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

The CMS Collaboration *

CERN, Geneva, Switzerland

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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 $\sqrt{s_{NN}} = 5.02$ 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 $R_{pPb}(\Upsilon(1S)) = 0.806 \pm 0.024(\text{stat}) \pm 0.059(\text{syst})$. Similar results for the excited states indicate a sequential suppression pattern, such that $R_{pPb}(\Upsilon(1S)) > R_{pPb}(\Upsilon(2S)) > R_{pPb}(\Upsilon(3S))$. The suppression of all states is much less pronounced in pPb than in PbPb collisions, and independent of transverse momentum p_T^{Υ} and center-of-mass rapidity y_{CM}^{Υ} of the individual Υ state in the studied range $p_T^{\Upsilon} < 30$ GeV/c and $|y_{CM}^{\Upsilon}| < 1.93$. 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.

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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 Υ(nS) (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 $\sqrt{s_{NN}} = 2.76$ TeV [33,34] and 5.02 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 Υ(nS) 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 Υ(nS) under the assumption that the cross sections scale as $\sigma_{pPb} = A\sigma_{pp}$, where

* *E-mail address:* cms-publication-committee-chair@cern.ch.

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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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [44], as well as in pp collisions at $\sqrt{s} = 2.76$ 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 $\sqrt{s_{\mathrm{NN}}} = 8.16$ 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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 $p_{\mathrm{T}}^{\mu} > 4$ 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 $\Upsilon(nS)$ 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 PYTHIA8.209 [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

Fig. 1 shows the invariant mass distributions of opposite-sign muon pairs for pp (top) and pPb (bottom) 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 (bottom) 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.

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_{lab}^{μ}). 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: $(m(nS)/m(1S))_{fit} = (m(nS)/m(1S))_{PDG}$. Similarly, the CB widths are also scaled by the ratio of the PDG mass values.

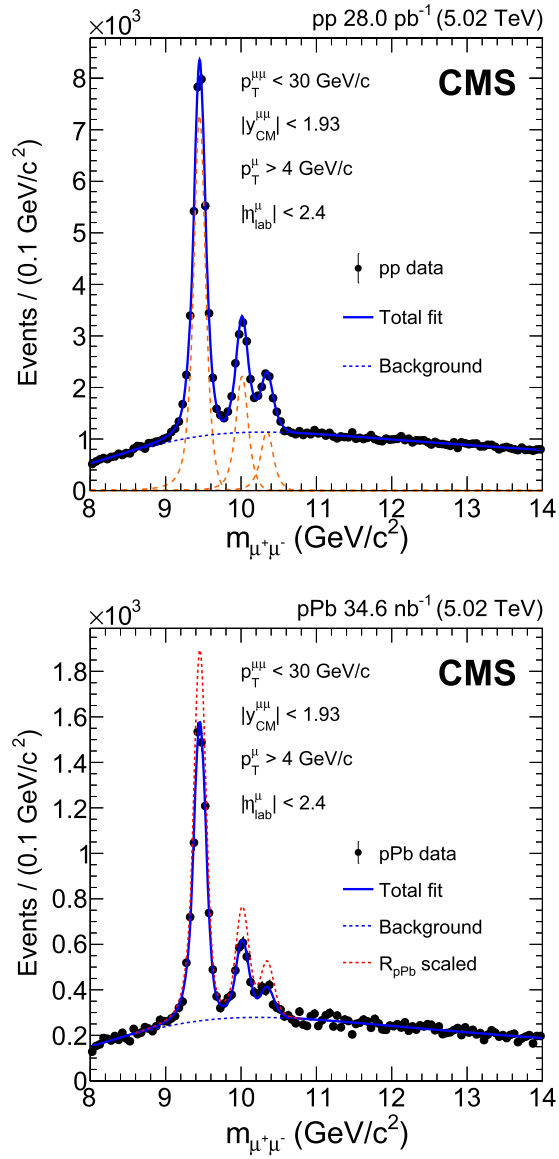

Fig. 1. Measured dimuon invariant mass distributions (closed circles) for pp (top) and pPb (bottom) collisions. The total unbinned maximum-likelihood fits to the data are shown as solid blue lines, with the background component indicated by dashed blue lines. The individual $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ signal shapes in pp are depicted as dashed orange lines in the top panel. The dashed red line in the bottom 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.

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 $p_T^{\mu} > 4\,\text{GeV}/c$ selection applied to single muons, which produces a hump-like feature in the combinatorial background at low invariant masses and at low dimuon $p_T^{\mu\mu}$. For dimuon $p_T^{\mu\mu} > 6\,\text{GeV}/c$, 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 $\Upsilon(n\text{S})$ 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 $\Upsilon(n\text{S})$ 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 $\Upsilon(n\text{S})$ 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 $\Upsilon(n\text{S})$ states are tabulated in Table 1. Two important sources of systematic uncertainty in the $\Upsilon(n\text{S})$ 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 $p_T^{\mu\mu}$, the model was varied in different kinematic regions. In higher $p_T^{\mu\mu}$ regions, a power law is used as the alternative background fit model. In lower $p_T^{\mu\mu}$ regions, the background model is constructed from a linear combination of four invariant-mass fits to four $p_T^{\mu\mu}$ subintervals of a MC simulation of dimuon decays.

Table 1
Ranges of typical systematic uncertainties in R_{pPb} and R_{FB} for $\Upsilon(n\text{S})$. 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%	

When estimating systematic uncertainties in the $\Upsilon(n\text{S})$ 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 $\Upsilon(n\text{S})$ 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 $\Upsilon(n\text{S})$ 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.

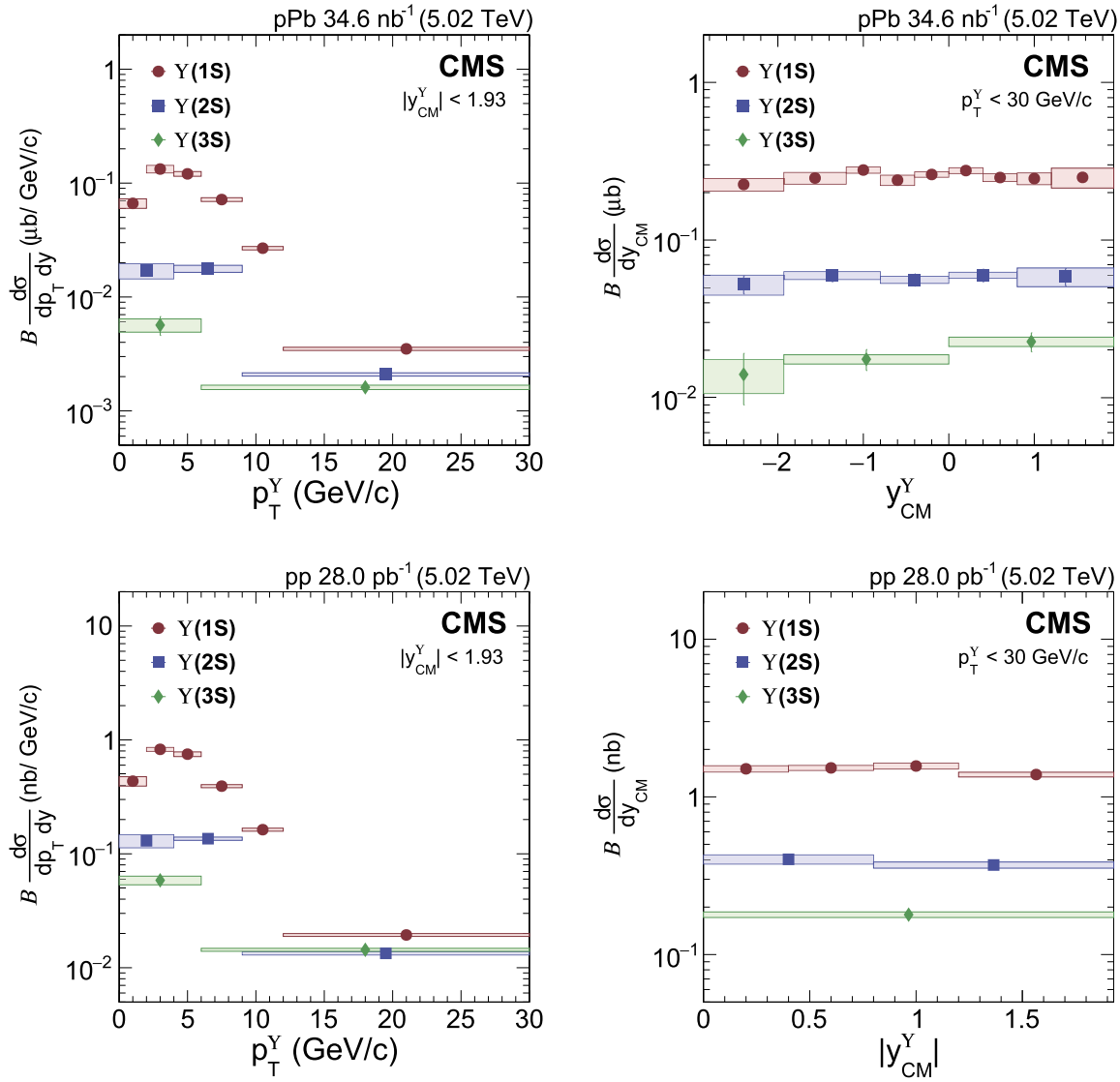

Fig. 2. Cross section times dimuon branching fraction of $\Upsilon(1S)$ (red circles), $\Upsilon(2S)$ (blue squares), and $\Upsilon(3S)$ (green diamonds) as functions of p^{Υ}_T (left) and y^{Υ}_{CM} (right) in pPb (upper row) and pp (lower row) collisions. For pPb collisions, the p-going side corresponds to $y^{\Upsilon}_{CM} > 0$. Because pp collisions are symmetric in the center-of-mass frame, the absolute value of rapidity $|y^{\Upsilon}_{CM}|$ 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.

Systematic uncertainties in efficiency corrections are estimated by combining two sources in quadrature. The first is the uncertainty in weighting MC $p^{\mu\mu}_T$ 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 $|y^{\Upsilon}_{CM}|$ and with decreasing p^{Υ}_T. Because of the asymmetry of pPb collisions, the most forward y^{Υ}_{CM} bins, which are at the edge of the detector, have larger systematic uncertainty than the most backward y^{Υ}_{CM} bins because the latter are closer to $y^{\Upsilon}_{lab} = 0$. The total systematic uncertainty also increases with increasing event activity for integrated p^{Υ}_T and y^{Υ}_{CM}.

5. Results

The product of the branching fraction of $\Upsilon(nS)$ to muon pairs, $\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-)$, and the double-differential production cross section, $d^2\sigma/dp^{\Upsilon}_T dy^{\Upsilon}_{CM}$, is obtained as

$$\mathcal{B}\big(\Upsilon(nS) \to \mu^+\mu^-\big)\frac{d^2\sigma}{dp^{\Upsilon}_T dy^{\Upsilon}_{CM}} = \frac{N^{\Upsilon(nS)}_{Fit}/(a\varepsilon)}{\mathcal{L}_{int}\Delta p^{\mu\mu}_T \Delta y^{\mu\mu}_{CM}}, \quad (1)$$

where $N^{\Upsilon(nS)}_{Fit}$ is the yield of $\Upsilon(nS)$ mesons extracted from the fit in a given $(p^{\mu\mu}_T, y^{\mu\mu}_{CM})$ bin, a is the dimuon acceptance correction, ε is the dimuon efficiency correction, and $\mathcal{L}_{int}$ is the integrated luminosity. Fig. 2 (upper row) shows the cross sections of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ in pPb collisions as functions of p^{Υ}_T (left) and

y^{Υ}_{CM} (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^{Υ}_{T} and when determining the R_{pPb} and R_{FB}, we restrict the CM rapidity range to the symmetric region $|y^{\mu\mu}_{CM}| < 1.93$ where data for both pp and pPb collisions are available. The $\Upsilon(nS)$ cross sections in pp collisions are also determined for $|y^{\Upsilon}_{CM}| < 1.93$ as functions of the kinematic variables. These are shown in Fig. 2 (lower row).

The quantity R_{pPb} is calculated as

$$R_{pPb}(p^{\Upsilon}_{T}, y^{\Upsilon}_{CM}) = \frac{(d^2\sigma/dp^{\Upsilon}_{T}dy^{\Upsilon}_{CM})_{pPb}}{A(d^2\sigma/dp^{\Upsilon}_{T}dy^{\Upsilon}_{CM})_{pp}}, \quad (2)$$

where $A = 208$ is the mass number of the Pb nucleus. Results for R_{pPb} are shown in Fig. 3 as functions of p^{Υ}_{T} and y^{Υ}_{CM}. We observe that all three $\Upsilon(nS)$ 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^{Υ}_{T} for $\Upsilon(1S)$ [43] in a similar midrapidity region as in CMS. The CMS data is consistent with no dependence, but the overall p^{Υ}_{T} dependence of the R_{pPb} ($\Upsilon(1S)$) in the two experiments is consistent within uncertainties. Moreover, our data shows no y^{Υ}_{CM} 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 $\psi(2S)$ was found to be smaller than that of J/ψ [38] in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for backward rapidity and $p^{J/\psi}_{T} < 10$ 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^{Υ}_{T} region studied. The measured R_{pPb} ($\Upsilon(1S)$) is systematically larger than that of $\Upsilon(2S)$, which in turn is systematically larger than the R_{pPb} ($\Upsilon(3S)$), 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^{Υ}_{CM} 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 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] (top) and predictions using energy loss only and energy loss with shadowing [17] (bottom). 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.

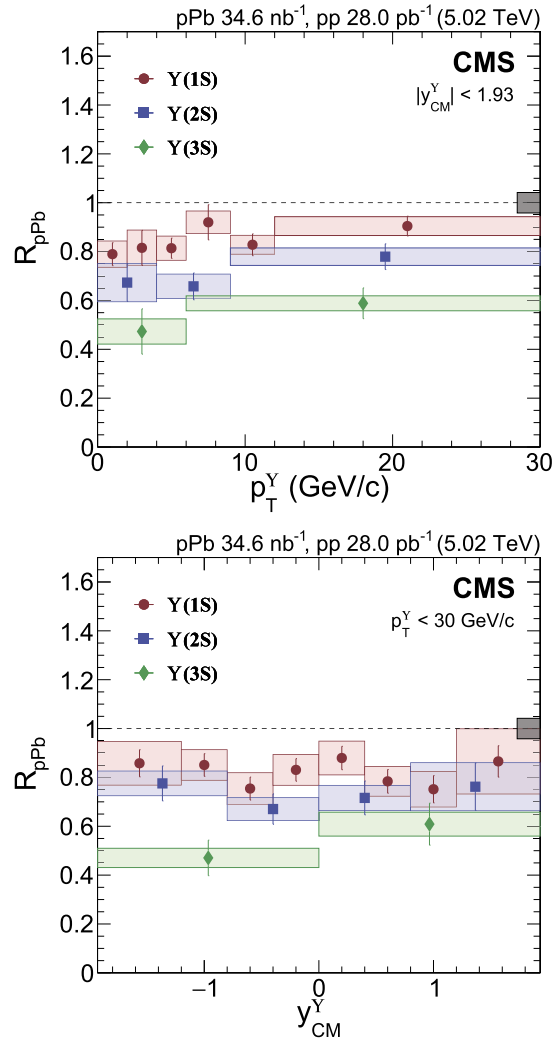

Fig. 3. R_{pPb} of $\Upsilon(1S)$ (red circles), $\Upsilon(2S)$ (blue squares), and $\Upsilon(3S)$ (green diamonds) as functions of p^{Υ}_{T} (top) and y^{Υ}_{CM} (bottom), where the bottom panel is integrated over $p^{\Upsilon}_{T} < 30$ GeV/c. Vertical bars on the points represent statistical and fit 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%).

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. Fig. 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. Fig. 6 shows the R_{pPb} of $\Upsilon(nS)$ states for $-1.93 < y^{\Upsilon}_{CM} < 0$ and $0 < y^{\Upsilon}_{CM} < 1.93$ in the low-p^{Υ}_{T} (top) and high-p^{Υ}_{T}

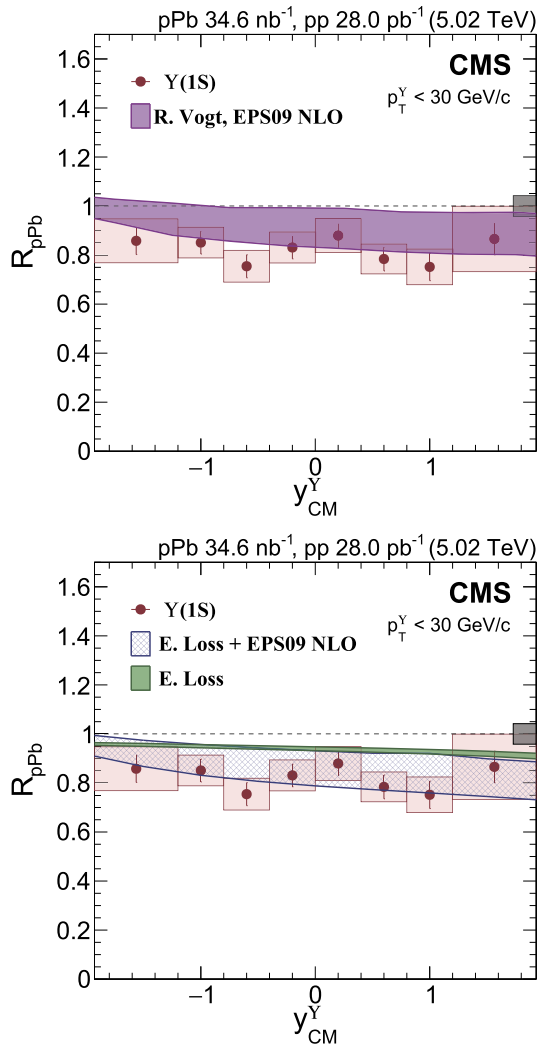

Fig. 4. R_{pPb} of Υ(1S) (red circles) versus y_{CM}^{Υ} with initial-state model calculations: nPDF modification [16] (top) and energy loss (E. Loss) with and without shadowing corrections [17] (bottom). The uncertainty range for each model calculation is shown. Vertical bars on the points represent 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%).

(bottom) regions. We find indication of greater differences between the suppression levels of low-p_T^{Υ} Υ(nS) states in the lead-going versus the proton-going y_{CM}^{Υ} directions. A similar observation was made by CMS in the charmonium sector [39], where the modification levels of ψ(2S) and J/ψ with $p_T < 10$ 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:

$$R_{FB}(p_T^{\Upsilon}, y_{CM}^{\Upsilon} > 0) = \frac{(d^2\sigma(p_T^{\Upsilon}, y_{CM}^{\Upsilon})/dp_T^{\Upsilon}dy_{CM}^{\Upsilon})}{(d^2\sigma(p_T^{\Upsilon}, -y_{CM}^{\Upsilon})/dp_T^{\Upsilon}dy_{CM}^{\Upsilon})}, \quad (3)$$

where y_{CM}^{Υ} is positive. We measure event activity near the measured Υ meson using the number of reconstructed tracks, N_{tracks}, in the region $|\eta_{lab}| < 2.4$ (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 $4 < |\eta_{lab}| < 5.2$. Fig. 7 shows the R_{FB} as a function N_{tracks} (top), and E_T (bottom). The uncorrected mean values of the event activity variables in minimum bias pPb collisions are $\langle N_{tracks}\rangle = 41$ and $\langle E_T\rangle = 14.7$ 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 Υ(1S) for integrated event activity for Υ mesons in the forward ($2.03 < y_{CM}^{\Upsilon} < 3.53$) and backward ($-4.46 < y_{CM}^{\Upsilon} < -2.96$) rapidity regions [42]. The LHCb Collaboration also measured Υ(1S) R_{FB} in the forward ($1.5 < y_{CM}^{\Upsilon} < 4.0$) and backward ($-5.0 < y_{CM}^{\Upsilon} < -2.5$) 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].

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

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

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 Υ(1S), Υ(2S), and Υ(3S), 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 Υ(1S) are 1.24×10^{-1} for Υ(2S) and 1.02×10^{-3} for Υ(3S), corresponding to significances of 1.2 and 3.1 standard deviations, respectively.

Fig. 8 illustrates that the measured modifications in Υ(nS) 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 Υ(nS) (where $n = 1, 2, 3$) family is studied in proton-lead (pPb) collisions at $\sqrt{s_{NN}} = 5.02$ 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 Υ(nS) yields to be suppressed. This suppression is observed over

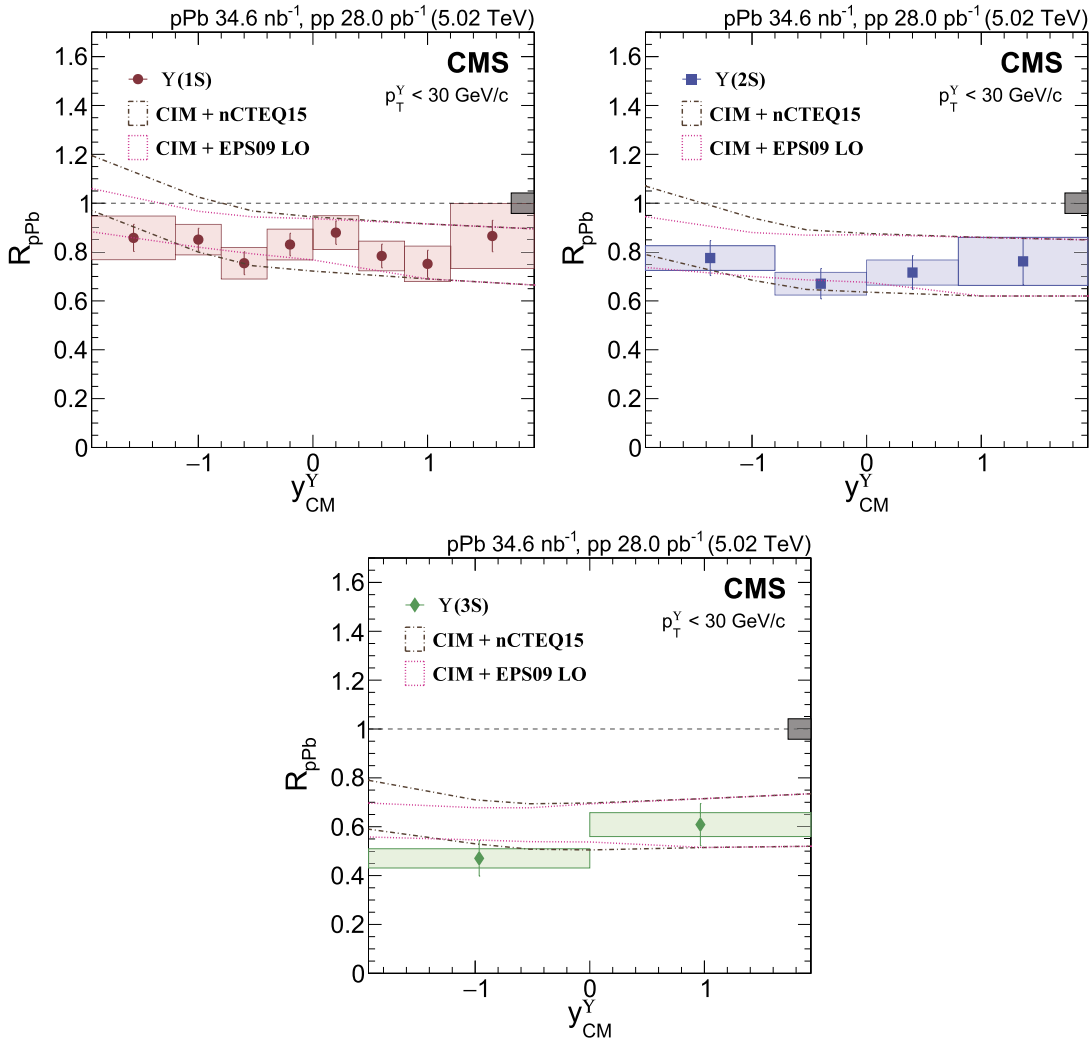

Fig. 5. R_{pPb} versus y_{CM}^{Υ} with CIM predictions [18] with shadowing corrections using nCTEQ15 and EPS09 for Υ(1S) (upper left; red circles), Υ(2S) (upper right; blue squares) and Υ(3S) (lower; green diamonds). The uncertainty range for each model calculation is shown. Vertical bars on the points 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%).

the entire kinematic range that is studied, i.e., transverse momentum $p_T^{\Upsilon} < 30\,\text{GeV}/c$ and center-of-mass rapidity $|y_{CM}^{\Upsilon}| < 1.93$. The suppression level is constant both as a function of p_T^{Υ} and of y_{CM}^{Υ} within the experimental uncertainties. An indication of higher separation of the excited states with $p_T^{\Upsilon} < 6\,\text{GeV}/c$ is observed in the Pb-going direction.

The forward-backward production ratios R_{FB} of Υ(nS) states are studied as a function of event activity in two regions: A midrapidity region (where the Υ(nS) states were measured), and a region with at least two units of rapidity separation from any measured Υ(nS) state. The R_{FB} values are consistent with unity for all states, independent of the region used to measure the event activity.

The integrated nuclear modification factors for Υ(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} (Υ(nS)) is observed, with Υ(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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as stated in "CMS data preservation, re-use and open access policy".

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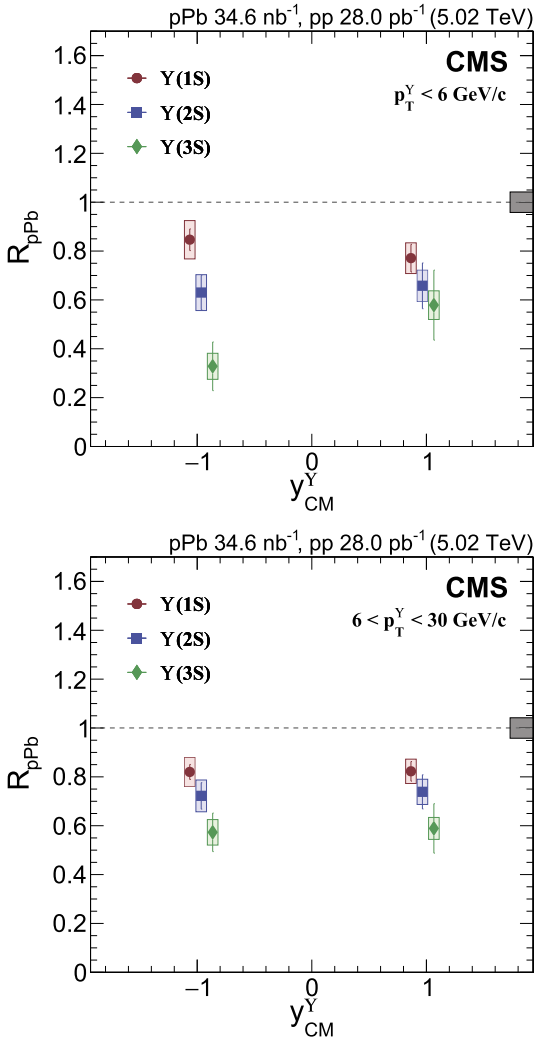

Fig. 6. R_{pPb} of Υ(1S) (red circles), Υ(2S) (blue squares), and Υ(3S) (green diamonds) at forward and backward rapidity for $0 < p_T^{\Upsilon} < 6$ GeV/c (top) and $6 < p_T^{\Upsilon} < 30$ GeV/c (bottom). The points are shifted horizontally for better visibility. Vertical bars on the points represent 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%).

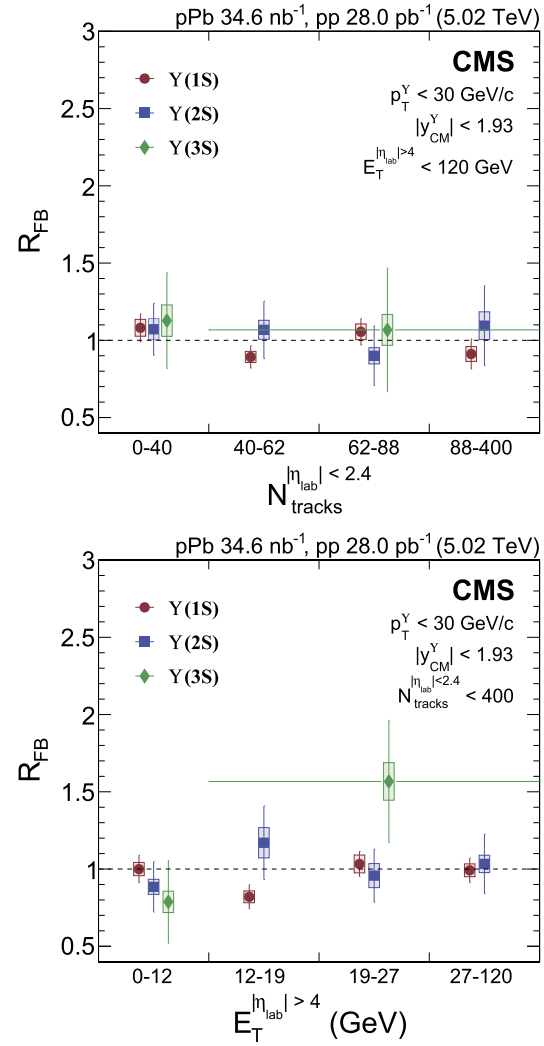

Fig. 7. R_{FB} versus N_{tracks} at mid-pseudorapidity (top) and *vs.* E_T at forward/backward pseudorapidity (bottom) of Υ(1S) (red circles), Υ(2S) (blue squares), and Υ(3S) (green diamonds) for $p_T^{\Upsilon} < 30$ GeV/c and $|y_{CM}^{\Upsilon}| < 1.93$. Vertical bars on the points represent statistical 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.

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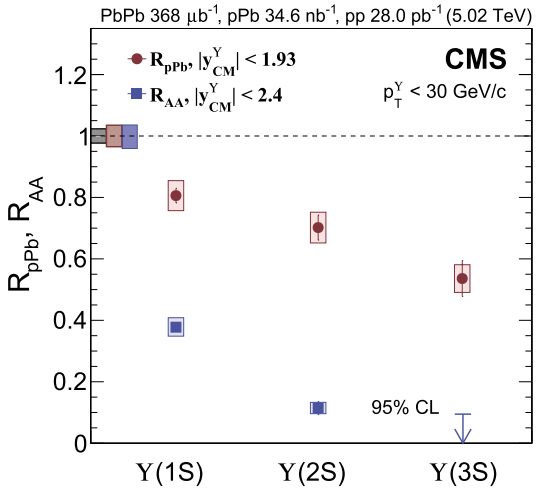

Fig. 8. R_{pPb} of Υ(1S), Υ(2S) and Υ(3S) (red circles) for the integrated kinematic range $0 < p_T^{\Upsilon} < 30$ GeV/c and $|y_{CM}^{\Upsilon}| < 1.93$. The R_{pPb} results are compared to the CMS results on Υ(nS) R_{AA} (blue squares for Υ(1S) and Υ(2S) and blue arrow for the upper limit at 95% confidence level (CL) on Υ(3S)) for $0 < p_T^{\Upsilon} < 30$ GeV/c and $|y_{CM}^{\Upsilon}| < 2.4$, 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].

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The CMS Collaboration

A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik, Vienna, Austria

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, 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

Vrije Universiteit Brussel, Brussel, 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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, P. Vischia, J. Zobec

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Centro Brasileiro de Pesquisas Fisicas, 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 do Estado do Rio de Janeiro, Rio de Janeiro, 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

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, Sã *o Paulo, Brazil*

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

University of Sofia, Sofia, Bulgaria

W. Fang [2], X. Gao [2], L. Yuan

Beihang University, Beijing, China

M. Ahmad, Z. Hu, Y. Wang

Department of Physics, Tsinghua University, 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

Institute of High Energy Physics, 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

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

M. Xiao

Zhejiang University, Hangzhou, China, Zhejiang, China

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger [10], M. Finger Jr. [10], A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran [11,12], E. Salama [12,13]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, 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

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, 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

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, 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

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, 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

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

A. Khvedelidze [10]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [10]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, I. Physikalisches Institut, 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 A, 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]

RWTH Aachen University, III. Physikalisches Institut B, Aachen, 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

Deutsches Elektronen-Synchrotron, 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

University of Hamburg, Hamburg, 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

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, 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

University of Ioánnina, Ioánnina, Greece

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

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

G. Bencze, C. Hajdu, D. Horvath [22], F. Sikler, V. Veszpremi, G. Vesztergombi [†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [21], J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati [23], C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak [24], D.K. Sahoo [23], S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra [25], 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

Panjab University, Chandigarh, 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

University of Delhi, Delhi, India

R. Bhardwaj [26], M. Bharti [26], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep [26], D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber [27], M. Maity [28], K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh [26], S. Thakur [26]

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Jha, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, R.K. Verma

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Tata Institute of Fundamental Research-B, Mumbai, India

S. Dube, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chenarani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], R. Aly [a,b,29], 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]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, 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,30], 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]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b,31], S. Costa [a,b,31], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b,31], C. Tuve [a,b]

[a] INFN Sezione di Catania, Catania, Italy
[b] Università di Catania, Catania, 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]

[a] INFN Sezione di Firenze, Firenze, Italy
[b] Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo [a,b], F. Ferro [a], R. Mulargia [a,b], E. Robutti [a], S. Tosi [a,b]

[a] INFN Sezione di Genova, Genova, Italy
[b] Università di Genova, Genova, 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]

[a] INFN Sezione di Milano-Bicocca, Milano, Italy
[b] Università di Milano-Bicocca, Milano, 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]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli 'Federico II', Napoli, Italy
[c] Università della Basilicata, Potenza, Italy
[d] Università G. Marconi, Roma, 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]

[a] INFN Sezione di Padova, Padova, Italy
[b] Università di Padova, Padova, Italy
[c] Università di Trento, Trento, 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]

[a] INFN Sezione di Pavia, Pavia, Italy
[b] Università di Pavia, Pavia, 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]

[a] INFN Sezione di Perugia, Perugia, Italy
[b] Università di Perugia, Perugia, 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]

[a] INFN Sezione di Pisa, Pisa, Italy
[b] Università di Pisa, Pisa, Italy

[c] Scuola Normale Superiore di Pisa, Pisa, Italy
[d] Università di Siena, Siena, 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]

[a] INFN Sezione di Roma, Rome, Italy
[b] Sapienza Università di Roma, Rome, 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]

[a] INFN Sezione di Torino, Torino, Italy
[b] Università di Torino, Torino, Italy
[c] Università del Piemonte Orientale, Novara, 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]

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of 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

Korea University, Seoul, Republic of Korea

J. Goh

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of 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

Seoul National University, Seoul, Republic of Korea

D. Jeon, J.H. Kim, J.S.H. Lee, I.C. Park, I.J. Watson

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Veckalns [32]

Riga Technical University, Riga, Latvia

V. Dudenas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

F. Mohamad Idris [33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [34], R. Lopez-Fernandez, A. Sánchez Hernández

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramírez García, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

J. Mijuskovic [3], N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler, P. Lujan

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, M.I.M. Awan, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk [35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

S. Afanasiev, A. Baginyan, P. Bunin, M. Gavrilenko, A. Golunov, I. Golutvin, I. Gorbunov, V. Karjavine, I. Kashunin, A. Lanev, A. Malakhov, V. Matveev [36,37], V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, V. Trofimov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim [38], E. Kuznetsova [39], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko [40], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

National Research Center 'Kurchatov Institute', Moscow, Russia

M. Chadeeva [41], P. Parygin, D. Philippov, E. Popova, V. Rusinov

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy [42], O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Barnyakov [43], V. Blinov [43], T. Dimova [43], L. Kardapoltsev [43], Y. Skovpen [43]

Novosibirsk State University (NSU), Novosibirsk, 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

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic [44], P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

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

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad Autónoma de Madrid, Madrid, 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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, 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 [45], L. Scodellaro, I. Vila, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D.U.J. Sonnadara

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

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 [46], 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 [47], 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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada [48], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, 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

ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

C. Amsler [49], 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

Universität Zürich, Zurich, Switzerland

C.M. Kuo, W. Lin, A. Roy, T. Sarkar [28], S.S. Yu

National Central University, Chung-Li, 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

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Bat, F. Boran, A. Celik [50], S. Damarseckin [51], Z.S. Demiroglu, F. Dolek, C. Dozen [52], I. Dumanoglu [53], G. Gokbulut, E.G. Guler [54], Y. Guler, I. Hos [55], C. Isik, E.E. Kangal [56], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [57], A.E. Simsek, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

B. Isildak [58], G. Karapinar [59], M. Yalvac [60]

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya [61], O. Kaya [62], Ö. Özçelik, S. Tekten [63], E.A. Yetkin [64]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak [53], Y. Komurcu, S. Sen [65]

Istanbul Technical University, Istanbul, Turkey

S. Cerci [66], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci [66]

Istanbul University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

E. Bhal, S. Bologna, J.J. Brooke, D. Burns [67], 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

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [68], 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

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, G.S. Chahal [69], 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 [70], 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

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, TX, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

A. Buccilli, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, AL, USA

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

Boston University, Boston, MA, USA

G. Benelli, B. Burkle, X. Coubez [18], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan [71], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir [72], R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

Brown University, Providence, RI, 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, Davis, Davis, CA, 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, Los Angeles, CA, 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, Riverside, Riverside, CA, 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, San Diego, La Jolla, CA, 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

University of California, Santa Barbara – Department of Physics, Santa Barbara, CA, 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

California Institute of Technology, Pasadena, CA, USA

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, PA, USA

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

University of Colorado Boulder, Boulder, CO, 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

Cornell University, Ithaca, NY, 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 [73], 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

Fermi National Accelerator Laboratory, Batavia, IL, 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

University of Florida, Gainesville, FL, USA

Y.R. Joshi

Florida International University, Miami, FL, 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 State University, Tallahassee, FL, USA

M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, FL, 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

University of Illinois at Chicago (UIC), Chicago, IL, USA

M. Alhusseini, B. Bilki [54], K. Dilsiz [74], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili [75], A. Moeller, J. Nachtman, H. Ogul [76], Y. Onel, F. Ozok [77], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi [78]

The University of Iowa, Iowa City, IA, 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

Johns Hopkins University, Baltimore, MD, 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

The University of Kansas, Lawrence, KS, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Kansas State University, Manhattan, KS, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, CA, 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

University of Maryland, College Park, MD, 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

Massachusetts Institute of Technology, Cambridge, MA, 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 Minnesota, Minneapolis, MN, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, MS, 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

University of Nebraska-Lincoln, Lincoln, NE, USA

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, NY, 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

Northeastern University, Boston, MA, USA

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

Northwestern University, Evanston, IL, 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[36], R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf

University of Notre Dame, Notre Dame, IN, USA

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

The Ohio State University, Columbus, OH, 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

Princeton University, Princeton, NJ, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, PR, 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, West Lafayette, IN, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, IN, 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

Rice University, Houston, TX, 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

University of Rochester, Rochester, NY, 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

Rutgers, The State University of New Jersey, Piscataway, NJ, USA

H. Acharya, A.G. Delannoy, S. Spanier

University of Tennessee, Knoxville, TN, USA

O. Bouhali [79], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [80], H. Kim, S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, TX, 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

Texas Tech University, Lubbock, TX, 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

Vanderbilt University, Nashville, TN, 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

University of Virginia, Charlottesville, VA, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

Wayne State University, Detroit, MI, 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

University of Wisconsin – Madison, Madison, WI, USA

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

[74] Also at Bingol University, Bingol, Turkey.
[75] Also at Georgian Technical University, Tbilisi, Georgia.
[76] Also at Sinop University, Sinop, Turkey.
[77] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[78] Also at Nanjing Normal University Department of Physics, Nanjing, China.
[79] Also at Texas A&M University at Qatar, Doha, Qatar.
[80] Also at Kyungpook National University, Daegu, Republic of Korea.