# 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 $\mathrm{pb}^{-1}$ and 464 $\mu\mathrm{b}^{-1}$, respectively. The double ratio of measured yields of prompt charmonia reconstructed through their decays into muon pairs, $(N_{\psi(2S)}/N_{J/\psi})_{\mathrm{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, 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 $0.36 \pm 0.08(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ in the first interval and $0.24 \pm 0.22(\mathrm{stat}) \pm 0.09(\mathrm{syst})$ 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 charm-anticharm pairs is large: Uncorrelated charm quarks and antiquarks may coalesce in the medium to form a bound charmonium state, leading to an enhanced production in heavy ion collisions [4,5]. Hints of the latter were found at the LHC in recent results from ALICE [6,7], which measured a weaker $J/\psi$ meson suppression than at RHIC, especially at low $p_T$.

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 $\psi(2S)$ less accessible experimentally than the $J/\psi$, 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 $(N_{\psi(2S)}/N_{J/\psi})_{\mathrm{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, 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

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



 

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 provided by the barrel and end cap detectors. Muons are 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 requested in the HF on each side of the interaction point. Centrality is defined using fractions of the inelastic hadronic cross section determined from the HF distributions, with 0% denoting the most central collisions [20].

The integrated luminosities are 28.0 pb$^{-1}$ for $pp$ data and 464 $\mu$b$^{-1}$ for PbPb data. The dimuon ratios reported in this Letter are unaffected by the small number of extra collisions potentially present in the collected events: The mean of the Poisson distribution of the number of collisions per bunch crossing (pileup), averaged over the full data sample, is approximately 0.9 for the $pp$ data and much smaller for the PbPb data. Dimuon events are selected by the level-1 trigger system, with no explicit muon momentum threshold. The 0%–30% most central events have a prescale needed to reduce their high trigger rates, corresponding to an effective integrated luminosity of 351 $\mu$b$^{-1}$.

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 PYTHIA 8.209 [21], are embedded in a realistic PbPb background event generated with HYDJET 1.9 [22] and propagated through the CMS detector with GEANT4 [23]. These events are processed through the trigger emulation 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 $|\eta^\mu| < 1.2$, $p_T^\mu > 1.8$ GeV/$c$ for $2.1 < |\eta^\mu| < 2.4$, and linearly interpolated in the intermediate $|\eta^\mu|$ 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 pseudoproper decay length $\ell_{J/\psi}^{3D} = cL_{xyz}m_{J/\psi}/|p_{\mu\mu}|$, where $L_{xyz}$ 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 $p_{\mu\mu}$ the dimuon momentum. Dimuons are discarded if their $\ell_{J/\psi}^{3D}$ is larger than a $l_0$ threshold, computed using MC simulations to keep 90% of the prompt $J/\psi$. Since the $\ell_{J/\psi}^{3D}$ resolution improves with increasing dimuon $p_T$, from ≈100 to ≈20 $\mu$m in this analysis, the $l_0$ cut values 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: $f_P = (f_{\text{pass}} - \epsilon_{NP})/(\epsilon_P - \epsilon_{NP})$, with $f_P$ the fraction of prompt charmonia and $f_{\text{pass}}$ 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 $\mu^+\mu^-$ invariant mass distributions in the region $2.2 < m_{\mu^+\mu^-} < 4.5\,\mathrm{GeV}/c^2$. The analysis is carried out differentially in charmonium $p_T$ and event centrality, as well as integrated over these variables, for two kinematic ranges: $|y| < 1.6$, $6.5 < p_T < 30\ \mathrm{GeV}/c$ and $1.6 < |y| < 2.4$, $3 < p_T < 30\ \mathrm{GeV}/c$. 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

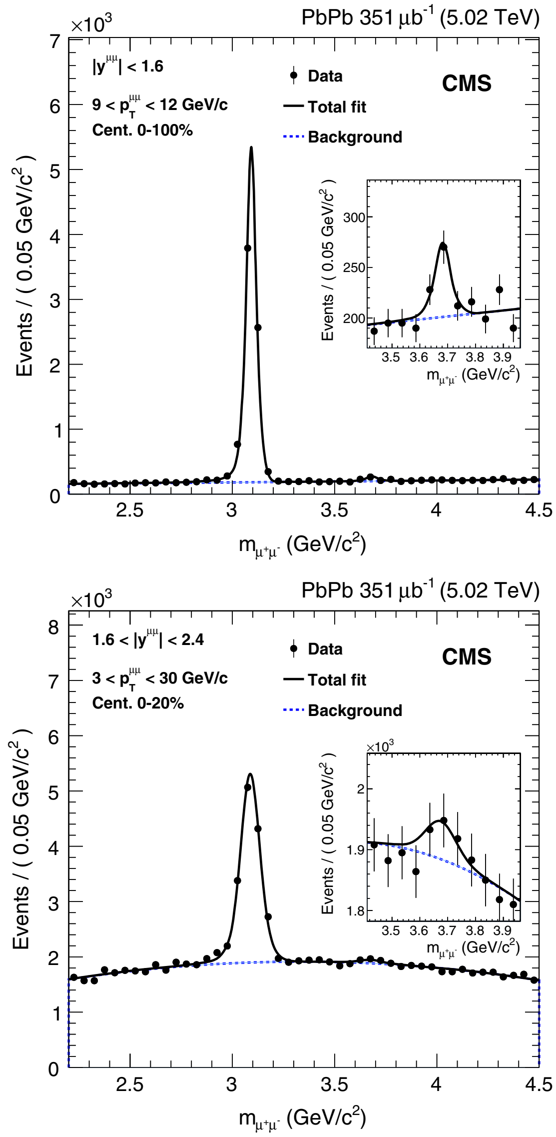


FIG. 1. Invariant mass spectrum of $\mu^+\mu^-$ pairs [restricting to the $\psi(2S)$ region in the insets] in PbPb collisions for (left) $|y| < 1.6$, $9 < p_T < 12\ \mathrm{GeV}/c$, all centrality, and (right) $1.6 < |y| < 2.4$, $3 < p_T < 30\ \mathrm{GeV}/c$, 0%–20% centrality. The results of the fits described in the text are also shown.

validated with two-dimensional fits to the dimuon mass and pseudoproper decay length 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,

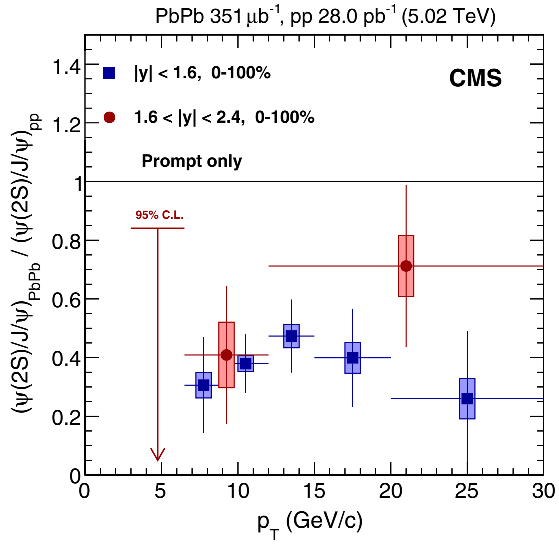


FIG. 2. Transverse momentum dependence of $(N_{\psi(2S)}/N_{J/\psi})_{\mathrm{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, for mid (squares) and forward (circles) rapidity, with both muons above the $p_T$ threshold described in the text. The arrow represents the 95% C.L. interval in the bin where the measurement is consistent with 0. The vertical lines (boxes) represent the statistical (systematic) uncertainties. The horizontal lines represent the width of the $p_T$ bins.

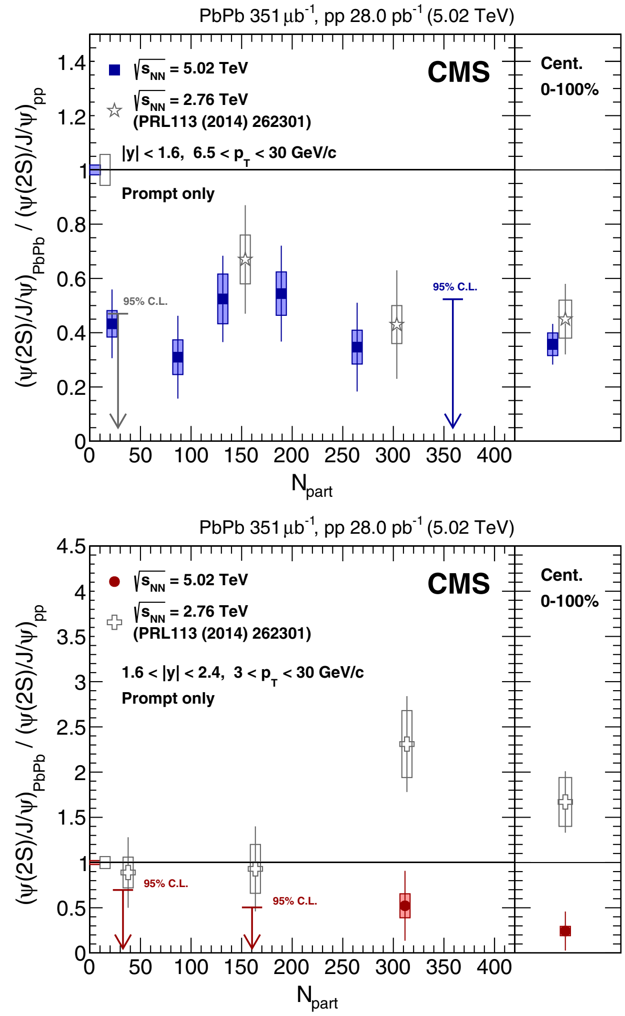


FIG. 3. Event centrality dependence of $(N_{\psi(2S)}/N_{J/\psi})_{\mathrm{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, for mid (left) and forward (right) rapidity, with both muons above the $p_T$ threshold described in the text. Values for the centrality-integrated sample are given in the right panels. The arrows represent 95% C.L. intervals in the bins where the measurement is consistent with 0. The vertical lines (boxes) represent the statistical (systematic) uncertainties. The statistical and systematic uncertainties in the $pp$ measurements, common to all points, are represented as boxes at unity. The measurements from CMS at $\sqrt{s_{NN}} = 2.76$ TeV [12] are also shown.

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, $\langle N_{\mathrm{part}}\rangle$, 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 $\langle N_{\mathrm{part}}\rangle$ 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: $0.36 \pm 0.08(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ in the $|y| < 1.6$ and $6.5 < p_T < 30$ GeV/$c$ range and $0.24 \pm 0.22(\mathrm{stat}) \pm 0.09(\mathrm{syst})$ 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 $\sqrt{s_{NN}} = 5.02$ 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 $(N_{\psi(2S)}/N_{J/\psi})_{\mathrm{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$ 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 (BMWFW) and Austrian Science Fund (FWF) (Austria); Belgian Fonds de la Recherche Scientifique (FNRS) and Belgian Fonds voor Wetenschappelijk Onderzoek (FWO) (Belgium); Conselho Nacional de Desenvolvimento Cientifico e Tecnelógica (CNPq), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Fundação de Amparo à Pesquisa do Estado de Rio de Janeiro (FAPERJ), and 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); Secretaría de Educación Superior, Ciencia, Tecnología e Innovación (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 Supercómputo 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

Force for Activating Research (STAR), and National Science and Technology Development Agency of Thailand (NSTDA) (Thailand); Scientific and Technical Research Council of Turkey (TUBITAK) and Turkish Atomic Energy Authority (TAEK) (Turkey); National Academy of Sciences of Ukraine (NASU) and State Fund for Fundamental Researches (SFFR) (Ukraine); Science and Technology Facilities Council (STFC) (United Kingdom); and US Department of Energy (DOE) and US National Science Foundation (NSF) (USA).

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A. M. Sirunyan,[1] A. Tumasyan,[1] W. Adam,[2] E. Asilar,[2] T. Bergauer,[2] J. Brandstetter,[2] E. Brondolin,[2] M. Dragicevic,[2] J. Erö,[2] M. Flechl,[2] M. Friedl,[2] R. Frühwirth,[2,b] V. M. Ghete,[2] C. Hartl,[2] N. Hörmann,[2] J. Hrubec,[2] M. Jeitler,[2,b] A. König,[2] I. Krätschmer,[2] D. Liko,[2] T. Matsushita,[2] I. Mikulec,[2] D. Rabady,[2] N. Rad,[2] B. Rahbaran,[2] H. Rohringer,[2] J. Schieck,[2,b]

J. Strauss,[2] W. Waltenberger,[2] C.-E. Wulz,[2,b] V. Chekhovsky,[3] O. Dvornikov,[3] Y. Dydyshka,[3] I. Emeliantchik,[3] A. Litomin,[3] V. Makarenko,[3] V. Mossolov,[3] R. Stefanovitch,[3] J. Suarez Gonzalez,[3] V. Zykunov,[3] N. Shumeiko,[4] S. Alderweireldt,[5] E. A. De Wolf,[5] X. Janssen,[5] J. Lauwers,[5] M. Van De Klundert,[5] H. Van Haevermaet,[5] P. Van Mechelen,[5] N. Van Remortel,[5] A. Van Spilbeeck,[5] S. Abu Zeid,[6] F. Blekman,[6] J. D'Hondt,[6] N. Daci,[6] I. De Bruyn,[6] K. Deroover,[6] S. Lowette,[6] S. Moortgat,[6] L. Moreels,[6] A. Olbrechts,[6] Q. Python,[6] K. Skovpen,[6] S. Tavernier,[6] W. Van Doninck,[6] P. Van Mulders,[6] I. Van Parijs,[6] H. Brun,[7] B. Clerbaux,[7] G. De Lentdecker,[7] H. Delannoy,[7] G. Fasanella,[7] L. Favart,[7] R. Goldouzian,[7] A. Grebenyuk,[7] G. Karapostoli,[7] T. Lenzi,[7] A. Léonard,[7] J. Luetic,[7] T. Maerschalk,[7] A. Marinov,[7] A. Randle-conde,[7] T. Seva,[7] C. Vander Velde,[7] P. Vanlaer,[7] D. Vannerom,[7] R. 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Zientek,[141] D. Winn,[142] S. Abdullin,[143] M. Albrow,[143] G. Apollinari,[143] A. Apresyan,[143] S. Banerjee,[143] L. A. T. Bauerdick,[143] A. Beretvas,[143] J. Berryhill,[143] P. C. Bhat,[143] G. Bolla,[143] K. Burkett,[143] J. N. Butler,[143] H. W. K. Cheung,[143] F. Chlebana,[143] S. Cihangir,[143,a] M. Cremonesi,[143] V. D. Elvira,[143] I. Fisk,[143] J. Freeman,[143] E. Gottschalk,[143] L. Gray,[143] D. Green,[143] S. Grünendahl,[143] O. Gutsche,[143] D. Hare,[143] R. M. Harris,[143] S. Hasegawa,[143] J. Hirschauer,[143] Z. Hu,[143] B. Jayatilaka,[143] S. Jindariani,[143] M. Johnson,[143] U. Joshi,[143] B. Klima,[143] B. Kreis,[143] S. Lammel,[143] J. Linacre,[143] D. Lincoln,[143] R. Lipton,[143] M. Liu,[143] T. Liu,[143] R. Lopes De Sá,[143] J. Lykken,[143] K. Maeshima,[143] N. Magini,[143] J. M. Marraffino,[143] S. Maruyama,[143] D. Mason,[143] P. McBride,[143] P. Merkel,[143] S. Mrenna,[143] S. Nahn,[143] V. O'Dell,[143] K. Pedro,[143] O. Prokofyev,[143] G. Rakness,[143] L. Ristori,[143] E. Sexton-Kennedy,[143] A. Soha,[143] W. J. Spalding,[143] L. Spiegel,[143] S. Stoynev,[143] J. Strait,[143] N. Strobbe,[143] L. Taylor,[143] S. Tkaczyk,[143] N. V. Tran,[143] L. Uplegger,[143] E. W. Vaandering,[143] C. Vernieri,[143] M. Verzocchi,[143] R. Vidal,[143] M. Wang,[143] H. A. Weber,[143] A. Whitbeck,[143] Y. Wu,[143] D. Acosta,[144] P. Avery,[144] P. Bortignon,[144] D. Bourilkov,[144] A. Brinkerhoff,[144] A. Carnes,[144] M. Carver,[144] D. Curry,[144] S. Das,[144] R. D. Field,[144] I. K. Furic,[144] J. Konigsberg,[144] A. Korytov,[144] J. F. Low,[144] P. Ma,[144] K. Matchev,[144] H. Mei,[144] G. Mitselmakher,[144] D. Rank,[144] L. Shchutska,[144] D. Sperka,[144] L. Thomas,[144] J. Wang,[144] S. Wang,[144] J. Yelton,[144] S. Linn,[145] P. Markowitz,[145] G. Martinez,[145] J. L. Rodriguez,[145] A. Ackert,[146] J. R. Adams,[146] T. Adams,[146] A. Askew,[146] S. Bein,[146] B. Diamond,[146] S. Hagopian,[146] V. Hagopian,[146] K. F. Johnson,[146] H. Prosper,[146] A. Santra,[146] R. Yohay,[146] M. M. Baarmand,[147] V. Bhopatkar,[147] S. Colafranceschi,[147] M. Hohlmann,[147] D. Noonan,[147] T. Roy,[147] F. Yumiceva,[147] M. R. Adams,[148] L. Apanasevich,[148] D. Berry,[148] R. R. Betts,[148] I. Bucinskaite,[148] R. Cavanaugh,[148] O. Evdokimov,[148] L. Gauthier,[148] C. E. Gerber,[148] D. J. Hofman,[148] K. Jung,[148] P. Kurt,[148] C. O'Brien,[148] I. D. Sandoval Gonzalez,[148] P. Turner,[148] N. Varelas,[148] H. Wang,[148] Z. Wu,[148] M. Zakaria,[148] J. Zhang,[148] B. Bilki,[149,qqq] W. Clarida,[149] K. Dilsiz,[149]

S. Durgut,[149] R. P. Gandrajula,[149] M. Haytmyradov,[149] V. Khristenko,[149] J.-P. Merlo,[149] H. Mermerkaya,[149,rrr] A. Mestvirishvili,[149] A. Moeller,[149] J. Nachtman,[149] H. Ogul,[149] Y. Onel,[149] F. Ozok,[149,sss] A. Penzo,[149] C. Snyder,[149] E. Tiras,[149] J. Wetzel,[149] K. Yi,[149] I. Anderson,[150] B. Blumenfeld,[150] A. Cocoros,[150] N. Eminizer,[150] D. Fehling,[150] L. Feng,[150] A. V. Gritsan,[150] P. Maksimovic,[150] C. Martin,[150] M. Osherson,[150] J. Roskes,[150] U. Sarica,[150] M. Swartz,[150] M. Xiao,[150] Y. Xin,[150] C. You,[150] A. Al-bataineh,[151] P. Baringer,[151] A. Bean,[151] S. Boren,[151] J. Bowen,[151] C. Bruner,[151] J. Castle,[151] L. Forthomme,[151] R. P. Kenny III,[151] S. Khalil,[151] A. Kropivnitskaya,[151] D. Majumder,[151] W. Mcbrayer,[151] M. Murray,[151] S. Sanders,[151] R. Stringer,[151] J. D. Tapia Takaki,[151] Q. Wang,[151] A. Ivanov,[152] K. Kaadze,[152] Y. Maravin,[152] A. Mohammadi,[152] L. K. Saini,[152] N. Skhirtladze,[152] S. Toda,[152] F. Rebassoo,[153] D. Wright,[153] C. Anelli,[154] A. Baden,[154] O. Baron,[154] A. Belloni,[154] B. Calvert,[154] S. C. Eno,[154] C. Ferraioli,[154] J. A. Gomez,[154] N. J. Hadley,[154] S. Jabeen,[154] R. G. Kellogg,[154] T. Kolberg,[154] J. Kunkle,[154] Y. Lu,[154] A. C. Mignerey,[154] F. Ricci-Tam,[154] Y. H. Shin,[154] A. Skuja,[154] M. B. Tonjes,[154] S. C. Tonwar,[154] D. Abercrombie,[155] B. Allen,[155] A. Apyan,[155] V. Azzolini,[155] R. Barbieri,[155] A. Baty,[155] R. Bi,[155] K. Bierwagen,[155] S. Brandt,[155] W. Busza,[155] I. A. Cali,[155] M. D'Alfonso,[155] Z. Demiragli,[155] L. Di Matteo,[155] G. Gomez Ceballos,[155] M. Goncharov,[155] D. Hsu,[155] Y. Iiyama,[155] G. M. Innocenti,[155] M. Klute,[155] D. Kovalskyi,[155] K. Krajczar,[155] Y. S. Lai,[155] Y.-J. Lee,[155] A. Levin,[155] P. D. Luckey,[155] B. Maier,[155] A. C. Marini,[155] C. Mcginn,[155] C. Mironov,[155] S. Narayanan,[155] X. Niu,[155] C. Paus,[155] C. Roland,[155] G. Roland,[155] J. Salfeld-Nebgen,[155] G. S. F. Stephans,[155] K. Tatar,[155] M. Varma,[155] D. Velicanu,[155] J. Veverka,[155] J. Wang,[155] T. W. Wang,[155] B. Wyslouch,[155] M. Yang,[155] V. Zhukova,[155] A. C. Benvenuti,[156] R. M. Chatterjee,[156] A. Evans,[156] A. Finkel,[156] A. Gude,[156] P. Hansen,[156] S. Kalafut,[156] S. C. Kao,[156] Y. Kubota,[156] Z. Lesko,[156] J. Mans,[156] S. Nourbakhsh,[156] N. Ruckstuhl,[156] R. Rusack,[156] N. Tambe,[156] J. Turkewitz,[156] J. G. Acosta,[157] S. Oliveros,[157] E. Avdeeva,[158] R. Bartek,[158,ttt] K. Bloom,[158] D. R. Claes,[158] A. Dominguez,[158,ttt] C. Fangmeier,[158] R. Gonzalez Suarez,[158] R. Kamalieddin,[158] I. Kravchenko,[158] A. Malta Rodrigues,[158] F. Meier,[158] J. Monroy,[158] J. E. Siado,[158] G. R. Snow,[158] B. Stieger,[158] M. Alyari,[159] J. Dolen,[159] J. George,[159] A. Godshalk,[159] C. Harrington,[159] I. Iashvili,[159] J. Kaisen,[159] A. Kharchilava,[159] A. Kumar,[159] A. Parker,[159] S. Rappoccio,[159] B. Roozbahani,[159] G. Alverson,[160] E. Barberis,[160] A. Hortiangtham,[160] A. Massironi,[160] D. M. Morse,[160] D. Nash,[160] T. Orimoto,[160] R. Teixeira De Lima,[160] D. Trocino,[160] R.-J. Wang,[160] D. Wood,[160] S. Bhattacharya,[161] O. Charaf,[161] K. A. Hahn,[161] A. Kubik,[161] A. Kumar,[161] N. Mucia,[161] N. Odell,[161] B. Pollack,[161] M. H. Schmitt,[161] K. Sung,[161] M. Trovato,[161] M. Velasco,[161] N. Dev,[162] M. Hildreth,[162] K. Hurtado Anampa,[162] C. Jessop,[162] D. J. Karmgard,[162] N. Kellams,[162] K. Lannon,[162] N. Marinelli,[162] F. Meng,[162] C. Mueller,[162] Y. Musienko,[162,ll] M. Planer,[162] A. Reinsvold,[162] R. Ruchti,[162] G. Smith,[162] S. Taroni,[162] M. Wayne,[162] M. Wolf,[162] A. Woodard,[162] J. Alimena,[163] L. Antonelli,[163] B. Bylsma,[163] L. S. Durkin,[163] S. Flowers,[163] B. Francis,[163] A. Hart,[163] C. Hill,[163] R. Hughes,[163] W. Ji,[163] B. Liu,[163] W. Luo,[163] D. Puigh,[163] B. L. Winer,[163] H. W. Wulsin,[163] S. Cooperstein,[164] O. Driga,[164] P. Elmer,[164] J. Hardenbrook,[164] P. Hebda,[164] D. Lange,[164] J. Luo,[164] D. Marlow,[164] T. Medvedeva,[164] K. Mei,[164] M. Mooney,[164] J. Olsen,[164] C. Palmer,[164] P. Piroué,[164] D. Stickland,[164] A. Svyatkovskiy,[164] C. Tully,[164] A. Zuranski,[164] S. Malik,[165] A. Barker,[166] V. E. Barnes,[166] S. Folgueras,[166] L. Gutay,[166] M. K. Jha,[166] M. Jones,[166] A. W. Jung,[166] A. Khatiwada,[166] D. H. Miller,[166] N. Neumeister,[166] J. F. Schulte,[166] X. Shi,[166] J. Sun,[166] F. Wang,[166] W. Xie,[166] N. Parashar,[167] J. Stupak,[167] A. Adair,[168] B. Akgun,[168] Z. Chen,[168] K. M. Ecklund,[168] F. J. M. Geurts,[168] M. Guilbaud,[168] W. Li,[168] B. Michlin,[168] M. Northup,[168] B. P. Padley,[168] R. Redjimi,[168] J. Roberts,[168] J. Rorie,[168] Z. Tu,[168] J. Zabel,[168] B. Betchart,[169] A. Bodek,[169] P. de Barbaro,[169] R. Demina,[169] Y. t. Duh,[169] T. Ferbel,[169] M. Galanti,[169] A. Garcia-Bellido,[169] J. Han,[169] O. Hindrichs,[169] A. Khukhunaishvili,[169] K. H. Lo,[169] P. Tan,[169] M. Verzetti,[169] A. Agapitos,[170] J. P. Chou,[170] E. Contreras-Campana,[170] Y. Gershtein,[170] T. A. Gómez Espinosa,[170] E. Halkiadakis,[170] M. Heindl,[170] D. Hidas,[170] E. Hughes,[170] S. Kaplan,[170] R. Kunnawalkam Elayavalli,[170] S. Kyriacou,[170] A. Lath,[170] K. Nash,[170] H. Saka,[170] S. Salur,[170] S. Schnetzer,[170] D. Sheffield,[170] S. Somalwar,[170] R. Stone,[170] S. Thomas,[170] P. Thomassen,[170] M. Walker,[170] A. G. Delannoy,[171] M. Foerster,[171] J. Heideman,[171] G. Riley,[171] K. Rose,[171] S. Spanier,[171] K. Thapa,[171] O. Bouhali,[172,uuu] A. Celik,[172] M. Dalchenko,[172] M. De Mattia,[172] A. Delgado,[172] S. Dildick,[172] R. Eusebi,[172] J. Gilmore,[172] T. Huang,[172] E. Juska,[172] T. Kamon,[172,vvv] R. Mueller,[172] Y. Pakhotin,[172] R. Patel,[172] A. Perloff,[172] L. Perniè,[172] D. Rathjens,[172] A. Rose,[172] A. Safonov,[172] A. Tatarinov,[172] K. A. Ulmer,[172] N. Akchurin,[173] C. Cowden,[173] J. Damgov,[173] F. De Guio,[173] C. Dragoiu,[173] P. R. Dudero,[173] J. Faulkner,[173] E. Gurpinar,[173] S. Kunori,[173] K. Lamichhane,[173] S. W. Lee,[173] T. Libeiro,[173] T. Peltola,[173] S. Undleeb,[173] I. Volobouev,[173] Z. Wang,[173] S. Greene,[174] A. Gurrola,[174] R. Janjam,[174] W. Johns,[174] C. Maguire,[174] A. Melo,[174] H. Ni,[174] P. Sheldon,[174] S. Tuo,[174] J. Velkovska,[174] Q. Xu,[174] M. W. Arenton,[175] P. Barria,[175] B. Cox,[175]

J. Goodell,[175] R. Hirosky,[175] A. Ledovskoy,[175] H. Li,[175] C. Neu,[175] T. Sinthuprasith,[175] X. Sun,[175] Y. Wang,[175] E. Wolfe,[175] F. Xia,[175] C. Clarke,[176] R. Harr,[176] P. E. Karchin,[176] J. Sturdy,[176] D. A. Belknap,[177] J. Buchanan,[177] C. Caillol,[177] S. Dasu,[177] L. Dodd,[177] S. Duric,[177] B. Gomber,[177] M. Grothe,[177] M. Herndon,[177] A. Hervé,[177] P. Klabbers,[177] A. Lanaro,[177] A. Levine,[177] K. Long,[177] R. Loveless,[177] I. Ojalvo,[177] T. Perry,[177] G. A. Pierro,[177] G. Polese,[177] T. Ruggles,[177] A. Savin,[177] N. Smith,[177] W. H. Smith,[177] D. Taylor,[177] and N. Woods[177]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Wien, Austria*
[3]*Institute for Nuclear Problems, Minsk, Belarus*
[4]*National Centre for Particle and High Energy Physics, Minsk, Belarus*
[5]*Universiteit Antwerpen, Antwerpen, Belgium*
[6]*Vrije Universiteit Brussel, Brussel, Belgium*
[7]*Université Libre de Bruxelles, Bruxelles, Belgium*
[8]*Ghent University, Ghent, Belgium*
[9]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[10]*Université de Mons, Mons, Belgium*
[11]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[12]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[13a]*Universidade Estadual Paulista, São Paulo, Brazil*
[13b]*Universidade Federal do ABC, São Paulo, Brazil*
[14]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
[15]*University of Sofia, Sofia, Bulgaria*
[16]*Beihang University, Beijing, China*
[17]*Institute of High Energy Physics, Beijing, China*
[18]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[19]*Universidad de Los Andes, Bogota, Colombia*
[20]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[21]*University of Split, Faculty of Science, Split, Croatia*
[22]*Institute Rudjer Boskovic, Zagreb, Croatia*
[23]*University of Cyprus, Nicosia, Cyprus*
[24]*Charles University, Prague, Czech Republic*
[25]*Universidad San Francisco de Quito, Quito, Ecuador*
[26]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[27]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[28]*Department of Physics, University of Helsinki, Helsinki, Finland*
[29]*Helsinki Institute of Physics, Helsinki, Finland*
[30]*Lappeenranta University of Technology, Lappeenranta, Finland*
[31]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[32]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
[33]*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
[34]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
[35]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[36]*Georgian Technical University, Tbilisi, Georgia*
[37]*Tbilisi State University, Tbilisi, Georgia*
[38]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[39]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[40]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[41]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[42]*University of Hamburg, Hamburg, Germany*
[43]*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
[44]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
[45]*National and Kapodistrian University of Athens, Athens, Greece*
[46]*University of Ioánnina, Ioánnina, Greece*

[47]*MTA-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*
[62a]*INFN Sezione di Bari, Bari, Italy*
[62b]*Università di Bari, Bari, Italy*
[62c]*Politecnico di Bari, Bari, Italy*
[63a]*INFN Sezione di Bologna, Bologna, Italy*
[63b]*Università di Bologna, Bologna, Italy*
[64a]*INFN Sezione di Catania, Catania, Italy*
[64b]*Università di Catania, Catania, Italy*
[65a]*INFN Sezione di Firenze, Firenze, Italy*
[65b]*Università di Firenze, Firenze, Italy*
[66]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[67a]*INFN Sezione di Genova, Genova, Italy*
[67b]*Università di Genova, Genova, Italy*
[68a]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[68b]*Università di Milano-Bicocca, Milano, Italy*
[69a]*INFN Sezione di Napoli, Roma, Italy*
[69b]*Università di Napoli 'Federico II', Roma, Italy*
[69c]*Università della Basilicata, Roma, Italy*
[69d]*Università G. Marconi, Roma, Italy*
[70a]*INFN Sezione di Padova, Padova, Italy*
[70b]*Università di Padova, Padova, Italy*
[70c]*Università di Trento*
[71a]*INFN Sezione di Pavia, Pavia, Italy*
[71b]*Università di Pavia, Pavia, Italy*
[72a]*INFN Sezione di Perugia, Perugia, Italy*
[72b]*Università di Perugia, Perugia, Italy*
[73a]*INFN Sezione di Pisa, Pisa, Italy*
[73b]*Università di Pisa, Pisa, Italy*
[73c]*Scuola Normale Superiore di Pisa, Pisa, Italy*
[74a]*INFN Sezione di Roma, Roma, Italy*
[74b]*Università di Roma, Roma, Italy*
[75a]*INFN Sezione di Torino, Novara, Italy*
[75b]*Università di Torino, Novara, Italy*
[75c]*Università del Piemonte Orientale, Novara, Italy*
[76a]*INFN Sezione di Trieste, Trieste, Italy*
[76b]*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*

[87]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[88]*Universidad Iberoamericana, Mexico City, Mexico*
[89]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[90]*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
[91]*University of Auckland, Auckland, New Zealand*
[92]*University of Canterbury, Christchurch, New Zealand*
[93]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[94]*National Centre for Nuclear Research, Swierk, Poland*
[95]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[96]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[97]*Joint Institute for Nuclear Research, Dubna, Russia*
[98]*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
[99]*Institute for Nuclear Research, Moscow, Russia*
[100]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[101]*Moscow Institute of Physics and Technology, Moscow, Russia*
[102]*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
[103]*P.N. Lebedev Physical Institute, Moscow, Russia*
[104]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[105]*Novosibirsk State University (NSU), Novosibirsk, Russia*
[106]*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
[107]*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
[108]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[109]*Universidad Autónoma de Madrid, Madrid, Spain*
[110]*Universidad de Oviedo, Oviedo, Spain*
[111]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[112]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[113]*Paul Scherrer Institut, Villigen, Switzerland*
[114]*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
[115]*Universität Zürich, Zurich, Switzerland*
[116]*National Central University, Chung-Li, Taiwan*
[117]*National Taiwan University (NTU), Taipei, Taiwan*
[118]*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
[119]*Cukurova University, Adana, Turkey*
[120]*Middle East Technical University, Physics Department, Ankara, Turkey*
[121]*Bogazici University, Istanbul, Turkey*
[122]*Istanbul Technical University, Istanbul, Turkey*
[123]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
[124]*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[125]*University of Bristol, Bristol, United Kingdom*
[126]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[127]*Imperial College, London, United Kingdom*
[128]*Brunel University, Uxbridge, United Kingdom*
[129]*Baylor University, Waco, Texas, USA*
[130]*The University of Alabama, Tuscaloosa, Alabama, USA*
[131]*Boston University, Boston, Massachusetts, USA*
[132]*Brown University, Providence, Rhode Island, USA*
[133]*University of California, Davis, Davis, California, USA*
[134]*University of California, Los Angeles, California, USA*
[135]*University of California, Riverside, Riverside, California, USA*
[136]*University of California, San Diego, La Jolla, USA*
[137]*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
[138]*California Institute of Technology, Pasadena, California, USA*
[139]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[140]*University of Colorado Boulder, Boulder, Colorado, USA*
[141]*Cornell University, Ithaca, New York, USA*
[142]*Fairfield University, Fairfield, Connecticut, USA*
[143]*Fermi National Accelerator Laboratory, Batavia, New York, USA*
[144]*University of Florida, Gainesville, Florida, USA*
[145]*Florida International University, Miami, Florida, USA*
[146]*Florida State University, Tallahassee, Florida, USA*

[147]*Florida Institute of Technology, Melbourne, Florida, USA*
[148]*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
[149]*The University of Iowa, Iowa City, Iowa, USA*
[150]*Johns Hopkins University, Baltimore, Maryland, USA*
[151]*The University of Kansas, Lawrence, Kansas, USA*
[152]*Kansas State University, Manhattan, Kansas, USA*
[153]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[154]*University of Maryland, College Park, Maryland, USA*
[155]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[156]*University of Minnesota, Minneapolis, Minnesota, USA*
[157]*University of Mississippi, Oxford, Mississippi, USA*
[158]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[159]*State University of New York at Buffalo, Buffalo, New York, USA*
[160]*Northeastern University, Boston, Massachusetts, USA*
[161]*Northwestern University, Evanston, Illinois, USA*
[162]*University of Notre Dame, Notre Dame, Indiana, USA*
[163]*The Ohio State University, Columbus, Ohio, USA*
[164]*Princeton University, Princeton, New Jersey, USA*
[165]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[166]*Purdue University, West Lafayette, Indiana, USA*
[167]*Purdue University Calumet, Hammond, Indiana, USA*
[168]*Rice University, Houston, Texas, USA*
[169]*University of Rochester, Rochester, New York, USA*
[170]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[171]*University of Tennessee, Knoxville, Tennessee, USA*
[172]*Texas A&M University, College Station, Texas, USA*
[173]*Texas Tech University, Lubbock, Texas, USA*
[174]*Vanderbilt University, Nashville, Tennessee, USA*
[175]*University of Virginia, Charlottesville, Virginia, USA*
[176]*Wayne State University, Detroit, Michigan, USA*
[177]*University of Wisconsin - Madison, Madison, Wisconsin, USA*

[a]Deceased.
[b]Also at Vienna University of Technology, Vienna, Austria.
[c]Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[d]Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
[e]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[f]Also at Universidade Federal de Pelotas, Pelotas, Brazil.
[g]Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[h]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[i]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[j]Also at Cairo University, Cairo, Egypt.
[k]Also at Fayoum University, El-Fayoum, Egypt.
[l]Also at British University in Egypt, Cairo, Egypt.
[m]Also at Ain Shams University, Cairo, Egypt.
[n]Also at Université de Haute Alsace, Mulhouse, France.
[o]Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[p]Also at Tbilisi State University, Tbilisi, Georgia.
[q]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[r]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[s]Also at University of Hamburg, Hamburg, Germany.
[t]Also at Brandenburg University of Technology, Cottbus, Germany.
[u]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[v]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[w]Also at University of Debrecen, Debrecen, Hungary.
[x]Also at Indian Institute of Science Education and Research, Bhopal, India.
[y]Also at Institute of Physics, Bhubaneswar, India.
[z]Also at University of Visva-Bharati, Santiniketan, India.
[aa]Also at University of Ruhuna, Matara, Sri Lanka.

[bb]Also at Isfahan University of Technology, Isfahan, Iran.
[cc]Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
[dd]Also at Yazd University, Yazd, Iran.
[ee]Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[ff]Also at Università degli Studi di Siena, Siena, Italy.
[gg]Also at Purdue University, West Lafayette, USA.
[hh]Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[ii]Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[jj]Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[kk]Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[ll]Also at Institute for Nuclear Research, Moscow, Russia.
[mm]Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[nn]Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[oo]Also at University of Florida, Gainesville, USA.
[pp]Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[qq]Also at INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy.
[rr]Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[ss]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[tt]Also at INFN Sezione di Roma, Università di Roma, Roma, Italy.
[uu]Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[vv]Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[ww]Also at National and Kapodistrian University of Athens, Athens, Greece.
[xx]Also at Riga Technical University, Riga, Latvia.
[yy]Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[zz]Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[aaa]Also at Adiyaman University, Adiyaman, Turkey.
[bbb]Also at Istanbul Aydin University, Istanbul, Turkey.
[ccc]Also at Mersin University, Mersin, Turkey.
[ddd]Also at Cag University, Mersin, Turkey.
[eee]Also at Piri Reis University, Istanbul, Turkey.
[fff]Also at Ozyegin University, Istanbul, Turkey.
[ggg]Also at Izmir Institute of Technology, Izmir, Turkey.
[hhh]Also at Marmara University, Istanbul, Turkey.
[iii]Also at Kafkas University, Kars, Turkey.
[jjj]Also at Istanbul Bilgi University, Istanbul, Turkey.
[kkk]Also at Yildiz Technical University, Istanbul, Turkey.
[lll]Also at Hacettepe University, Ankara, Turkey.
[mmm]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[nnn]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[ooo]Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[ppp]Also at Utah Valley University, Orem, USA.
[qqq]Also at Argonne National Laboratory, Argonne, USA.
[rrr]Also at Erzincan University, Erzincan, Turkey.
[sss]Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[ttt]Also at Catholic University of America.
[uuu]Also at Texas A&M University at Qatar, Doha, Qatar.
[vvv]Also at Kyungpook National University, Daegu, Korea.