Dijet Azimuthal Decorrelations in \(pp\) Collisions at \(\sqrt{s} = 7\) TeV

V. Khachatryan et al.*  
(CMS Collaboration)

(Received 26 January 2011; published 22 March 2011)

Measurements of dijet azimuthal decorrelations in \(pp\) collisions at \(\sqrt{s} = 7\) TeV using the CMS detector at the CERN LHC are presented. The analysis is based on an inclusive dijet event sample corresponding to an integrated luminosity of 2.9 fb\(^{-1}\). The results are compared to predictions from perturbative QCD calculations and various Monte Carlo event generators. The dijet azimuthal distributions are found to be sensitive to initial-state gluon radiation.

DOI: 10.1103/PhysRevLett.106.122003  
PACS numbers: 13.85.Ni, 12.38.Bx, 12.38.Qk, 13.87.Ce

High-energy proton-proton collisions with high momentum transfer are described within the framework of quantum chromodynamics (QCD) as pointlike scatterings between the proton constituents, collectively referred to as partons. The outgoing partons manifest themselves, through quark and gluon soft radiation and hadronization processes, as localized streams of particles, identified as jets. At Born level, dijets are produced with equal transverse momenta \(p_T\) with respect to the beam axis and back to back in the azimuthal angle \(\Delta \phi_{\text{dijet}} = |\phi_{\text{jet}1} - \phi_{\text{jet}2}| = \pi\). Soft-gluon emission will decorrelate the two highest \(p_T\) (leading) jets and cause small deviations from \(\pi\). Larger decorrelations from \(\pi\) occur in the case of hard multijet production. Three-jet topologies dominate the region of \(2\pi/3 < \Delta \phi_{\text{dijet}} < \pi\), whereas angles smaller than \(2\pi/3\) are populated by four-jet events.

Dijet azimuthal decorrelations, i.e., the deviation of \(\Delta \phi_{\text{dijet}}\) from \(\pi\) for the two leading jets in hard-scattering events, can be used to study QCD radiation effects over a wide range of jet multiplicities without the need to measure all the additional jets. Such studies are important because an accurate description of multiple-parton radiation is still lacking in perturbative QCD (pQCD). Experiments therefore rely on Monte Carlo (MC) event generators to take these higher-order processes into account in searches for new physics and for a wide variety of precision measurements. The observable chosen to study the radiation effects is the differential dijet cross section in \(\Delta \phi_{\text{dijet}}\), normalized by the dijet cross section integrated over the entire \(\Delta \phi_{\text{dijet}}\) phase space: \(\int \sigma_{\text{dijet}}(d\sigma_{\text{dijet}}/d\Delta \phi_{\text{dijet}})\). By normalizing the \(\Delta \phi_{\text{dijet}}\) distributions in this manner, many experimental and theoretical uncertainties are significantly reduced. Measurements of dijet azimuthal decorrelations at the Tevatron have previously been reported by the D0 Collaboration [1]. In this Letter, we present the first measurements of dijet azimuthal decorrelations in \(pp\) collisions at \(\sqrt{s} = 7\) TeV at the CERN Large Hadron Collider (LHC).

The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid, of 6 m internal diameter, providing an axial field of 3.8 T. Charged particle trajectories are measured by the silicon pixel and strip tracker, covering \(0 < \phi < 2\pi\) in azimuth and \(|\eta| < 2.5\), where pseudorapidity \(\eta = -\ln[\tan(\theta/2)]\) and \(\theta\) is the polar angle relative to the counterclockwise proton beam direction with respect to the center of the detector. A lead-tungstate crystal electromagnetic calorimeter and a brass-scintillator hadronic calorimeter surround the tracking volume. The calorimeter cells are grouped in projective towers of granularity \(\Delta \eta \times \Delta \phi = 0.087 \times 0.087\) at central pseudorapidities. The granularity becomes coarser at forward pseudorapidities. A preshower detector made of silicon sensor planes and lead absorbers is installed in front of the electromagnetic calorimeter at \(1.653 < |\eta| < 2.6\). Muons are measured in gas-ionization detectors embedded in the steel magnetic field return yoke. A detailed description of the CMS detector can be found elsewhere [2].

CMS uses a two-tiered trigger system to select events on-line: level 1 and the high level trigger. In this analysis, events were selected by using two inclusive single-jet triggers that required a level-1 jet with \(p_T > 20\) (30) GeV and a high level trigger jet with \(p_T > 30\) (50) GeV. The jets at level 1 and the high level trigger are reconstructed by using energies measured by the electromagnetic and hadronic calorimeters and are not corrected for the jet energy response of the calorimeters. The trigger efficiency for a given corrected \(p_T\) threshold of the leading jet \((p_T^{\text{max}})\) was measured by using events selected by a lower-threshold trigger. For the event selection, \(p_T^{\text{max}}\) thresholds were chosen so that this efficiency exceeded 99%. The corresponding off-line corrected \(p_T^{\text{max}}\) values are 80 (110) GeV for the low (high) threshold jet trigger.

Jets were reconstructed off-line by using the anti-\(k_T\) clustering algorithm with a distance parameter \(R = 0.5\) [3].

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

Published by American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
The four-vectors of particles reconstructed by the CMS particle-flow algorithm were used as input to the jet-clustering algorithm. The particle-flow algorithm combines information from all CMS subdetectors to provide a complete list of long-lived particles in the event. Muons, electrons, photons, and charged and neutral hadrons are reconstructed individually. As a result, the residual corrections to the jet four-vectors, arising from the detector response, are relatively small (at the level of 5%–10% in the central region) [4]. A detailed description of the particle-flow algorithm can be found elsewhere [5,6].

Spurious jets from noise and noncollision backgrounds were eliminated by applying loose quality cuts on the jet properties [7]. Events were required to have a primary vertex reconstructed along the beam axis and within 24 cm of the detector center [8]. Further cuts were applied to reject interactions from the beam halo. Events were selected having two leading jets each with \( p_T > 30 \text{ GeV} \) and rapidity \( |y| < 1.1 \), where \( y = \frac{1}{2} \ln [(E + p_z)/(E - p_z)] \), with \( E \) being the total jet energy and \( p_z \) the projection of the jet momentum along the beam axis. Each event is put into one of a five mutually exclusive regions, which are based on the \( p_T \) in the event. The five regions are 80 < \( p_T \) < 110 GeV, 110 < \( p_T \) < 140 GeV, 140 < \( p_T \) < 200 GeV, 200 < \( p_T \) < 300 GeV, and 300 GeV < \( p_T \). The data correspond to an integrated luminosity of 0.3 pb\(^{-1}\) for the lowest \( p_T \) region and 2.9 pb\(^{-1}\) for the other \( p_T \) regions. The uncertainty on the integrated luminosity is estimated to be 11% [9]. After the application of all selection criteria, the numbers of events remaining in each of the five \( p_T \) regions, starting from the lowest, are 60 837, 160 388, 69 009, 14 383, and 2284.

The \( \Delta \varphi_{\text{dijet}} \) distributions are corrected for event migration effects due to the finite jet \( p_T \) and position resolutions of the detector. The distributions are sensitive to the jet \( p_T \) resolution because fluctuations in the jet response can cause low-energy jets to be misidentified as leading jets, and events can migrate between different \( p_T \) regions. The finite resolution in azimuthal angle causes event migration between \( \Delta \varphi_{\text{dijet}} \) bins, while the resolution in rapidity can move jets in and out of the central rapidity region (\(|y| < 1.1\)). The correction factors were determined by using two independent MC samples: PYTHIA 6.422 (PYTHIA6) [10] tune D6T [11], and HERWIG++ 2.4.2 [12]. The \( p_T \), rapidity, and azimuthal angle of each generated jet were smeared according to the measured resolutions [13].

The ratio of the two dijet azimuthal distributions was smeared according to the measured resolutions [13]. Typical values are between 2.5% and 3.5%. The resulting uncertainties on the normalized \( \Delta \varphi_{\text{dijet}} \) distributions range from 5% at \( \Delta \varphi_{\text{dijet}} \approx \pi/2 \) to 1% at \( \Delta \varphi_{\text{dijet}} \approx \pi \). The effect of the jet \( p_T \) resolution uncertainty on the \( \Delta \varphi_{\text{dijet}} \) distributions was estimated by varying the jet \( p_T \) resolutions by ±10% [13] and comparing the \( \Delta \varphi_{\text{dijet}} \) unfolding correction before and after the change. This yields a variation on the normalized \( \Delta \varphi_{\text{dijet}} \) distributions ranging from 5% at \( \Delta \varphi_{\text{dijet}} \approx \pi/2 \) to 1% at \( \Delta \varphi_{\text{dijet}} \approx \pi \). The uncertainties on the unfolding correction factors were estimated by comparing the corrections from different event generators and PYTHIA6 tunes that vary significantly in their modeling of the jet kinematic distributions and \( \Delta \varphi_{\text{dijet}} \) distributions. The resulting uncertainty varies from 8% at \( \Delta \varphi_{\text{dijet}} \approx \pi/2 \) to 1.5% at \( \Delta \varphi_{\text{dijet}} \approx \pi \). The systematic uncertainty from using a parametrized model to simulate the finite jet \( p_T \) and position resolutions of the detector to determine the unfolding correction factors was estimated to be about 2.5% in all \( p_T \) regions. The combined systematic uncertainty, calculated as the quadratic sum of all systematic uncertainties, varies from 11% at \( \Delta \varphi_{\text{dijet}} \approx \pi/2 \) to 3% at \( \Delta \varphi_{\text{dijet}} \approx \pi \).

The corrected differential \( \Delta \varphi_{\text{dijet}} \) distributions, normalized to the integrated dijet cross section, are shown in Fig. 1 for the five \( p_T \) regions. The distributions are scaled by multiplicative factors for presentation purposes. Each data point is plotted at the abscissa value for which the predicted differential \( \Delta \varphi_{\text{dijet}} \) distribution has the same value as the bin average obtained by using PYTHIA6 tune D6T, which provides a good description of the data [14].

The \( \Delta \varphi_{\text{dijet}} \) distributions are strongly peaked at \( \pi \) and become steeper with increasing \( p_T \). The simulated \( \Delta \varphi_{\text{dijet}} \) distributions from the PYTHIA6 (D6T and Z2 [15] tunes), PYTHIA 8.135 (PYTHIA8) [16], HERWIG++, and MADGRAPH 4.4.32 [17] event generators are presented for comparison. The MADGRAPH generator is based on leading-order matrix element multiparton final-state predictions, using PYTHIA6 for parton showering and hadronization, and the Manganese method [18] to map the parton-level event into a parton shower history. The MADGRAPH predictions included tree-level processes of up to four partons. For PYTHIA6, PYTHIA8, and MADGRAPH event generators the CTEQ6L [19] parton distribution functions (PDFs) were used; for HERWIG++, the MRST2001 PDFs [20].

Figure 2 shows the ratios of the measured \( \Delta \varphi_{\text{dijet}} \) distributions to the predictions of PYTHIA6, PYTHIA8, HERWIG++, and MADGRAPH in the five \( p_T \) regions.
FIG. 1 (color online). Normalized $\Delta \varphi_{\text{dijet}}$ distributions in several $p_T^{\text{max}}$ regions, scaled by the multiplicative factors given in the figure for easier presentation. The curves represent predictions from PYTHIA6, PYTHIA8, HERWIG++, and MADGRAPH. The error bars on the data points include statistical and systematic uncertainties.

The combined systematic uncertainty on the experimental measurements is shown by the shaded band. The predictions from PYTHIA6 and HERWIG++ describe the shape of the data distributions well, while MADGRAPH (PYTHIA8) predicts less (more) azimuthal decorrelation than is observed in the data.

Figure 3 displays the ratios of the measured $\Delta \varphi_{\text{dijet}}$ distributions to the next-to-leading-order (NLO) predictions of pQCD calculations from the parton-level generator NLOJET++ [21] within the FASTNLO framework [22]. The predictions include $2 \rightarrow 3$ processes at NLO, normalized to $\sigma_{\text{dijet}}$ at NLO:

$$\frac{1}{\sigma_{\text{dijet}}} \bigg|_{\text{NLO}} \times \frac{d\sigma_{\text{dijet}}}{d\Delta \varphi_{\text{dijet}}} \bigg|_{\text{NLO}}.$$ 

The predictions near $\Delta \varphi_{\text{dijet}} = \pi$ have been excluded because of their sensitivity to higher-order corrections not included in the present calculations.

Uncertainties due to the renormalization ($\mu_r$) and factorization ($\mu_f$) scales are evaluated by varying the default choice of $\mu_r = \mu_f = p_T^{\text{max}}$ between $p_T^{\text{max}}/2$ and $2p_T^{\text{max}}$ in the following six combinations: $(\mu_r, \mu_f) = (p_T^{\text{max}}/2, p_T^{\text{max}}/2)$, $(2p_T^{\text{max}}, 2p_T^{\text{max}})$, $(p_T^{\text{max}}, p_T^{\text{max}}/2)$, $(p_T^{\text{max}}/2, p_T^{\text{max}})$, and $(2p_T^{\text{max}}, 2p_T^{\text{max}})$. These scale variations modify the predictions of the normalized $\Delta \varphi_{\text{dijet}}$ distributions by less than 50%. The PDFs and the associated uncertainties were obtained from CTEQ6.6 [19]. The PDF uncertainties were derived by using the 22 CTEQ6.6 uncertainty eigenvectors and found to be 9% at $\Delta \varphi_{\text{dijet}} \sim \pi/2$ and 2% at $\Delta \varphi_{\text{dijet}} < \pi$. Following the proposal of the PDF4LHC working group [23], the impact of other global PDF fits [24–26] was investigated and found to be negligible in the context of this analysis.

Nonperturbative corrections due to hadronization and multiple-parton interactions were applied to the pQCD predictions. The correction factors were determined from the PYTHIA6 and HERWIG++ simulations and modify the predictions from $+4\%$ ($\Delta \varphi_{\text{dijet}} \sim \pi$) to $-13\%$ ($\Delta \varphi_{\text{dijet}} \sim \pi/2$). The uncertainty due to the nonperturbative corrections is estimated to be $6\%$ at $\Delta \varphi_{\text{dijet}} \sim \pi/2$ and $2\%$ at $\Delta \varphi_{\text{dijet}} \sim \pi$. The effects due to the scale variations, as well as the uncertainties due to PDFs and nonperturbative corrections, are also shown in Fig. 3. The NLO predictions provide a good description of the shape of the data.
FIG. 3 (color online). Ratios of measured normalized \( \Delta \varphi_{\text{dijet}} \) distributions to NLO pQCD predictions with nonperturbative corrections in several \( p_T^{\text{max}} \) regions. The error bars on the data points include statistical and systematic uncertainties. The effects on the NLO pQCD predictions due to \( \mu_r \) and \( \mu_f \) scale variations and PDF uncertainties, as well as the uncertainties from the nonperturbative corrections, are shown.

distributions over much of the \( \Delta \varphi_{\text{dijet}} \) range. Compared to the data, the reduced decorrelation in the theoretical prediction and the increased sensitivity to the \( \mu_r \) and \( \mu_f \) scale variations for \( \Delta \varphi_{\text{dijet}} < 2 \pi/3 \) shown in Fig. 3 are attributed to the fact that the pQCD prediction in this region is effectively available only at leading order, since the contribution from tree-level four-parton final states dominates.

The sensitivity of the \( \Delta \varphi_{\text{dijet}} \) distributions to initial-state parton shower radiation (ISR) is investigated by varying the input parameter \( k_{\text{ISR}} \) [PARP(67)] in PYTHIA6 tune D6T. The product of \( k_{\text{ISR}} \) and the square of the hard-scattering scale gives the maximum allowed parton virtuality (i.e., the maximum allowed \( p_T \)) in the initial-state shower. Previous studies have shown that \( k_{\text{ISR}} \) is the only parameter in PYTHIA6 that has significant impact on the \( \Delta \varphi_{\text{dijet}} \) distributions [27]. The default value of \( k_{\text{ISR}} \) in PYTHIA6 tune D6T is 2.5, determined from the D0 dijet azimuthal decorrelation results [1]. Figure 4 shows comparisons of the measured \( \Delta \varphi_{\text{dijet}} \) distributions to PYTHIA6 distributions with various \( k_{\text{ISR}} \) values. The effects are more pronounced for smaller \( \Delta \varphi_{\text{dijet}} \) angles, where multigluon radiation dominates. Varying \( k_{\text{ISR}} \) by \( \pm 0.5 \) about its default value yields a change of about 30% on the PYTHIA6 prediction for \( \Delta \varphi_{\text{dijet}} \sim \pi/2 \), suggesting that our results could be used to tune parameters in the MC event generators that control radiative effects in the initial state. In PYTHIA6 tune D6T, the maximum \( p_T \) allowed in the final-state radiation parton shower is controlled through the parameter PARP(71). We varied the value of this parameter from 2.5 to 8 (the default value is 4.0) and observed less than \( \sim 10\% \) changes in the \( \Delta \varphi_{\text{dijet}} \) distributions in all \( p_T \) regions.

In summary, we have measured dijet azimuthal decorrelations in different leading-jet \( p_T \) regions from \( pp \) collisions at \( \sqrt{s} = 7 \) TeV. The PYTHIA6 and HERWIG++ event generators are found to best describe the shape of the measured distributions over the entire range of \( \Delta \varphi_{\text{dijet}} \).

\( \Delta \varphi_{\text{dijet}} \) distributions are found to be sensitive to initial-state gluon radiation.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC.

FIG. 4 (color online). Ratios of measured normalized \( \Delta \varphi_{\text{dijet}} \) distributions to PYTHIA6 tune D6T with various values of \( k_{\text{ISR}} \) in several \( p_T^{\text{max}} \) regions. The shaded bands indicate the total systematic uncertainty.
machine. We thank the technical and administrative staff at CERN and other CMS institutes and acknowledge support from FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MESRS (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); BRITEURCA, CERN, IPNEC-CEA, IN2P3, and CEA-DSM (France); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); BNL (USA); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); BRITEURCA, CERN, IPNEC-CEA, IN2P3, and CEA-DSM (France); INFN (Italy); NRF and WCU (Korea);LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); BNL (USA); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); BRITEURCA, CERN, IPNEC-CEA, IN2P3, and CEA-DSM (France); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); BNL (USA); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); BRITEURCA, CERN, IPNEC-CEA, IN2P3, and CEA-DSM (France); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); BNL (USA); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); BRITEURCA, CERN, IPNEC-CEA, IN2P3, and CEA-DSM (France); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); BNL (USA); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).
26 Lappeenranta University of Technology, Lappeenranta, Finland
27 Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
28 DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
29 Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
30 Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
31 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
32 Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
33 E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia
34 Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
35 RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
36 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
37 RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
38 Deutsches Elektronen-Synchrotron, Hamburg, Germany
39 University of Hamburg, Hamburg, Germany
40 Institut für Experimentelle Kernphysik, Karlsruhe, Germany
41 Institute of Nuclear Physics “Demokritos,” Aghia Paraskevi, Greece
42 University of Athens, Athens, Greece
43 University of Ioánnina, Ioánnina, Greece
44 KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
45 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
46 University of Debrecen, Debrecen, Hungary
47 Panjab University, Chandigarh, India
48 University of Delhi, Delhi, India
49 Bhabha Atomic Research Centre, Mumbai, India
50 Tata Institute of Fundamental Research - EHEP, Mumbai, India
51 Tata Institute of Fundamental Research - HECR, Mumbai, India
52 Institute for Research and Fundamental Sciences (IPM), Tehran, Iran
53a INFN Sezione di Bari, Bari, Italy
53b Università di Bari, Bari, Italy
53c Politecnico di Bari, Bari, Italy
54a INFN Sezione di Bologna, Bologna, Italy
54b Università di Bologna, Bologna, Italy
55a INFN Sezione di Catania, Catania, Italy
55b Università di Catania, Catania, Italy
56a INFN Sezione di Firenze, Firenze, Italy
56b Università di Firenze, Firenze, Italy
57 INFN Laboratori Nazionali di Frascati, Frascati, Italy
58a INFN Sezione di Genova, Genova, Italy
59a INFN Sezione di Milano-Bicocca, Milano, Italy
59b Università di Milano-Bicocca, Milano, Italy
60a INFN Sezione di Napoli, Napoli, Italy
60b Università di Napoli “Federico II,” Napoli, Italy
61a INFN Sezione di Padova, Padova, Italy
61b Università di Trento (Trento), Padova, Italy
61c Università di Trento (Trento), Padova, Italy
62a INFN Sezione di Pavia, Pavia, Italy
62b Università di Pavia, Pavia, Italy
63a INFN Sezione di Perugia, Perugia, Italy
63b Università di Perugia, Perugia, Italy
64a INFN Sezione di Pisa, Pisa, Italy
64b Università di Pisa, Pisa, Italy
64c Scuola Normale Superiore di Pisa, Pisa, Italy
65a INFN Sezione di Roma, Roma, Italy
65b Università di Roma “La Sapienza,” Roma, Italy
66a INFN Sezione di Torino, Torino, Italy
66b Università di Torino, Torino, Italy
66c Università del Piemonte Orientale (Novara), Torino, Italy
67a INFN Sezione di Trieste, Trieste, Italy
67b Università di Trieste, Trieste, Italy
68 Kangwon National University, Chunchon, Korea
The University of Iowa, Iowa City, Iowa, USA
Johns Hopkins University, Baltimore, Maryland, USA
The University of Kansas, Lawrence, Kansas, USA
Kansas State University, Manhattan, Kansas, USA
Lawrence Livermore National Laboratory, Livermore, California, USA
University of Maryland, College Park, Maryland, USA
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
University of Minnesota, Minneapolis, Minnesota, USA
University of Mississippi, University, Mississippi, USA
University of Nebraska-Lincoln, Lincoln, Nebraska, USA
State University of New York at Buffalo, Buffalo, New York, USA
Northeastern University, Boston, Massachusetts, USA
Northwestern University, Evanston, Illinois, USA
University of Notre Dame, Notre Dame, Indiana, USA
The Ohio State University, Columbus, Ohio, USA
Princeton University, Princeton, New Jersey, USA
University of Puerto Rico, Mayaguez, Puerto Rico, USA
Purdue University, West Lafayette, Indiana, USA
Purdue University Calumet, Hammond, Indiana, USA
Rice University, Houston, Texas, USA
University of Rochester, Rochester, New York, USA
The Rockefeller University, New York, New York, USA
Rutgers, the State University of New Jersey, Piscataway, New York, USA
University of Tennessee, Knoxville, Tennessee, USA
Texas A&M University, College Station, Texas, USA
Texas Tech University, Lubbock, Texas, USA
Vanderbilt University, Nashville, Tennessee, USA
University of Virginia, Charlottesville, Virginia, USA
Wayne State University, Detroit, Michigan, USA
University of Wisconsin, Madison, Wisconsin, USA

aDeceased.
bAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
cAlso at Universidade Federal do ABC, Santo Andre, Brazil.
dAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
eAlso at Suez Canal University, Suez, Egypt.
fAlso at Fayoum University, El-Fayoum, Egypt.
gAlso at Soltan Institute for Nuclear Studies, Warsaw, Poland.
hAlso at Massachusetts Institute of Technology, Cambridge, MA, USA.
iAlso at Université de Haute-Alsace, Mulhouse, France.
jAlso at Brandenburg University of Technology, Cottbus, Germany.
kAlso at Moscow State University, Moscow, Russia.
lAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
mAlso at Eőtvös Loránd University, Budapest, Hungary.
Also at Tata Institute of Fundamental Research - HECR, Mumbai, India.
oAlso at University of Visva-Bharati, Santiniketan, India.
pAlso at Facoltà Ingegneria Università di Roma “La Sapienza,” Roma, Italy.
qAlso at Università della Basilicata, Potenza, Italy.
rAlso at Università degli studi di Siena, Siena, Italy.
sAlso at California Institute of Technology, Pasadena, CA, USA.
tAlso at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
uAlso at University of California, Los Angeles, Los Angeles, CA, USA.
vAlso at University of Florida, Gainesville, FL, USA.
wAlso at Université de Genève, Geneva, Switzerland.
xAlso at Scuola Normale e Sezione dell’ INFN, Pisa, Italy.
yAlso at INFN Sezione di Roma, Università di Roma “La Sapienza,” Roma, Italy.
zAlso at University of Athens, Athens, Greece.
aaAlso at The University of Kansas, Lawrence, KS, USA.