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S. Chatrchyan
Yerevan Physics Institute, Yerevan, Armenia

Kenneth A. Bloom
University of Nebraska - Lincoln, kbloom2@unl.edu

S. Bose
University of Nebraska - Lincoln, sbose2@unl.edu

Jamila Butt
University of Nebraska-Lincoln

Daniel Claes
University of Nebraska - Lincoln, dclaes@unl.edu

See next page for additional authors

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Authors
S. Chatrchyan, Kenneth A. Bloom, S. Bose, Jamila Butt, Daniel Claes, Aaron Dominguez, Michael Eads, J Keller, T Kelly, Ilya Kravchenko, J. Lazo-Flores, Helena Malbouisson, Sudhir Malik, and Gregory Snow

Measurement of the Inclusive Jet Cross Section in pp Collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.*[*]
(CMS Collaboration)

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The inclusive jet cross section is measured in pp collisions with a center-of-mass energy of 7 TeV at the Large Hadron Collider using the CMS experiment. The data sample corresponds to an integrated luminosity of 34 pb^{-1}. The measurement is made for jet transverse momenta in the range 18–1100 GeV and for absolute values of rapidity less than 3. The measured cross section extends to the highest values of jet p_T ever observed and, within the experimental and theoretical uncertainties, is generally in agreement with next-to-leading-order perturbative QCD predictions.

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The measurement of the inclusive jet cross section is a benchmark of the standard model (SM) at hadron colliders [1,2]. At the Large Hadron Collider (LHC), jets produced in the high center-of-mass energy collisions test the SM at the smallest distance scales presently possible can constrain parton momentum distributions in the proton and are sensitive to the strong coupling constant. Significant deviations from predictions of the inclusive jet cross section at high transverse momentum p_T could also be an indication of new phenomena beyond the SM. Results from the Tevatron $p\bar{p}$ collider demonstrate agreement with next-to-leading-order (NLO) theoretical predictions from perturbative quantum chromodynamics (pQCD) for jets in the approximate p_T range of 50–700 GeV, using about 1 fb^{-1} of data at a center-of-mass energy $\sqrt{s} = 1.96$ TeV [3–5]. Early results from the ATLAS Collaboration for jets in the p_T range 60–600 GeV, based on a 17 pb^{-1} data sample of pp collisions at $\sqrt{s} = 7$ TeV at the LHC [6], also indicate agreement with theoretical predictions. Using a data sample corresponding to 34 pb^{-1} of integrated luminosity from pp collisions recorded by the CMS detector at the LHC with $\sqrt{s} = 7$ TeV, we significantly extend the p_T range from previous measurements of the inclusive jet p_T spectrum to 18–1100 GeV and for rapidities $|y| < 3.0$. The rapidity y is defined as $y = \frac{1}{2}\ln[(E + p_z)/(E - p_z)]$, where E is the jet energy and p_z is the component of the jet momentum along the beam axis. The inclusive jet cross section is defined as $d^2\sigma_{\mathrm{jet}}/(dp_T dy) = N_{\mathrm{jet}}/(\Delta p_T \Delta y)[1/(\epsilon\mathcal{L})]$, where N_{jet} is the number of jets per bin, Δp_T and Δy are the bin widths in p_T and y, $\mathcal{L}$ is the total integrated luminosity, and ϵ is the product of event and jet selection efficiencies. All jets with $p_T > 18$ GeV in a proton-proton collision event are used in the measurement. In this Letter, the inclusive jet cross section is compared with theoretical predictions at NLO in pQCD.

The CMS detector has silicon pixel and microstrip trackers covering pseudorapidities up to $|\eta| = 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the counterclockwise proton beam direction. Together with a 3.8 T solenoid, the trackers enable track reconstruction down to transverse momenta of about 100 MeV and a resolution of about 1% at 100 GeV. A high-granularity electromagnetic crystal calorimeter (ECAL) extends up to $|\eta| = 3.0$ and has an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. A hermetic hadronic calorimeter (HCAL) extends up to $|\eta| = 5.0$ with a transverse hadronic energy resolution of about $100\%/\sqrt{E_T[\mathrm{GeV}]} \oplus 5\%$. The calorimeter components relevant to this work may be described in terms of a cylindrical barrel region, extending up to $|\eta| = 1.5$, and two end caps, covering $1.5 < |\eta| < 3.0$. An efficient muon system is used to reconstruct and identify muons up to $|\eta| = 2.4$. Events are collected using a two-level trigger system, consisting of a hardware level-1 and a software high level trigger. Jets formed online by the trigger system use the energies measured in the ECAL and HCAL and are uncorrected for the jet energy response of the calorimeters. This study uses inclusive single-jet triggers corresponding to p_T thresholds of 6, 15, 30, 50, 70, 100, and 140 GeV. Finally, a minimum-bias trigger is defined as a signal from at least one of two beam scintillator counters in coincidence with a signal from one of two beam pickup timing devices. The CMS coordinate system is right handed, with the origin centered at the nominal collision point, the x axis pointing radially toward the center of the LHC, the y axis pointing vertically upward, and the z axis pointing along the beam direction. More details about the CMS detector can be found in Ref. [7].

This measurement uses the infrared- and collinear-safe anti-k_T jet algorithm [8] as implemented in Ref. [9]. The algorithm is a sequential clustering algorithm similar to the well-known k_T algorithm [10,11] except that it uses $1/p_T^2$ instead of p_T^2 as the weighting factor for the scaled

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

distance. The algorithm produces jets that are cone shaped in the rapidity-azimuth plane, except when jets overlap. The CMS particle-flow (PF) algorithm reconstructs individual particles (leptons, photons, charged and neutral hadrons) by linking tracks, ECAL clusters, and HCAL clusters. The momentum or energy of each particle is measured based on information from all subdetectors. Broadly speaking, electrons are reconstructed from tracks and calibrated ECAL clusters; muons are reconstructed using tracks; charged hadrons are reconstructed from tracks and calibrated ECAL and HCAL clusters; photons and neutral hadrons are reconstructed from calibrated ECAL and HCAL clusters, respectively. A detailed description of the PF algorithm and performance can be found in Ref. [12] and references therein. Jets are reconstructed by clustering particles, including leptons. Because the energy response of each reconstructed particle is close to unity, the jet momentum response is also close to unity and only small corrections (at the level of 5%–10%) are needed [13,14]. The bulk of these corrections are derived from simulation [15] with residual corrections determined from data. First, using an exclusive dijet sample containing back-to-back jets in azimuth, a residual relative correction of up to 8% removes any remaining pseudorapidity dependence of the jet momentum response. Second, using an exclusive data sample containing a single hadronic jet recoiling back to back in azimuth against a well measured photon [14], a small residual absolute correction of about 1% restores the response to unity. Jet momenta are further corrected for the pileup of multiple proton-proton collisions [16], which ranged from nearly zero additional collisions at the very early period of LHC data taken in 2010 to an average of about three near the end of the 2010 running period. Finally, the jet momentum resolution is determined as a function of the jet p_T and y from simulation. Comparing the p_T balance in dijet events between data and simulation, the jet p_T resolution from simulation is scaled to be about 10% larger in the barrel and about 20% larger in the end caps to match that from data [13,14].

The efficiency of a given inclusive single-jet trigger is determined as the ratio of its trigger rate to either the minimum-bias trigger rate or the rate of the lower-p_T trigger preceding it. The minimum jet p_T is chosen so that the trigger efficiency exceeds 99% for each data set. All events are required to have a primary vertex (PV) satisfying the following selection: the fit for the PV must include at least three associated tracks, the PV must lie within 0.15 cm of the beam axis, and the z coordinate of the PV must lie within the luminous collision region $|z_{\mathrm{PV}}| <$ 24 cm. This selection rejects noncollision and beam-related backgrounds. Loose jet identification criteria [17] are applied requiring that each jet within the tracker's fiducial acceptance have at least two particles, of which at least one must be a charged hadron. Further, at most 90% of the jet energy is allowed to be from photons or neutral hadrons. Beyond the tracker acceptance, each jet is required to have both electromagnetic and hadronic energy. To remove effects from anomalous calorimeter noise, beam halo, or cosmic-ray backgrounds, events are rejected if the missing transverse momentum is both larger than 50% of the total visible transverse energy and larger than 100 GeV. The missing transverse momentum is defined as the modulus of the negative transverse vector sum over the momenta of all reconstructed particles in the event. Any inefficiency in selecting jets, due to the above criteria, is estimated from simulation to be negligible.

Because of resolution effects, a jet may fall into a different p_T bin than the one corresponding to the true underlying, hadron-level jet. Such bin-to-bin migrations distort the rapidly falling p_T spectrum. Each p_T bin width is chosen to be larger than the reconstructed jet p_T resolution in the bin to minimize the migration effects and large enough to ensure that statistical fluctuations do not dominate the measurement. The jet p_T spectra are corrected for resolution effects where the true jet p_T spectrum is modeled by a power-law ansatz motivated by the parton model, modified by a kinematic cutoff term at high p_T: $f(p_T; \alpha, \beta, \gamma) = N_0[p_T]^{-\alpha}[1 - \frac{1}{\sqrt{s}} 2p_T \cosh(y_{\min})]^{\beta} \times \exp[-\gamma/p_T]$, where N_0 is a normalization factor, α, β, γ are fit parameters, and $y_{\min}$ is the low-edge of the rapidity bin y under consideration. Similar parametrizations have been previously used by other experiments [5,6,18]. The function is then smeared using the jet p_T resolutions in bins of p_T and y. The parameters of the model are extracted by fitting the smeared transverse momentum spectrum to the experimental data. The data points are placed at the bin center, defined as the point where the value of the predicted function is equal to its mean value over the bin width. The p_T resolution corrections for each bin in p_T and y, determined by taking the ratio of the function to the smeared function, range from 5% to 10% as a function of p_T in the central rapidity bin and range from about 10% to 50% in the most-forward rapidity bin. Jet migrations across y bins due to y resolution are found to be negligible within the tracker's fiducial acceptance. Using simulation, migrations of up to 5% are observed and corrected across bins whose boundaries lie near the tracker acceptance.

The primary sources of systematic uncertainties in the cross section measurement arise from the jet momentum scale and resolution, as well as the integrated luminosity. The jet transverse momentum scale is sensitive to several effects including (a) the photon energy scale (known to 1.0% [19] and used to derive the residual absolute response corrections), (b) the relative response across detector regions (known to within 2.6% [14]), (c) pile-up effects (known to within 0.2% for very low pile-up conditions with low-p_T jet triggers or for intermediate pile-up conditions with high-p_T jet triggers), and (d) the calibration extrapolation to transverse momenta above available photon energies (dominated by uncertainties in jet fragmentation and estimated to be within 4% at 1100 GeV [14]). With those considerations, the total uncertainty in the jet transverse momentum scale is determined to be between 3% and 4% in the ranges $18 < p_T < 1100$ GeV and $|\eta| < 3.0$. The jet momentum resolutions for different y bins are known to within 10% at $|y| < 1.5$, increasing to 15% for $1.5 < |y| < 2.0$, 25% for $2.0 < |y| < 2.5$, and 30% for $2.5 < |y| < 3.0$ [13]. The integrated luminosity of the proton-proton collisions is known with a precision of 4% [20] and directly translates into a 4% normalization uncertainty on the inclusive jet cross section.

The next-to-leading-order perturbative QCD theoretical predictions are derived using NLOJET++ 2.0.1 [21,22] within the framework of FASTNLO 1.4 [23]. Other NLO calculations are available in Refs. [24–26]. The FASTNLO framework is used for propagating uncertainties due to different parton distribution function (PDF) sets, α_s values, and scale choices. Nonperturbative (NP) corrections for hadronization and multiple parton interactions are estimated using PYTHIA 6.422 [27] and HERWIG++ 2.4.2 [28], which are applied to the NLO pQCD prediction. The correction is defined as the average of the models, and the associated theoretical uncertainty is assumed to be half of the difference between the two predictions. For low-p_T jets, the NP correction can be as large as 30%, with a relative uncertainty of 100%. Uncertainties from any residual dependence on the choice of renormalization scale μ_r and factorization scale μ_f are determined by varying the scales according to the following combinations [29]: $(\frac{1}{2}\mu_r, \frac{1}{2}\mu_f)$, $(\frac{1}{2}\mu_r, \mu_f)$, $(\mu_r, \frac{1}{2}\mu_f)$, $(\mu_r, 2\mu_f)$, $(2\mu_r, \mu_f)$, and $(2\mu_r, 2\mu_f)$. The default choice is $\mu_r = \mu_f = p_T$. These scale variations modify the prediction of the inclusive jet cross section by about 5%–10%. Following the PDF4LHC Working Group recommendation [30], PDF uncertainties are evaluated via a prescribed envelope, defined as the maximum variation between different NLO PDF sets constructed from CT10 [31], MSTW2008NLO [32], and NNPDF2.0 [33], including their respective uncertainties and using their respective default values of the strong coupling constant $\alpha_s(m_Z) = 0.1180$, 0.1190, and 0.1202. The middle of the envelope is taken as the central prediction. The uncertainties are on the order of 10% up to a p_T of 800 GeV, except when approaching the kinematic limit where they can be as large as 40%. More detailed comparisons with individual NLO PDF sets are reported separately in Ref. [34]. Finally, an additional uncertainty from the current knowledge of the strong coupling constant is calculated from the CT10as PDF set [31] with values of $\alpha_s(m_Z)$ varied conservatively by ± 0.002 and added in quadrature to the PDF uncertainty. The uncertainties due to these variations in $\alpha_s(m_Z)$ are between 2.5% and 5.0%. The PDF uncertainties are dominated by differences between PDF sets in the PDF4LHC recommendation for $50 < p_T < 500$ GeV, and by uncertainties within a single PDF set for $p_T > 500$ GeV.

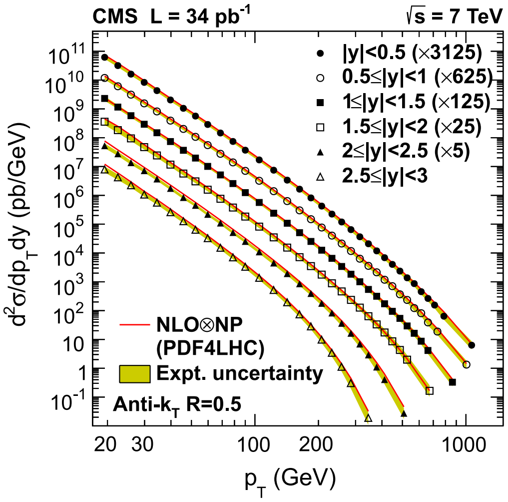

FIG. 1 (color online). Fully corrected inclusive jet differential cross section as a function of p_T for six different rapidity intervals, scaled by the factors shown in the legend for easier viewing. The next-to-leading-order (NLO) theoretical predictions, corrected for nonperturbative (NP) effects via multiplicative factors, are superimposed. The statistical uncertainties are smaller than the symbol used to represent each data point.

The fully corrected inclusive jet cross section is shown in Figs. 1 and 2. Figure 1 shows the jet p_T spectra between 18 and 1100 GeV, falling over 10 orders of magnitude in rate, and for six different rapidity bins. The comparison with the theoretical NLO prediction, corrected for NP effects, is more easily discerned in Fig. 2, which provides the ratio of the jet p_T spectra from data to the theoretical prediction for each of the six rapidity bins. The total theoretical systematic uncertainty from the prediction is superimposed as solid lines above and below unity, and the total systematic uncertainty due to experimental effects is centered on the data points as a shaded band. The central predictions for the CT10, MSTW2008NLO, and NNPDF2.0 PDF sets are also overlayed. The PDF uncertainties are large and asymmetric at high jet p_T, dominating the theoretical uncertainty band. Nevertheless, compared to the PDF4LHC recommendation, similar trends between data and the central prediction of each PDF set are observed. Within the experimental and theoretical uncertainties, the predictions are seen to be consistent with the data across a wide range of jet p_T and rapidities, although the predictions are systematically above the data.

In conclusion, using a data sample corresponding to 34 pb^{-1} of integrated luminosity from pp collisions recorded by the CMS detector at the LHC with a center-of-mass energy of 7 TeV, the jet transverse momentum spectrum has been measured for $18 < p_T < 1100$ GeV and for six rapidity bins up to $|y| = 3.0$. The dominant systematic uncertainties arise from the absolute jet momentum scale and resolution, as well as the integrated luminosity

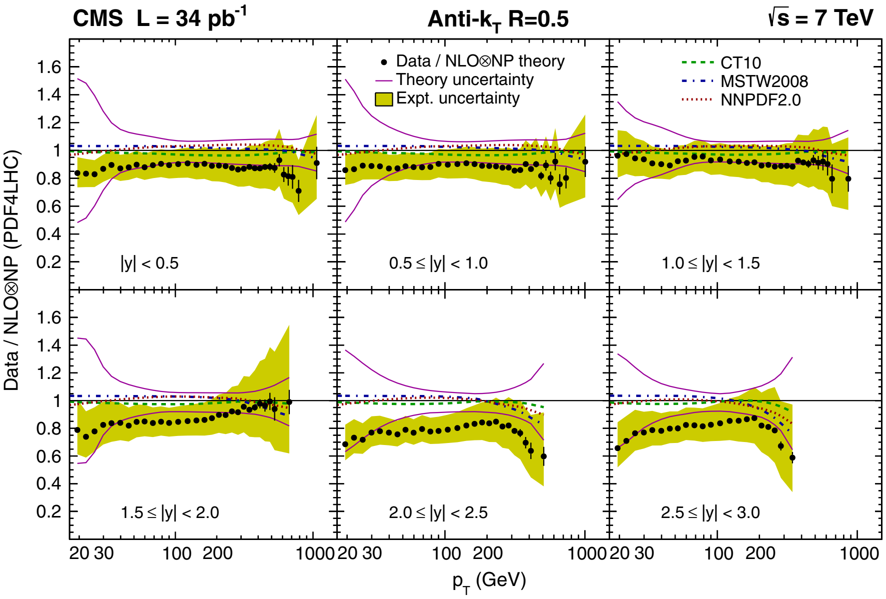

FIG. 2 (color online). Ratios of the fully corrected measured jet p_T differential cross section to the theoretical prediction as a function of p_T. The error bars show the experimental statistical uncertainties. The shaded band about the data points represents the total experimental systematic uncertainty. The solid lines represent the total theoretical systematic uncertainty. The central predictions for the CT10 (dashed line), MSTW2008NLO (dash-dotted line), and NNPDF2.0 (dotted line) PDF sets are also shown.

measurement. The NLO pQCD predictions for the inclusive jet cross section, corrected for nonperturbative effects and using the PDF4LHC recommendations, are generally in agreement with the data. This measurement extends to the highest values of jet p_T ever observed.

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E. Yazgan,[155] E. Appelt,[156] E. Brownson,[156] D. Engh,[156] C. Florez,[156] W. Gabella,[156] M. Issah,[156] W. Johns,[156] P. Kurt,[156] C. Maguire,[156] A. Melo,[156] P. Sheldon,[156] B. Snook,[156] S. Tuo,[156] J. Velkovska,[156] M. W. Arenton,[157] M. Balazs,[157] S. Boutle,[157] B. Cox,[157] B. Francis,[157] R. Hirosky,[157] A. Ledovskoy,[157] C. Lin,[157] C. Neu,[157] R. Yohay,[157] S. Gollapinni,[158] R. Harr,[158] P. E. Karchin,[158] P. Lamichhane,[158] M. Mattson,[158] C. Milstène,[158] A. Sakharov,[158] M. Anderson,[159] M. Bachtis,[159] J. N. Bellinger,[159] D. Carlsmith,[159] S. Dasu,[159] J. Efron,[159] K. Flood,[159] L. Gray,[159] K. S. Grogg,[159] M. Grothe,[159] R. Hall-Wilton,[159] M. Herndon,[159] P. Klabbers,[159] J. Klukas,[159] A. Lanaro,[159] C. Lazaridis,[159] J. Leonard,[159] R. Loveless,[159] A. Mohapatra,[159] F. Palmonari,[159] D. Reeder,[159] I. Ross,[159] A. Savin,[159] W. H. Smith,[159] J. Swanson,[159] and M. Weinberg[159]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik der OeAW, Wien, Austria*
[3]*National Centre for Particle and High Energy Physics, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Université de Mons, Mons, Belgium*
[10]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[11]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[12]*Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil*
[13]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
[14]*University of Sofia, Sofia, Bulgaria*
[15]*Institute of High Energy Physics, Beijing, China*
[16]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[17]*Universidad de Los Andes, Bogota, Colombia*
[18]*Technical University of Split, Split, Croatia*
[19]*University of Split, Split, Croatia*
[20]*Institute Rudjer Boskovic, Zagreb, Croatia*
[21]*University of Cyprus, Nicosia, Cyprus*
[22]*Charles University, Prague, Czech Republic*
[23]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[24]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[25]*Department of Physics, University of Helsinki, Helsinki, Finland*
[26]*Helsinki Institute of Physics, Helsinki, Finland*
[27]*Lappeenranta University of Technology, Lappeenranta, Finland*
[28]*Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[29]*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France*
[30]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
[31]*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
[32]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France*
[33]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[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*
[58]*INFN Sezione di Genova, Genova, Italy*
[59a]*INFN Sezione di Milano-Biccoca, 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 Padova, 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, 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*
[69]*Kyungpook National University, Daegu, Korea*
[70]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[71]*Korea University, Seoul, Korea*
[72]*University of Seoul, Seoul, Korea*
[73]*Sungkyunkwan University, Suwon, Korea*
[74]*Vilnius University, Vilnius, Lithuania*
[75]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[76]*Universidad Iberoamericana, Mexico City, Mexico*
[77]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[78]*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
[79]*University of Auckland, Auckland, New Zealand*
[80]*University of Canterbury, Christchurch, New Zealand*
[81]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[82]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[83]*Soltan Institute for Nuclear Studies, Warsaw, Poland*
[84]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[85]*Joint Institute for Nuclear Research, Dubna, Russia*
[86]*Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia*
[87]*Institute for Nuclear Research, Moscow, Russia*
[88]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[89]*Moscow State University, Moscow, Russia*
[90]*P. N. Lebedev Physical Institute, Moscow, Russia*

[91]*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
[92]*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
[93]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[94]*Universidad Autónoma de Madrid, Madrid, Spain*
[95]*Universidad de Oviedo, Oviedo, Spain*
[96]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[97]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[98]*Paul Scherrer Institut, Villigen, Switzerland*
[99]*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
[100]*Universität Zürich, Zurich, Switzerland*
[101]*National Central University, Chung-Li, Taiwan*
[102]*National Taiwan University (NTU), Taipei, Taiwan*
[103]*Cukurova University, Adana, Turkey*
[104]*Middle East Technical University, Physics Department, Ankara, Turkey*
[105]*Bogazici University, Istanbul, Turkey*
[106]*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[107]*University of Bristol, Bristol, United Kingdom*
[108]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[109]*Imperial College, London, United Kingdom*
[110]*Brunel University, Uxbridge, United Kingdom*
[111]*Baylor University, Waco, Texas, USA*
[112]*Boston University, Boston, Massachusetts, USA*
[113]*Brown University, Providence, Rhode Island, USA*
[114]*University of California, Davis, Davis, California, USA*
[115]*University of California, Los Angeles, Los Angeles, California, USA*
[116]*University of California, Riverside, Riverside, California, USA*
[117]*University of California, San Diego, La Jolla, California, USA*
[118]*University of California, Santa Barbara, Santa Barbara, California, USA*
[119]*California Institute of Technology, Pasadena, California, USA*
[120]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[121]*University of Colorado at Boulder, Boulder, Colorado, USA*
[122]*Cornell University, Ithaca, New York, USA*
[123]*Fairfield University, Fairfield, Connecticut, USA*
[124]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[125]*University of Florida, Gainesville, Florida, USA*
[126]*Florida International University, Miami, Florida, USA*
[127]*Florida State University, Tallahassee, Florida, USA*
[128]*Florida Institute of Technology, Melbourne, Florida, USA*
[129]*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
[130]*The University of Iowa, Iowa City, Iowa, USA*
[131]*Johns Hopkins University, Baltimore, Maryland, USA*
[132]*The University of Kansas, Lawrence, Kansas, USA*
[133]*Kansas State University, Manhattan, Kansas, USA*
[134]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[135]*University of Maryland, College Park, Maryland, USA*
[136]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[137]*University of Minnesota, Minneapolis, Minnesota, USA*
[138]*University of Mississippi, University, Mississippi, USA*
[139]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[140]*State University of New York at Buffalo, Buffalo, New York, USA*
[141]*Northeastern University, Boston, Massachusetts, USA*
[142]*Northwestern University, Evanston, Illinois, USA*
[143]*University of Notre Dame, Notre Dame, Indiana, USA*
[144]*The Ohio State University, Columbus, Ohio, USA*
[145]*Princeton University, Princeton, New Jersey, USA*
[146]*University of Puerto Rico, Mayaguez, Puerto Rico*
[147]*Purdue University, West Lafayette, Indiana, USA*
[148]*Purdue University Calumet, Hammond, Indiana, USA*
[149]*Rice University, Houston, Texas, USA*
[150]*University of Rochester, Rochester, New York, USA*
[151]*The Rockefeller University, New York, New York, USA*

[152]*Rutgers, the State University of New Jersey, Piscataway, New Jersey, USA*
[153]*University of Tennessee, Knoxville, Tennessee, USA*
[154]*Texas A&M University, College Station, Texas, USA*
[155]*Texas Tech University, Lubbock, Texas, USA*
[156]*Vanderbilt University, Nashville, Tennessee, USA*
[157]*University of Virginia, Charlottesville, Virginia, USA*
[158]*Wayne State University, Detroit, Michigan, USA*
[159]*University of Wisconsin, Madison, Wisconsin, USA*

[a] Deceased.
[b] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[c] Also at Universidade Federal do ABC, Santo Andre, Brazil.
[d] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[e] Also at Suez Canal University, Suez, Egypt.
[f] Also at British University, Cairo, Egypt.
[g] Also at Fayoum University, El-Fayoum, Egypt.
[h] Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.
[i] Also at Massachusetts Institute of Technology, Cambridge, MA, USA.
[j] Also at Université de Haute-Alsace, Mulhouse, France.
[k] Also at Brandenburg University of Technology, Cottbus, Germany.
[l] Also at Moscow State University, Moscow, Russia.
[m] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[n] Also at Eötvös Loránd University, Budapest, Hungary.
[o] Also at Tata Institute of Fundamental Research–HECR, Mumbai, India.
[p] Also at University of Visva-Bharati, Santiniketan, India.
[q] Also at Sharif University of Technology, Tehran, Iran.
[r] Also at Shiraz University, Shiraz, Iran.
[s] Also at Isfahan University of Technology, Isfahan, Iran.
[t] Also at Facoltà Ingegneria Università di Roma “La Sapienza,” Roma, Italy.
[u] Also at Università della Basilicata, Potenza, Italy.
[v] Also at Università degli studi di Siena, Siena, Italy.
[w] Also at California Institute of Technology, Pasadena, CA, USA.
[x] Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[y] Also at University of California, Los Angeles, Los Angeles, CA, USA.
[z] Also at University of Florida, Gainesville, FL, USA.
[aa] Also at Université de Genève, Geneva, Switzerland.
[bb] Also at Scuola Normale e Sezione dell’ INFN, Pisa, Italy.
[cc] Also at University of Athens, Athens, Greece.
[dd] Also at The University of Kansas, Lawrence, KS, USA.
[ee] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[ff] Also at Paul Scherrer Institut, Villigen, Switzerland.
[gg] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[hh] Also at Gaziosmanpasa University, Tokat, Turkey.
[ii] Also at Adiyaman University, Adiyaman, Turkey.
[jj] Also at Mersin University, Mersin, Turkey.
[kk] Also at Izmir Institute of Technology, Izmir, Turkey.
[ll] Also at Kafkas University, Kars, Turkey.
[mm] Also at Suleyman Demirel University, Isparta, Turkey.
[nn] Also at Ege University, Izmir, Turkey.
[oo] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[pp] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[qq] Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
[rr] Also at Utah Valley University, Orem, UT, USA.
[ss] Also at Institute for Nuclear Research, Moscow, Russia.
[tt] Also at Erzincan University, Erzincan, Turkey.