-1} \) of \( pp \) and 1.7 \( \text{nb}^{-1} \) of \( \text{Pb} + \text{Pb} \) collision data at 5.02 TeV per nucleon pair recorded with the ATLAS detector at the Large Hadron Collider. The Z boson tag is used to select hard-scattered partons with specific kinematics, and to observe how their showers are modified as they propagate through the quark-gluon plasma created in \( \text{Pb} + \text{Pb} \) collisions. Compared with \( pp \) collisions, charged-particle yields in \( \text{Pb} + \text{Pb} \) collisions show significant modifications as a function of charged-particle \( p_T \) in a way that depends on event centrality and Z boson \( p_T \). The data are compared with a variety of theoretical calculations and provide new information about the medium-induced energy loss of partons in a \( p_T \) regime difficult to measure through other channels.

DOI: 10.1103/PhysRevLett.126.072301

Collisions of heavy nuclei at ultrarelativistic energies at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) are understood to produce an extended region of hot and dense matter where partons exist in a deconfined state known as the quark-gluon plasma (QGP). The high density of unscreened color charges in the QGP causes the showers of hard-scattered partons with large transverse momentum \( p_T \) to be modified as they traverse the medium [1]. These modifications are observed in measurements of dijet and photon-jet momentum imbalance [2–5], and in jet fragmentation functions [6,7].

The large integrated luminosity of \( \text{Pb} + \text{Pb} \) collisions delivered during LHC Run 2 has enabled measurements of jets produced in association with a high-\( p_T \) Z boson. At leading order, the Z boson and the jet are produced back to back in the azimuthal plane, with equal \( p_T \). Since Z bosons and their decay leptons, or similarly, photons, do not participate in the strong interaction and are not modified by the QGP [8,9], they provide an estimate of the \( p_T \) and azimuthal direction of the partner hard-scattered parton before the developing shower is modified through interactions with the QGP [10,11]. Measurements of photon-tagged fragmentation functions at the LHC [12,13] and photon-hadron correlations at RHIC [14,15] used this feature to perform detailed studies of jet quenching. At fixed \( p_T \), jets balancing Z bosons and photons arise from processes with different \( Q^2 \), and can test the sensitivity of the energy loss process to parton virtuality. Additionally, the use of isolated photons at low photon \( p_T \) \((\lesssim 60 \text{ GeV})\) is difficult due to the large hadron-decay background, motivating the use of Z bosons. A measurement of \( Z + \) jet production with \( p_T^Z > 60 \text{ GeV} \) by CMS demonstrates that the total \( p_T \) carried inside the jet cone is decreased in \( \text{Pb} + \text{Pb} \) events compared with that in \( pp \) events [16]. However, the modification of the jet’s constituent particle \( p_T \) distributions, or any lower \( p_T^Z \) selections, have not yet been studied.

This Letter presents a measurement of the yield of charged particles produced opposite in azimuth to a Z boson with \( p_T^Z > 15 \text{ GeV} \) in \( \text{Pb} + \text{Pb} \) and \( pp \) collisions at a nucleon-nucleon center-of-mass energy \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) with the ATLAS detector at the LHC. The \( \text{Pb} + \text{Pb} \) and \( pp \) data were recorded in 2018 and 2017, respectively, and correspond to integrated luminosities of up to 1.7 \( \text{nb}^{-1} \) and 260 \( \text{pb}^{-1} \). The charged particles are required to have \( p_T^{\text{ch}} > 1 \text{ GeV} \) and be approximately back to back with the Z boson in the transverse plane, with azimuthal separation \( \Delta \phi \) larger than \( 3\pi/4 \) [17]. In simulations of \( pp \) collisions, particles meeting these criteria reside primarily in the leading jet azimuthally opposite to the Z boson. The per-Z yields of charged particles, \( N_{\text{ch},i} \), are reported as a function of \( p_T^{\text{ch},i} \), \((1/N_Z)(d^2N_{\text{ch}}/dp_T^{\text{ch}}d\Delta\phi)\), in \( pp \) and \( \text{Pb} + \text{Pb} \) collisions. To quantify the modification resulting from the partons’ propagation through the QGP, the ratio of particle yields between \( \text{Pb} + \text{Pb} \) and \( pp \) collisions, \( I_{AA} \), is reported and compared with the expectations from theoretical calculations. This measurement explores phenomena similar to those in measurements of the photon-tagged jet fragmentation function [12]. However, requiring a

---

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

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
reconstructed jet may result in a bias towards events with less energy loss than average [18–20]. Since there is no such requirement in this measurement, it provides additional insight into energy loss in an unbiased way, at low \( p_T^{\ell/\nu} \) values which have not yet been measured at the LHC and where theoretical models have not been tested.

The ATLAS experiment [21] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near \( 4\pi \) coverage in solid angle. It consists of an inner tracking detector surrounded by a superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range \( |\eta| < 2.5 \). It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors [22,23]. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile calorimeters [22,23] are used for hadron calorimeter and muon spectrometer. The inner tracking detector covers the pseudorapidity range \( |\eta| < 2.5 \). It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile calorimeters [22,23] are used for hadron calorimeter and muon spectrometer.

During Pb + Pb data taking, the muon system was operational for only triggering. During Pb + Pb data taking, the muon system was operational for only triggering. During Pb + Pb data taking, the muon system was operational for only triggering. During Pb + Pb data taking, the muon system was operational for only triggering. During Pb + Pb data taking, the muon system was operational for only triggering. During Pb + Pb data taking, the muon system was operational for only triggering. During Pb + Pb data taking, the muon system was operational for only triggering. During Pb + Pb data taking, the muon system was operational for only triggering.

Events with a high-\( p_T \) electron or muon are initially selected for analysis by the single-lepton triggers described in Refs. [24,25]. The centrality of Pb + Pb events is defined using the total transverse energy measured in the FCAL [4,26]. \( \Sigma E^\text{p}\text{b}_{T} \). Pb + Pb events are divided into three categories which correspond to the 0%–10%, 10%–30%, and 30%–80% centrality intervals in minimum-bias (MB) events, the smaller values indicating larger nuclear overlap regions and thus larger, hotter QGP regions. The orientation of the underlying event (UE) elliptic flow is determined from the azimuthal distribution of the FCAL energy [27,28].

In \( pp \) events, the average number of interactions per bunch crossing ranged from 2 to 4, and thus all charged-particle tracks are required to originate from the primary reconstructed vertex [29].

Monte Carlo simulations of \( \sqrt{s} = 5.02 \text{ TeV} \) \( pp \) collisions with Z bosons decaying in the dielectron and dimuon channels, as well as data-driven studies, are used to correct the data for bin migration and reconstruction inefficiencies. Generated events were passed through a GEANT4 simulation [30,31] of the ATLAS detector under the same conditions present during data taking and were digitized and reconstructed in the same way as the data. The Z boson events were generated at next-to-leading order (NLO) with the POWHEG-BOX v2 program [32–35] interfaced to the PYTHIA 8.186 parton shower model [36]. The NLO CT10 parton distribution function (PDF) set [37] was used in the matrix element, while the CTEQ6L1 PDF set [38] and the AZNLO tuned set of parameters [39] were used to model the parton shower.

Four million events were generated to serve as the simulation sample for \( pp \) collisions. To model Pb + Pb events, fifteen million simulated \( pp \) events were overlaid at the detector-hit level with MB Pb + Pb events in data. This data-overlay sample was reweighted on an event-by-event basis to match the \( \Sigma E^\text{p}\text{b}_{T} \) distribution for Pb + Pb events containing Z bosons.

The Z bosons in \( pp \) and Pb + Pb events are reconstructed in opposite-sign dielectron and dimuon decay channels using procedures similar to those described in Refs. [9,40]. Reconstructed electrons are required to have a transverse momentum \( p_T^e > 20 \text{ GeV} \), to lie within the fiducial acceptance of the EM barrel (\( |\eta^e| < 1.37 \)) or end cap (\( 1.52 < |\eta^e| < 2.47 \)) detectors, and to satisfy “loose” likelihood-based identification criteria, which have been optimized separately for \( pp \) and Pb + Pb events [41]. Reconstructed muons are required to have a transverse momentum \( p_T^\mu > 20 \text{ GeV} \), to lie within the fiducial acceptance of the muon spectrometer (\( |\eta^\mu| < 2.5 \)), and to pass the “medium” selection requirements described in Ref. [42]. The \( Z \rightarrow \ell\ell \) candidates are required to be within the mass range \( 76 < m_{\ell\ell} < 106 \text{ GeV} \) and have \( p_T^{\ell/\nu} > 15 \text{ GeV} \). This selection ensures that the contribution from multijet and other backgrounds is smaller than 1.5% (0.1%) for the dielectron (dimuon) channel, and is considered negligible. In total, there are approximately 21 000 (28 000) \( Z \rightarrow e\ell \) (\( Z \rightarrow \mu\mu \)) events in \( pp \) data, and 3400 (4100) events in Pb + Pb data.

Each Z data event is assigned a series of weights, derived from simulation and data, to account for the trigger, reconstruction, selection and selection efficiencies of its decay leptons. Individual lepton trigger efficiencies are determined directly in \( pp \) and Pb + Pb data using tag-and-probe techniques [24,25], and are 0.70–0.80 for each muon and 0.75–0.95 for each electron. Reconstruction and selection efficiencies are determined using simulation and are 0.65–0.80 for muons and 0.65–0.95 for electrons. Although the efficiencies may vary substantially with the individual lepton \( p_T, \eta, \) and \( \phi \), the resulting dependence on \( p_T^Z \) is weak due to the large Z mass and weak correlation between bosons and their decay leptons.

Charged-particle tracks are reconstructed from hits in the inner detector using an algorithm [43] which, in Pb + Pb collisions, is optimized for the high-occupancy conditions [44]. They are required to meet several criteria intended to select primary charged particles [6]. All reconstructed tracks with \( p_T > 1 \text{ GeV}, |\eta| < 2.5 \) and \( \Delta\phi > 3\pi/4 \) are considered. The charged-particle yield is corrected for reconstruction and selection inefficiency on a per-track basis using a simulation-derived efficiency which varies
from 0.6 to 0.8 depending on both detector occupancy and track kinematics. A small correction, typically 1%–2%, accounts for the contribution of reconstructed tracks not associated with primary particles. The $p_T^{ch}$ resolution is found to have a negligible effect ($\lesssim 0.3\%$) on the results and is not corrected for.

The contribution to the yield from UE particles in Pb + Pb collisions is estimated using MB events and is statistically subtracted from the measured yields. For each $Z$ event in data, 40–160 unique MB events are used for this estimation. These MB events are centrality matched to within 1% in peripheral events, decreasing to within 0.1% in central events. Furthermore, to match the azimuthal modulation of the UE, the elliptic flow angles [28] in the $Z$ data event and in the matching MB event must match within $\pi/16$. The signal-to-background ratio varies strongly with $p_T^{ch}$, $p_T^{Z}$, and Pb + Pb centrality, with a minimum of $5 \times 10^{-3}$ at the lowest $p_T^{ch}$ and $p_T^{Z}$ values in the most central events. In $pp$ events, the UE is known to have larger activity in a $Z$ event than in an ordinary MB $pp$ collision [45,46], necessitating a different procedure. Here, the UE is determined in events with $1 < p_T^{Z} < 12$ GeV in the azimuthal region perpendicular to the $Z$ boson to avoid the contribution from jet particles.

The data are further corrected for bin migration resulting from the finite resolution in the $p_T^{Z}$ measurement. This is evaluated by comparing the per-Z yields between $pp$, $Pb+Pb$ events, or the additional requirement to match the triangular flow angles, are investigated. However, since these variations give statistically compatible results, they are not included. As a check of the background subtraction procedure, the full analysis is performed on simulated $Z$ events overlaid with HIJING [49] Pb + Pb background, and compared with the generator-level distributions. An absolute uncertainty in the background estimation of 0.3% is derived using this study.

Finally, an internal consistency check is performed by comparing the per-Z yields between the electron and muon decay channels. A difference was observed in the $15 < p_T^{Z} < 30$ GeV selections and was included as an uncertainty of at most 4% in $pp$ and 14% in central Pb + Pb events.

For the yields at low $p_T^{ch}$ and in central events, the uncertainty from the UE determination is dominant and can be as large as 30%. For yields at high $p_T^{ch}$ and in lower-multiplicity events, the uncertainties associated with the track selection and the lepton energy scale are typically dominant, and as large as 5%. Uncertainty sources common to $Pb + Pb$ and $pp$ are canceled in the $I_{AA}$ ratio when possible, such that the resulting measurement is dominated by uncertainties specific to $Pb + Pb$ events. In all cases, the statistical uncertainty in the $I_{AA}$ is larger than the total systematic uncertainty.

Figure 1 presents the charged-particle yield per $Z$ boson, in $Pb + Pb$ and $pp$ events, as a function of $p_T^{ch}$, for the selection $\Delta \phi > 3\pi/4$. The yields in $Pb + Pb$ collisions are observed to be modified relative to those in $pp$ collisions.
To better reveal the modification, Fig. 2 presents $I_{AA}$ values, the ratios of yields in Pb + Pb events to those in pp events. The $I_{AA}$ values are suppressed below unity at large $p_T^{ch}$, with a systematically larger suppression in more central events and for lower $p_T^{ch}$ selections. For $p_T^{ch} > 60$ GeV, the $I_{AA}$ values at low $p_T^{ch}$, less than 2–3 GeV, are significantly different than those at high $p_T^{ch}$, and typically greater than unity. Lower $p_T^{ch}$ selections are compatible with a similar increase at low $p_T^{ch}$, although the uncertainties limit the significance of this enhancement. The suppression over a wide range of $p_T^{ch}$ values, and the general enhancement of the $I_{AA}$ above unity at lower $p_T^{ch}$, are qualitatively similar to those observed in the ratios of jet fragmentation functions in photon-tagged events [12].

Figure 3 compares the $I_{AA}$ in 0%–10% Pb + Pb events with the following theoretical calculations, where available, which use the same kinematic selections as the data: (1) a perturbative calculation within the framework of soft-collinear effective field theory with Glauber gluons (SCET$_G$) in the soft-gluon-emission (energy-loss) limit, with jet-medium coupling $g = 2.0 \pm 0.2$ [50,51]; (2) the Hybrid Strong/Weak Coupling model [52], which combines initial production using PYTHIA 8 with a parameterization of energy loss derived from holographic methods, including backreaction effects; (3) JEWEL, an MC event generator which simulates QCD jet evolution in heavy-ion collisions, including radiative and elastic energy loss processes, and configured to include medium recoils [53]; and (4) a coupled linearized Boltzmann transport (COLBT) and hydrodynamics model [54,55], which includes jet-induced medium excitations. All models qualitatively reproduce the degree of suppression at large $p_T^{ch}$, greater than 10 GeV. The Hybrid model, JEWEL, and COLBT qualitatively capture the increase at low $p_T^{ch}$. For these three models, removing the backreaction, medium recoils, and jet-induced medium excitations, respectively, results in a significant underprediction of the data in this region. Several of these models also capture the relative difference in the $I_{AA}$ between the three $p_T^{ch}$ selections. A full evaluation of theoretical uncertainties is needed to further discriminate between the mechanisms of energy loss and medium response in the data.
In conclusion, this Letter presents a measurement of charged-particle yields produced in the azimuthal direction opposite to a Z boson with \( p_T > 15 \text{ GeV} \). The measurement is performed using 260 \( \text{pb}^{-1} \) of \( pp \) and up to 1.7 \( \text{nb}^{-1} \) of \( \text{Pb} + \text{Pb} \) collision data at 5.02 TeV with the ATLAS detector at the Large Hadron Collider. The per-\( Z \) yields are systematically modified in \( \text{Pb} + \text{Pb} \) collisions compared with \( pp \) collisions due to the interactions between the parton shower and the hot and dense QGP medium. The charged-particle \( p_T \) distribution in \( \text{Pb} + \text{Pb} \) collisions is softer than that in \( pp \) collisions, with a suppression at high \( p_T^b \) and an enhancement at low \( p_T^b \). The degree of modification varies with \( \text{Pb} + \text{Pb} \) event centrality, consistent with a larger and hotter QGP being created in more central events. At high \( p_T^Z \), the modification pattern is qualitatively similar to that observed in measurements of photon-tagged jet fragmentation functions. In addition to the particular theoretical comparisons presented here, the photon-tagged jet fragmentation functions. In conclusion, this Letter presents a measurement of charged-particle yields produced in the azimuthal direction opposite to a Z boson with \( p_T > 15 \text{ GeV} \). The measurement is performed using 260 \( \text{pb}^{-1} \) of \( pp \) and up to 1.7 \( \text{nb}^{-1} \) of \( \text{Pb} + \text{Pb} \) collision data at 5.02 TeV with the ATLAS detector at the Large Hadron Collider. The per-\( Z \) yields are systematically modified in \( \text{Pb} + \text{Pb} \) collisions compared with \( pp \) collisions due to the interactions between the parton shower and the hot and dense QGP medium. The charged-particle \( p_T \) distribution in \( \text{Pb} + \text{Pb} \) collisions is softer than that in \( pp \) collisions, with a suppression at high \( p_T^b \) and an enhancement at low \( p_T^b \). The degree of modification varies with \( \text{Pb} + \text{Pb} \) event centrality, consistent with a larger and hotter QGP being created in more central events. At high \( p_T^Z \), the modification pattern is qualitatively similar to that observed in measurements of photon-tagged jet fragmentation functions. In addition to the particular theoretical comparisons presented here, the data will allow systematic tests of models across centrality and \( p_T^Z \) selections. The data can also test energy loss models for low-\( p_T \) partons that are otherwise difficult to access experimentally at the LHC, but which are valuable for direct comparison to future measurements at RHIC.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IFRF, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; ORSTOM, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MINE/IFA, Romania; MES of Russia and NRC KI, Russia Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; ERC, ERDF, Horizon 2020, Marie Skłodowska-Curie Actions and COST, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [56].


[17] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the $z$ axis along the beam pipe. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$ axis. The pseudo-rapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.


SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China
Tsung-Dao Lee Institute, Shanghai, China
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
Department of Physics, University of Hong Kong, Hong Kong, China
Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
JICLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
Department of Physics, Indiana University, Bloomington, Indiana, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
INFN Sezione di Lecce, Italy
Dipartimento di Matematica e Fisica,Università del Salento, Lecce, Italy
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
INFN Sezione di Napoli, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
INFN Sezione di Pavia, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
INFN Sezione di Roma, Italy
Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Italy
Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
INFN-TIFPA, Italy
Università degli Studi di Trento, Trento, Italy
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Joint Institute for Nuclear Research, Dubna, Russia
Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
072301-20