Relative Modification of Prompt (2S) and J/ Yields from pp to PbPb Collisions at \[\sqrt{s}\text{NN} = 5.02\ \text{TeV}\]

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.
Relative Modification of Prompt $\psi(2S)$ and $J/\psi$ Yields from $pp$ to PbPb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

A.M. Sirunyan et al.*
(CMS Collaboration)

(Received 4 November 2016; revised manuscript received 5 March 2017; published 20 April 2017)

The relative modification of the prompt $\psi(2S)$ and $J/\psi$ yields from $pp$ to PbPb collisions, at the center-of-mass energy of 5.02 TeV per nucleon pair, is presented. The analysis is based on $pp$ and PbPb data samples collected by the CMS experiment at the LHC in 2015, corresponding to integrated luminosities of 28.0 pb$^{-1}$ and 464 pb$^{-1}$, respectively. The double ratio of measured yields of prompt charmonia reconstructed through their decays into muon pairs, $(N_{\psi(2S)}/N_{J/\psi})_{\text{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, is determined as a function of PbPb collision centrality and charmonium transverse momentum $p_T$, in two kinematic intervals: $|y| < 1.6$ covering $6.5 < p_T < 30$ GeV/c and $1.6 < |y| < 2.4$ covering $3 < p_T < 30$ GeV/c. The centrality-integrated double ratios are $0.36 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$ in the first interval and $0.24 \pm 0.22(\text{stat}) \pm 0.09(\text{syst})$ in the second. The double ratio is lower than unity in all the measured bins, suggesting that the $\psi(2S)$ yield is more suppressed than the $J/\psi$ yield in the explored phase space.

DOI: 10.1103/PhysRevLett.118.162301

Quarkonium production is expected to be significantly influenced by the formation of a quark-gluon plasma (QGP) in heavy ion collisions, thereby providing an important probe of the QGP properties. While the early-formed mesons propagate through the medium and probe its space-time evolution, the overall production rates can also reflect later production mechanisms. The suppression of charmonium production due to Debye screening of the color charges in the plasma was proposed 30 years ago [1]. The $J/\psi$ suppression observed in PbPb collisions at the SPS by NA50 [2] and in AuAu collisions at RHIC by PHENIX [3] is compatible with this picture. Another effect, referred to as regeneration, might be at work at a sufficiently high collision energy, when the number of charmonium pairs is large: Uncorrelated charm quarks and antiquarks may coalesce in the medium to form a bound states. The suppression of charmonium production due to Debye screening of the color charges in the plasma was proposed 30 years ago [1].

The study of the modification of the excited $\psi(2S)$ state is of particular interest. The strength of medium effects on its production might be significantly different from that of the $J/\psi$ because of the larger size and weaker binding of the $\psi(2S)$ state. The smaller binding energy should make it easier for the $\psi(2S)$ to dissociate in the medium, leading to sequential melting [8]. However, the smaller production cross section and branching fraction to dimuons make the $J/\psi$ less accessible experimentally than the $\psi(2S)$, especially when a large background is present, such as in heavy ion collisions. At the SPS fixed-target facility, the $\psi(2S)$ production in heavy ion collisions was seen to be more suppressed than the $J/\psi$ by NA38 [9], NA50 [10], and NA60 [11], in SU, PbPb, and InIn collisions, respectively.

A useful variable to compare the strength of medium effects on the $J/\psi$ and $\psi(2S)$ in PbPb collisions is the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{\text{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, which is the ratio of the corresponding nuclear modification factors. While Debye screening in the hot medium should make the double ratio smaller than unity, the presence of regeneration effects could make it exceed unity, if uncorrelated quark coalescence produces $\psi(2S)$ mesons more frequently than $J/\psi$ mesons. The double ratio allows for the partial to total cancellation of corrections (including acceptance, efficiency, and integrated luminosity) and their associated uncertainties. The CMS measurement of the prompt charmonium double ratio at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 2.76$ TeV [12] showed that the $\psi(2S)$ is more suppressed than the $J/\psi$ at midrapidity and high transverse momentum ($|y| < 1.6, 6.5 < p_T < 30$ GeV/c), while at more forward rapidity and intermediate $p_T (1.6 < |y| < 2.4, 3 < p_T < 30$ GeV/c), a smaller suppression of the $\psi(2S)$ than the $J/\psi$ was favored. This behavior could be reproduced by introducing a different time dependence of the $J/\psi$ and $\psi(2S)$ regeneration processes [13] or by considering different possible heavy quark potentials [14]. A similar measurement from the ALICE experiment [15], integrated over $p_T$ and at forward...
rapidity \((2.5 < y < 4)\), favored the \(\psi(2S)\) to be more suppressed than the \(J/\psi\), as expected in other models \([16,17]\). The medium effects (Debye screening, regeneration, and others) affecting the two charmonia might have different dependences on the collision energy, emphasizing the relevance of performing measurements at several energies.

In this Letter, we report a new study of \(J/\psi\) and \(\psi(2S)\) relative production in \(pp\) and \(PbPb\) data collected with the CMS experiment at the CERN LHC in 2015, at \(\sqrt{s_{NN}} = 5.02\) TeV. The larger integrated luminosities allow for a more precise and differential measurement of the double ratio as a function of centrality and, for the first time, as a function of the charmonium \(p_T\).

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Forward calorimeters extend the coverage outside the solenoid, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the pseudorapidity range \(|\eta| < 2.4\) in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker leads to a relative transverse momentum resolution between 1% and 2% for a typical muon in this analysis \((p_T < 30\) GeV/c) \([18]\). A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. \([19]\).

Hadronic collisions are selected using information from the forward hadron calorimeters (HF), covering \(2.9 < |\eta| < 5.2\), in coincidence with a bunch crossing identified by beam pick-up timing detectors. A primary vertex reconstructed with at least two tracks is also required. In addition, a filter is applied on the compatibility of the silicon pixel cluster width distribution and the vertex position. For \(PbPb\) collisions only, at least three towers above 3 GeV are required to survive standard quality selection criteria \([18]\). In order to remove cosmic-ray muons, the transverse and longitudinal distances of closest approach between the muon trajectory and the reconstructed primary vertex are required to be less than 0.3 and 20 cm, respectively. The fit probability that the two muon tracks originate from a common vertex is required to be larger than 1%.

Nonprompt charmonia, originating from the decays of \(B\) mesons, are resolved using the pseudorapidity decay length \(\ell_{J/\psi} = c L_{\psi} m_{J/\psi}/|p_\mu|\), where \(L_{\psi}\) is the distance between the primary and dimuon vertices, \(m_{J/\psi}\) the mass of the \(J/\psi\) meson (assumed for all dimuon candidates), and \(p_\mu\) the dimuon momentum. Dimuons are discarded if their \(\ell_{J/\psi}\) is larger than a \(l_0\) cut value also depend on \(p_T\). This selection removes more than 80% of the nonprompt \(J/\psi\). The double ratio of prompt charmonia is deduced from the double ratio of charmonia passing the \(\ell_{J/\psi}^{3D}\) selection. This is accomplished taking into account the \(\ell_{J/\psi}^{3D}\) selection efficiencies for prompt \((\epsilon_P)\) and nonprompt \((\epsilon_{NP})\) charmonia, both estimated from simulation studies.

Simulated events are used to tune the muon selection criteria and the signal fitting parameters, as well as for acceptance and efficiency studies. These Monte Carlo (MC) samples, produced using \(\text{PYTHIA} 8.209\) \([21]\), are embedded in a realistic \(PbPb\) background event generated with \(\text{HYDJET 1.9}\) \([22]\) and propagated through the CMS detector with \(\text{GEANT4}\) \([23]\). These events are processed through the trigger simulation and the event reconstruction chain.

The muon reconstruction algorithm starts by finding tracks in the muon detectors, which are then fitted together with tracks reconstructed in the silicon tracker. Kinematic limits are imposed on the single muons so that their reconstruction efficiency stays above 10%. These limits are \(p_T^\mu > 3.5\) GeV/c for \(|p_T^\mu| < 1.2\), \(p_T^\mu > 1.8\) GeV/c for \(2.1 < |p_T^\mu| < 2.4\), and linearly interpolated in the intermediate \(|p_T^\mu|\) region. The muons are required to match those used online by the dimuon trigger, to be of opposite charge, and to survive standard quality selection criteria \([18]\). In order to remove cosmic-ray muons, the transverse and longitudinal distances of closest approach between the muon trajectory and the reconstructed primary vertex are required to be less than 0.3 and 20 cm, respectively. The fit probability that the two muon tracks originate from a common vertex is required to be larger than 1%.

Nonprompt charmonia, originating from the decays of \(B\) mesons, are resolved using the pseudorapidity decay length \(\ell_{J/\psi} = c L_{\psi} m_{J/\psi}/|p_\mu|\), where \(L_{\psi}\) is the distance between the primary and dimuon vertices, \(m_{J/\psi}\) the mass of the \(J/\psi\) meson (assumed for all dimuon candidates), and \(p_\mu\) the dimuon momentum. Dimuons are discarded if their \(\ell_{J/\psi}\) is larger than a \(l_0\) cut value also depend on \(p_T\). This selection removes more than 80% of the nonprompt \(J/\psi\). The double ratio of prompt charmonia is deduced from the double ratio of charmonia passing the \(\ell_{J/\psi}^{3D}\) selection. This is accomplished taking into account the \(\ell_{J/\psi}^{3D}\) selection efficiencies for prompt \((\epsilon_P)\) and nonprompt \((\epsilon_{NP})\) charmonia, both estimated from simulation studies. The contamination from nonprompt charmonia is also accounted for, using dimuons failing the \(\ell_{J/\psi}^{3D}\) selection: \(f_P = (f_{pass} - \epsilon_{NP})/\epsilon_P\) the fraction of prompt charmonia and \(f_{pass}\) the fraction of charmonia passing the \(\ell_{J/\psi}^{3D}\) selection. This correction changes the double ratio by values that depend on the analysis bin but are always smaller than 0.09.

The \(\psi(2S)\) to \(J/\psi\) yield ratios, \(N_{\psi(2S)}/N_{J/\psi}\), are extracted in \(pp\) and \(PbPb\) collisions from unbinned maximum extended likelihood fits of the \(e^+e^-\) invariant
mass distributions in the region $2.2 < m_{\mu^+\mu^-} < 4.5 \text{GeV/c}^2$.
The analysis is carried out differentially in charmonium $p_T$ and event centrality, as well as integrated over these variables, for two kinematic ranges: $|y| < 1.6$, $6.5 < p_T < 30 \text{ GeV/c}$ and $1.6 < |y| < 2.4$, $3 < p_T < 30 \text{ GeV/c}$. The different lower $p_T$ thresholds reflect the detector acceptance.

In the fit of the $pp$ dimuon mass distribution, the $J/\psi$ resonance is described by two Crystal Ball (CB) functions [24], with common mean and tail parameters but independent widths and free relative amplitudes (seven free parameters). In the PbPb case, the CB tail parameters and the ratio between the widths of the two CB functions are fixed to the values extracted from simulation studies. In both cases, the shape of the $\psi(2S)$ is determined by the shape of the $J/\psi$, all parameters being identical except for the mean and width, which are scaled by the $\psi(2S)$ over $J/\psi$ mass ratio. The background is described by a polynomial of order $N$, where $N$ is the lowest value that provides a good description of the data and is determined in each analysis bin by performing a log-likelihood ratio (LLR) test between polynomials of different orders while keeping the signal parameters fixed; it is never larger than 3.

Integrated over centrality, rapidity, and $p_T$, the fits yield about 38 000 (293 000) $J/\psi$ and 530 (11 200) $\psi(2S)$ mesons in PbPb ($pp$) collisions. Examples of such fits for the PbPb data are shown in Fig. 1, for two cases of very different $\psi(2S)$ signal-to-background ratios.

The systematic uncertainties arise from the signal and background fitting model assumptions, the imperfect efficiency cancellation, and the nonprompt residual contamination. These uncertainties are derived separately for $pp$ and PbPb data, and the total systematic uncertainty is computed as the quadratic sum of the partial terms.

In order to determine the uncertainty associated with the fitting procedure, the signal and background models are independently varied in each analysis bin. For the signal, the fixed parameters are released one by one. As a further test, the signal parameters are fixed to the values obtained from a $\psi(2S)$ simulation, instead of the $J/\psi$ simulation. A different signal shape is also tried: a CB function plus a Gaussian function. For the background model, the fitted mass range is varied and an exponential of a polynomial is used, redoing LLR tests to choose the best order for the polynomial in each analysis bin. The maximum difference of the single ratio $N[\psi(2S)]/N(J/\psi)$ between the nominal and alternative fits, performed for the signal and background separately, is taken as the corresponding systematic uncertainty. These uncertainties depend crucially on the signal-to-background ratio in the $\psi(2S)$ region. The absolute uncertainties on the double ratio remain below 0.02 and 0.11 for the $pp$ and PbPb contributions, respectively.

The nonprompt $J/\psi$ and $\psi(2S)$ fractions in $pp$ collisions, as well as the $J/\psi$ fraction in PbPb collisions, are validated with two-dimensional fits to the dimuon mass and pseudopseudor rapidity distributions [25]. The PbPb event sample does not have enough $\psi(2S)$ events to provide a reliable two-dimensional fit. The variation in the double ratio when using nonprompt fractions from the two-dimensional fits is taken as a systematic uncertainty, never exceeding 0.07.

Finally, residual noncancellations of efficiencies in the double ratio are evaluated with MC studies, considering a broad range of $p_T$ spectra compatible with the $pp$ and PbPb data within their uncertainties. The corresponding systematic uncertainty varies between 0.01 and 0.05, with the exception of the lowest $p_T$ bin, where it reaches 0.10. If the quarkonium acceptances were different in $pp$ and PbPb,
they would not perfectly cancel in the double ratio. This would be the case if some physics effects (such as polarization or energy loss) would affect quarkonia in PbPb collisions with a strong kinematic dependence within an analysis bin. As in previous analyses [12,26–28], such possible effects are considered as part of the physics under study and not as systematic uncertainties.

The measured double ratio is shown in Figs. 2 and 3 as a function of $p_T$ and event centrality, respectively. Centrality is commonly represented by the average number of participating nucleons, $N_{\text{part}}$, computed with the Glauber model [29]. In terms of centrality percentiles, the bins correspond to 0%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, and 50%–100% in the midrapidity region and 0%–20%, 20%–40%, and 40%–100% for the forward rapidity region. The most “peripheral” bins are rather wide, and, since quarkonium yields scale with the number of nucleon-nucleon collisions, most charmonia are produced close to the most central edge of the bins. The $N_{\text{part}}$ values used in the following are computed for events following a flat centrality distribution. When the measured double ratio is consistent with zero within one standard deviation of its statistical uncertainty, its corresponding 95% confidence level (C.L.) interval is computed, using the Feldman-Cousins procedure [30]. The numerical values of all measurements, including the 95% C.L. intervals, are tabulated in Supplemental Material [31].

The rightmost panels in Fig. 3 show the double ratio integrated over $p_T$ and centrality: 0.36 ± 0.08(stat) ± 0.05(syst) in the $|y| < 1.6$ and 6.5 < $p_T$ < 30 GeV/c range and 0.24 ± 0.22(stat) ± 0.09(syst) in the 1.6 < $|y| < 2.4$ and 3 < $p_T$ < 30 GeV/c range.

The double ratios measured at 5.02 TeV and reported in this Letter are below unity in all bins. Assuming that the $J/\psi$ is suppressed in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, as suggested by results at lower energy in the same kinematic range by CMS [25] or at both energies but in a different rapidity range by ALICE [6,7], the $\psi(2S)$ is more suppressed than the $J/\psi$ in PbPb collisions. This difference in suppression is already present in the most peripheral ranges probed by this analysis, starting at 40% or
50% centrality. No strong dependencies are observed with centrality or transverse momentum.

In Fig. 3, a reasonable agreement with the measurement made at $\sqrt{s_{NN}} = 2.76$ TeV can be seen in most of the bins. Systematic uncertainties are uncorrelated between the two data sets. In the range $1.6 < |y| < 2.4$ and $3 < p_T < 30$ GeV/c, the double ratios are consistently lower in the 5.02 TeV data, especially in the most central collisions. The difference is at the level of around 3 standard deviations in the centrality-integrated sample.

In summary, the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{\text{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$ was measured to compare the relative production of $J/\psi$ and $\psi(2S)$ mesons in $pp$ and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of transverse momentum and collision centrality. The double ratio is below unity in all bins, suggesting that the $\psi(2S)$ yield is more suppressed than the $J/\psi$ yield in the kinematic range explored. The 5.02 TeV data do not show the enhancement in the double ratio previously seen for collisions at 2.76 TeV in the $1.6 < |y| < 2.4$ and $3 < p_T < 30$ GeV/c range. No strong variations are observed with charmonium $p_T$ or collision centrality. These results should significantly contribute to a deeper understanding of the medium effects at play in $J/\psi$ and $\psi(2S)$ production, in particular, by better constraining the energy dependence of the regeneration effects potentially affecting the two charmonium states.

We congratulate our colleagues in the Conseil Européen pour la Recherche Nucléaire (CERN) accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: Bundesministerium für Wissenschaft, Forschung und Wirtschaft (BMWF) and Austrian Science Fund (FWF) (Austria); Belgian Fonds de la Recherche Scientifique (FRS) and Belgian Fonds voor Wetenschappelijk Onderzoek (FWO) (Belgium); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) (Brazil); Bulgarian Ministry of Education and Science (MES) (Bulgaria); CERN; Chinese Academy of Sciences (CAS), Ministry of Science and Technology (MoST), and Chinese National Natural Science Foundation of China (NSFC) (China); Colombian Funding Agency (COLCIENCIAS) (Colombia); Croatian Ministry of Science, Education and Sport (MSES) and Croatian Science Foundation (CSF) (Croatia); Research Promotion Foundation (RPF) (Cyprus); Secretaria de Educação Superior, Ciencia, Tecnologia e Inovacion (SENESCYT) (Ecuador); Ministry of Education and Research (MoER), Estonian Research Council via IUT23-4 and IUT23-6 (ERC IUT), and European Regional Development Fund (ERDF) (Estonia); Academy of Finland, Finnish Ministry of Education and Culture (MEC), and Helsinki Institute of Physics (HIP) (Finland); Commissariat à l’Énergie Atomique et aux Énergies Alternatives (CEA) and Centre National de la Recherche Scientifique (CNRS)/Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) (France); Bundesministerium für Bildung und Forschung (BMBF), Deutsche Forschungsgemeinschaft (DFG), and Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF) (Germany); General Secretariat for Research and Technology (GSRT) (Greece); Országos Tudományos Kutatási Alapprogramok (OTKA) and National Innovation Office (NIH) (Hungary); Department of Atomic Energy (DAE) and Department of Science and Technology (DST) (India); Institute for Research in Fundamental Studies (IPM) (Iran); Science Foundation (SFI) (Ireland); Istituto Nazionale di Fisica Nucleare (INFN) (Italy); Korean Ministry of Education, Science and Technology (MSIP) and National Research Foundation of Korea (NRF) (Republic of Korea); Lithuanian Academy of Sciences (LAS) (Lithuania); Ministry of Education (MOE) and University of Malaya (UM) (Malaysia); Benemérita Universidad Autónoma de Puebla (BUAP), Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (CINVESTAV), Consejo Nacional de Ciencia y Tecnología (CONACYT), Laboratorio Nacional de Supercomputo del Sureste (LNS), Secretaría de Educación Pública (SEP), and Universidad Autónoma de San Luis Potosí (UASLP-FAI) (Mexico); Ministry of Business, Innovation and Employment (MBIE) (New Zealand); Pakistan Atomic Energy Commission (PAEC) (Pakistan); Ministry of Science and Higher Education (MSHE) and National Science Centre (NSC) (Poland); Fundação para a Ciência e a Tecnologia (FCT) (Portugal); Joint Institute for Nuclear Research (JINR) (Dubna); Ministry of Education and Science of the Russian Federation (MON), Federal Agency of Atomic Energy of the Russian Federation (RosAtom), Russian Academy of Sciences (RAS), and Russian Foundation for Basic Research (RFBR) (Russia); Ministry of Education, Science and Technological Development of Serbia (MESTD) (Serbia); Secretaría de Estado de Investigación, Desarrollo e Innovación (SEIDI) and Programa Consolider-Ingenio 2010 (CPAN) (Spain); Swiss Funding Agencies (Switzerland); Ministry of Science and Technology (MST) (Taipei); Thailand Center of Excellence in Physics (ThEPCenter), Institute for the Promotion of Teaching Science and Technology of Thailand (IPST), Special Task...
B. Alessandro  

X. Du and R. Rapp, Sequential regeneration of charmonia in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), J. High Energy Phys. 05 (2016) 179.


CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at \( \sqrt{s} = 7 \text{ TeV} \), J. Instrument. 7, P10002 (2012).


CMS Collaboration, Dependence on pseudorapidity and centrality of charged hadron production in PbPb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), J. High Energy Phys. 08 (2011) 141.


CMS Collaboration, Suppression of non-prompt \( J/\psi \), prompt \( J/\psi \), and \( \Upsilon(1S) \) in PbPb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), J. High Energy Phys. 05 (2012) 063.

CMS Collaboration, Indications of Suppression of Excited \( \Upsilon \) States in PbPb Collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), Phys. Rev. Lett. 107, 052302 (2011).


CMS Collaboration, Event activity dependence of \( \text{Y(nS)} \) production in \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) pp and \( \sqrt{s} = 2.76 \text{ TeV} \) pp collisions, J. High Energy Phys. 04 (2014) 103.


47 MTU-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
48 Wigner Research Centre for Physics, Budapest, Hungary
49 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
50 University of Debrecen, Debrecen, Hungary
51 National Institute of Science Education and Research, Bhubaneswar, India
52 Panjab University, Chandigarh, India
53 University of Delhi, Delhi, India
54 Saha Institute of Nuclear Physics, Kolkata, India
55 Indian Institute of Technology Madras, Madras, India
56 Bhabha Atomic Research Centre, Mumbai, India
57 Tata Institute of Fundamental Research-A, Mumbai, India
58 Tata Institute of Fundamental Research-B, Mumbai, India
59 Indian Institute of Science Education and Research (IISER), Pune, India
60 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
61 University College Dublin, Dublin, Ireland
62 a INFN Sezione di Bari, Bari, Italy
62 b Università di Bari, Bari, Italy
62 c Politecnico di Bari, Bari, Italy
63 a INFN Sezione di Bologna, Bologna, Italy
63 b Università di Bologna, Bologna, Italy
64 a INFN Sezione di Catania, Catania, Italy
64 b Università di Catania, Catania, Italy
65 a INFN Sezione di Firenze, Firenze, Italy
65 b Università di Firenze, Firenze, Italy
66 INFN Laboratori Nazionali di Frascati, Frascati, Italy
67 a INFN Sezione di Genova, Genova, Italy
67 b Università di Genova, Genova, Italy
68 a INFN Sezione di Milano-Bicocca, Milano, Italy
68 b Università di Milano-Bicocca, Milano, Italy
69 a INFN Sezione di Napoli, Roma, Italy
69 b Università di Napoli ‘Federico II’, Roma, Italy
69 c Università della Basilicata, Roma, Italy
69 d Università G. Marconi, Roma, Italy
70 a INFN Sezione di Padova, Padova, Italy
70 b Università di Padova, Padova, Italy
70 c Università di Trento
71 a INFN Sezione di Pavia, Pavia, Italy
71 b Università di Pavia, Pavia, Italy
72 a INFN Sezione di Perugia, Perugia, Italy
72 b Università di Perugia, Perugia, Italy
73 a INFN Sezione di Pisa, Pisa, Italy
73 b Università di Pisa, Pisa, Italy
73 c Scuola Normale Superiore di Pisa, Pisa, Italy
74 a INFN Sezione di Roma, Roma, Italy
74 b Università di Roma, Roma, Italy
75 a INFN Sezione di Torino, Novara, Italy
75 b Università di Torino, Novara, Italy
76 a Università del Piemonte Orientale, Novara, Italy
76 b INFN Sezione di Trieste, Trieste, Italy
76 c Università di Trieste, Trieste, Italy
77 Kyungpook National University, Daegu, Korea
78 Chonbuk National University, Jeonju, Korea
79 Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
80 Hanyang University, Seoul, Korea
81 Korea University, Seoul, Korea
82 Seoul National University, Seoul, Korea
83 University of Seoul, Seoul, Korea
84 Sungkyunkwan University, Suwon, Korea
85 Vilnius University, Vilnius, Lithuania
86 National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia