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Suppression of Excited Υ States Relative to the Ground State in Pb-Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

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The relative yields of Υ mesons produced in pp and Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and reconstructed via the dimuon decay channel are measured using data collected by the CMS experiment. Double ratios are formed by comparing the yields of the excited states, $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$, to the ground state, $\Upsilon(1\mathrm{S})$, in both Pb-Pb and pp collisions at the same center-of-mass energy. The double ratios, $[\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})]_{\mathrm{Pb-Pb}}/[\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})]_{pp}$, are measured to be $0.308 \pm 0.055(\mathrm{stat}) \pm 0.019(\mathrm{syst})$ for the $\Upsilon(2\mathrm{S})$ and less than 0.26 at 95% confidence level for the $\Upsilon(3\mathrm{S})$. No significant $\Upsilon(3\mathrm{S})$ signal is found in the Pb-Pb data. The double ratios are studied as a function of collision centrality, as well as Υ transverse momentum and rapidity. No significant dependencies are observed.

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A key expectation of quantum chromodynamics (QCD) is that at high temperature, T, the degrees of freedom will change and color fields and forces can act over ranges greater than typical hadronic sizes, a phenomenon referred to as color deconfinement. Studies of relativistic heavy ion collisions are motivated in large part by the goal of developing a detailed understanding of the properties of the deconfined phase, the quark-gluon plasma (QGP). Heavy quarkonia are some of the most promising probes of deconfinement, and hence have been the focus of detailed scrutiny. Quarkonium production is studied because of its sensitivity to color deconfinement via QCD Debye screening, as first proposed in Ref. [1]. Most of the early studies have focused on the charmonium family, but the high energies and collision rates available at the LHC enable studies of bottomonium states [2–6]. Measurements of bottomonium suppression were performed [7] also at RHIC, and will be continued with upgraded detectors [8]. Comparisons of Υ data at the different collision energies will help to elucidate the temperature dependence of the suppression effects.

A detailed study of the modification of quarkonia states from pp to Pb-Pb collisions can provide information about the onset and properties of the QGP [9,10]. In particular, suppression of heavy quarkonia via QCD Debye screening, or any other modification of the heavy-quark potential, requires the presence of a color-deconfined phase. Furthermore, the specific level of suppression for a given state depends on the QGP temperature. It is expected that different states will dissociate at different temperatures, with a suppression pattern ordered sequentially with binding energy [11,12]. The sequential suppression pattern was first observed for the $\Upsilon(\mathrm{nS})$ family by CMS [4,5].

Recent theoretical studies consider not only the screening effect on the real part of the heavy-quark potential, but also incorporate an imaginary part [13–17], which represents effects such as Landau damping and gluodissociation of the quarkonium states. These mechanisms broaden the width of the states and also contribute to the suppression of the observed yields. A recent calculation [17], where the melting temperatures are estimated using a complex potential, indicates that the $\Upsilon(3\mathrm{S})$ state is expected to melt essentially at T_{c} (where $T_{\mathrm{c}} = 172.5$ MeV for that study), the $\Upsilon(2\mathrm{S})$ state should melt at $T \approx 215$ MeV, and the ground state should survive up to $T \approx 460$ MeV. Existing models incorporate several mechanisms leading to the observed bottomonium suppression: screening, thermal decay widths, quarkonium evolution in the high-temperature phase, regeneration effects, recombination effects, and feed-down contributions [18–21]. The creation of quarkonia from uncorrelated quarks, i.e., recombination, is expected to be negligible for bottomonia compared to expectations for the charmonium family [22–25] because the recombination is driven by the number of heavy quark pairs present in a single event, which is much smaller for beauty than for charm. Since the bottom production cross section at 5.02 TeV is of the order of 100–200 μb [26], this will result in the production of only 2 $\mathrm{b\bar{b}}$ pairs per central nucleon-nucleon collision. By comparison, the charm cross section is of the order of 1 mb at 200 GeV. Because of the expected small recombination contribution,

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measurements of Υ suppression are useful to compare to theoretical calculations of quarkonium in hot nuclear matter and to understand the behavior of quarkonia in high temperature QCD.

Double ratios are useful to quantify the relative modifications of the Υ excited states. Theoretically, the uncertainties associated with perturbative QCD calculations (renormalization and factorization scales, b quark mass, nuclear parton distribution functions) affect the cross sections in the same way for all Υ states, and thus cancel in the ratio of excited to ground state yields. Experimentally, the efficiencies and acceptances cancel almost completely in these double ratios, reducing the measurement uncertainties.

This Letter reports the double ratios

$$\frac{(\Upsilon(2S)/\Upsilon(1S))_{\text{Pb-Pb}}}{(\Upsilon(2S)/\Upsilon(1S))_{pp}} \quad \text{and} \quad \frac{(\Upsilon(3S)/\Upsilon(1S))_{\text{Pb-Pb}}}{(\Upsilon(3S)/\Upsilon(1S))_{pp}}$$

comparing pp and Pb-Pb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 5.02$ TeV, using data collected with the CMS detector during the 2015 LHC run. The increase in the collision energy and integrated luminosity allows for a more detailed study compared to the previous measurement at a collision energy of $\sqrt{s_{\text{NN}}} = 2.76$ TeV [4]. In particular, we present a more sensitive search for the $\Upsilon(3S)$ state in Pb-Pb collisions and a more accurate measurement of the $\Upsilon(2S)$ suppression in peripheral Pb-Pb collisions (those with a large impact parameter between the lead ions). The increase in center-of-mass energy was predicted to lead to a $\simeq 16\%$ higher medium temperature [18] and to correspondingly stronger suppression effects.

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 endcap sections. Forward calorimeters extend the coverage provided by the barrel and endcap 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 (p_{T}) resolution between 1% and 2% for a typical muon in this analysis [27]. 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. [28].

For Pb-Pb collisions, the centrality measurement is based on the sum of transverse energy measured in two hadron forward (HF) calorimeters, which cover the range $2.9 < |\eta| < 5.2$. In order to select hadronic Pb-Pb (pp) collisions, at least three (one) towers with energy deposits above 3 GeV are required in each of the HF calorimeters, both at forward and backward rapidity. A primary vertex reconstructed with at least two tracks is also required. In addition, a filter on the compatibility of the silicon pixel cluster width and the vertex position is applied [29]. The combined efficiency for this event selection, and the remaining nonhadronic contamination, is $99 \pm 2\%$. We focus on events where a hard collision is needed in order to produce Υ mesons. Hence, the fraction of such events removed by the minimum-bias trigger requirement is negligible. The event centrality observable corresponds to the fraction of the total inelastic hadronic cross section, starting at 0% for the most central collisions and evaluated as percentiles of the distribution of the energy deposited in the HF [30]. The average number of nucleons that participate in the interaction for a given centrality class, N_{part}, is estimated using a Glauber Monte Carlo (MC) simulation [31]. The Glauber model parameters used for 5.02 TeV Pb-Pb collisions and a description of the method are given in Ref. [32].

The Υ mesons are identified via their decay to muons. This analysis uses event samples collected with a dimuon trigger that requires two muons with no explicit single-muon momentum threshold. The same trigger algorithm is used in pp as well as Pb-Pb collisions. The algorithm uses information from the muon chambers, which are shielded from the large multiplicities present in Pb-Pb collisions. Therefore, the performance of the trigger is the same in both collision systems, and across all centralities studied. The trigger sampled an integrated luminosity of 28.0 pb^{-1} in pp collisions. The Pb-Pb sample was collected in two ways: by prescaling the dimuon trigger, and by combining the dimuon trigger with an additional selection on 30%–100% centrality collisions. The first setup collected data corresponding to an integrated luminosity of $368\,\mu\text{b}^{-1}$, and the corresponding data set is used to derive the centrality-integrated (0%–100%) double ratios and those in the 0%–30% centrality range. For the second setup, the lower rate allowed the sampling of the full integrated luminosity of 464 μb^{-1}. This sample is used to analyze the centrality dependence of the double ratio in the 30%–100% range. We also studied a possible contamination from photo-production processes in the peripheral region and found it to be negligible.

Single muons are selected in the kinematic region $p_T^\mu > 4$ GeV/c, $|\eta^\mu| < 2.4$, and are required to survive standard quality selection criteria [27]. The reconstruction algorithm was adapted to account for the high track multiplicity in a Pb-Pb event, using a combination of regional and iterative tracking algorithms [33]. The muon momentum is derived from the fit obtained with a Kalman filter algorithm [27] applied to the tracker hits and provides an Υ mass resolution of around 1% in both pp and Pb-Pb.

When forming a muon pair, the two reconstructed muon candidates are required to match the dimuon trigger and to originate from a common vertex with a χ^2 probability larger than 1%. The Υ transverse momentum and rapidity ranges studied in this analysis are $p_T < 30$ GeV/c and $|y| < 2.4$. The Υ ratios are not affected by the small number of additional collision vertices (pileup) present in the pp and Pb-Pb samples.

Figure 1 shows the invariant mass distributions of opposite-charge muon pairs for centrality-integrated Pb-Pb collisions. The double ratios are computed from the signal yields obtained independently from unbinned maximum likelihood fits to the pp and Pb-Pb spectra. The analysis of the $\Upsilon(2S)$ double ratio is performed in three p_T bins, two $|y|$ bins, and nine centrality bins, while the $\Upsilon(3S)$ double ratio is studied in four centrality bins. As a cross-check, simultaneous fits of the two dimuon invariant mass distributions, where the double ratios are directly extracted, were also performed. The two procedures give consistent results.

The shape of each Υ state is modeled with the sum of two crystal ball functions [34], with parameters fixed from MC simulation studies. The mass parameter of the $\Upsilon(1S)$ resonance is left free to account for possible shifts in the momentum scale of the reconstructed tracks, and is found to be consistent between pp and Pb-Pb data. The masses of the excited states are fixed to the $\Upsilon(1S)$ mass scaled by the ratio of the world average mass values [35]. The systematic uncertainty in the double ratio from the choice of signal model is evaluated by testing two fit variations. One uses the same function, but allowing all previously fixed parameters to float one by one and propagating as systematic uncertainty the maximum observed deviations from the double ratios obtained with the nominal signal model. The second fit variation uses a sum of a crystal ball function and Gaussian function as an alternative fit model. The total uncertainties related to the signal model are determined by summing in quadrature the two systematic components, and are in the ranges 1%–10% and 9%–15% for the $\Upsilon(2S)$ and $\Upsilon(3S)$ double ratios, respectively.

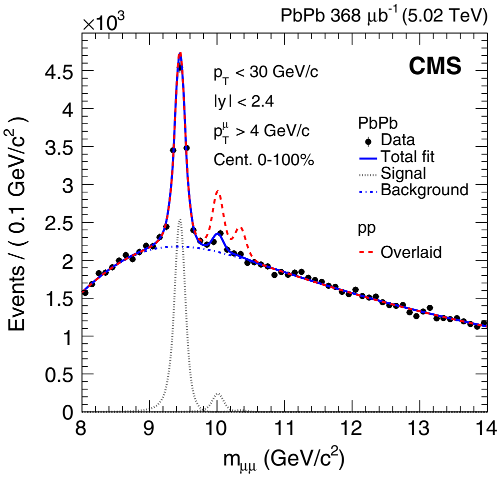

FIG. 1. Measured dimuon invariant mass distribution in Pb-Pb data. The total fit (solid blue line) and the background component (dot-dashed blue line) are also shown, as are the individual $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ signal shapes (dotted gray lines). The dashed red line represents the pp signal shape added to the Pb-Pb background and normalized to the $\Upsilon(1S)$ mass peak in Pb-Pb.

The background is modeled with an error function multiplied by an exponential function as in Ref. [4], a parametrization selected, in each analysis bin, through a log-likelihood ratio test comparing several functional forms, while fixing the signal parameters. For the two highest p_{T} bins in this analysis, using an exponential without the error function provides the best fit. Possible deviations in the results when choosing an alternative background model, in the form of a fourth-order polynomial, are studied using pseudoexperiments. For this purpose, the nominal background and signal models are used to generate pseudoinvariant mass distributions in each bin of the analysis. These distributions are then fit with the nominal model as well as using the alternative background model. The average resulting differences between nominal and alternative fit model are found to be in the 2%–15% range for the $\Upsilon(2S)$ and $\Upsilon(3S)$ double ratios, respectively. The signal and background model uncertainties are the dominant sources of systematic uncertainty in this analysis.

Possible effects of noncancellation of reconstruction, trigger, and muon identification efficiencies in the double ratios are studied by comparing the results of simulations using PYTHIA 8.209 [36] tune CUETP8M1 (for the low-occupancy pp environment) with those obtained using PYTHIA 8 embedded in HYDJET 1.9 [37] (for the high-occupancy Pb-Pb data). The Υ transverse momentum distributions in the MC samples are reweighted to match the signal p_{T} spectra seen in data, since the reconstruction efficiency depends on p_T. The rapidity distributions in simulation are consistent with those in data; hence, no reweighting is applied as a function of y. The maximum deviation from unity of the double ratio of efficiencies, among all the analysis bins, was found to be 1.4%, a value taken as a systematic uncertainty.

Acceptance corrections are not applied because they are expected to cancel in the Pb-Pb over pp ratio for each state. If, however, the Υ meson acceptances were different in pp and Pb-Pb because of physical effects, such as a change in polarization or strong kinematical differences from pp to Pb-Pb collisions within an analysis bin, these would not cancel in the double ratio. The hypothesis that such potential effects can be neglected is supported by the absence of significant changes of the $\Upsilon(nS)$ polarizations in pp collisions as a function of event activity [38]. Moreover, when studying the p_T and $|y|$ distributions in the pp and Pb-Pb data samples, it is observed that they have similar shapes. As in previous analyses [2–4,39,40], possible differences in Pb-Pb and pp acceptances due to physical effects are not considered as systematic uncertainties.

Figure 2 shows the $\Upsilon(2S)$ double ratio as a function of N_{part}. The box drawn around the line at unity represents the global uncertainty, that applies to all measurements, including the centrality-integrated datum point. It amounts to 3.1%, and includes the systematic and statistical uncertainties from the pp single ratio, as well as the uncertainty due to possible noncancellation of reconstruction, trigger, and muon-identification efficiencies. A large relative suppression of the $\Upsilon(2S)$ state compared to the $\Upsilon(1S)$ state in Pb-Pb collisions with respect to the pp data is observed. The centrality-integrated $\Upsilon(2S)$ double ratio is $0.308 \pm 0.055(\text{stat}) \pm 0.019(\text{syst})$, where the systematic uncertainty reflects the signal and background variations in Pb-Pb and pp data, as well as the uncertainty on the combined detection efficiency. In the most peripheral bin (70%–100%), the double ratio is consistent with unity. In the most central bin (0%–5%), the $\Upsilon(2S)$ signal is consistent with zero within one standard deviation of the statistical uncertainty. Therefore, a 95% confidence level (C.L.) interval is derived for this centrality bin, obtained using the Feldman-Cousins method [41]. The relative $\Upsilon(2S)$ suppression is similar at 5.02 and 2.76 TeV [4]. The results presented here have an improvement in the statistical precision compared to the previous measurement by almost a factor of 2.

Predictions of Υ suppression from Krouppa and Strickland [18], incorporating color-screening effects on the bottomonium family and reflecting feed-down contributions from decays of heavy quarkonia, are in overall agreement with the $\Upsilon(2S)$ double ratio results presented in Fig. 2. In this model, the dynamical evolution is treated using anisotropic hydrodynamics, where the relevant initial conditions are changed by varying the viscosity to entropy ratio, η/s, and the initial momentum-space anisotropy. In order to maintain agreement with charged multiplicity and elliptic flow measurements, the initial temperature is then uniquely determined as well. The temperatures reported in this model are in the range $T = 641, 631, 629$ MeV corresponding to $4\pi\eta/s = 1, 2, 3$, respectively. Another theoretical curve from Du *et al.* [21], based on a kinetic-rate equation approach first presented in Ref. [20] and containing a small component of regenerated bottomonia, shows a similar level of agreement with the data. In this model, the absence of a regeneration component would lead to almost complete suppression of the $\Upsilon(2S)$, i.e., a double ratio of zero for the centrality range $N_{\text{part}} > 250$. Such a scenario is ruled out by our data.

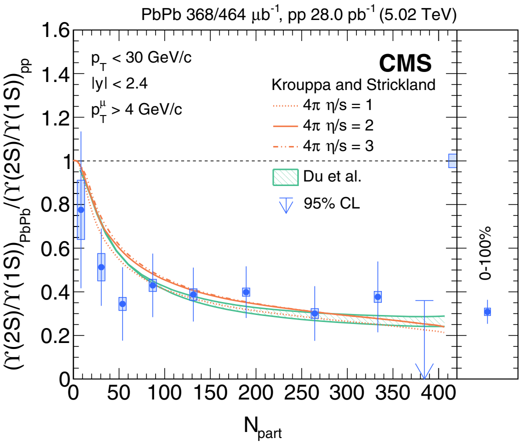

FIG. 2. Double ratio of the $\Upsilon(2S)$ as a function of centrality. The centrality-integrated value is shown in the right panel. The error bars represent the statistical uncertainty in the Pb-Pb data while the boxes represent the systematic uncertainty due to signal and background variations. The global systematic uncertainty is represented as a grey box drawn around the line at unity. Calculations by Krouppa and Strickland (orange curves [18]) and by Du *et al.* (green hatched band [20,21]) are also shown.

Figure 3 shows the $\Upsilon(2S)$ double ratio as a function of p_T and $|y|$. A large relative $\Upsilon(2S)$ suppression is observed throughout the kinematic range studied, with no significant

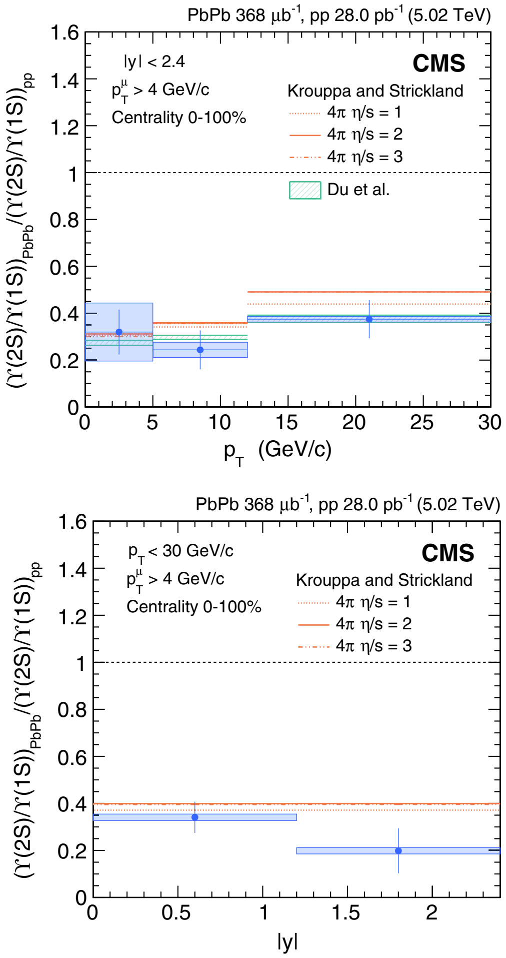

FIG. 3. Double ratio of the $\Upsilon(2S)$ as functions of p_T (top) and $|y|$ (bottom). The error bars depict the statistical uncertainty while the boxes represent the systematic uncertainties in the signal and background models as well as the combined detection efficiency. Calculations by Krouppa and Strickland (orange curves [18]) and by Du *et al.* (green hatched band [20,21]) are also shown.

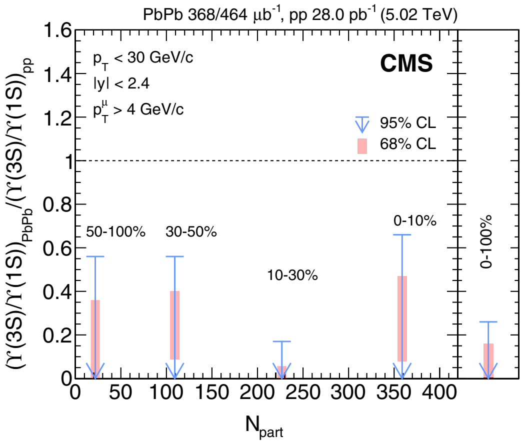

FIG. 4. Confidence intervals at 95% C.L. (blue arrows) and 68% C.L. (red boxes) of the $\Upsilon(3S)$ double ratio as a function of centrality. The centrality-integrated limit is shown in the right panel.

variations with p_T or $|y|$. Predictions of Υ suppression as functions of p_T [18,20] and $|y|$ [18] are in overall agreement with the data.

For the $\Upsilon(3S)$, as seen in Fig. 1, the signal yield in the Pb-Pb data is consistent with zero in the centrality-integrated sample. Figure 4 shows the extracted $\Upsilon(3S)$ double-ratio confidence intervals, at 95% and 68% C.L. In all four centrality bins, the $\Upsilon(3S)$ double ratio is significantly below unity, showing that the $\Upsilon(3S)$ state is strongly suppressed relative to the $\Upsilon(1S)$ state, even in the most peripheral (50%–100%) Pb-Pb collisions probed in this analysis. The centrality-integrated $\Upsilon(3S)$ double ratio is smaller than 0.26 at 95% C.L. We excluded the possibility that the stringent limit in the 10%–30% centrality bin is due to a large downward fluctuation in the background by studying the invariant mass region of the $\Upsilon(3S)$ in each centrality bin. We also calculated upper limits under the assumption that the observed counts are equal to the expected background and found an upper limit that increases only slightly to the range 0.2–0.3 for the 10%–30% bin.

In summary, the $\Upsilon(2S)$ and $\Upsilon(3S)$ double ratios have been measured at 5.02 TeV, using pp and Pb-Pb data samples significantly larger than those used in the corresponding 2.76 TeV measurements. The centrality-integrated double ratios are $0.308 \pm 0.055(\mathrm{stat}) \pm 0.019(\mathrm{syst})$ for the $\Upsilon(2S)$ and < 0.26 at 95% C.L. for the $\Upsilon(3S)$. The large relative suppression of the $\Upsilon(2S)$ does not show significant variations with p_T or $|y|$ within the explored phase space window of $p_T < 30$ GeV/c and $|y| < 2.4$. The $\Upsilon(2S)$ double ratio is compatible with unity in the most peripheral collisions (70%–100%) and with zero in the most central ones (0%–5%), but a flat centrality dependence is not excluded, given the current uncertainties. The 95% C.L. intervals for the $\Upsilon(3S)$ double ratio exclude unity in the four centrality bins of this analysis, including the most peripheral collisions (50%–100%).

We congratulate our colleagues in the 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: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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