Quantum chromodynamics (QCD) predicts that strongly interacting matter undergoes a phase transition to a deconfined state, often referred to as the quark-gluon plasma (QGP), in which quarks and gluons are no longer bound within hadrons. Calculations in lattice QCD [1,2] indicate that the transition should occur at a critical temperature $T_c \approx 150$–175 MeV, corresponding to an energy density $\epsilon_c \approx 1$ GeV/fm$^3$.

If the QGP is formed in heavy-ion collisions, it is expected to screen the confining potential of heavy quark-antiquark pairs [3], leading to the melting of charmonia ($J/\psi$, $\psi'$, $\chi_c$, ...) and bottomonia ($Y(1S)$, $Y(2S)$, $Y(3S)$, $\chi_b$, ...). The melting temperature depends on the binding energy of the quarkonium state. The ground states $J/\psi$, and $Y(1S)$, are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. Quenched lattice QCD calculations [4,5] predict that the $Y(nS)$ states melt at $1.2\ T_c\ (3S)$, $1.6\ T_c\ (2S)$, and above $4\ T_c\ (1S)$, while modern spectral-function approaches with complex potentials [6,7] favor somewhat lower dissolution temperatures. This sequential melting pattern is generally considered a “smoking-gun” signature of the QCD deconfinement transition. However, a large fraction of the observed $Y(1S)$ yield is due to decays of heavier states (around 50% for the $Y(1S)$ [8]). Therefore the melting of the excited states is expected to result in a significant suppression of the observed $Y(1S)$ yield, even if the medium is not hot enough to directly dissolve it.

Observations of a larger $J/\psi$ and $\psi(2S)$ suppression in heavy-ion collisions with respect to proton-nucleus collisions were reported by the NA38 [9], NA50 [10,11], and NA60 [12] fixed-target experiments at the Super Proton Synchrotron (SPS), respectively, in sulfur-uranium, lead-lead, and indium-indium collisions, at center-of-mass energies per nucleon pair ($\sqrt{s_{NN}}$) of about 20 GeV. The PHENIX experiment, at the Relativistic Heavy Ion Collider (RHIC), extended the $J/\psi$ suppression measurements to Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [13]. Recent results from ATLAS and CMS show $J/\psi$ suppression at LHC [14,15]. At RHIC, bottomonia production becomes measurable [16], though with limited integrated luminosities. PHENIX observed that the dimuon yield in the $Y$ mass region for minimum bias Au-Au collisions is less than 65%, at the 90% confidence level, of the value expected by extrapolating the proton-proton yields [17].

A new era of detailed studies of the bottomonium family in heavy-ion collisions has started at the Large Hadron Collider (LHC). The measurement reported in this Letter is performed with data recorded by the Compact Muon Solenoid (CMS) experiment during the first lead-lead (Pb-Pb) LHC run, at the end of 2010, and during the proton-proton ($pp$) run of March 2011, both at $\sqrt{s_{NN}} = 2.76$ TeV. The integrated luminosity used in this analysis corresponds to $7.28\ \mu$b$^{-1}$ for Pb-Pb and 225 nb$^{-1}$ for $pp$ collisions, the latter corresponding approximately to the equivalent nucleon-nucleon luminosity of the Pb-Pb run. The momentum resolution of the CMS detector results in well-resolved $Y$ peaks in the dimuon mass spectrum. The CMS Collaboration has previously studied $Y$ production in $pp$ data at $\sqrt{s} = 7$ TeV [18], using techniques to extract the $Y$ yields that are very similar to the ones used in the study reported in this Letter.

A detailed description of the CMS detector can be found in [19]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon (Si) pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass or scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition, CMS has extensive...
forward calorimetry, in particular, two steel or quartz-fiber Čerenkov hadron forward (HF) calorimeters, which cover the pseudorapidity range $2.9 < \eta < 5.2$.

In this analysis, $Y$ states are identified through their dimuon decay. The silicon pixel and strip tracker measures charged-particle trajectories in the range $|\eta| < 2.5$. The tracker consists of 66 M pixel and 10 M strip detector channels, providing a vertex resolution of $\sim 15 \text{ \mu m}$ in the transverse plane. Muons are detected in the $|\eta| < 2.4$ range, with detection planes based on three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Because of the strong magnetic field and the fine granularity of the Si tracker, the muon transverse momentum measurement ($p_T$) based on information from the Si tracker alone has a resolution between 1% and 2% for a typical muon in this analysis.

In both the Pb-Pb and $pp$ runs, the events are selected by the CMS two-level trigger. At the first, hardware level, two independent muon candidates are required in the muon detectors. No selection is made on momentum or pseudorapidity, but in the $pp$ case more stringent quality requirements are imposed for each muon in order to reduce the higher trigger rate. In both cases, the software-based higher-level trigger accepts the lower-level decision without applying further criteria. The single-muon trigger efficiencies are measured from reconstructed $J/\psi \rightarrow \mu \mu$ decays, for muons with $p_T > 4 \text{ GeV/c}$. The values of these efficiencies, $(96.1 \pm 1.0)\%$ in the Pb-Pb data set and $(95.5 \pm 0.6)\%$ in the $pp$ data set, are consistent.

For the Pb-Pb data, events are preselected offline if they contain a reconstructed primary vertex made of at least two tracks, and a coincidence in both HF calorimeters of energy deposits larger than 3 GeV in at least three towers. These criteria reduce contributions from single-beam interactions (e.g., beam-gas and beam-halo collisions with the beam pipe), ultraperipheral electromagnetic collisions, and cosmic-ray muons. A small fraction of the most peripheral Pb-Pb collisions is not selected by these requirements, which accept $(97 \pm 3)\%$ of the hadronic inelastic cross section [20]. For the $pp$ run, a similar event filter is applied, relaxing the HF coincidence to one tower in each HF, with at least 3 GeV deposited. This filter removes only 1% of the $pp$ events satisfying the dimuon trigger.

The muon offline reconstruction is seeded with $\approx 99\%$ efficiency by tracks in the muon detectors, called stand-alone muons. These tracks are then matched to tracks reconstructed in the Si tracker by means of an algorithm optimized for the heavy-ion environment [21,22]. For muons from $Y$ decays the Si-tracking efficiency is $\approx 85\%$. This efficiency is lower than in $pp$, as in Pb-Pb the Si-track reconstruction is seeded by a greater number of pixel hits to reduce the large number of random combinations arising from the high multiplicity of each event. Combined fits of the muon and Si-tracker tracks are used to obtain the results presented in this Letter. The heavy-ion dedicated reconstruction algorithm is applied to the $pp$ data in order to avoid potential biases.

Identical, very-loose selection criteria are applied to the muons in the $pp$ and Pb-Pb data. Their transverse (longitudinal) distance of closest approach from the event vertex is required to be less than 3 (15) cm. Tracks are only kept if they have 11 or more hits in the silicon tracker and the $\chi^2$ per degree of freedom of the combined (tracker) track fit is lower than 20 (4). The two muon trajectories are fit with a common vertex constraint, and events are retained if the fit $\chi^2$ probability is larger than 1%. This removes background arising primarily from the displaced, semileptonic decays of charm and bottom hadrons. As determined from Monte Carlo simulation of the $Y(1S)$ signal, these selection criteria are found to reduce the efficiency by 3.9%, which is consistent with the signal loss observed in both $pp$ and Pb-Pb data. The available event sample limits to 20 GeV/c the dimuon transverse momentum range probed in this study.

Only muons with a transverse momentum ($p_T^\mu$) higher than 4 GeV/c are considered, resulting in a $Y$ acceptance of approximately 25% for the $|y^\mu| < 2.4$ rapidity range. This requirement optimizes the significance of the $Y(1S)$ signal in Pb-Pb data and is applied to both data sets. The acceptance of a $Y$ state depends on its mass, since the excited states give rise to higher-momenta muons. In consequence, requiring higher $p_T^\mu$ increases the acceptance for the excited states relative to the ground state. In the corresponding analysis performed with the higher statistics (3.1 pb$^{-1}$) 7 TeV data [18], looser criteria were applied ($p_T^\mu > 3.5 \text{ GeV/c}$ and $|\eta| < 1.6$, or $p_T^\mu > 2.5 \text{ GeV/c}$ and $1.6 < |\eta| < 2.4$), where $\eta^\mu$ is the muon pseudorapidity. The looser ($p_T^\mu > 4 \text{ GeV/c}$) requirements used here enhance the $Y(2S + 3S)/Y(1S)$ yield ratio by $\approx 60\%$ in the $pp$ data at 2.76 TeV. It was checked that, applying identical $pp$ reconstruction algorithms and $p_T^\mu$ requirements, the $Y(2S + 3S)/Y(1S)$ yield ratio is consistent, within statistical uncertainties, between the 2.76 and 7 TeV $pp$ data sets [15].

The dimuon invariant-mass spectra with the selection criteria applied are shown in Fig. 1 for the $pp$ and Pb-Pb data sets. Within the 7–14 GeV/c$^2$ mass range, there are 561 (628) opposite-sign muon pairs in the $pp$ (Pb-Pb) data set. The three $Y$ peaks are clearly observed in the $pp$ case, but the $Y(2S)$ and $Y(3S)$ are not visible over the residual background in Pb-Pb collisions.

An extended unbinned maximum likelihood fit to the two invariant-mass distributions of Fig. 1 is performed to extract the yields, following the method described in [18]. The measured mass line shape of each $Y$ state is parametrized by a “crystal ball” (CB) function, i.e., a Gaussian resolution function with the lowside tail replaced by a power law describing final-state radiation (FSR). Since the three $Y$ resonances partially overlap in the measured dimuon mass, they are fit simultaneously. Therefore, the
The quality of the unbinned fit is checked \textit{a posteriori} by comparing the obtained line shapes to the binned data of Fig. 1. The $\chi^2$ probabilities are 74\% and 77\%, respectively, for $pp$ and Pb-Pb.

The ratios of the observed (uncorrected) yields of the $Y(2S)$ and $Y(3S)$ excited states to the $Y(1S)$ ground state in the $pp$ and Pb-Pb data are

\begin{equation}
Y(2S + 3S)/Y(1S)_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02, \quad (1)
\end{equation}

\begin{equation}
Y(2S + 3S)/Y(1S)_{Pb-Pb} = 0.24^{+0.13}_{-0.12} \pm 0.02, \quad (2)
\end{equation}

where the first uncertainty is statistical and the second is systematic.

The systematic uncertainties are computed by varying the line shape in the following ways: (1) the CB-tail parameters are varied randomly according to their covariance matrix and within conservative values covering imperfect knowledge of the amount of detector material and FSR in the underlying process; (2) the resolution is varied by $\pm 5$ MeV/$c^2$, which is a conservative variation given the current understanding of the detector performance and reasonable changes that can be anticipated in the $Y$-resonance kinematics between $pp$ and Pb-Pb data; (3) the background shape is changed from quadratic to linear while the mass range of the fit is varied from 6–15 to 8–12 GeV/$c^2$; the observed root-mean-square of the results is taken as the systematic uncertainty. The quadratic sum of these three systematic uncertainties gives a relative uncertainty on the ratio of 10\% (3\%) for the Pb-Pb ($pp$) data. The ratio of the $Y(2S + 3S)/Y(1S)$ ratios in Pb-Pb and $pp$ benefits from an almost complete cancellation of possible acceptance and/or efficiency differences among the reconstructed resonances. A simultaneous fit to the $pp$ and Pb-Pb mass spectra gives the double ratio

\begin{equation}
\frac{Y(2S + 3S)/Y(1S)_{Pb-Pb}}{Y(2S + 3S)/Y(1S)_{pp}} = 0.31^{+0.19}_{-0.15} \text{(stat)} \pm 0.03 \text{(syst)}, \quad (3)
\end{equation}

where the systematic uncertainty (9\%) arises from varying the line shape as described above in the simultaneous fit, thus taking into account partial cancellations of systematic effects.

The single-muon lower momentum requirement is a posteriori varied from 3 to 5 GeV/$c$ in steps of 500 MeV/$c$, and it is found that $p_T$ requirements other than 4 GeV/$c$ produce lower values of the double ratio. Fitting the $pp$ and Pb-Pb spectra with free and independent mass resolution parameters leads to an increase of the double ratio by 15\%.

To evaluate possible imperfect cancellations of acceptance and efficiency effects in the double ratio, a full [24] detector simulation is performed. The effect of the higher Pb-Pb underlying event activity is accounted for by embedding, at the level of detector signals, $Y(1S)$ and $Y(2S)$ decays simulated by \textsc{pythia} 6.424 [25] in Pb-Pb events simulated with \textsc{hydjet} [26]. Track characteristics, such as the number of hits and the $\chi^2$ of the track fit, have similar distributions in data and simulation. As mentioned above, the trigger efficiency is evaluated with data, by using single-muon-triggered data events, and reconstructing $J/\psi$ signal with and without the dimuon trigger.
requirement. The same exercise is carried out with the simulation and it agrees with the efficiency measured in data at the 2% level. The track efficiency in the silicon detector is measured with standalone muons, applying all selection criteria. The efficiencies in data and simulation agree within the 4% statistical uncertainty of the efficiency determined from data.

The difference in reconstruction and selection efficiencies between the Y states is less than 5% and the relative variation with charged-particle multiplicity is about 10% from pp to central Pb-Pb collisions, producing a maximum change of 0.5% on the double ratio. The good agreement between single-muon trigger efficiencies extracted from data for the pp and Pb-Pb trigger requirements, applied to the Y(1S) and Y(2S) trigger efficiencies derived from simulation, leads to a negligible effect on the double ratio. The single-muon trigger efficiencies extracted from data agree within 1.5% for the pp and Pb-Pb trigger requirements, and the Y(1S) and Y(2S) trigger efficiencies agree within 3%, according to simulation: the potential trigger bias on the double ratio is negligible. Even doubling the size of these variations, to take the Y(3S) into account, leads to a negligible change in the double ratio. The magnitudes of the statistical and systematic uncertainties on the double ratio, respectively, 55% and 9%, are significantly larger than the systematic uncertainties associated with possible imperfect cancellation of acceptance and efficiency effects. Therefore no additional uncertainty from these sources is applied.

Finally, using an ensemble of $1 \times 10^6$ pseudoexperiments, generated with the signal line shape obtained from the pp data [Fig. 1(a)], the background line shapes from both data sets, and a double ratio [Eq. (3)] equal to unity within statistical and systematic uncertainties, the probability of finding the measured value of 0.31 or below is estimated to be 0.9%. In other words, in the absence of a suppression due to physics mechanisms, the probability of a downward departure of the ratio from unity of this significance or greater is 0.9%, i.e., that corresponding to 2.4 sigma in a one-tailed integral of a Gaussian distribution.

Other studies from the CMS experiment show that the Y(1S) is suppressed by about 40% [15] in minimum bias Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Since a large fraction of the Y(1S) yield arises from decays of heavier bottomonium states [8], this Y(1S) suppression could be indirectly caused by the suppression of the excited states reported in this Letter.

Production yields of quarkonium states can also be modified, from pp to Pb-Pb collisions, in the absence of QGP formation, by cold nuclear matter effects [27]. However, such effects should have a small impact on the Y double ratio reported here. The nuclear modifications of the parton distribution functions (shadowing) should have an equivalent effect on the three Y states, because their production involves very similar partons, canceling in the ratio, at least to first order. The same should happen to any other initial-state nuclear effect. In principle, the larger and more loosely bound excited quarkonium states are more likely to be broken up by final-state interactions while traversing the nuclear matter, something extensively studied in the context of charmonium suppression at lower energies [28]. This “nuclear absorption” becomes weaker with increasing energy, and should be negligible at the LHC. At RHIC energies, the STAR experiment [29] has reported a $Y(1S + 2S + 3S)$ yield in d-Au collisions of $0.78 \pm 0.28 \pm 0.20$ times the yield expected by scaling pp collisions, compatible with the absence of absorption. Furthermore, the double ratio presented here would only be sensitive to a difference between the nuclear dependences of the three states and already at much lower energies the Fermilab E772 experiment observed [30], in proton-nucleus collisions, no such difference, within uncertainties, between the Y(1S) and the sum Y(2S + 3S).

Future high-statistics heavy-ion and proton-nucleus runs at the LHC will provide further quarkonia measurements, which should help disentangle nuclear from medium effects and aid the interpretation of the result reported in this Letter.

In summary, a comparison of the relative yields of $Y$ resonances has been performed in Pb-Pb and pp collisions at the same center-of-mass energy per nucleon pair of 2.76 TeV. The double ratio of the Y(2S) and Y(3S) excited states to the Y(1S) ground state in Pb-Pb and pp collisions, $[Y(2S + 3S)/Y(1S)]_{Pb-Pb}/[Y(2S + 3S)/Y(1S)]_{pp}$, is found to be $0.31^{+0.19}_{-0.15}(stat) \pm 0.03(syst)$, for muons of $p_T > 4$ GeV/c and $|\eta| < 2.4$. The probability to obtain the measured value, or lower, if the true double ratio is unity, has been calculated to be less than 1%.

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC 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); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NCPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA an 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 (U.S.). Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Associazione per lo Sviluppo Scientifico e Tecnologico del Piemonte (Italy); the Belgian Federal Science Policy Office; the Fonds pour la Formation à l’industrie et dans l’Agriculture (FRIA-Belgium); and the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium).

R. A. Ofierzynski,144 B. Pollack,144 A. Pozdnyakov,144 M. Schmitt,144 S. Stoynev,144 M. Velasco,144 S. Won,144 L. Antonelli,145 D. Berry,145 A. Brinkerhoff,145 M. Hildreth,145 C. Jessop,145 D. J. Karmgard,145 J. Kolb,145

(CMS Collaboration)

1Yerevan Physics Institute, Yerevan, Armenia
2Institut für Hochenergiephysik der OeAW, Wien, Austria
3National Centre for Particle and High Energy Physics, Minsk, Belarus
4Universiteit Antwerpen, Antwerpen, Belgium
5Vrije Universiteit Brussel, Brussel, Belgium
6Université Libre de Bruxelles, Bruxelles, Belgium
7Ghent University, Ghent, Belgium
8Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9Université de Mons, Mons, Belgium
10Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
11Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
12Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
13Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
14University of Sofia, Sofia, Bulgaria
15Institute of High Energy Physics, Beijing, China
16State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
17Universidad de Los Andes, Bogota, Colombia
18Technical University of Split, Split, Croatia
19University of Split, Split, Croatia

052302-11
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 Nucléaire 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) Saha Institute of Nuclear Physics, Kolkata, India
50) Bhabha Atomic Research Centre, Mumbai, India
51) Tata Institute of Fundamental Research-EHEP, Mumbai, India
52) Tata Institute of Fundamental Research-HECR, Mumbai, India
53) Institute for Research and Fundamental Sciences (IPM), Tehran, Iran
54a) INFN Sezione di Bari, Bari, Italy
54b) Università di Bari, Bari, Italy
54c) Politecnico di Bari, Bari, Italy
55a) INFN Sezione di Bologna, Bologna, Italy
55b) Università di Bologna, Bologna, Italy
56a) INFN Sezione di Catania, Catania, Italy
56b) Università di Catania, Catania, Italy
57a) INFN Sezione di Firenze, Firenze, Italy
57b) Università di Firenze, Firenze, Italy
58) INFN Laboratori Nazionali di Frascati, Frascati, Italy
59) INFN Sezione di Genova, Genova, Italy
60a) INFN Sezione di Milano-Bicocca, Milano, Italy
60b) Università di Milano-Bicocca, Milano, Italy
61a) INFN Sezione di Napoli, Napoli, Italy
61b) Università di Napoli “Federico II,” Napoli, Italy
62a) INFN Sezione di Padova, Padova, Italy
62b) Università di Padova, Padova, Italy
62c) Università di Trento (Trento), Padova, Italy
63a) INFN Sezione di Pavia, Pavia, Italy
63b) Università di Pavia, Pavia, Italy
64a) INFN Sezione di Perugia, Perugia, Italy
64b) Università di Perugia, Perugia, Italy
65a) INFN Sezione di Pisa, Pisa, Italy
65b) Università di Pisa, Pisa, Italy
65c) Scuola Normale Superiore di Pisa, Pisa, Italy
University of Colorado at Boulder, Boulder, Colorado 80309, USA
Cornell University, Ithaca, New York 14853, USA
Fairfield University, Fairfield, Connecticut 06824, USA
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
University of Florida, Gainesville, Florida 32611, USA
Florida International University, Miami, Florida 33199, USA
Florida State University, Tallahassee, Florida 32306, USA
Florida Institute of Technology, Melbourne, Florida 32901, USA
University of Illinois at Chicago (UIC), Chicago, Illinois 60607, USA
The University of Iowa, Iowa City, Iowa 52242, USA
Johns Hopkins University, Baltimore, Maryland 21218, USA
The University of Kansas, Lawrence, Kansas 66045, USA
Kansas State University, Manhattan, Kansas 66506, USA
Lawrence Livermore National Laboratory, Livermore, California 94720, USA
University of Maryland, College Park, Maryland 20742, USA
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
University of Minnesota, Minneapolis, Minnesota 55455, USA
University of Mississippi, University, Mississippi 38677, USA
University of Nebraska-Lincoln, Lincoln, Nebraska 68588, USA
State University of New York at Buffalo, Buffalo, New York 14260, USA
Northeastern University, Boston, Massachusetts 02115, USA
Northwestern University, Evanston, Illinois 60208, USA
University of Notre Dame, Notre Dame, Indiana 46556, USA
The Ohio State University, Columbus, Ohio 43210, USA
Princeton University, Princeton, New Jersey 08544, USA
University of Puerto Rico, Mayaguez, Puerto Rico 00680
Purdue University, West Lafayette, Indiana 47907, USA
Purdue University Calumet, Hammond, Indiana 46323, USA
Rice University, Houston, Texas 77251, USA
University of Rochester, Rochester, New York 14627, USA
The Rockefeller University, New York, New York 10021, USA
Rutgers, the State University of New Jersey, Piscataway, New Jersey 08854, USA
University of Tennessee, Knoxville, Tennessee 37996, USA
Texas A&M University, College Station, Texas 77843, USA
Texas Tech University, Lubbock, Texas 79409, USA
Vanderbilt University, Nashville, Tennessee 37235, USA
University of Virginia, Charlottesville, Virginia 22901, USA
Wayne State University, Detroit, Michigan 48202, USA
University of Wisconsin, Madison, Wisconsin 53706, USA

Deceased.

Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
Also at Universidade Federal do ABC, Santo Andre, Brazil.
Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
Also at Suez Canal University, Suez, Egypt.
Also at British University, Cairo, Egypt.
Also at Fayoum University, El-Fayoum, Egypt.
Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.
Also at Massachusetts Institute of Technology, Cambridge, MA, USA.
Also at Université de Haute-Alsace, Mulhouse, France.
Also at Brandenburg University of Technology, Cottbus, Germany.
Also at Moscow State University, Moscow, Russia.
Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
Also at Eötvös Loránd University, Budapest, Hungary.
Also at Tata Institute of Fundamental Research-HECR, Mumbai, India.
Also at University of Visva-Bharati, Santiniketan, India.
Also at Sharif University of Technology, Tehran, Iran.
Also at Shiraz University, Shiraz, Iran.
Also at Isfahan University of Technology, Isfahan, Iran.