EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-181
2022/10/31

CMS-HIN-18-005

Nuclear modification of Υ states in pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

Production cross sections of Υ(1S), Υ(2S), and Υ(3S) states decaying into $\mu^+\mu^-$ in proton-lead (pPb) collisions are reported using data collected by the CMS experiment at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$. A comparison is made with corresponding cross sections obtained with pp data measured at the same collision energy and scaled by the Pb nucleus mass number. The nuclear modification factor for Υ(1S) is found to be $R_{\mathrm{pPb}}(\Upsilon(1\mathrm{S})) = 0.806 \pm 0.024\,(\mathrm{stat}) \pm 0.059\,(\mathrm{syst})$. Similar results for the excited states indicate a sequential suppression pattern, such that $R_{\mathrm{pPb}}(\Upsilon(1\mathrm{S})) > R_{\mathrm{pPb}}(\Upsilon(2\mathrm{S})) > R_{\mathrm{pPb}}(\Upsilon(3\mathrm{S}))$. The suppression of all states is much less pronounced in pPb than in PbPb collisions, and independent of transverse momentum $p_{\mathrm{T}}^{\Upsilon}$ and center-of-mass rapidity $y_{\mathrm{CM}}^{\Upsilon}$ of the individual Υ state in the studied range $p_{\mathrm{T}}^{\Upsilon} < 30\,\mathrm{GeV}/c$ and $|y_{\mathrm{CM}}^{\Upsilon}| < 1.93$. Models that incorporate final-state effects of bottomonia in pPb collisions are in better agreement with the data than those which only assume initial-state modifications.

Published in Physics Letters B as doi:10.1016/j.physletb.2022.137397.

*See Appendix A for the list of collaboration members

1 Introduction

Properties of the color-deconfined quark-gluon plasma (QGP) created in high-energy collisions of heavy nuclei can be studied using heavy-quark resonances produced by initial hard scatterings [1–6]. Yields of various quarkonium states, which have a short formation time in their rest frames and can typically escape the QGP before they decay, encode information on the evolution of the plasma starting from its early stages [1, 2, 4, 6–9]. Debye screening and gluo-dissociation [10–14] in the QGP produced in lead-lead (PbPb) collisions are understood to modify yields of quarkonium states hierarchically, according to their binding energies. Each state dissociates when a high enough temperature is reached in the QGP [4–6, 9, 15]. To interpret the quarkonium-state suppression patterns observed in heavy ion collisions as signals of color deconfinement in the hot plasma, it is essential to understand initial state and final state "cold nuclear matter" (CNM) effects. In this context, initial state refers to the partons in the relevant quantum chromodynamics process that stem from the colliding proton (p) or nucleus and scatter to produce a heavy quark pair but before it hadronizes into a quarkonium state. Examples of CNM effects that have been discussed in pA collisions include shadowing of the parton distribution functions in the nucleus (initial state) [16], energy loss in the nucleus (initial and final states) [17], and interactions with hadronic comovers (final state) [18]. For a recent review, see Ref. [7]. Traditionally, all modifications observed in pPb collisions were assumed to be due to CNM effects. However, it is worth noting that this assumption has been questioned given recent evidence of collective behavior in pp and pPb collisions with the highest amount of emitted particles, further referred to as high-activity [19–25]. This might be explained by assuming the formation of a QGP-like medium [26].

Bottomonia serve as particularly powerful probes for studying the QGP, since their high masses require that their production be dominated by initial hard scattering of partons in the collisions [7, 27–30]. When compared to charmonia, their yields are considerably less modified by regeneration or recombination in the QGP [30–32]. Measurements by the CMS experiment showing sequential modification of $\Upsilon(n\mathrm{S})$ (where $n = 1, 2, 3$) decaying via the dimuon channel in PbPb compared with pp collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{\mathrm{NN}}}} = 2.76\,\mathrm{TeV}$ [33, 34] and $5.02\,\mathrm{TeV}$ [35, 36] were used to infer model-dependent [32, 37] QGP temperatures. This effect is consistent with models that incorporate sequential suppression due to color screening [5, 8, 30]. Similar measurements of $\Upsilon(n\mathrm{S})$ production in pPb collisions can help to disentangle hot and cold nuclear matter effects and to investigate various CNM mechanisms.

Nuclear modification factors R_{pPb} are ratios of particle production cross sections in pPb collisions over the corresponding cross sections in pp collisions scaled to account for the number of nucleons in the Pb nucleus. The R_{pPb} values quantify the modification of hard probe production in pPb collisions due to the nuclear environment created by a single lead nucleus in the initial state. In this analysis, these factors are determined for $\Upsilon(n\mathrm{S})$ under the assumption that the cross sections scale as $\sigma_{\mathrm{pPb}} = A\sigma_{\mathrm{pp}}$, where A is the mass number of Pb. With this assumption, also known as the A-scaling hypothesis, values of R_{pPb} different from unity indicate modifications that go beyond simple superposition of binary nucleon-nucleon collisions. These R_{pPb} values, together with measurements of the nuclear modification factors R_{AA} in PbPb collisions [36], can be used to investigate the relative contributions of hot and cold nuclear matter effects.

Since pPb collisions create an imbalance of nuclear matter in the proton-going (forward rapidity) and lead-going (backward rapidity) directions, they can be used to investigate differences in CNM effects in these regions of varying nuclear matter density within the same collision system. In the charmonium sector, CMS has found hints of differences in the level of suppression between the excited and ground state in the lead-going region [38, 39]. One CNM modification mechanism that relies on the abundance of nuclear matter is dissociation by interaction with comoving particles, where the cross section of interaction increases with particle multiplicity in the rapidity region of the produced Υ meson [18, 40]. This is quantified by measuring the forward-backward production ratios R_{FB} of Υ states in pPb collisions.

The LHCb [41] and ALICE [42] Collaborations reported measurements of the $\Upsilon(n\mathrm{S})/\Upsilon(1\mathrm{S})$ yield ratios (LHCb for $n = 2$ and 3; ALICE for $n = 2$), along with R_{pPb} and R_{FB} for $\Upsilon(1\mathrm{S})$ in pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ using Υ mesons detected in the forward rapidity region. In those studies, the proton reference was obtained by interpolating results from event samples collected at other collision energies, i.e., 2.76, 7, and 8 TeV. In the midrapidity region, the ATLAS Collaboration studied bottomonia in pPb collisions using same-energy pp reference data [43], reporting $\Upsilon(n\mathrm{S})/\Upsilon(1\mathrm{S})$ (for $n = 2$ and 3), as well as $\Upsilon(1\mathrm{S})$ yields self-normalized to their activity-integrated values, and R_{pPb} ($\Upsilon(1\mathrm{S})$). The CMS Collaboration previously reported the $\Upsilon(n\mathrm{S})/\Upsilon(1\mathrm{S})$ (for $n = 2$ and 3) yield ratios versus event activity in the pPb system at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ [44], as well as in pp collisions at $\sqrt{s} = 2.76\,\mathrm{TeV}$ [44] and 7 TeV [45]. More recently, the LHCb [46] and ALICE [47] Collaborations measured R_{pPb} and R_{FB} for both $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ at the higher energy $\sqrt{s_{_{\mathrm{NN}}}} = 8.16\,\mathrm{TeV}$, using pp reference data interpolated from measurements at $\sqrt{s} = 2.76$, 7, 8, and 13 TeV. Data for PbPb collisions are not available at 8.16 TeV for direct comparison. These bottomonium measurements in pPb have focused on the ground state and indicate that the level of suppression is consistent with that expected from shadowing calculations, but they provide little information on the behavior of the excited states.

In this Letter, we analyze pPb and pp collision data from the CERN LHC collected with the CMS detector at the same nucleon-nucleon center-of-mass (CM) energy of $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$. The yields of $\Upsilon(n\mathrm{S})$ mesons are measured using their decay to two muons. By comparing the yields measured in the two colliding systems, the R_{pPb} and R_{FB} factors are determined including all bottomonium states for the first time. Because models that incorporate final-state CNM effects are the only ones to predict different modifications for the excited states, these measurements for the ordering of excited state R_{pPb} values may reveal these types of final-state mechanisms. Ordered suppression could arise from various causes — e.g., the size of the states, their cross section with potential comovers, or their binding energy. These results are compared with measurements of the $\Upsilon(n\mathrm{S})$ nuclear modification factors R_{AA} in PbPb collisions [36] using PbPb data also collected at 5.02 TeV with the CMS detector, allowing a model-dependent comparison of bottomonia in hot and cold nuclear matter.

2 The CMS detector

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. Muons are detected in the range $|\eta_{\mathrm{lab}}| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. In the barrel region $|\eta_{\mathrm{lab}}| < 1.2$ muon detection planes are based on drift tube technology, while the endcap region $0.9 < |\eta_{\mathrm{lab}}| < 2.4$ uses cathode strip chambers. Resistive plate chambers provide additional muon detection capability in the range $|\eta_{\mathrm{lab}}| < 1.6$. Matching muons to tracks measured in the silicon tracker leads to a relative transverse momentum p_{T} resolution on the order of 1% for a typical muon used in this analysis [48]. In addition, two steel and quartz-fiber hadron forward calorimeters cover the range $2.9 < |\eta_{\mathrm{lab}}| < 5.2$. A 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. [49].

A two-tiered system is used to select collision events of interest from the detector. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [50]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [51].

3 Data selection and simulated samples

The events used for this analysis are selected using the trigger systems described above, requiring two muon candidates in the muon detectors with no explicit cuts in muon transverse momentum, p_{T}^{μ}, or muon pseudorapidity measured in the laboratory, $\eta_{\mathrm{lab}}^{\mu}$. The event samples used in this analysis correspond to integrated luminosities of $28.0 \pm 0.6\,\mathrm{pb}^{-1}$ and $34.6 \pm 1.2\,\mathrm{nb}^{-1}$ for pp [52] and pPb [53] collisions, respectively. The uncertainties in the integrated luminosity determination are considered as a global uncertainty in all results. All recorded pPb events are required to have an energy deposit above 3 GeV in the hadron forward calorimeters on each side of the interaction point in order to suppress background from ultra-peripheral collisions and beam-gas events, while having a high efficiency for the selection of beam-beam hadronic collisions.

In the case of pPb collisions, the value of the integrated luminosity represents the combined luminosity of collisions with proton and lead beams traveling in either direction. While in the symmetric pp and PbPb collision systems the CM and laboratory (lab) reference frames coincide, in the case of pPb collisions the difference between the energy-per-nucleon of the two beams induces a shift between the two frames. For pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$, the rapidity y is shifted in the CM frame by $\delta y = 0.465$ compared to the lab frame. The rapidity range of the reconstructed dimuons in the lab frame $|y_{\mathrm{lab}}^{\mu\mu}| < 2.4$ corresponds to a CM frame rapidity range of either $-2.87 < y_{\mathrm{CM}}^{\mu\mu} < 1.93$ (Pbp) or $-1.93 < y_{\mathrm{CM}}^{\mu\mu} < 2.87$ (pPb), depending on the direction of the proton beam. In order to minimize the influence of asymmetric detector conditions, data are taken with both beam directions and then combined by inverting the rapidity of one of the datasets.

For both pp and pPb data, we select events with muon candidates in the kinematic range $p_{\mathrm{T}}^{\mu} > 4\,\mathrm{GeV}/c$, $|\eta_{\mathrm{lab}}^{\mu}| < 2.4$. The muon tracks are required to have at least 6 hits in the silicon tracker, at least one hit in the silicon pixel detector, and match with at least one segment in any detection plane of the muon system. The distance of the track from the closest primary vertex [54] must be less than 20 cm in the longitudinal direction and 0.3 cm in the transverse direction. When forming a muon pair, each of the two muons is required to match the hardware trigger that prompted recording of the event and to originate from a common vertex with a χ^2 probability larger than 1%, as obtained by a Kalman vertex filter algorithm [55]. For pPb data, an additional filter is used to remove events that contain multiple interactions per bunch crossing (pileup) [38]. This filter reduces the fraction of pileup events from 3% to less than 0.2%, and reduces the effective luminosity of pPb collisions by 4.1% compared to the numbers noted above.

Dedicated Monte Carlo (MC) simulations of collision data are used to validate fitting techniques and to correct the extracted $\Upsilon(n\mathrm{S})$ yields for losses due to finite detector acceptance and efficiency. Simulated samples are independently generated for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons, in pp collisions using PYTHIA 8.209 [56], assuming no polarization based on measurements at the LHC [57, 58]. To simulate pPb collisions, the rapidities of all particles in the generated pp events are boosted by $\delta y = 0.465$ in the Pb-going direction to mimic the y_{CM} shift in data. The CMS detector response is simulated using GEANT4 [59]. The reconstructed p_T^{Υ} distributions of the simulated Υ states are weighted using a fit to the ratio of the p_T^{Υ} spectra in data and simulation. The rapidity distributions in simulation are consistent with those in data.

4 Analysis

4.1 Signal extraction

Figure 1 shows the invariant mass distributions of opposite-sign muon pairs for pp (left) and pPb (right) collisions. The dimuon data are integrated in the dimuon range $p_T^{\mu\mu} < 30\,\text{GeV}/c$ and $|y_{CM}^{\mu\mu}| < 1.93$. The yields of the Υ states, uncorrected for detector acceptance and efficiency, are obtained via unbinned maximum-likelihood fits to the invariant mass spectra, shown as solid blue lines. A dashed red line is used in Fig. 1 (right) to depict the expected $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ yields under the $R_{pPb} = 1$ hypothesis, obtained by scaling the signal shape of each state by the inverse of its finally measured R_{pPb} value (including the ratio of the efficiencies corresponding to pp and pPb collisions). This comparison illustrates that the $\Upsilon(nS)$ yields are suppressed in pPb relative to pp collisions in the integrated kinematic region. We bin the data in the dimuon kinematic variables $p_T^{\mu\mu}$ and $y_{CM}^{\mu\mu}$, as well as in event activity variables which we discuss below.

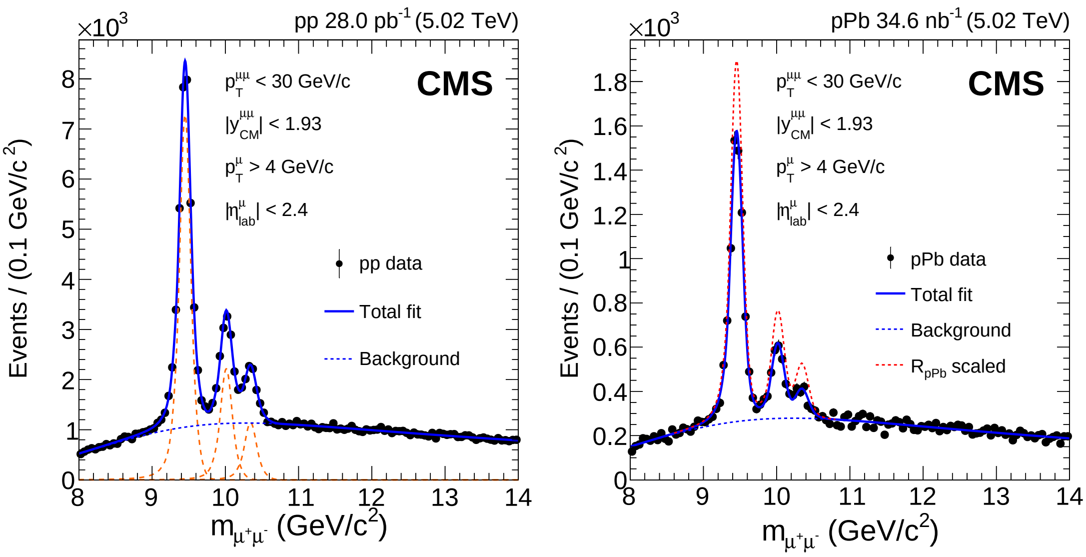

Figure 1: Measured dimuon invariant mass distributions (closed circles) for pp (left) and pPb (right) collisions. The total unbinned maximum-likelihood fits to the data are shown as solid blue lines, with the background component indicated by dashed blue lines. The individual $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ signal shapes in pp are depicted as dashed orange lines in the left panel. The dashed red line in the right panel is obtained by scaling the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ signal shapes in pPb (solid blue line) under the assumption that R_{pPb} is unity.

Quarkonium peaks can be modeled by a Crystal Ball (CB) function [60], whose low-mass power-law tail accounts for dimuons that undergo bremsstrahlung radiation in the detector material as well as final-state radiation. We model the shape of each Υ state with a sum of two

CB functions. A parameter representing the relative CB widths is left free in the fit, to accommodate muons with different momentum resolutions (depending on their η^{μ}_{lab}). The relative contributions of the two CBs are also allowed to vary, both in the kinematic and event activity variables.

To eliminate unnecessary degrees-of-freedom in the fits, the relative widths and relative contributions of the two CB functions are constrained to be the same for all three Υ states, consistent with fits to simulated samples. Furthermore, parameters governing the shape of the radiative tail are constrained to be the same for all six CB functions in the fit. The mass parameter of the $\Upsilon(1S)$ is left free to account for possible systematic shifts in the momentum scale of the reconstructed tracks. The final value of this parameter is consistent between fits to pp and pPb data. Since any changes in the momentum scale should affect all measured $\Upsilon(nS)$ similarly, we constrain the masses of the excited states such that their ratio matches the Particle Data Group (PDG) world-average values [61] as follows: $(m(nS)/m(1S))_{\text{fit}} = (m(nS)/m(1S))_{\text{PDG}}$. Similarly, the CB widths are also scaled by the ratio of the PDG mass values.

The parameters governing the tail shapes and ratio of CB widths are found to be correlated across kinematic bins. Rather than allowing the parameters to be completely unconstrained, we instead allow them to vary around their mean values within an interval estimated from a set of preliminary fits. The deviation of each parameter is translated into a Gaussian probability that is multiplied with the fit likelihood. The width of each Gaussian function is set to the RMS value of the corresponding parameter in the preliminary fits. In the case of pPb collisions, the central value of the parameter determining the relative contributions of the two CB functions is constrained in this manner as well.

As a result of the large number of free parameters in the preliminary fits, it is possible for parameters to converge to different values in repeated fits. By fitting the data across all the analysis bins, we find certain parameter values to be normally distributed. Each normally distributed parameter is first restricted to its mean value across the preliminary fits, in order to enable the rest of the parameters to converge consistently across the bins. We take an iterative approach to this constraining technique to avoid biasing the final parameter values. The mean values of parameters from preliminary fits are obtained separately in different rapidity regions to allow for differences in Υ meson reconstruction resolution in the barrel and end-cap regions of the detector, where muons pass through different amounts of material and are detected using different technologies.

The background is modeled with a shifted and scaled error function multiplied by an exponential. The exponential function models the dominant combinatorial background, which falls with increasing dimuon invariant mass according to a statistical phase space factor. The use of an error function is motivated by the effect of the $p_{\text{T}}^{\mu} > 4\,\text{GeV}/c$ selection applied to single muons, which produces a hump-like feature in the combinatorial background at low invariant masses and at low dimuon $p_{\text{T}}^{\mu\mu}$. For dimuon $p_{\text{T}}^{\mu\mu} > 6\,\text{GeV}/c$, this feature moves to lower invariant masses outside the fit region and we model the background solely with an exponential function.

4.2 Acceptance and efficiency corrections

The $\Upsilon(nS)$ yields that are extracted using fits to the invariant mass spectra are corrected to account for geometric limitations of the detector and inefficiencies of the online and offline selection algorithms. The dedicated MC simulations of $\Upsilon(nS)$ decays are used to determine the acceptance, which is the fraction of generated Υ mesons in a given kinematic region that decay to muons satisfying the kinematic requirements applied in this analysis.

The efficiency of dimuon reconstruction, event triggering, and muon identification are studied using dedicated MC simulations of $\Upsilon(n\mathrm{S})$ decays, after they have undergone full detector response simulation. The dimuon efficiency is determined as the fraction of generated Υ mesons in simulation that are identified as such, having satisfied all the same conditions that are required of muon pairs in collision data. Since pure PYTHIA-based MC samples are used for pPb collisions, we verify that the efficiency correction does not exhibit any dependence on multiplicity. This was also found in the related study of charmonium states reconstructed via muon pairs in pPb collisions [38].

Additional corrections are estimated to compensate for possible discrepancies between simulation and data efficiencies. To estimate such discrepancies, muon triggering, track reconstruction, and identification efficiencies are measured using single muons from prompt J/ψ meson decays in both simulation and data, as described in Ref. [48]. The ratios of the single-muon detection efficiencies between J/ψ data and simulation are estimated. These ratios differ significantly from unity in the case of muon triggering and identification in pPb collisions and muon triggering and track reconstruction in pp collisions. These ratios are used to correct the simulation-based efficiencies. For the bulk of muons in this analysis this correction to the efficiencies is small ($\sim$1%, but for some regions of phase space it can grow to at most 10%).

4.3 Systematic uncertainties

Typical ranges of total and individual sources of systematic uncertainties in R_{pPb} and R_{FB} for all three $\Upsilon(n\mathrm{S})$ states are tabulated in Table 1. Two important sources of systematic uncertainty in the $\Upsilon(n\mathrm{S})$ yields originate from an incomplete knowledge of the signal and background shapes. The signal shape systematic uncertainty is estimated using an alternative fit model of the signal, consisting of a single CB function in combination with a Gaussian function. This alternative fit model provides a comparable goodness-of-fit to the nominal one. For the background uncertainty estimation, a similar method of recalculating yields using an alternative fit model for the background is used. Because the background shape evolves with $p_{\mathrm{T}}^{\mu\mu}$, the model was varied in different kinematic regions. In higher $p_{\mathrm{T}}^{\mu\mu}$ regions, a power law is used as the alternative background fit model. In lower $p_{\mathrm{T}}^{\mu\mu}$ regions, the background model is constructed from a linear combination of four invariant-mass fits to four $p_{\mathrm{T}}^{\mu\mu}$ subintervals of a MC simulation of dimuon decays.

When estimating systematic uncertainties in the $\Upsilon(n\mathrm{S})$ yields using nominal and alternative models for signal and background distributions, we employ a method that helps to reduce the contribution of statistical fluctuations. We perform pseudo-experiments where we generate a set of invariant mass distributions by MC sampling the shape fitted to the dimuon invariant mass spectra in each analysis bin. Each generated invariant-mass distribution is fitted separately with the nominal and alternative signal models, using the nominal background model in both cases. The systematic uncertainty is evaluated as the mean of absolute values of relative differences between yields extracted using the nominal and alternative models. Similarly, additional pseudo-experiments are performed to estimate the uncertainty associated to the choice of the background model.

The procedure for constraining the parameters of the signal model introduces another source of systematic uncertainty. In order to estimate the systematic uncertainty on the yields we perform a set of preliminary fits to the dedicated $\Upsilon(n\mathrm{S})$ MC simulations, in which the parameter phase space is iteratively reduced in the same way as for data. For each parameter, we use the mean value obtained from the last iteration of MC fits as an alternative value for the mean of the Gaussian probability function used to constrain the parameters when fitting to data. In the case of pPb, the value of the parameter determining the relative contributions of the two CB functions in the free-parameter fit to MC is used as its alternative value. We compare the yields from the nominal fits with those extracted using the alternative mean of the constraining Gaussians and calculate the deviations of the yields for each constrained parameter. The largest of these deviations is assigned as the systematic uncertainty.

Systematic uncertainties in the acceptance corrections are estimated by varying the parameters of the fit used to weight MC $p_T^{\mu\mu}$ spectra within uncertainties, and recording the largest produced deviation. For the R_{pPb} measurement, the Υ states are assumed to be unpolarized in both pp and pPb collisions. We also assume that if the production mechanism of $\Upsilon(nS)$ leads to a different polarization, then it remains the same for both pp and pPb collisions. As a consequence, the acceptance ratio under a different polarization scenario will remain equal to unity. Therefore the uncertainty in the polarization would not affect the nuclear modification factor.

Systematic uncertainties in efficiency corrections are estimated by combining two sources in quadrature. The first is the uncertainty in weighting MC $p_T^{\mu\mu}$ spectra, which is estimated by determining the efficiency using the MC samples with and without weighting. The second source of uncertainty arises from the data-to-simulation ratio of single-muon detection efficiencies that are used to correct the purely simulation-based dimuon efficiencies. The systematic uncertainty in the efficiency of each stage of muon detection (triggering, tracking, muon identification) is studied by varying the selection criterion for that stage, while the statistical uncertainty is determined by repeating such variations one hundred times and estimating the standard deviation.

The total systematic uncertainty from uncorrelated sources is obtained by combining the uncertainties in quadrature in the signal and background extractions, as well as in the acceptance and efficiency corrections. The combined systematic uncertainty in the results increases slightly with increasing $|y_{CM}^{\Upsilon}|$ and with decreasing p_T^{Υ}. Because of the asymmetry of pPb collisions, the most forward y_{CM}^{Υ} bins, which are at the edge of the detector, have larger systematic uncertainty than the most backward y_{CM}^{Υ} bins because the latter are closer to $y_{lab}^{\Upsilon} = 0$. The total systematic uncertainty also increases with increasing event activity for integrated p_T^{Υ} and y_{CM}^{Υ}.

Table 1: Ranges of typical systematic uncertainties in R_{pPb} and R_{FB} for $\Upsilon(nS)$. For acceptance and efficiency the range quoted covers the efficiency of all three Υ states. The uncertainties in luminosity are global uncertainties that apply to all three Υ states. The luminosity uncertainty cancels in the calculation of the R_{FB}.

Source	Υ(1S)	Υ(2S)	Υ(3S)
		R_{pPb}	
Background	0.3–12%	1–6%	2–8%
Signal	1–8%	2–10%	3–9%
Acceptance		$\lesssim$1%	
Efficiency		4–6%	
Luminosity (pPb)		3.5%	
Luminosity (pp)		2.3%	
		R_{FB}	
Background	2–4%	4–7%	5–7%
Signal	2–3%	2–5%	5–6%
Acceptance		$\lesssim$1%	
Efficiency		$\approx$2%	

5 Results

The product of the branching fraction of $\Upsilon(n\mathrm{S})$ to muon pairs, $\mathcal{B}(\Upsilon(n\mathrm{S}) \to \mu^+\mu^-)$, and the double-differential production cross section, $\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}^\Upsilon \mathrm{d}y_\mathrm{CM}^\Upsilon$, is obtained as

$$\mathcal{B}\big(\Upsilon(n\mathrm{S}) \to \mu^+\mu^-\big)\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}^\Upsilon \mathrm{d}y_\mathrm{CM}^\Upsilon} = \frac{N_\mathrm{Fit}^{\Upsilon(n\mathrm{S})}/(a\varepsilon)}{\mathcal{L}_\mathrm{int}\Delta p_\mathrm{T}^{\mu\mu}\,\Delta y_\mathrm{CM}^{\mu\mu}}, \qquad (1)$$

where $N_\mathrm{Fit}^{\Upsilon(n\mathrm{S})}$ is the yield of $\Upsilon(n\mathrm{S})$ mesons extracted from the fit in a given ($p_\mathrm{T}^{\mu\mu}$, $y_\mathrm{CM}^{\mu\mu}$) bin, a is the dimuon acceptance correction, ε is the dimuon efficiency correction, and $\mathcal{L}_\mathrm{int}$ is the integrated luminosity. Figure 2 (upper row) shows the cross sections of $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(3\mathrm{S})$ in pPb collisions as functions of p_T^Υ (left) and y_CM^Υ (right). The error bars on the points are those from the fits to obtain the yields, which take into account the Poisson statistical uncertainties in the invariant mass distribution and the uncertainties associated with correlations between the parameters used in the probability density functions to fit the data. The filled boxes represent the systematic uncertainties, as discussed in the previous section. When investigating the pPb cross section dependence on p_T^Υ and when determining the R_pPb and R_FB, we restrict the CM rapidity range to the symmetric region $|y_\mathrm{CM}^{\mu\mu}| < 1.93$ where data for both pp and pPb collisions are available. The $\Upsilon(n\mathrm{S})$ cross sections in pp collisions are also determined for $|y_\mathrm{CM}^\Upsilon| < 1.93$ as functions of the kinematic variables. These are shown in Fig. 2 (lower row).

The quantity R_pPb is calculated as

$$R_\mathrm{pPb}(p_\mathrm{T}^\Upsilon, y_\mathrm{CM}^\Upsilon) = \frac{(\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}^\Upsilon \mathrm{d}y_\mathrm{CM}^\Upsilon)_\mathrm{pPb}}{A(\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}^\Upsilon \mathrm{d}y_\mathrm{CM}^\Upsilon)_\mathrm{pp}}, \qquad (2)$$

where $A = 208$ is the mass number of the Pb nucleus. Results for R_pPb are shown in Fig. 3 as functions of p_T^Υ and y_CM^Υ. We observe that all three $\Upsilon(n\mathrm{S})$ states are suppressed in pPb relative to pp collisions throughout the kinematic region explored, suggesting modification by CNM effects in pPb collisions. Similar to the PbPb case [36], the level of suppression for each Υ state in pPb collisions is consistent with a constant value in the kinematic region studied, although the level of suppression seen in PbPb is much stronger. The ATLAS Collaboration reported an increasing R_pPb with p_T^Υ for $\Upsilon(1\mathrm{S})$ [43] in a similar midrapidity region as in CMS. The CMS data is consistent with no dependence, but the overall p_T^Υ dependence of the R_pPb ($\Upsilon(1\mathrm{S})$) in the two experiments is consistent within uncertainties. Moreover, our data shows no y_CM^Υ dependence, which is consistent with the ATLAS result.

In the charmonium sector, the CMS Collaboration found hints of an ordered suppression pattern. The R_pPb of $\psi(2\mathrm{S})$ was found to be smaller than that of J/ψ [38] in pPb collisions at $\sqrt{s_\mathrm{NN}} = 5.02\,\mathrm{TeV}$ for backward rapidity and $p_\mathrm{T}^{\mathrm{J}/\psi} < 10\,\mathrm{GeV}/c$ [39]. The results presented here suggest a similar ordered suppression of the Υ states in the backward rapidity region as well as across the entire p_T^Υ region studied. The measured R_pPb ($\Upsilon(1\mathrm{S})$) is systematically larger than that of $\Upsilon(2\mathrm{S})$, which in turn is systematically larger than the R_pPb ($\Upsilon(3\mathrm{S})$), suggesting different levels of modification to the three states by final-state effects in these regions. In the forward rapidity region, the measured R_pPb of the three states appear more mutually consistent.

We further compare the y_CM^Υ dependence of the measured R_pPb to predictions from three CNM models: shadowing, energy loss, and comover interaction. The shadowing calculations incorporate next-to-leading order nuclear modifications of the PDFs (nPDFs) [16], according to

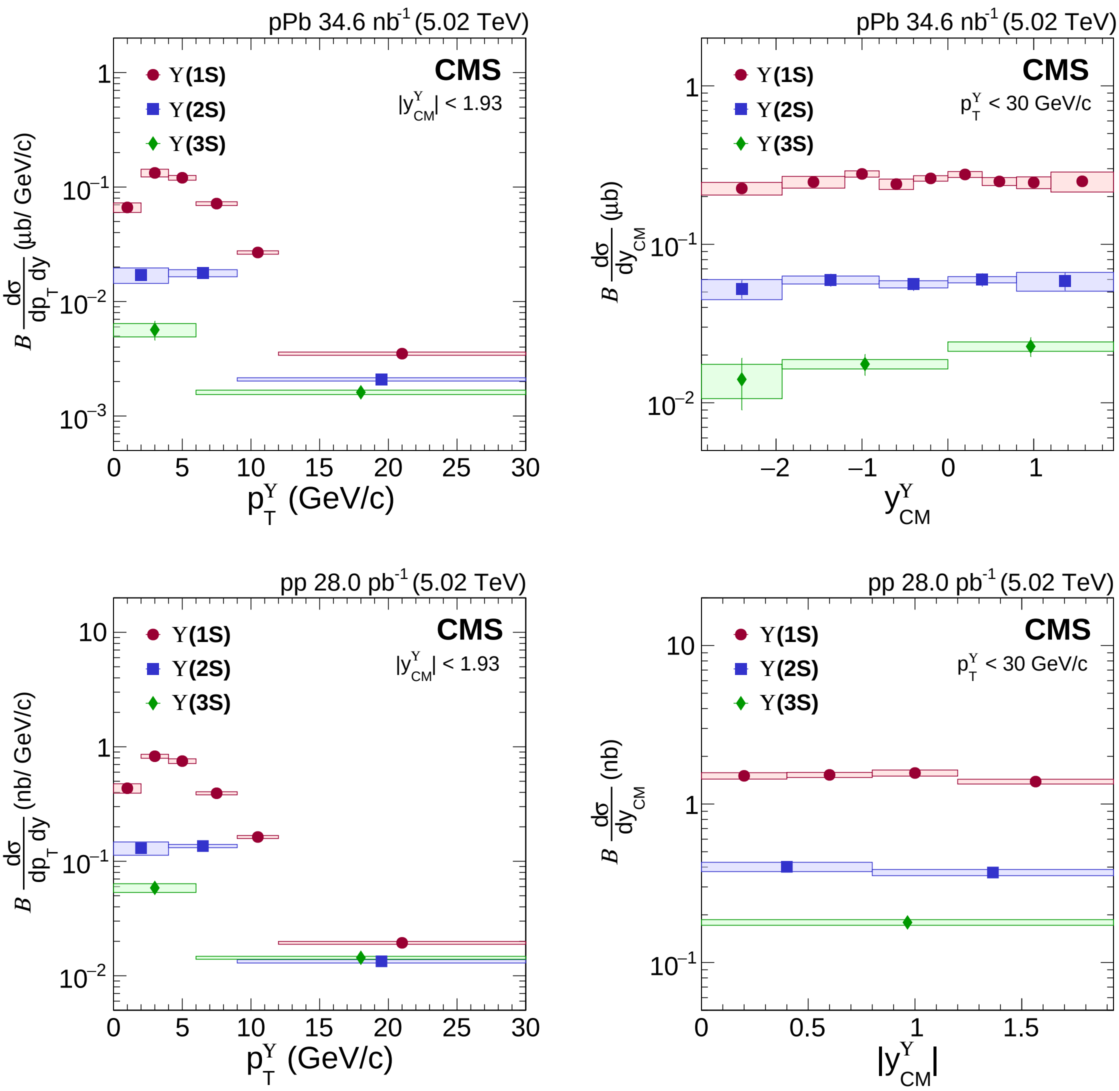

Figure 2: Cross section times dimuon branching fraction of $\Upsilon(1S)$ (red circles), $\Upsilon(2S)$ (blue squares), and $\Upsilon(3S)$ (green diamonds) as functions of p_T^{Υ} (left) and y_{CM}^{Υ} (right) in pPb (upper row) and pp (lower row) collisions. For pPb collisions, the p-going side corresponds to $y_{CM}^{\Upsilon} > 0$. Because pp collisions are symmetric in the center-of-mass frame, the absolute value of rapidity $|y_{CM}^{\Upsilon}|$ is used in the lower right panel. Vertical bars represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. A 3.5 (2.3)% global uncertainty in determining the integrated luminosity of pPb (pp) collisions, applicable to all points, is not included in the point-by-point uncertainties.

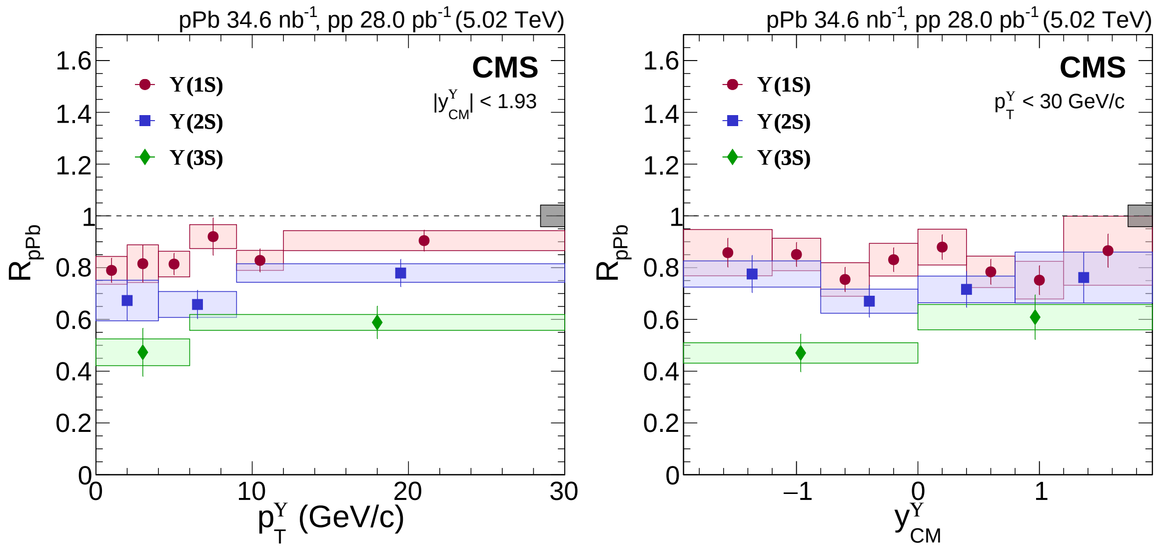

Figure 3: R_{pPb} of $\Upsilon(1S)$ (red circles), $\Upsilon(2S)$ (blue squares), and $\Upsilon(3S)$ (green diamonds) as functions of $p_{\mathrm{T}}^{\Upsilon}$ (left) and $y_{\mathrm{CM}}^{\Upsilon}$ (right), where the right panel is integrated over $p_{\mathrm{T}}^{\Upsilon} < 30\,\mathrm{GeV}/c$. Vertical bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization (4.2%).

EPS09 [62]. Predictions using coherent energy loss [17] are made with and without using EPS09. Since they affect the quarkonium system before hadronization, both shadowing and energy loss are initial-state effects. Finally, predictions using the comover interaction model (CIM) [18] are provided with two different leading-order nPDF calculations: EPS09 and nCTEQ15 [63]. Since the comovers in the CIM interact with the quarkonium system after hadronization, it is deemed to be a final-state CNM effect.

In Fig. 4, the measured R_{pPb} ($\Upsilon(1S)$) is compared to predictions from shadowing [16] (left) and predictions using energy loss only and energy loss with shadowing [17] (right). The uncertainty in the models comes from the nPDFs. The combined energy loss with shadowing model is in better agreement with our data, but given the current uncertainties in theory and experiment, the models using only shadowing or energy loss cannot be ruled out. The shadowing model, which includes only initial-state effects, predicts equal modification of all bottomonium states and therefore is incompatible with the $\Upsilon(2S)$ and $\Upsilon(3S)$ data.

In contrast to shadowing and energy-loss models, the CIM predicts different degrees of modification for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states [18, 40], since higher excited states have a larger size and hence increased comover interactions. In addition, comover modification of quarkonium states is expected to be stronger in regions where the comover densities are larger, such as in the nucleus-going direction in asymmetric proton-nucleus collisions and in regions of higher event activity. Figure 5 shows comparisons of predicted R_{pPb} in the CIM [18], including shadowing corrections from both nCTEQ15 and EPS09 nPDFs, with the measured R_{pPb} for $\Upsilon(1S)$ (upper left), $\Upsilon(2S)$ (upper right), and $\Upsilon(3S)$ (lower). The CIM R_{pPb} predictions show similar ordered suppression to that found in the data, an effect missing in models with only initial-state effects.

By comparing the R_{pPb} ($\Upsilon(nS)$) in the forward (proton-going) and backward (lead-going) directions, we can investigate the dependence of bottomonium suppression on the amount of nuclear matter present. Figure 6 shows the R_{pPb} of $\Upsilon(nS)$ states for $-1.93 < y_{\mathrm{CM}}^{\Upsilon} < 0$ and

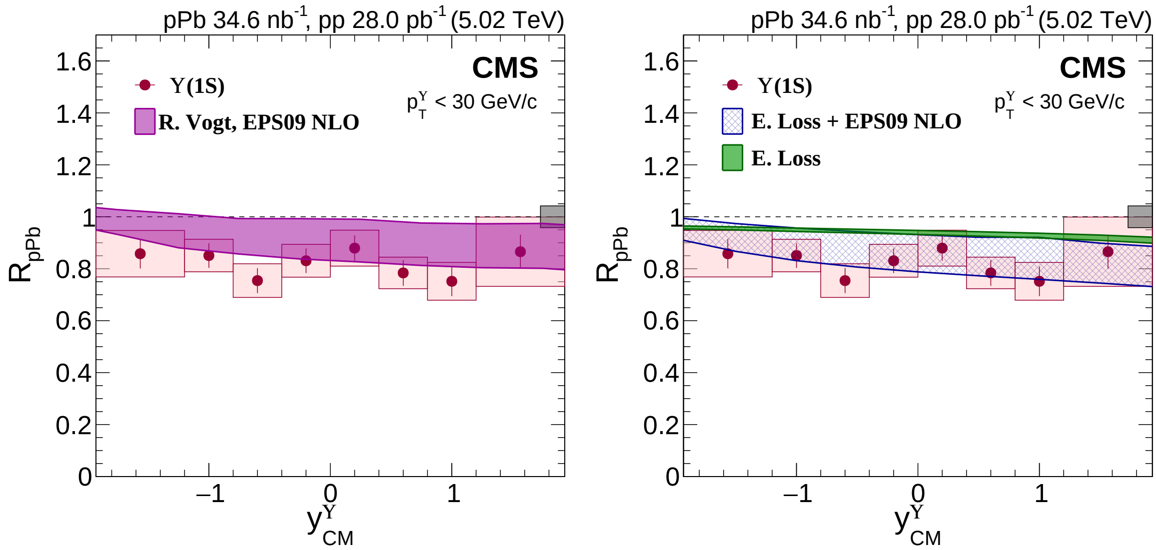

Figure 4: R_{pPb} of $\Upsilon(1S)$ (red circles) versus y^{Υ}_{CM} with initial-state model calculations: nPDF modification [16] (left) and energy loss (E. Loss) with and without shadowing corrections [17] (right). The uncertainty range for each model calculation is shown. Vertical bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization (4.2%).

$0 < y^{\Upsilon}_{\text{CM}} < 1.93$ in the low-p^{Υ}_{T} (left) and high-p^{Υ}_{T} (right) regions. We find indication of greater differences between the suppression levels of low-p^{Υ}_{T} $\Upsilon(n\text{S})$ states in the lead-going versus the proton-going y^{Υ}_{CM} directions. A similar observation was made by CMS in the charmonium sector [39], where the modification levels of $\psi(2\text{S})$ and J/ψ with $p_{\text{T}} < 10\,\text{GeV}/c$ were more separated in the backward region, whereas both states experienced similar modification in the forward region.

We study the forward-backward production ratio of Υ mesons in pPb collisions defined as follows,

$$R_{\text{FB}}(p^{\Upsilon}_{\text{T}}, y^{\Upsilon}_{\text{CM}} > 0) = \frac{(\text{d}^2\sigma(p^{\Upsilon}_{\text{T}}, y^{\Upsilon}_{\text{CM}})/\text{d}p^{\Upsilon}_{\text{T}}\text{d}y^{\Upsilon}_{\text{CM}})}{(\text{d}^2\sigma(p^{\Upsilon}_{\text{T}}, -y^{\Upsilon}_{\text{CM}})/\text{d}p^{\Upsilon}_{\text{T}}\text{d}y^{\Upsilon}_{\text{CM}})}, \quad (3)$$

where y^{Υ}_{CM} is positive. We measure event activity near the measured Υ meson using the number of reconstructed tracks, N_{tracks}, in the region $|\eta_{\text{lab}}| < 2.4$ (a detailed discussion of the event-activity variables can be found in Ref. [44]). To measure event activity further from the Υ meson, we use the sum of deposited transverse energy E_{T} in $4 < |\eta_{\text{lab}}| < 5.2$. Figure 7 shows the R_{FB} as a function N_{tracks} (left), and E_{T} (right). The uncorrected mean values of the event activity variables in minimum bias pPb collisions are $\langle N_{\text{tracks}} \rangle = 41$ and $\langle E_{\text{T}} \rangle = 14.7\,\text{GeV}$. The measured R_{FB} remains consistent with unity at all levels of event activity for all three Υ states. This observation is independent of the η region used to measure event activity. The ALICE Collaboration determined a value of R_{FB} consistent with unity for $\Upsilon(1S)$ for integrated event activity for Υ mesons in the forward ($2.03 < y^{\Upsilon}_{\text{CM}} < 3.53$) and backward ($-4.46 < y^{\Upsilon}_{\text{CM}} < -2.96$) rapidity regions [42]. The LHCb Collaboration also measured $\Upsilon(1S)$ R_{FB} in the forward ($1.5 < y^{\Upsilon}_{\text{CM}} < 4.0$) and backward ($-5.0 < y^{\Upsilon}_{\text{CM}} < -2.5$) rapidity regions and reported an integrated R_{FB} of slightly less than unity [41]. In contrast to Υ results reported here, the R_{FB} for prompt and nonprompt J/ψ were found by CMS to decrease with increasing E_{T} [38].

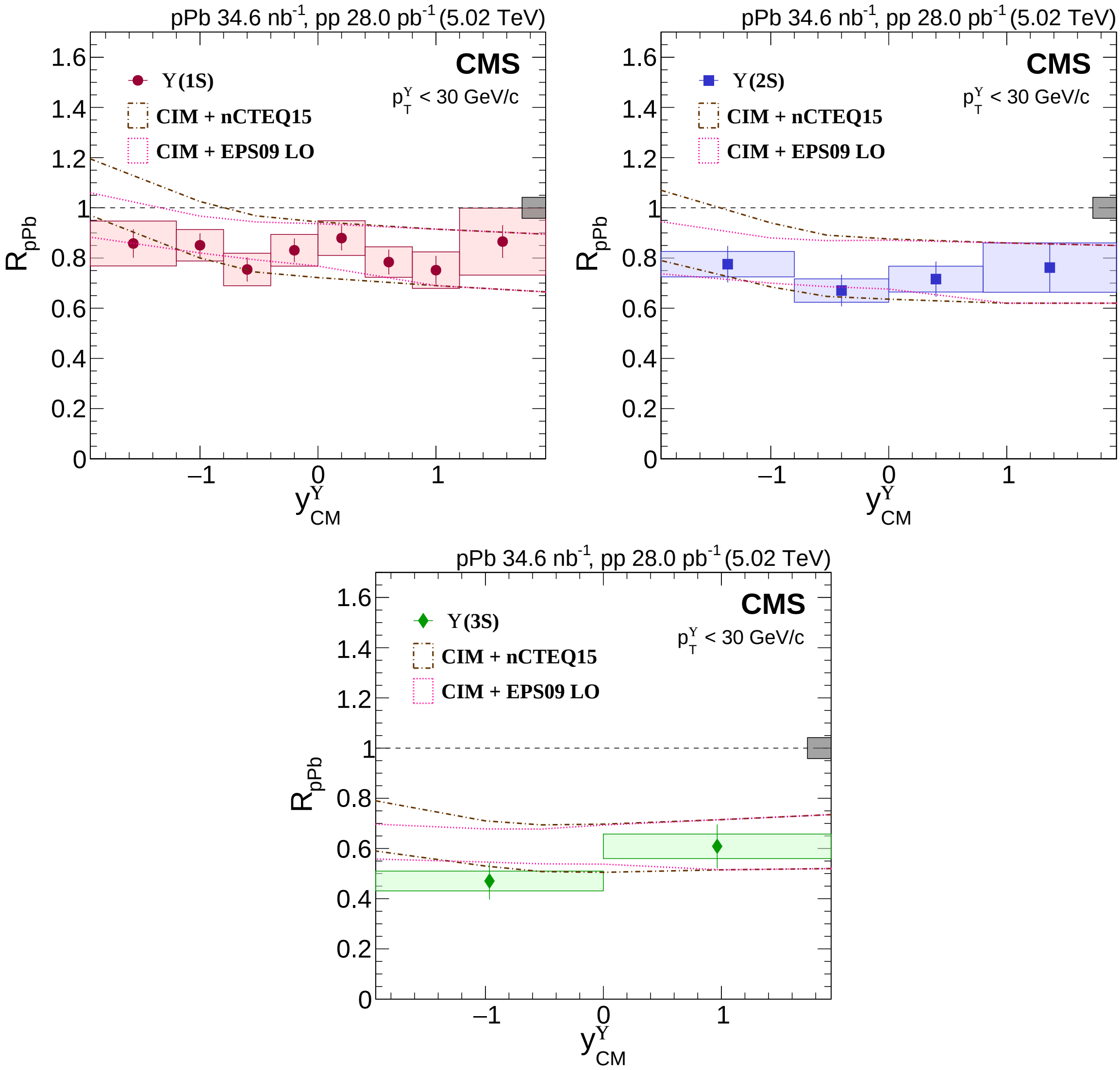

Figure 5: R_{pPb} versus $y_{\mathrm{CM}}^{\Upsilon}$ with CIM predictions [18] with shadowing corrections using nCTEQ15 and EPS09 for $\Upsilon(1S)$ (upper left; red circles), $\Upsilon(2S)$ (upper right; blue squares) and $\Upsilon(3S)$ (lower; green diamonds). The uncertainty range for each model calculation is shown. Vertical bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization (4.2%).

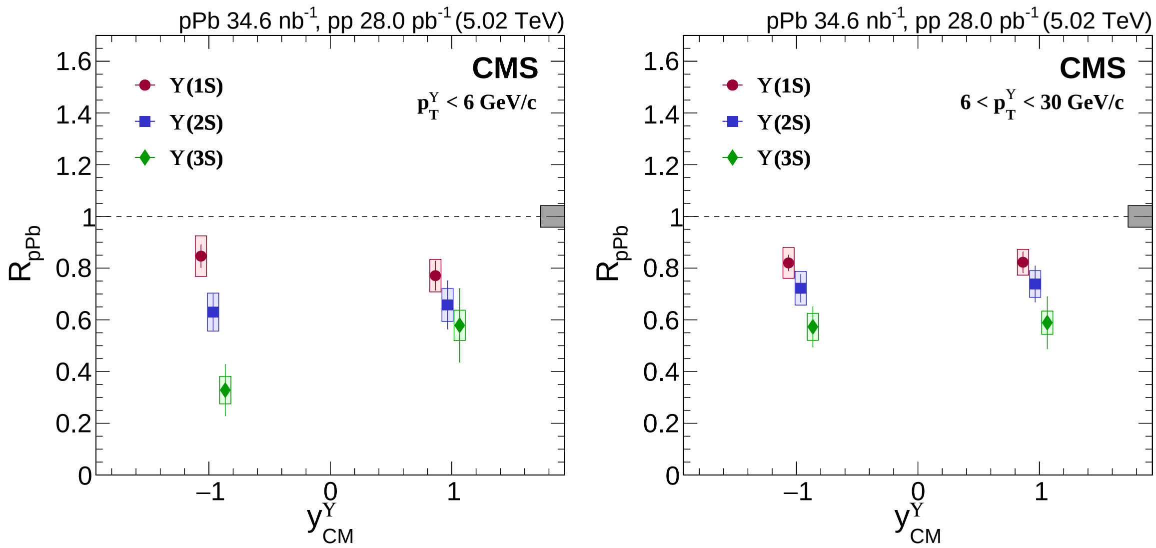

Figure 6: R_{pPb} of Υ(1S) (red circles), Υ(2S) (blue squares), and Υ(3S) (green diamonds) at forward and backward rapidity for $0 < p_{\mathrm{T}}^{\Upsilon} < 6\,\mathrm{GeV}/c$ (left) and $6 < p_{\mathrm{T}}^{\Upsilon} < 30\,\mathrm{GeV}/c$ (right). The points are shifted horizontally for better visibility. Vertical bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization (4.2%).

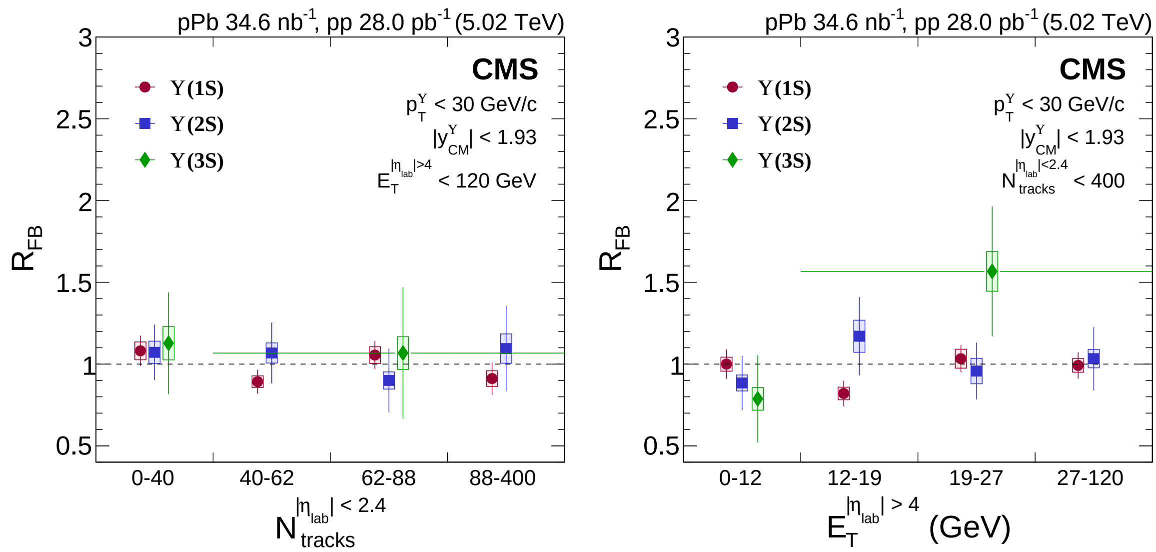

Figure 7: R_{FB} versus N_{tracks} at mid-pseudorapidity (left) and *vs.* E_{T} at forward/backward pseudorapidity (right) of Υ(1S) (red circles), Υ(2S) (blue squares), and Υ(3S) (green diamonds) for $p_{\mathrm{T}}^{\Upsilon} < 30\,\mathrm{GeV}/c$ and $|y_{\mathrm{CM}}^{\Upsilon}| < 1.93$. Vertical bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. For Υ(3S), a wide bin is used for high event activity, with the width indicated by a horizontal bar.

Figure 8 shows the integrated R_{pPb} of Υ states as well as the R_{AA} observed in PbPb collisions [36] at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$. The 95% confidence level upper limit on the $\Upsilon(3\mathrm{S})$ R_{AA} is depicted using an arrow. The data indicate an ordering of nuclear modification for the Υ family with $R_{\mathrm{pPb}}(1S) > R_{\mathrm{pPb}}(2S) > R_{\mathrm{pPb}}(3S)$:

$$R_{\mathrm{pPb}}(\Upsilon(1\mathrm{S})) = 0.806 \pm 0.024\,(\mathrm{stat}) \pm 0.059\,(\mathrm{syst}),$$
$$R_{\mathrm{pPb}}(\Upsilon(2\mathrm{S})) = 0.702 \pm 0.041\,(\mathrm{stat}) \pm 0.058\,(\mathrm{syst}),$$
$$R_{\mathrm{pPb}}(\Upsilon(3\mathrm{S})) = 0.536 \pm 0.058\,(\mathrm{stat}) \pm 0.050\,(\mathrm{syst}).$$

We determine the p-value of the observed suppression of Υ states in pPb relative to pp collisions against the hypothesis of A-scaling, which predicts no nuclear modification. Given the uncertainties in the measured R_{pPb} values for $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(3\mathrm{S})$, we determine these p-values to be 1.16×10^{-3}, 1.36×10^{-5}, and 6.84×10^{-10}, respectively.

Given that initial-state CNM models predict equal nuclear modification to all three Υ states in contrast to final-state CNM, which result in different levels of nuclear modification, we can determine the p-value of the observed additional suppression of each excited state compared to the ground state. This can be done under the hypothesis that no final-state CNM effects are evident, and the R_{pPb} of the excited and ground states are equal. The p-values of the measured lower R_{pPb} values of the excited states relative to $\Upsilon(1\mathrm{S})$ are 1.24×10^{-1} for $\Upsilon(2\mathrm{S})$ and 1.02×10^{-3} for $\Upsilon(3\mathrm{S})$, corresponding to significances of 1.2 and 3.1 standard deviations, respectively.

Figure 8 illustrates that the measured modifications in $\Upsilon(n\mathrm{S})$ production in pPb collisions are considerably smaller than those seen in PbPb collisions [36]. A direct comparison of the R_{AA} to the R_{pPb} requires model-dependent scaling of the R_{pPb} to reflect modification by two lead nuclei in PbPb collisions instead of one. Such a comparison of the observed modification effect of CNM on bottomonia in pPb to the nucleus-nucleus collision environment is needed to determine if hot nuclear matter effects in the QGP result in additional suppression of bottomonia in PbPb. Additional modification in PbPb compared to pPb collisions is expected from the presence of color deconfinement as predicted by Refs. [2, 3, 5, 7, 64], and by larger comover interaction effects in the dense medium [18].

Tabulated results are provided in the HEPData record for this analysis [65].

6 Summary

The $\Upsilon(n\mathrm{S})$ (where $n = 1, 2, 3$) family is studied in proton-lead (pPb) collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ and the production cross sections are presented. Using pp collision data obtained at the same collision energy, the nuclear modification factors R_{pPb} in pPb collisions for the three Υ states are measured. Compared to the hypothesis of scaling by the number of nucleons A, we find the $\Upsilon(n\mathrm{S})$ yields to be suppressed. This suppression is observed over the entire kinematic range that is studied, i.e., transverse momentum $p_{\mathrm{T}}^{\Upsilon} < 30\,\mathrm{GeV}/c$ and center-of-mass rapidity $|y_{\mathrm{CM}}^{\Upsilon}| < 1.93$. The suppression level is constant both as a function of $p_{\mathrm{T}}^{\Upsilon}$ and of $y_{\mathrm{CM}}^{\Upsilon}$ within the experimental uncertainties. An indication of higher separation of the excited states with $p_{\mathrm{T}}^{\Upsilon} < 6\,\mathrm{GeV}/c$ is observed in the Pb-going direction.

The forward-backward production ratios R_{FB} of $\Upsilon(n\mathrm{S})$ states are studied as a function of event activity in two regions: A midrapidity region (where the $\Upsilon(n\mathrm{S})$ states were measured), and a region with at least two units of rapidity separation from any measured $\Upsilon(n\mathrm{S})$ state. The R_{FB}

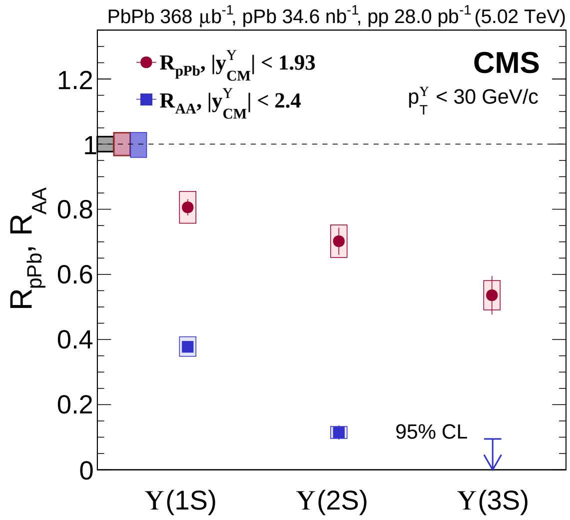

Figure 8: R_{pPb} of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ (red circles) for the integrated kinematic range $0 < p_{\mathrm{T}}^{\Upsilon} < 30\,\mathrm{GeV}/c$ and $|y_{\mathrm{CM}}^{\Upsilon}| < 1.93$. The R_{pPb} results are compared to the CMS results on $\Upsilon(nS)$ R_{AA} (blue squares for $\Upsilon(1S)$ and $\Upsilon(2S)$ and blue arrow for the upper limit at 95% confidence level (CL) on $\Upsilon(3S)$) for $0 < p_{\mathrm{T}}^{\Upsilon} < 30\,\mathrm{GeV}/c$ and $|y_{\mathrm{CM}}^{\Upsilon}| < 2.4$, at the same energy [36]. Vertical bars represent statistical and fit uncertainties and filled boxes around points represent systematic uncertainties. The gray and red boxes around the line at unity depict the uncertainty in the pp and pPb luminosity normalizations (2.3 and 3.5%), respectively. The blue box around unity depicts the global uncertainty pertaining to PbPb data ($^{+3.6\%}_{-4.1\%}$) [36].

values are consistent with unity for all states, independent of the region used to measure the event activity.

The integrated nuclear modification factors for $\Upsilon(nS)$ in pPb collisions are compared with those measured in PbPb collisions. The nuclear modification factors R_{AA} in PbPb collisions are much smaller than the corresponding R_{pPb} value for each state. However, a similar ordering of the measured R_{pPb} $(\Upsilon(nS))$ is observed, with $\Upsilon(1S)$ the least suppressed. This suggests the presence of final-state effects in pPb collisions, consistent with predictions from models that break up the bound quarkonium states via interactions with comoving particles from the underlying event. These results will help us to understand how bottomonia are modified in heavy-ion collisions.

Acknowledgments

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 and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Science and Higher Education and the National Science Center, contracts Opus 2014/15/B/ST2/03998 and 2015/19/B/ST2/02861 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, projects no. 0723-2020-0041 and no. FSWW-2020-0008 (Russia); MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Stavros Niarchos Foundation (Greece); the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] T. Matsui and H. Satz, "J/ψ suppression by quark-gluon plasma formation", *Phys. Lett. B* **178** (1986) 416, `doi:10.1016/0370-2693(86)91404-8`.

[2] J. W. Harris and B. Müller, "The search for the quark gluon plasma", *Ann. Rev. Nucl. Part. Sci* **46** (1996) 71, `doi:10.1146/annurev.nucl.46.1.71`, `arXiv:hep-ph/9602235`.

[3] J. F. Gunion and R. Vogt, "Determining the existence and nature of the quark-gluon plasma by upsilon suppression at the LHC", *Nucl. Phys. B* **492** (1997) 301, `doi:10.1016/S0550-3213(97)80037-5`, `arXiv:hep-ph/9610420`.

[4] S. Kim, P. Petreczky, and A. Rothkopf, "In-medium quarkonium properties from a lattice QCD based effective field theory", *Nucl. Phys. A* **956** (2016) 713, doi:10.1016/j.nuclphysa.2015.12.011, arXiv:1512.05289.

[5] A. Emerick, X. Zhao, and R. Rapp, "Bottomonia in the quark-gluon plasma and their production at RHIC and LHC", *Eur. Phys. J. A* **48** (2012) 72, doi:10.1140/epja/i2012-12072-y, arXiv:1111.6537.

[6] A. Rothkopf, "What lattice QCD spectral functions can tell us about heavy quarkonium in the QGP", *PoS* **ICHEP2016** (2016) 362, doi:10.22323/1.282.0362, arXiv:1611.06517.

[7] A. Andronic et al., "Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions", *Eur. Phys. J. C* **76** (2016) 107, doi:10.1140/epjc/s10052-015-3819-5, arXiv:1506.03981.

[8] S. Digal, P. Petreczky, and H. Satz, "Quarkonium feed down and sequential suppression", *Phys. Rev. D* **64** (2001) 094015, doi:10.1103/PhysRevD.64.094015, arXiv:hep-ph/0106017.

[9] Y. Burnier, O. Kaczmarek, and A. Rothkopf, "Quarkonium at finite temperature: Towards realistic phenomenology from first principles", *JHEP* **12** (2015) 101, doi:10.1007/JHEP12(2015)101, arXiv:1509.07366.

[10] M. Laine, O. Philipsen, P. Romatschke, and M. Tassler, "Real-time static potential in hot QCD", *JHEP* **03** (2007) 054, doi:10.1088/1126-6708/2007/03/054, arXiv:hep-ph/0611300.

[11] J.-P. Blaizot, D. De Boni, P. Faccioli, and G. Garberoglio, "Heavy quark bound states in a quark-gluon plasma: Dissociation and recombination", *Nucl. Phys. A* **946** (2016) 49, doi:10.1016/j.nuclphysa.2015.10.011, arXiv:1503.03857.

[12] S. Chen and M. He, "Gluo-dissociation of heavy quarkonium in the quark-gluon plasma reexamined", *Phys. Rev. C* **96** (2017) 034901, doi:10.1103/PhysRevC.96.034901, arXiv:1705.10110.

[13] M. C. Chu and T. Matsui, "Dynamic Debye screening for a heavy-quark-anti-quark pair traversing a quark-gluon plasma", *Phys. Rev. D* **39** (1989) 1892, doi:10.1103/PhysRevD.39.1892.

[14] N. Brambilla, J. Ghiglieri, A. Vairo, and P. Petreczky, "Static quark-antiquark pairs at finite temperature", *Phys. Rev. D* **78** (2008) 014017, doi:10.1103/PhysRevD.78.014017, arXiv:0804.0993.

[15] Y. Burnier and A. Rothkopf, "Complex heavy-quark potential and Debye mass in a gluonic medium from lattice QCD", *Phys. Rev. D* **95** (2017) 054511, doi:10.1103/PhysRevD.95.054511, arXiv:1607.04049.

[16] R. Vogt, "Shadowing effects on J/ψ and Y production at energies available at the CERN Large Hadron Collider", *Phys. Rev. C* **92** (2015) 034909, doi:10.1103/PhysRevC.92.034909, arXiv:1507.04418.

[17] F. Arleo and S. Peigné, "Quarkonium suppression in heavy-ion collisions from coherent energy loss in cold nuclear matter", *JHEP* **10** (2014) 073, doi:10.1007/JHEP10(2014)073, arXiv:1407.5054.

[18] E. G. Ferreiro and J.-P. Lansberg, "Is bottomonium suppression in proton-nucleus and nucleus-nucleus collisions at LHC energies due to the same effects?", *JHEP* **10** (2018) 094, doi:10.1007/JHEP10(2018)094, arXiv:1804.04474. [Erratum: doi:10.1007/JHEP03(2019)063].

[19] CMS Collaboration, "Observation of long-range near-side angular correlations in proton-proton collisions at the LHC", *JHEP* **09** (2010) 091, doi:10.1007/JHEP09(2010)091, arXiv:1009.4122.

[20] CMS Collaboration, "Observation of long-range, near-side angular correlations in pPb collisions at the LHC", *Phys. Lett. B* **718** (2013) 795, doi:10.1016/j.physletb.2012.11.025, arXiv:1210.5482.

[21] ALICE Collaboration, "Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions", *Nature Phys.* **13** (2017) 535, doi:10.1038/nphys4111, arXiv:1606.07424.

[22] CMS Collaboration, "Evidence for collective multiparticle correlations in p-Pb collisions", *Phys. Rev. Lett.* **115** (2015) 012301, doi:10.1103/physrevlett.115.012301, arXiv:1502.05382.

[23] ATLAS Collaboration, "Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV proton-lead collisions with the ATLAS detector", *Phys. Rev. Lett.* **110** (2013), no. 18, 182302, doi:10.1103/PhysRevLett.110.182302, arXiv:1212.5198.

[24] ATLAS Collaboration, "Measurements of long-range azimuthal anisotropies and associated Fourier coefficients for pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 13 TeV and p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the ATLAS detector", *Phys. Rev. C* **96** (2017), no. 2, 024908, doi:10.1103/PhysRevC.96.024908, arXiv:1609.06213.

[25] ATLAS Collaboration, "Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in pp collisions at $\sqrt{s_{\mathrm{NN}}} = 13$ TeV with the ATLAS detector", *Phys. Rev. Lett.* **124** (2020), no. 8, 082301, doi:10.1103/PhysRevLett.124.082301, arXiv:1909.01650.

[26] K. Dusling, W. Li, and B. Schenke, "Novel collective phenomena in high-energy proton-proton and proton-nucleus collisions", *Int. J. Mod. Phys. E* **25** (2016) 1630002, doi:10.1142/S0218301316300022, arXiv:1509.07939.

[27] R. Vogt, "Cold nuclear matter effects on J/ψ and Υ production at the LHC", *Phys. Rev. C* **81** (2010) 044903, doi:10.1103/PhysRevC.81.044903, arXiv:1003.3497.

[28] M. Strickland, "Thermal bottomonium suppression", *AIP Conf. Proc.* **1520** (2013) 179, doi:10.1063/1.4795953, arXiv:1207.5327.

[29] F. Arleo and S. Peigne, "Heavy-quarkonium suppression in p-A collisions from parton energy loss in cold QCD matter", *JHEP* **03** (2013) 122, doi:10.1007/JHEP03(2013)122, arXiv:1212.0434.

[30] B. Krouppa, A. Rothkopf, and M. Strickland, "Bottomonium suppression using a lattice QCD vetted potential", *Phys. Rev. D* **97** (2018) 016017, doi:10.1103/PhysRevD.97.016017, arXiv:1710.02319.

[31] B. Chen and J. Zhao, "Bottomonium continuous production from unequilibrium bottom quarks in ultrarelativistic heavy ion collisions", *Phys. Lett. B* **772** (2017) 819, doi:10.1016/j.physletb.2017.07.054, arXiv:1704.05622.

[32] X. Du, R. Rapp, and M. He, "Color screening and regeneration of bottomonia in high-energy heavy-ion collisions", *Phys. Rev. C* **96** (2017) 054901, doi:10.1103/PhysRevC.96.054901, arXiv:1706.08670.

[33] CMS Collaboration, "Indications of suppression of excited Υ states in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", *Phys. Rev. Lett.* **107** (2011) 052302, doi:10.1103/PhysRevLett.107.052302, arXiv:1105.4894.

[34] CMS Collaboration, "Suppression of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ production in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", *Phys. Lett. B* **770** (2017) 357, doi:10.1016/j.physletb.2017.04.031, arXiv:1611.01510.

[35] CMS Collaboration, "Suppression of excited Υ states relative to the ground state in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Rev. Lett.* **120** (2018) 142301, doi:10.1103/PhysRevLett.120.142301, arXiv:1706.05984.

[36] CMS Collaboration, "Measurement of nuclear modification factors of Υ(1S), Υ(2S), and Υ(3S) mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Lett. B* **790** (2019) 270, doi:10.1016/j.physletb.2019.01.006, arXiv:1805.09215.

[37] B. Krouppa and M. Strickland, "Predictions for bottomonia suppression in 5.023 TeV Pb-Pb collisions", *Universe* **2** (2016) 16, doi:10.3390/universe2030016, arXiv:1605.03561.

[38] CMS Collaboration, "Measurement of prompt and nonprompt J/ψ production in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Eur. Phys. J. C* **77** (2017) 269, doi:10.1140/epjc/s10052-017-4828-3, arXiv:1702.01462.

[39] CMS Collaboration, "Measurement of prompt $\psi(2S)$ production cross sections in proton-lead and proton-proton collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Lett. B* **790** (2019) 509, doi:10.1016/j.physletb.2019.01.058, arXiv:1805.02248.

[40] E. G. Ferreiro, "Excited charmonium suppression in proton-nucleus collisions as a consequence of comovers", *Phys. Lett. B* **749** (2015) 98, doi:10.1016/j.physletb.2015.07.066, arXiv:1411.0549.

[41] LHCb Collaboration, "Study of Υ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV", *JHEP* **07** (2014) 094, doi:10.1007/JHEP07(2014)094, arXiv:1405.5152.

[42] ALICE Collaboration, "Production of inclusive Υ(1S) and Υ(2S) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Lett. B* **740** (2015) 105, doi:10.1016/j.physletb.2014.11.041, arXiv:1410.2234.

[43] ATLAS Collaboration, "Measurement of quarkonium production in proton-lead and proton-proton collisions at 5.02 TeV with the ATLAS detector", *Eur. Phys. J. C* **78** (2018) 171, doi:10.1140/epjc/s10052-018-5624-4, arXiv:1709.03089.

[44] CMS Collaboration, "Event activity dependence of Υ(nS) production in $\sqrt{s_{NN}} = 5.02$ TeV pPb and $\sqrt{s} = 2.76$ TeV pp collisions", *JHEP* **04** (2014) 103, doi:10.1007/JHEP04(2014)103, arXiv:1312.6300.

[45] CMS Collaboration, "Investigation into the event-activity dependence of Υ(nS) relative production in proton-proton collisions at $\sqrt{s} = 7$ TeV", *JHEP* **11** (2020) 001, doi:10.1007/JHEP11(2020)001, arXiv:2007.04277.

[46] LHCb Collaboration, "Study of Υ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV", *JHEP* **11** (2018) 194, doi:10.1007/JHEP11(2018)194, arXiv:1810.07655.

[47] ALICE Collaboration, "Υ production in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV", *Phys. Lett. B* **806** (2020) 135486, doi:10.1016/j.physletb.2020.135486, arXiv:1910.14405.

[48] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV", *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[49] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[50] CMS Collaboration, "Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s_{\mathrm{NN}}} = 13$ TeV", *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[51] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[52] CMS Collaboration, "CMS luminosity calibration for the pp reference run at $\sqrt{s} = 5.02$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-16-001, 2016.

[53] CMS Collaboration, "Luminosity calibration for the 2013 proton-lead and proton-proton data taking", CMS Physics Analysis Summary CMS-PAS-LUM-13-002, 2014.

[54] CMS Collaboration, "Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid", CMS Technical proposal CERN-LHCC-2015-010, CMS-TDR-15-02, CERN, 2015.

[55] R. Kalman, "A new approach to linear filtering and prediction problems", *J. Basic Eng. D* **82** (1960) 35, doi:10.1115/1.3662552.

[56] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[57] CMS Collaboration, "Measurement of the Υ(1S), Υ(2S) and Υ(3S) polarizations in pp collisions at $\sqrt{s_{\mathrm{NN}}} = 7$ TeV", *Phys. Rev. Lett.* **110** (2013), no. 8, 081802, doi:10.1103/PhysRevLett.110.081802, arXiv:1209.2922.

[58] LHCb Collaboration, "Measurement of the Υ(nS) polarizations in pp collisions at $\sqrt{s_{\mathrm{NN}}} = 7$ and 8 TeV", *JHEP* **12** (2017) 110, doi:10.1007/JHEP12(2017)110, arXiv:1709.01301.

[59] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[60] M. J. Oreglia, "A study of the reactions $\psi' \to \gamma\gamma\psi$". PhD thesis, Stanford University, 1980. SLAC Report R-236 p.184.

[61] Particle Data Group, M. Tanabashi et al., "Review of particle physics", *Phys. Rev. D* **98** (2018) 030001, doi:10.1103/PhysRevD.98.030001.

[62] K. J. Eskola, H. Paukkunen, and C. A. Salgado, "EPS09: A new generation of NLO and LO nuclear parton distribution functions", *JHEP* **04** (2009) 065, doi:10.1088/1126-6708/2009/04/065, arXiv:0902.4154.

[63] K. Kovařík et al., "nCTEQ15 – global analysis of nuclear parton distributions with uncertainties in the CTEQ framework", *Phys. Rev. D* **93** (2016) 085037, doi:10.1103/PhysRevD.93.085037, arXiv:1509.00792.

[64] N. Brambilla et al., "Heavy quarkonium: progress, puzzles, and opportunities", *Eur. Phys. J. C* **71** (2011) 1534, doi:10.1140/epjc/s10052-010-1534-9, arXiv:1010.5827.

[65] HEPData record for this analysis, 2021. doi:10.17182/hepdata.88291.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, F. Ambrogi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, W. Waltenberger, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish, E.A. De Wolf, D. Di Croce, T. Janssen, T. Kello[2], A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, L. Moureaux, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, I. Khvastunov[3], M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[4], E. Coelho, E.M. Da Costa, G.G. Da Silveira[5], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, J. Martins[6], D. Matos Figueiredo, M. Medina Jaime[7], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[4], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista (a), Universidade Federal do ABC (b), São Paulo, Brazil
C.A. Bernardes, L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D.S. Lemos, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China
W. Fang[2], X. Gao[2], L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
G.M. Chen[8], H.S. Chen[8], M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z.-A. Liu, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[8], J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

Zhejiang University, Hangzhou, China, Zhejiang, China
M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, D. Majumder, B. Mesic, M. Roguljic, A. Starodumov[9], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger[10], M. Finger Jr.[10], A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[11,12], E. Salama[12,13]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik,

M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
E. Brücken, F. Garcia, J. Havukainen, J.K. Heikkilä, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
P. Luukka, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[14], M. Titov, G.B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
S. Ahuja, C. Amendola, F. Beaudette, M. Bonanomi, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[15], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte[15], J.-C. Fontaine[15], D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[10]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[10]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Erdmann, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler,

J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, W. Haj Ahmad[16], O. Hlushchenko, T. Kress, T. Müller, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[17]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[18], V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, L.I. Estevez Banos, E. Gallo[19], A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem[18], M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann[20], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, R.E. Sosa Ricardo, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, T. Dreyer, A. Ebrahimi, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaup, C.E.N. Niemeyer, A. Reimers, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[17], C. Heidecker, U. Husemann, M.A. Iqbal, S. Kudella, S. Maier, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, D. Savoiu, D. Schäfer, M. Schnepf, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf, S. Wozniewski

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University,

Budapest, Hungary
M. Bartók[21], R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[22], F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[21], J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[24], C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak[25], D.K. Sahoo[24], S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra[26], R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

University of Delhi, Delhi, India
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[27], M. Bharti[27], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[27], D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber[28], M. Maity[29], K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh[27], S. Thakur[27]

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Jha, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, R.K. Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri,

F. Rezaei Hosseinabadi

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Bari, Italy, Università di Bari [b], Bari, Italy, Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,30], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], J.A. Merlin[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna [a], Bologna, Italy, Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,31], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Catania, Italy, Università di Catania [b], Catania, Italy
S. Albergo[a,b,32], S. Costa[a,b,32], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,32], C. Tuve[a,b]

INFN Sezione di Firenze [a], Firenze, Italy, Università di Firenze [b], Firenze, Italy
G. Barbagli[a], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], F. Fiori[a], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, D. Piccolo

INFN Sezione di Genova [a], Genova, Italy, Università di Genova [b], Genova, Italy
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Milano, Italy, Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], V. Ciriolo[a,b,17], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,17], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Napoli, Italy, Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A.O.M. Iorio[a,b], L. Layer[a,b], L. Lista[a,b], S. Meola[a,d,17], P. Paolucci[a,17], B. Rossi[a], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Padova, Italy, Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a],

F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S.Y. Hoh[a,b], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko[a], M. Tosi[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Pavia, Italy, Università di Pavia [b], Pavia, Italy
A. Braghieri[a], D. Fiorina[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Perugia, Italy, Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa [a], Pisa, Italy, Università di Pisa [b], Pisa, Italy, Scuola Normale Superiore di Pisa [c], Pisa, Italy, Università di Siena [d], Siena, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], S. Donato[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Rome, Italy, Sapienza Università di Roma [b], Rome, Italy
F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a,b], R. Tramontano[a,b]

INFN Sezione di Torino [a], Torino, Italy, Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], J.R. González Fernández[a], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Salvatico[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], D. Trocino[a,b]

INFN Sezione di Trieste [a], Trieste, Italy, Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], F. Vazzoler[a,b], A. Zanetti[a]

Kyungpook National University, Daegu, Korea
B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea, Seoul, Korea
J. Goh

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon

University of Seoul, Seoul, Korea
D. Jeon, J.H. Kim, J.S.H. Lee, I.C. Park, I.J. Watson

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns[33]

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
F. Mohamad Idris[34], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[35], R. Lopez-Fernandez, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramírez García, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic[3], N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler, P. Lujan

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I.M. Awan, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, A. Baginyan, P. Bunin, M. Gavrilenko, A. Golunov, I. Golutvin, I. Gorbunov, V. Karjavine, I. Kashunin, A. Lanev, A. Malakhov, V. Matveev[37,38], V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, V. Trofimov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim[39], E. Kuznetsova[40], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Center 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[41], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva[42], P. Parygin, D. Philippov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy[43], O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov[44], V. Blinov[44], T. Dimova[44], L. Kardapoltsev[44], Y. Skovpen[44]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[45], P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, S. Sanchez Cruz

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Russo[46], L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
D.U.J. Sonnadara

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[47], D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, O. Karacheban[20], J. Kaspar, J. Kieseler, M. Krammer[1], N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[17], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters,

D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[48], J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[49], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, R.A. Manzoni, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
C. Amsler[50], C. Botta, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

National Central University, Chung-Li, Taiwan
C.M. Kuo, W. Lin, A. Roy, T. Sarkar[29], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, A. Celik[51], S. Damarseckin[52], Z.S. Demiroglu, F. Dolek, C. Dozen[53], I. Dumanoglu[54], G. Gokbulut, E.G. Guler[55], Y. Guler, I. Hos[56], C. Isik, E.E. Kangal[57], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[58], A.E. Simsek, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[59], G. Karapinar[60], M. Yalvac[61]

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[62], O. Kaya[63], Ö. Özçelik, S. Tekten[64], E.A. Yetkin[65]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[54], Y. Komurcu, S. Sen[66]

Istanbul University, Istanbul, Turkey
S. Cerci[67], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci[67]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
E. Bhal, S. Bologna, J.J. Brooke, D. Burns[68], E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[69], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, G.S. Chahal[70], D. Colling, P. Dauncey, G. Davies, M. Della Negra, P. Everaerts, G. Hall, G. Iles, M. Komm, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, A. Morton, J. Nash[71], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee[17], N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, Texas, USA
A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
A. Buccilli, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

Boston University, Boston, Massachusetts, USA
A. Albert, D. Arcaro, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, D. Sperka, D. Spitzbart, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, Rhode Island, USA
G. Benelli, B. Burkle, X. Coubez[18], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan[72], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir[73], R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, H. Folsom, G. Funk, J. Jay, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, S. Tuli, G. Waegel, Z. Wang, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si,

S. Wimpenny, B.R. Yates, Y. Zhang

University of California, San Diego, La Jolla, California, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, New York, USA
J. Alexander, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, J.R. Patterson, D. Quach, A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena[74], F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, M. Wang, H.A. Weber, A. Woodard

University of Florida, Gainesville, Florida, USA
D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, Florida, USA
Y.R. Joshi

Florida State University, Tallahassee, Florida, USA

T. Adams, A. Askew, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, Illinois, USA
M.R. Adams, L. Apanasevich, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, V. Kumar, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, B. Bilki[55], K. Dilsiz[75], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[76], A. Moeller, J. Nachtman, H. Ogul[77], Y. Onel, F. Ozok[78], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi[79]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, A.V. Gritsan, W.T. Hung, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, Kansas, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, Minnesota, USA
R.M. Chatterjee, A. Evans, S. Guts[†], P. Hansen, J. Hiltbrand, Sh. Jain, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, Mississippi, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow[†], B. Stieger, W. Tabb

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Bhattacharya, J. Bueghly, G. Fedi, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, Y. Musienko[37], R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf

The Ohio State University, Columbus, Ohio, USA
J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

Princeton University, Princeton, New Jersey, USA
G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, Indiana, USA
A. Barker, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, Texas, USA
A. Baty, U. Behrens, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, Texas, USA
O. Bouhali[80], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[81], H. Kim, S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, F. De Guio, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, Virginia, USA
M.W. Arenton, P. Barria, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, Michigan, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

University of Wisconsin - Madison, Madison, WI, Wisconsin, USA
K. Black, T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-Reichert

†: Deceased
1: Also at TU Wien, Wien, Austria
2: Also at Université Libre de Bruxelles, Bruxelles, Belgium
3: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
4: Also at Universidade Estadual de Campinas, Campinas, Brazil
5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
6: Also at UFMS, Nova Andradina, Brazil
7: Also at Universidade Federal de Pelotas, Pelotas, Brazil
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at National Research Center 'Kurchatov Institute', Moscow, Russia
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Suez University, Suez, Egypt
12: Now at British University in Egypt, Cairo, Egypt
13: Now at Ain Shams University, Cairo, Egypt
14: Also at Purdue University, West Lafayette, Indiana, USA
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
19: Also at University of Hamburg, Hamburg, Germany
20: Also at Brandenburg University of Technology, Cottbus, Germany
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd

University, Budapest, Hungary
24: Also at IIT Bhubaneswar, Bhubaneswar, India
25: Also at Institute of Physics, Bhubaneswar, India
26: Also at G.H.G. Khalsa College, Punjab, India
27: Also at Shoolini University, Solan, India
28: Also at University of Hyderabad, Hyderabad, India
29: Also at University of Visva-Bharati, Santiniketan, India
30: Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
31: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
32: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
33: Also at Riga Technical University, Riga, Latvia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at St. Petersburg Polytechnic University, St. Petersburg, Russia
40: Also at University of Florida, Gainesville, Florida, USA
41: Also at Imperial College, London, United Kingdom
42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
43: Also at INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy, Padova, Italy
44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
46: Also at Università degli Studi di Siena, Siena, Italy
47: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
48: Also at National and Kapodistrian University of Athens, Athens, Greece
49: Also at Universität Zürich, Zurich, Switzerland
50: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
51: Also at Burdur Mehmet Akif Ersoy University, Burdur, Turkey
52: Also at Şırnak University, Sirnak, Turkey
53: Also at Department of Physics, Tsinghua University, Beijing, China
54: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
55: Also at Beykent University, Istanbul, Turkey
56: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey
57: Also at Mersin University, Mersin, Turkey
58: Also at Piri Reis University, Istanbul, Turkey
59: Also at Ozyegin University, Istanbul, Turkey
60: Also at Izmir Institute of Technology, Izmir, Turkey
61: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
62: Also at Marmara University, Istanbul, Turkey
63: Also at Milli Savunma University, Istanbul, Turkey
64: Also at Kafkas University, Kars, Turkey
65: Also at Istanbul Bilgi University, Istanbul, Turkey
66: Also at Hacettepe University, Ankara, Turkey

67: Also at Adiyaman University, Adiyaman, Turkey
68: Also at Vrije Universiteit Brussel, Brussel, Belgium
69: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
70: Also at IPPP Durham University, Durham, United Kingdom
71: Also at Monash University, Faculty of Science, Clayton, Australia
72: Also at Bethel University, St. Paul, Minneapolis, USA
73: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
74: Also at California Institute of Technology, Pasadena, California, USA
75: Also at Bingol University, Bingol, Turkey
76: Also at Georgian Technical University, Tbilisi, Georgia
77: Also at Sinop University, Sinop, Turkey
78: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
79: Also at Nanjing Normal University Department of Physics, Nanjing, China
80: Also at Texas A&M University at Qatar, Doha, Qatar
81: Also at Kyungpook National University, Daegu, Korea