

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletbMeasurement of nuclear modification factors of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration*

CERN, Switzerland



ARTICLE INFO

Article history:

Received 23 May 2018

Received in revised form 2 January 2019

Accepted 7 January 2019

Available online 17 January 2019

Editor: M. Doser

Keywords:

CMS

Physics

Bottomonium

Quarkonium suppression

Quark gluon plasma

Heavy ion collisions

ABSTRACT

The cross sections for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production in lead–lead (PbPb) and proton–proton (pp) collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been measured using the CMS detector at the LHC. The nuclear modification factors, R_{AA} , derived from the PbPb-to-pp ratio of yields for each state, are studied as functions of meson rapidity and transverse momentum, as well as PbPb collision centrality. The yields of all three states are found to be significantly suppressed, and compatible with a sequential ordering of the suppression, $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$. The suppression of $\Upsilon(1S)$ is larger than that seen at $\sqrt{s_{NN}} = 2.76$ TeV, although the two are compatible within uncertainties. The upper limit on the R_{AA} of $\Upsilon(3S)$ integrated over p_T , rapidity and centrality is 0.096 at 95% confidence level, which is the strongest suppression observed for a quarkonium state in heavy ion collisions to date.

© 2019 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

The measurement of quarkonium production in heavy ion collisions is one of the most promising ways to study the properties of strongly interacting matter at high energy density and temperature. It has been predicted that in such an environment, a strongly interacting medium of deconfined quarks and gluons (the quark–gluon plasma, QGP) is formed [1,2]. Bottomonium states have been the subject of studies in heavy ion collisions for several reasons. Bottomonia are produced during the early stages of collisions via hard parton scattering. Their spectral functions are modified as a consequence of Debye screening of the heavy-quark potential at finite temperatures [3,4], as well as by thermal broadening of their widths due to interactions with gluons [5,6]. These in-medium effects have been studied in numerical simulations of quantum chromodynamics (QCD) on a space–time lattice, and captured as real and imaginary components of the heavy-quark potential [7]. One of the most remarkable signatures of these interactions with the medium is the sequential suppression of quarkonium states in heavy ion collisions compared to the production in proton–proton (pp) collisions, both in the charmonium (J/ψ , $\psi(2S)$, χ_c , etc.) and the bottomonium ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b , etc.) families [8]. This scenario follows from the expectation that the suppression of quarkonia is stronger for states with smaller binding energy.

The quarkonium yield can also increase in the presence of QGP, from the recombination of uncorrelated quarks [9–12]. However, recombination-like processes for bottomonia are expected to be negligible compared to the charmonium family [13–15], because these processes are driven by the number of heavy-quark pairs present in a single event, which is much smaller for beauty than for charm. The dissociation temperatures for the Υ states, above which suppression occurs, are expected to be correlated with their binding energies, and are predicted to be $T_{\text{dissoc}} \approx 2T_c$, $1.2T_c$ and $1T_c$ for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states, respectively, where T_c is the critical temperature for deconfinement [16]. Therefore, measurements of the yields of each Υ state can provide information about the thermal properties of the medium during its hot early phase.

Modifications of particle production in nucleus–nucleus (AA) collisions are quantified using the nuclear modification factor, R_{AA} , which is the ratio of the yield measured in AA to that in pp collisions, scaled by the mean number of binary NN collisions. Comparisons of the bottomonium data with dynamical models incorporating the heavy-quark potential effects found in high-temperature lattice QCD are thus expected to extend our understanding of the nature of colour deconfinement in heavy ion collisions. Measurements of both the charmonium (J/ψ and $\psi(2S)$) [17–20] and bottomonium ($\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$) [21,22] families have been carried out at a nucleon–nucleon (NN) center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV and, most recently, at $\sqrt{s_{NN}} = 0.2$ TeV at RHIC [23–25]. At $\sqrt{s_{NN}} = 5.02$ TeV, measurements by the CMS Col-

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

laboration show strong suppression of J/ψ and $\psi(2S)$ mesons [26, 27], as well as of both $\Upsilon(2S)$ and $\Upsilon(3S)$ relative to the $\Upsilon(1S)$ ground state [28]. The suppression of the excited $\Upsilon(2S)$ relative to the $\Upsilon(1S)$ ground state persists at very forward rapidity, $2.5 < y < 4$ [29]. These measurements provide new constraints for theoretical models of the medium [9,11].

In this Letter, we report measurements of the differential cross sections and nuclear modification factors for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons using their decay into two oppositely charged muons in lead–lead (PbPb) and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Results are presented as functions of the Υ transverse momentum (p_T) and rapidity (y), as well as PbPb collision centrality (i.e., the degree of overlap of the two lead nuclei). The data were collected with the CMS detector at the CERN LHC in 2015.

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 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 pseudorapidity interval of $|\eta| < 2.4$ using gas-ionization chambers made of three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. These are embedded in the steel flux-return yoke of the solenoid. The silicon tracker is composed of pixel detectors followed by microstrip detectors. The p_T of muons matched to tracks reconstructed in the silicon detector is measured with a resolution between 1% and 2% for typical muons used in this analysis [30]. In addition, CMS has extensive forward calorimetry, including two steel and quartz-fiber Cherenkov hadron forward (HF) calorimeters that cover the range of $2.9 < |\eta| < 5.2$. The HF calorimeters are segmented into towers and the granularity is $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$ radians. These are used in the present analysis to select PbPb collision events and to define their centrality class. Centrality, defined as the fraction of the total inelastic hadronic cross section with 0% representing collisions with the largest overlap of the two nuclei, is determined experimentally using the total energy in both HF calorimeters [31]. A more detailed description of the CMS detector, together with a definition of the coordinate system and the kinematic variables, can be found in Ref. [32].

3. Data selection and simulation samples

The Υ mesons are identified using their dimuon decay channel. In both pp and PbPb collisions, the dimuon events are selected by a fast hardware-based trigger system, which requires two muon candidates in a given bunch crossing with no explicit requirement on the muon momentum beyond the intrinsic selection due to the acceptance coverage of the CMS muon detectors. In pp collisions, this trigger registered an integral luminosity of 28.0 pb^{-1} . The PbPb data were taken with two triggers based on the same algorithm used for pp data. The first mode, designed to enhance the event count for muon pairs from peripheral events, added an additional selection that the collision centrality be in the 30–100% range. This trigger sampled the full integrated luminosity of $464 \text{ } \mu\text{b}^{-1}$. The second mode, using just the pp trigger alone, was prescaled during part of the data taking and therefore sampled a smaller effective integrated luminosity of $368 \text{ } \mu\text{b}^{-1}$. Data taken with this latter trigger were used to analyze the yields in the 0–30% and 0–100% centrality bins.

In order to keep hadronic collisions and reject beam-related background processes (beam-gas collisions and beam scraping

events), an offline event selection is applied. Events are required to have at least one reconstructed primary vertex. In pp collisions at least 25% of the tracks have to pass a tight track-quality selection [33]. A filter on the compatibility of the silicon pixel detector cluster width and the vertex position is also applied [34]. The PbPb collision events have an additional requirement of the presence of at least three towers in the HF on both sides of the interaction point with an energy above 3 GeV. The combined efficiency for this event selection, and the remaining contamination due to non-hadronic ultra-peripheral events which can raise the efficiency above 100%, is $(99 \pm 2)\%$ [35,36]. The minimum-bias trigger requirement removes a negligible fraction of the events with a hard collision needed to produce Υ mesons. We also studied a possible contamination from photoproduction processes in the peripheral region and found it to be negligible. Multiple-collision events (pileup) have a negligible effect on the measurement, since the average number of additional collisions per bunch crossing is approximately 0.9 for pp and much smaller for PbPb data.

Muons are selected in the kinematic range of $p_T^\mu > 4$ GeV and $|\eta^\mu| < 2.4$, and are also required to be reconstructed using the combined information of the tracker and muon detectors (so-called “global muons” defined in Ref. [30]). To remove cosmic ray muons, the distance of the muon track from the closest primary vertex must be less than 20 cm in the beam direction and 3 mm in the transverse direction. Pairs of oppositely charged muons are fitted with a common vertex constraint and kept if the fit χ^2 probability is larger than 1%. The studied dimuon kinematic range is limited to $p_T^{\mu^+\mu^-} < 30$ GeV and $|y^{\mu^+\mu^-}| < 2.4$. Dimuons in this p_T range comprise 99% of those passing all of the analysis selection criteria.

Simulated Monte Carlo (MC) Υ events are used to calculate correction factors for all of the results presented, including the geometrical acceptance and reconstruction efficiency, as well as the trigger and offline selection efficiency. The samples are generated using PYTHIA 8.209 [37] for the pp collisions and PYTHIA 8.209 embedded in HYDJET 1.9 for the PbPb events [38]. The PbPb simulation is tuned to reproduce the observed charged-particle multiplicity and p_T spectrum in PbPb data. The CMS detector response is simulated using GEANT4 [39]. Since the simulated p_T spectrum of Υ is not identical to the spectrum observed in data, an event-by-event weight is applied to the simulations in order to match the two distributions. The weight is given by a function fit to the ratio of data over MC p_T spectra.

4. Analysis procedure

4.1. Signal extraction

The yields of Υ mesons are extracted using unbinned maximum-likelihood fits to the invariant mass spectra, following the same procedure for pp and PbPb data. The signal of each Υ state is modeled by a double Crystal-Ball (CB) function which is the sum of two CB functions [40]. This choice together with leaving the width parameter for the first CB free in the fit, is made in order to account for the different mass resolution in the barrel compared to the endcap region of the detector. A parameter relates the widths of the two CB functions, the second one being constrained to be narrower. The mass and the two radiative-tail

parameters of both CB functions for a given state are kept the same, as these are not affected by the detector resolution. The mass parameter of the ground state is left free to allow for possible shifts in the absolute momentum calibration of the reconstructed tracks. For the excited states ($\Upsilon(2S)$ and $\Upsilon(3S)$), the yields can vary while all other fit parameters are fixed to be identical to those for the ground state except for the mean and width which are fixed to values found by multiplying those for $\Upsilon(1S)$ by the ratio of the published masses of the states [41]. In the pp data fits, the two radiative-tail parameters and the parameter for the ratio of the two widths are allowed to vary within a Gaussian probability density function (PDF). The mean and the width of the constraining Gaussian function represent the average and its uncertainty, respectively, from the fits in all the rapidity bins of the analysis with no fixed parameters. In the PbPb fits, in addition, the parameter for the fraction of the two CB functions is also constrained. In this case, the mean and the width of the constrained parameters represent the corresponding parameter values and their uncertainties from the pp fits to each kinematic region. The background PDF is an error function multiplied by an exponential, with the yield, the error function's two parameters, and the decay parameter of the exponential all allowed to vary in the final fit. For bins with $p_T > 6$ GeV, an exponential without the error function provides the best fit, and was used for the nominal result.

Fig. 1 shows the dimuon invariant mass distributions in pp and PbPb collisions along with the fits using the model described above, for the kinematic range $p_T^{\mu^+\mu^-} < 30$ GeV and $|y^{\mu^+\mu^-}| < 2.4$.

4.2. Corrections

In order to obtain the normalized cross sections, the yields extracted from the fits to the dimuon invariant mass spectra are corrected for acceptance and efficiency, and scaled by the integrated luminosity. The acceptance corresponds to the fraction of dimuon events originating from Υ mesons within the kinematic range of the analysis. The acceptance values for the considered kinematic region are 22.5% ($\Upsilon(1S)$), 27.8% ($\Upsilon(2S)$), and 31.0% ($\Upsilon(3S)$) for PbPb collisions and differ by $< 1\%$ from the corresponding pp data values, with the small difference being due to a small residual difference in the kinematic spectra after weighting the MC to data.

The dimuon efficiency is defined as the probability that a muon pair within the acceptance is reconstructed offline, satisfies the trigger condition, and passes the analysis quality criteria described in Section 3. The dimuon efficiency is calculated using MC. The individual components of the efficiency (track reconstruction, muon identification and selection, and triggering) are also measured using single muons from J/ψ meson decays in both simulated and collision data, with the *tag-and-probe* (T&P) method [30]. For the muons used in this analysis, data and MC efficiencies are seen to differ only in the case of the trigger efficiency, and there only by $\lesssim 1\%$. For this case, scaling factors (SF), calculated as the ratio of data over simulated efficiencies as function of p_T^μ and η^μ , are applied to each dimuon on an event-by-event basis. The other components of the T&P efficiency are used only for the estimation of systematic uncertainties. The average efficiencies integrated over the full kinematic range are 73.5% ($\Upsilon(1S)$), 74.4% ($\Upsilon(2S)$), and 75.0% ($\Upsilon(3S)$) in PbPb collisions, and they are 8–9% higher for pp collisions.

The integrated luminosity of 28.0pb^{-1} with an uncertainty of 2.3% [42] is used to normalize the yields for pp data. For PbPb collisions, the number of minimum bias collision events sampled by the trigger (N_{MB}), together with the average nuclear overlap function (T_{AA}), are used for the normalization. The overlap function T_{AA} is given by the number of binary NN collisions divided

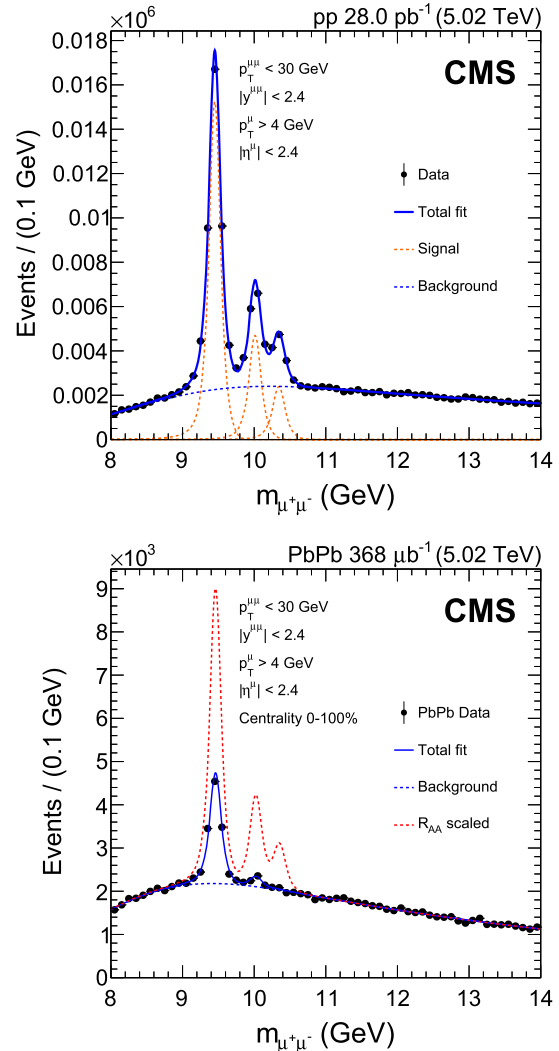


Fig. 1. Invariant mass distribution of muon pairs in pp (top) and PbPb (bottom) collisions, for the kinematic range $p_T^{\mu^+\mu^-} < 30$ GeV and $|y^{\mu^+\mu^-}| < 2.4$. In both figures, the results of the fits to the data are shown as solid blue lines. The separate yields for each Υ state in pp are shown as dashed red lines in the top panel. The dashed red lines in the bottom panel are derived from the fits to PbPb (blue solid line). In order to show the suppression of all three Υ states, the amplitudes of the corresponding peaks are increased above those found in the fit by the inverse of the measured R_{AA} for the corresponding Υ meson.

by the inelastic NN cross section, and can be interpreted as the NN-equivalent integrated luminosity per heavy ion collision. Values of T_{AA} are calculated with a Glauber model MC simulation [43, 44], which is also used to obtain the average number of participating nucleons, $\langle N_{part} \rangle$. This latter number is highly correlated with the impact parameter of the collision, and is used as the abscissa when plotting results as a function of PbPb collision centrality.

4.3. Systematic uncertainties

Point-to-point systematic uncertainties arise from the choices of signal and background PDFs and of the central value in the fit constraints, as well as from acceptance and efficiency corrections. Larger relative uncertainties are obtained when the background level is higher (at lower p_T or more forward y regions), and, in particular for the $\Upsilon(3S)$, when the absolute yield is small.

The uncertainty from the choice of signal model is estimated by fitting the data using a single CB function in combination with a Gaussian function instead of a double CB function. The uncertainties are determined by calculating the difference between the yield obtained with the alternative model compared to the nominal one. For the PbPb (pp) yields, the differences are in the range of 1–7% (0.1–4.6%) for the $\Upsilon(1S)$, 2–19% (0.1–1.3%) for the $\Upsilon(2S)$, and 5–78% (0.7–7%) for the $\Upsilon(3S)$ mesons.

The systematic uncertainty from the choice of the central value in the fit constraints is estimated by using instead of the average parameter values from the pp fits, the values in each pp analysis bin when all parameters were left floating. The differences in the PbPb (pp) signal yields, typically below 4% (4.5%) for the $\Upsilon(1S)$, below 8% (3%) for the $\Upsilon(2S)$, and 45% (2%) for the $\Upsilon(3S)$, are quoted as a systematic uncertainty.

The systematic uncertainty due to the choice of background model is estimated using two alternative background functions. One is in the form of a fourth-order polynomial function and the other is an exponential plus an additional linear function. The maximal deviations of the PbPb (pp) yield between these two models compared to the nominal are quoted as the uncertainty and are typically in the range of 1–6% (1–5%) for the $\Upsilon(1S)$, 2–23% (2–4%) for the $\Upsilon(2S)$, and 5–200% (3–5%) for the $\Upsilon(3S)$ mesons.

For the estimation of systematic uncertainties due to acceptance and efficiency corrections, the source of uncertainty is the imperfect knowledge of the simulated p_T distribution shape. To take this source into account, the function used to weight the MC p_T spectra event-by-event is modified within its fit uncertainty. The acceptance and efficiency obtained from the simulated p_T distribution are compared with and without the variation of the function, with the difference between the two used as an estimate of the systematic uncertainty. In addition, there is a systematic uncertainty for the efficiency in the T&P correction arising from the uncertainty in the SFs of the single-muon efficiency. The systematic uncertainties of the SFs are taken into account for trigger, tracking, and muon identification. The uncertainties in the single muon efficiencies are propagated to the dimuon efficiency values to estimate the systematic uncertainty from this source. The statistical uncertainty inherent in the data set used for the T&P studies is also considered as an additional component of the systematic uncertainty in the corrected yields. The PbPb (pp) systematic uncertainties are in the range of 3.5–6.4% (2.6–3.9%) in the case of the total efficiency correction and in the range of 0.1–3.0% (0.1–0.8%) for the acceptance correction.

Finally, several sources of correlated uncertainties (i.e., global uncertainties common to all points) are considered: for the pp dataset from the pp integrated luminosity, and for the PbPb dataset from the T_{AA} and the N_{MB} estimations. The uncertainty on the integrated luminosity measurement for the pp dataset is 2.3% [42]. The uncertainty for N_{MB} in PbPb collisions is 2%, which accounts for the inefficiency of trigger and event selection. For the R_{AA} calculation, T_{AA} uncertainties (Table 2 in Appendix A) are estimated by varying the Glauber model parameters within their uncertainties (Table 1 in Appendix A) [36]. The total combined uncertainty is calculated by adding the results from the various sources in quadrature. The global uncertainty for the differential cross section results arises from the integrated luminosity in pp collisions and N_{MB} in PbPb collisions. For the R_{AA} results, the global uncertainty combines the uncertainties from T_{AA} , pp luminosity, and PbPb N_{MB} for the bins integrated over centrality. For the centrality dependent R_{AA} results, the uncertainty from T_{AA} is included bin-by-bin, while the total uncertainty from the pp measurement is included in the global uncertainty. Using the updated uncertainties of the Glauber model parameters in Ref. [45], instead of those from Ref. [36], would reduce the T_{AA} uncertain-

ties by 0.1–1.1% and the total systematic uncertainties for R_{AA} by less than 0.7% (with the largest change for the 70–100% centrality bin). However, in order to allow direct comparisons to previous results [27,36,46,47], these updated parameters are not used in this analysis. The bin migration effect due to the momentum resolution is negligible for the kinematic range of this measurement.

5. Results

The Υ cross sections and values of R_{AA} are measured in several p_T and y bins. The rapidity studies are performed in the range $0 < |y| < 2.4$. This rapidity range is evenly divided into six, three, and two bins for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, respectively. For the investigation of the behavior of the R_{AA} as a function of centrality, the bin limits of the centrality classes are chosen as follows: [0, 5, 10, 20, 30, 40, 50, 60, 70, 100%] for the $\Upsilon(1S)$ and $\Upsilon(2S)$, and [0, 30, 100%] for the $\Upsilon(3S)$. When plotted as a function of each variable (p_T , y or centrality), values are integrated over the full kinematic range of the other variables. The $\Upsilon(3S)$ mesons show a very strong suppression in PbPb collisions, with yields which are statistically consistent with zero for all bins. The upper limits at 68% and 95% confidence level (CL) for the $\Upsilon(3S)$ cross section and R_{AA} are found using the Feldman–Cousins method [48], with the appropriate systematic uncertainties being included in the upper limit computation.

5.1. Differential cross sections in pp and PbPb collisions

The differential production cross section of Υ mesons decaying in the dimuon channel in pp collisions is given by

$$\mathcal{B} \frac{d\sigma^2}{dy dp_T} = \frac{N / (\mathcal{A}\varepsilon)}{\mathcal{L}_{\text{int}} \Delta y \Delta p_T}. \quad (1)$$

The branching fraction for the decay $\Upsilon \rightarrow \mu^+ \mu^-$ is denoted by \mathcal{B} . The quantity N corresponds to the extracted yield of Υ mesons in a given (p_T , y) bin, $(\mathcal{A}\varepsilon)$ represents the average acceptance and efficiency in the given bin, \mathcal{L}_{int} is the integrated luminosity, and Δp_T and Δy are the widths of the given bin. For PbPb data, \mathcal{L}_{int} is replaced by $(N_{MB} T_{AA})$, as explained in Section 4.2, to compare the pp and PbPb data under the hypothesis of binary-collision scaling.

Fig. 2 shows the differential production cross sections of Υ mesons as a function of p_T in pp and PbPb collisions. The data points are placed at the center of each bin. The corresponding results as a function of $|y|$ are shown in Fig. 3.

5.2. Nuclear modification factor R_{AA}

The nuclear modification factor is derived from the pp cross sections and PbPb normalized yields as

$$R_{AA}(p_T, y) = \frac{N^{AA}(p_T, y)}{\langle T_{AA} \rangle \sigma^{pp}(p_T, y)}, \quad (2)$$

where $\langle T_{AA} \rangle$ is the average value of T_{AA} computed in each centrality bin. The quantities N^{AA} and σ^{pp} refer to the normalized yield of Υ mesons in PbPb collisions corrected by acceptance and efficiency, and the pp cross section for a given kinematic range, respectively.

Fig. 4 shows the nuclear modification factor for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as functions of p_T and $|y|$. Within the systematic uncertainties, the R_{AA} values show no clear dependence on p_T or y . The excited Υ states are found to have larger suppression than the ground state, with $R_{AA} < 0.2$ over the full kinematic

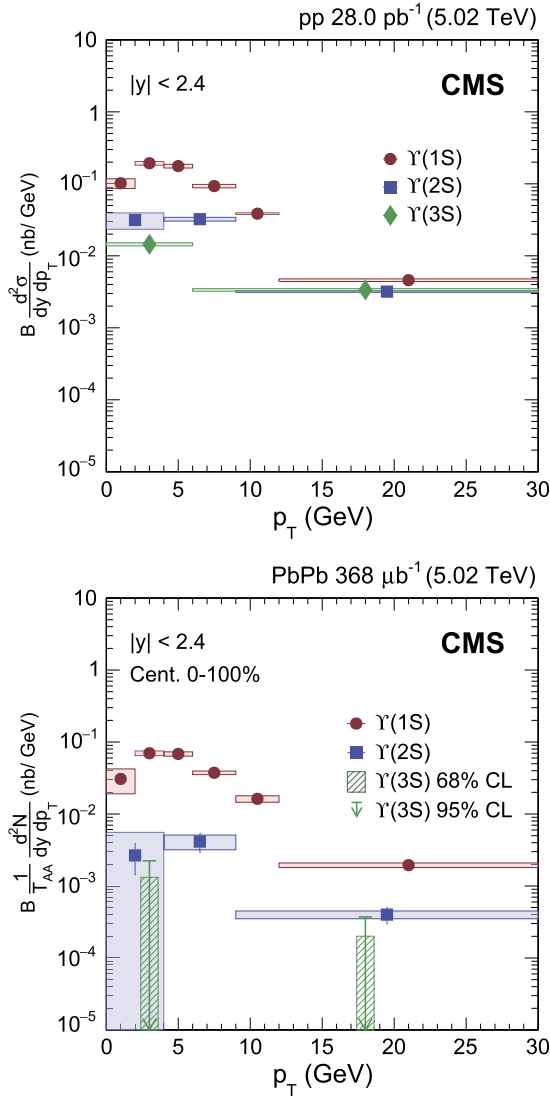


Fig. 2. Differential cross sections of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as a function of p_T for pp (top) and PbPb (bottom) collisions. The error bars represent the statistical uncertainties and the boxes the systematic uncertainties. For the $\Upsilon(3S)$ meson in PbPb collisions, the upper limits at 68% (green box) and 95% (green arrow) CL are shown, and are calculated for the same bins as for the pp dataset. The global integrated luminosity uncertainties of 2.3% in pp collisions and $^{+3.4\%}_{-3.9\%}$ in PbPb collisions are not shown.

range explored here. The kinematic dependence of R_{AA} is useful to constrain models of Υ meson suppression in a deconfined medium [9].

The dependence of R_{AA} on PbPb collision centrality, as quantified using the average $\langle N_{part} \rangle$, is depicted in Fig. 5. The strong suppression of the $\Upsilon(3S)$ meson is observed in both centrality bins studied, 0–30% and 30–100%. The R_{AA} decreases with increasing centrality in the case of the $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons. A hint of this centrality dependence of R_{AA} for $\Upsilon(2S)$ was first seen in data at $\sqrt{s_{NN}} = 2.76$ TeV [21] and is now confirmed using the larger data sample at 5.02 TeV.

Fig. 6 shows a comparison between the measured R_{AA} for $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons and two models of bottomonium suppression from Krouppa and Strickland [9], and from Du, He, and Rapp [12]. Both models incorporate color-screening effects on the bottomonium family and feed-down contributions from decays of heavier quarkonia. No regeneration in QGP or cold nuclear matter effects are considered by the first model, but are included in the sec-

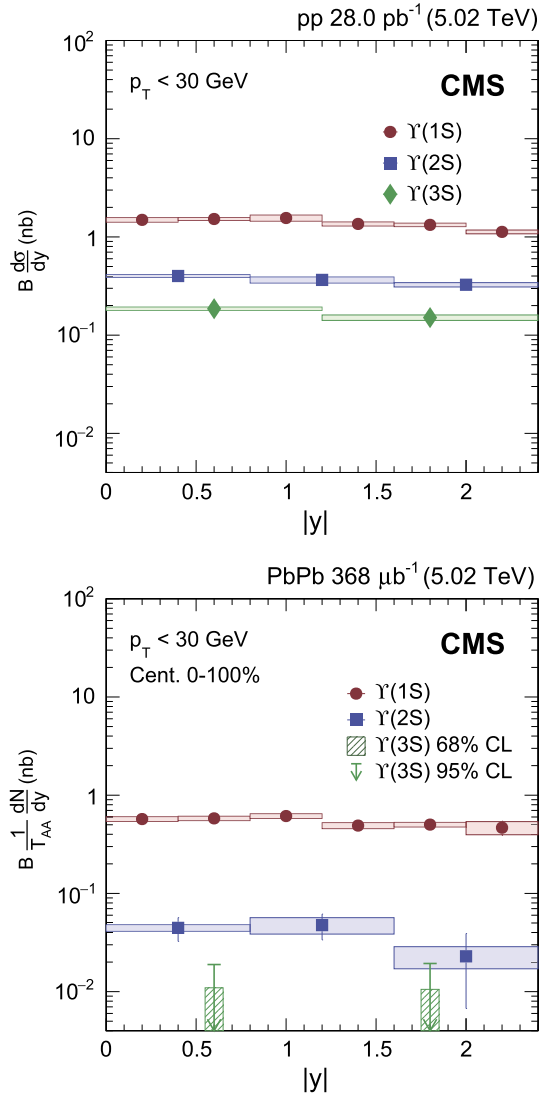


Fig. 3. Differential cross sections of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as a function of rapidity for pp (top) and PbPb (bottom) collisions. The error bars represent the statistical uncertainties and the boxes the systematic uncertainties. For the $\Upsilon(3S)$ meson in PbPb collisions, the upper limits at 68% (green box) and 95% (green arrow) CL are shown. The global integrated luminosity uncertainties of 2.3% in pp collisions and $^{+3.4\%}_{-3.9\%}$ in PbPb collisions are not shown.

ond. Krouppa and Strickland treat the dynamical evolution using anisotropic hydrodynamics, where the relevant initial conditions are changed by varying the viscosity to entropy ratio, η/s , and the initial momentum-space anisotropy. The initial temperature is determined by requiring agreement with charged particle multiplicity and elliptic flow measurements. The model of Du, He, and Rapp uses a kinetic-rate equation to simulate the time evolution of bottomonium abundances in ultra-relativistic heavy ion collisions. It considers medium effects with temperature-dependent binding energies, and a lattice-QCD-based equation of state for the fireball evolution. Within the current theoretical and experimental uncertainties, both models are in agreement with the results.

Fig. 7 compares centrality-integrated R_{AA} values at $\sqrt{s_{NN}} = 2.76$ TeV to those at 5.02 TeV. The centrality-integrated R_{AA} for $\Upsilon(1S)$ is measured to be $0.376 \pm 0.013(\text{stat}) \pm 0.035(\text{syst})$, to be compared with the result at 2.76 TeV, $0.453 \pm 0.014(\text{stat}) \pm 0.046(\text{syst})$ [21]. The suppression at 5.02 TeV is larger by a factor of $\sim 1.20 \pm 0.15$ (in which only the T_{AA} uncertainty was considered correlated and therefore removed), although the two

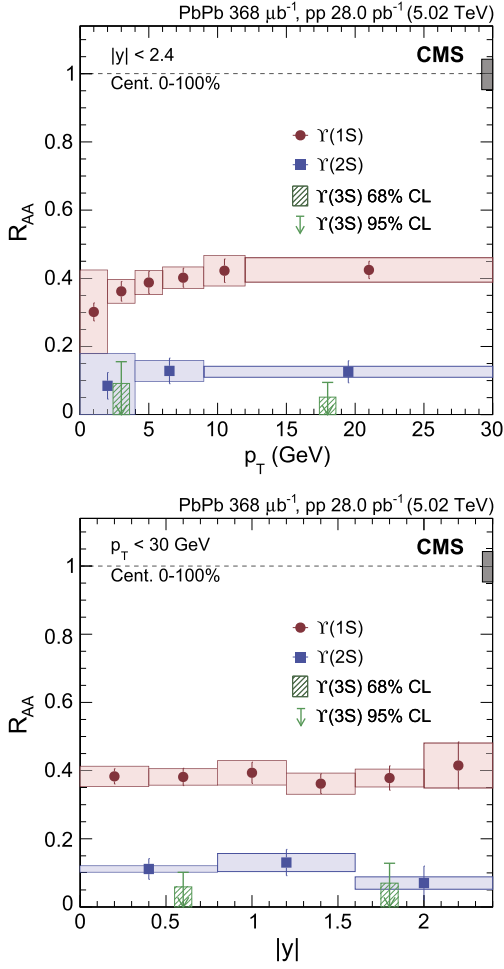


Fig. 4. Nuclear modification factors for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as functions of p_T (top) and rapidity (bottom). The error bars represent the statistical uncertainties and the boxes the systematic uncertainties. For the $\Upsilon(3S)$ meson, the upper limits at 68% (green box) and 95% (green arrow) CL are shown. The gray box near the line at unity displays the global uncertainty, which combines the uncertainties from T_{AA} , pp luminosity, and PbPb N_{MB} .

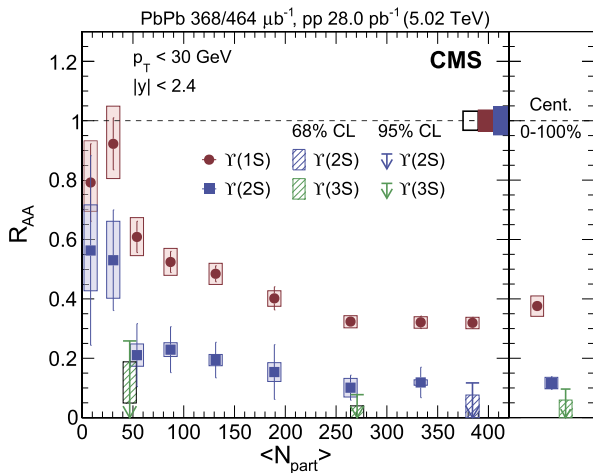


Fig. 5. Nuclear modification factors for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons as a function of $\langle N_{part} \rangle$. The boxes at the dashed line at unity represent global uncertainties: the open box for the integrated luminosity in pp collisions and N_{MB} in PbPb collisions, while the full boxes show the uncertainties of pp yields for $\Upsilon(1S)$ and $\Upsilon(2S)$ states (with the larger box corresponding to the excited state). For the $\Upsilon(3S)$ meson, the upper limits at 68% (green box) and 95% (green arrow) CL are shown.

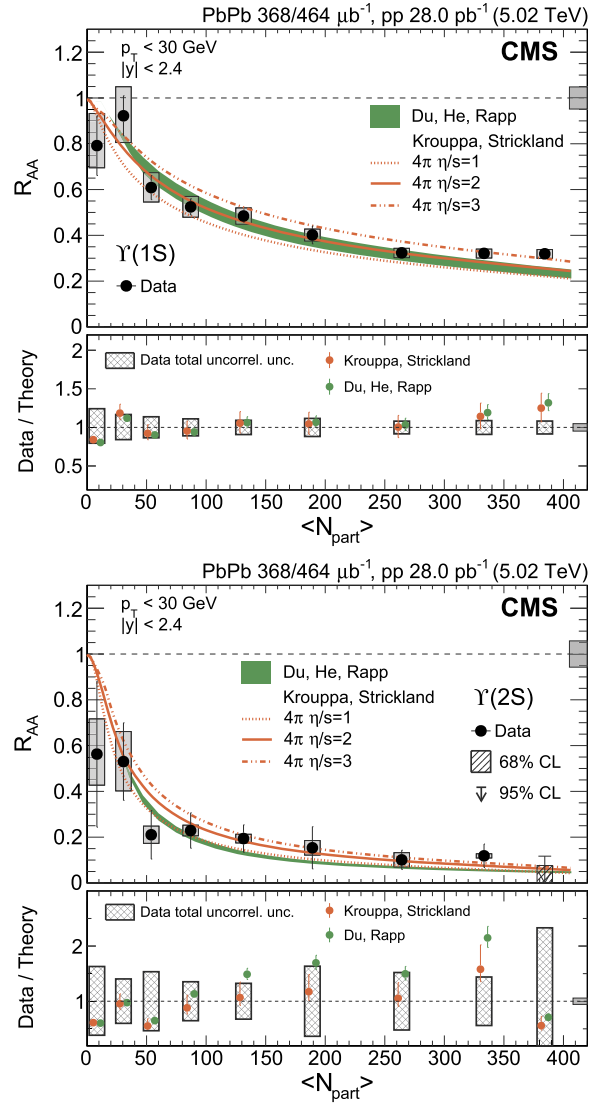


Fig. 6. Nuclear modification factors for the $\Upsilon(1S)$ (top) and $\Upsilon(2S)$ (bottom) mesons as a function of $\langle N_{part} \rangle$ compared to calculations from Krouppa and Strickland [9], and Du, He, and Rapp [12]. The box at the dashed line at unity represents the global uncertainty from the integrated luminosity in pp collisions, N_{MB} in PbPb collisions, and the total uncertainty in the pp yields. The data to theory ratios are shown in the bottom panels. For Ref. [9], the points correspond to the $4\pi \eta/s = 2$ curve, while the error bars show the difference between this one and the other two η/s curves. For Ref. [12], the points and error bars correspond to the center and width of the published theory band, respectively.

R_{AA} values are compatible within the uncertainties. The centrality-integrated results for the $\Upsilon(2S)$ and $\Upsilon(3S)$ states at 5.02 TeV are $R_{AA}(\Upsilon(2S)) = 0.117 \pm 0.022$ (stat) ± 0.019 (syst) and $R_{AA}(\Upsilon(3S)) = 0.022 \pm 0.038$ (stat) ± 0.016 (syst) (< 0.096 at 95% CL). Despite having a bigger binding energy than the already measured $\psi(2S)$ meson [18,19,27], no $\Upsilon(3S)$ meson signal is found in the PbPb data, in any of the studied kinematic regions. This suggests a p_T - and binding-energy-dependent interplay of different phenomena affecting quarkonium states that is yet to be fully understood [49].

Since the suppression is expected to be larger for higher temperatures in the medium, the R_{AA} results for the $\Upsilon(1S)$ meson at the two different collision energies can provide information on the medium temperature. The temperatures reported in the model of Krouppa and Strickland shown in Fig. 6 are $T = 641, 631, \text{ and } 629$ MeV corresponding to $4\pi \eta/s = 1, 2, \text{ and } 3$, respectively. For the model of Du, He, and Rapp, the temperatures are in

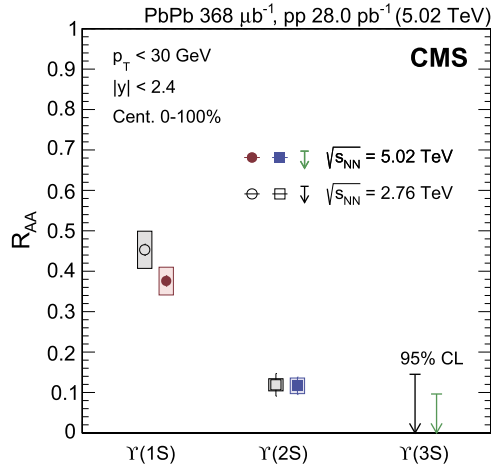


Fig. 7. Comparison of R_{AA} values for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV [21] for integrated centrality in the full kinematic range. The error bars represent the statistical uncertainties and the boxes the systematic uncertainties, including global uncertainties.

the range $T = 550\text{--}800$ MeV. The models, which are also in agreement with the results at 2.76 TeV [12,50], predict increases in the medium temperature for PbPb collisions of $\sim 16\%$ (Krouppa and Strickland) and $\sim 7\%$ (Du, He, and Rapp) between $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV.

6. Summary

Data from pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV collected with the CMS detector were analyzed to measure the cross sections of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons and their nuclear modification factors as functions of Υ transverse momentum (p_T) and rapidity (y), as well as PbPb collision centrality. A gradual decrease in R_{AA} with $\langle N_{part} \rangle$ for the $\Upsilon(1S)$ and $\Upsilon(2S)$ states is observed, while no significant dependence on p_T or y is found in the measured region. The suppression of $\Upsilon(1S)$ is larger than that seen at $\sqrt{s_{NN}} = 2.76$ TeV, although the two are compatible within uncertainties. The R_{AA} of the $\Upsilon(3S)$ state is measured to be below 0.096 at 95% confidence level, making this the strongest suppression observed for a quarkonium state in heavy ion collisions to date.

Acknowledgements

The authors would like to take this opportunity to acknowledge the invaluable contributions of Roy J. Glauber to the field of heavy ion nuclear physics. Without his work, our understanding of the modifications of particle production in heavy ion collisions, of which this paper is only one of very many, would not have been possible.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF,

Table 1

Glauber model parameters for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Parameter	Value
Nuclear radius (fm)	6.62 ± 0.06
Skin depth (fm)	0.546 ± 0.010
d_{min} (fm)	0.4 ± 0.4
σ_{NN}^{inel} (mb)	70 ± 5

Table 2

Centrality classes, average number of participating nucleons ($\langle N_{part} \rangle$), number of binary collisions ($\langle N_{coll} \rangle$), and the nuclear overlap (T_{AA}) for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, obtained using the Glauber model parameters of Table 1.

Centrality class	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$	(T_{AA}) (mb^{-1})
0–5%	$384.3^{+1.8}_{-2.0}$	1819^{+130}_{-137}	$25.98^{+0.47}_{-0.77}$
5–10%	$333.3^{+3.3}_{-3.2}$	1432^{+100}_{-106}	$20.46^{+0.38}_{-0.61}$
10–20%	$264.2^{+3.6}_{-3.8}$	1005^{+69}_{-73}	$14.35^{+0.33}_{-0.46}$
20–30%	$189.2^{+4.0}_{-4.1}$	606^{+41}_{-44}	$8.66^{+0.29}_{-0.33}$
30–40%	$131.4^{+4.0}_{-4.0}$	349^{+25}_{-26}	$4.98^{+0.24}_{-0.24}$
40–50%	$87.0^{+3.7}_{-3.7}$	186^{+15}_{-15}	$2.66^{+0.18}_{-0.17}$
50–60%	$53.9^{+3.2}_{-3.1}$	$90.7^{+8.9}_{-8.7}$	$1.30^{+0.12}_{-0.12}$
60–70%	$30.6^{+2.6}_{-2.4}$	$40.1^{+5.0}_{-4.6}$	$0.57^{+0.071}_{-0.064}$
70–100%	$8.3^{+1.0}_{-0.6}$	$7.7^{+1.2}_{-0.7}$	$0.11^{+0.018}_{-0.011}$
0–30%	$270.7^{+3.2}_{-3.4}$	$1079^{+74.3}_{-78.6}$	$15.41^{+0.33}_{-0.47}$
30–100%	$46.8^{+2.4}_{-1.2}$	$98.4^{+8.0}_{-6.4}$	$1.41^{+0.094}_{-0.061}$
0–100%	$114^{+2.6}_{-2.6}$	393^{+27}_{-28}	$5.61^{+0.16}_{-0.19}$

DFG, and HGF (Germany); GSRT (Greece); NKfia (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS and RFBR (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPcenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Appendix A. Glauber model values

Centrality variables computed using a Glauber model [44] are summarized in Tables 1 and 2, where d_{\min} is the minimum distance allowed between nucleons and $\sigma_{\text{NN}}^{\text{inel}}$ is the inelastic nucleon–nucleon (NN) cross section [36].

References

- [1] F. Karsch, E. Laermann, Thermodynamics and in-medium hadron properties from lattice QCD, in: R.C. Hwa, X.-N. Wang (Eds.), *Quark–Gluon Plasma III*, World Scientific Publishing Co. Pte. Ltd., 2004, arXiv:hep-lat/0305025.
- [2] E.V. Shuryak, Theory of hadronic plasma, *Sov. Phys. JETP* 47 (1978) 212, http://jetp.ac.ru/cgi-bin/dn/e_047_02_0212.pdf.
- [3] T. Matsui, H. Satz, J/ψ suppression by quark–gluon plasma formation, *Phys. Lett. B* 178 (1986) 416, [https://doi.org/10.1016/0370-2693\(86\)91404-8](https://doi.org/10.1016/0370-2693(86)91404-8).
- [4] S. Digal, P. Petreczky, H. Satz, Quarkonium feed down and sequential suppression, *Phys. Rev. D* 64 (2001) 094015, <https://doi.org/10.1103/PhysRevD.64.094015>, arXiv:hep-ph/0106017.
- [5] N. Brambilla, J. Ghiglieri, A. Vairo, P. Petreczky, Static quark–antiquark pairs at finite temperature, *Phys. Rev. D* 78 (2008) 014017, <https://doi.org/10.1103/PhysRevD.78.014017>, arXiv:0804.0993.
- [6] N. Brambilla, M.A. Escobedo, J. Ghiglieri, J. Soto, A. Vairo, Heavy quarkonium in a weakly-coupled quark–gluon plasma below the melting temperature, *J. High Energy Phys.* 09 (2010) 038, arXiv:1007.4156.
- [7] N. Brambilla, et al., Heavy quarkonium: progress, puzzles, and opportunities, *Eur. Phys. J. C* 71 (2011) 1534, <https://doi.org/10.1140/epjc/s10052-010-1534-9>, arXiv:1010.5827.
- [8] A. Andronic, et al., Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions, *Eur. Phys. J. C* 76 (2016) 107, <https://doi.org/10.1140/epjc/s10052-015-3819-5>, arXiv:1506.03981.
- [9] B. Krouppa, M. Strickland, Predictions for bottomonia suppression in 5.023 TeV Pb–Pb collisions, *Universe* 2 (2016) 16, <https://doi.org/10.3390/universe2030016>, arXiv:1605.03561.
- [10] N. Brambilla, M.A. Escobedo, J. Soto, A. Vairo, Quarkonium suppression in heavy-ion collisions: an open quantum system approach, *Phys. Rev. D* 96 (2017) 034021, <https://doi.org/10.1103/PhysRevD.96.034021>, arXiv:1612.07248.
- [11] A. Emerick, X. Zhao, R. Rapp, Bottomonia in the quark–gluon plasma and their production at RHIC and LHC, *Eur. Phys. J. A* 48 (2012) 72, <https://doi.org/10.1140/epja/i2012-12072-y>, arXiv:1111.6537.
- [12] X. Du, R. Rapp, M. He, Color screening and regeneration of bottomonia in high-energy heavy-ion collisions, *Phys. Rev. C* 96 (2017) 054901, <https://doi.org/10.1103/PhysRevC.96.054901>, arXiv:1706.08670.
- [13] R.L. Thews, M. Schroedter, J. Rafelski, Enhanced J/ψ production in deconfined quark matter, *Phys. Rev. C* 63 (2001) 054905, <https://doi.org/10.1103/PhysRevC.63.054905>, arXiv:hep-ph/0007323.
- [14] M.I. Gorenstein, A.P. Kostyuk, H. Stoecker, W. Greiner, Statistical coalescence model with exact charm conservation, *Phys. Lett. B* 509 (2001) 277, [https://doi.org/10.1016/S0370-2693\(01\)00516-0](https://doi.org/10.1016/S0370-2693(01)00516-0), arXiv:hep-ph/0010148.
- [15] A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Evidence for charmonium generation at the phase boundary in ultra-relativistic nuclear collisions, *Phys. Lett. B* 652 (2007) 259, <https://doi.org/10.1016/j.physletb.2007.07.036>, arXiv:nucl-th/0701079.
- [16] A. Mócsy, P. Petreczky, Color screening melts quarkonium, *Phys. Rev. Lett.* 99 (2007) 211602, <https://doi.org/10.1103/PhysRevLett.99.211602>, arXiv:0706.2183.
- [17] CMS Collaboration, Suppression and azimuthal anisotropy of prompt and non-prompt J/ψ production in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, *Eur. Phys. J. C* 77 (2017) 252, <https://doi.org/10.1140/epjc/s10052-017-4781-1>, arXiv:1610.00613.
- [18] CMS Collaboration, Measurement of prompt $\psi(2S) \rightarrow J/\psi$ yield ratios in Pb–Pb and p–p collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, *Phys. Rev. Lett.* 113 (2014) 262301, <https://doi.org/10.1103/PhysRevLett.113.262301>, arXiv:1410.1804.
- [19] ALICE Collaboration, Differential studies of inclusive J/ψ and $\psi(2S)$ production at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, *J. High Energy Phys.* 05 (2016) 179, [https://doi.org/10.1007/JHEP05\(2016\)179](https://doi.org/10.1007/JHEP05(2016)179), arXiv:1506.08804.
- [20] ALICE Collaboration, Inclusive, prompt and non-prompt J/ψ production at mid-rapidity in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, *J. High Energy Phys.* 07 (2015) 051, [https://doi.org/10.1007/JHEP07\(2015\)051](https://doi.org/10.1007/JHEP07(2015)051), arXiv:1504.07151.
- [21] CMS Collaboration, Suppression of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ production in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, *Phys. Lett. B* 770 (2017) 357, <https://doi.org/10.1016/j.physletb.2017.04.031>, arXiv:1611.01510.
- [22] ALICE Collaboration, Suppression of $\Upsilon(1S)$ at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, *Phys. Lett. B* 738 (2014) 361, <https://doi.org/10.1016/j.physletb.2014.10.001>, arXiv:1405.4493.
- [23] A. Adare, et al., PHENIX, J/ψ production vs centrality, transverse momentum, and rapidity in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV, *Phys. Rev. Lett.* 98 (2007) 232301, <https://doi.org/10.1103/PhysRevLett.98.232301>, arXiv:nucl-ex/0611020.
- [24] L. Adamczyk, et al., STAR, Energy dependence of J/ψ production in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 39, 62.4$ and 200 GeV, *Phys. Lett. B* 771 (2017) 13, <https://doi.org/10.1016/j.physletb.2017.04.078>, arXiv:1607.07517.
- [25] L. Adamczyk, et al., STAR, Suppression of Υ production in d+Au and Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV, *Phys. Lett. B* 735 (2014) 127, <https://doi.org/10.1016/j.physletb.2014.06.028>, arXiv:1312.3675, Erratum: <https://doi.org/10.1016/j.physletb.2015.01.046>.
- [26] CMS Collaboration, Relative modification of prompt $\psi(2S)$ and J/ψ yields from pp to PbPb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, *Phys. Rev. Lett.* 188 (2017) 162301, <https://doi.org/10.1103/PhysRevLett.188.162301>, arXiv:1611.01438.
- [27] CMS Collaboration, Measurement of prompt and nonprompt charmonium suppression in PbPb collisions at 5.02 TeV, arXiv:1712.08959, 2017.
- [28] CMS Collaboration, Strong suppression of Υ excited states in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, *Phys. Rev. Lett.* 120 (2018) 142301, <https://doi.org/10.1103/PhysRevLett.120.142301>, arXiv:1706.05984.
- [29] ALICE Collaboration, Υ suppression at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, arXiv:1805.04387, 2018.
- [30] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, *J. Instrum.* 7 (2012) P10002, <https://doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.
- [31] CMS Collaboration, Dependence on pseudorapidity and centrality of charged hadron production in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, *J. High Energy Phys.* 08 (2011) 141, [https://doi.org/10.1007/JHEP08\(2011\)141](https://doi.org/10.1007/JHEP08(2011)141), arXiv:1107.4800.
- [32] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [33] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* 9 (2014) P10009, <https://doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [34] CMS Collaboration, Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV, *J. High Energy Phys.* 02 (2010) 041, [https://doi.org/10.1007/JHEP02\(2010\)041](https://doi.org/10.1007/JHEP02(2010)041), arXiv:1002.0621.
- [35] CMS Collaboration, Observation and studies of jet quenching in PbPb collisions at nucleon–nucleon center-of-mass energy $= 2.76$ TeV, *Phys. Rev. C* 84 (2011) 024906, <https://doi.org/10.1103/PhysRevC.84.024906>, arXiv:1102.1957.
- [36] CMS Collaboration, Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, *J. High Energy Phys.* 04 (2017) 039, [https://doi.org/10.1007/JHEP04\(2017\)039](https://doi.org/10.1007/JHEP04(2017)039), arXiv:1611.01664.
- [37] T. Sjöstrand, S. Ask, R. Jesper Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, O.C. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* 191 (2015) 159, <https://doi.org/10.1016/j.cpc.2015.01.024>, arXiv:1410.3012.
- [38] I.P. Lokhtin, A.M. Snigirev, A model of jet quenching in ultrarelativistic heavy ion collisions and high- p_t hadron spectra at RHIC, *Eur. Phys. J. C* 45 (2006) 211, <https://doi.org/10.1140/epjc/s2005-02426-3>, arXiv:hep-ph/0506189.
- [39] S. Agostinelli, et al., GEANT4, GEANT4 – a simulation toolkit, *Nucl. Instrum. Methods A* 506 (2003) 250, [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8).
- [40] M.J. Oreglia, A Study of the Reactions $\psi(2S)^+ \rightarrow \gamma\gamma\psi(2S)$, Ph.D. thesis, Stanford University, 1980, SLAC Report R-236, p. 184, <http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-236.pdf>.
- [41] Particle Data Group, C. Patrignani, et al., Review of particle physics, *Chin. Phys. C* 40 (2016) 100001, <https://doi.org/10.1088/1674-1137/40/10/100001>.
- [42] CMS Collaboration, CMS luminosity calibration for the pp reference run at $\sqrt{s} = 5.02$ TeV, CMS physics analysis summary, CMS-PAS-LUM-16-001, <https://cds.cern.ch/record/2235781>, 2016.
- [43] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Glauber modeling in high energy nuclear collisions, *Annu. Rev. Nucl. Part. Sci.* 57 (2007) 205, <https://doi.org/10.1146/annurev.nucl.57.090506.123020>, arXiv:nucl-ex/0701025.
- [44] C. Loizides, J. Nagle, P. Steinberg, Improved version of the PHOBOS Glauber Monte Carlo, *SoftwareX* 1–2 (2015) 13, <https://doi.org/10.1016/j.softx.2015.05.001>, arXiv:1408.2549.
- [45] C. Loizides, J. Kamin, D. d’Enterria, Improved Monte Carlo Glauber predictions at present and future nuclear colliders, *Phys. Rev. C* 97 (2018) 054910, <https://doi.org/10.1103/PhysRevC.97.054910>.
- [46] CMS Collaboration, Measurement of the B^\pm meson nuclear modification factor in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, *Phys. Rev. Lett.* 119 (2017) 152301, <https://doi.org/10.1103/PhysRevLett.119.152301>, arXiv:1705.04727.
- [47] CMS Collaboration, Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, *Phys. Lett. B* 782 (2018) 474, <https://doi.org/10.1016/j.physletb.2018.05.074>, arXiv:1708.04962.
- [48] G.J. Feldman, R.D. Cousins, A unified approach to the classical statistical analysis of small signals, *Phys. Rev. D* 57 (1998) 3873, <https://doi.org/10.1103/PhysRevD.57.3873>, arXiv:physics/9711021.
- [49] G. Aarts, et al., Heavy-flavor production and medium properties in high-energy nuclear collisions – what next?, *Eur. Phys. J. A* 53 (2017) 93, <https://doi.org/10.1140/epja/i2017-12282-9>, arXiv:1612.08032.
- [50] B. Krouppa, R. Ryblewski, M. Strickland, Bottomonia suppression in 2.76 TeV Pb–Pb collisions, *Phys. Rev. C* 92 (2015) 061901, <https://doi.org/10.1103/PhysRevC.92.061901>, arXiv:1507.03951.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler¹, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskiy, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, T. Maerschalk, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, S. Salva, D. Trocino, M. Tytgat, W. Verbeke, M. Vit, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, P. David, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

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

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

S. Ahuja^a, C.A. Bernardes^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a, Romero Abad^b, J.C. Ruiz Vargas^b

^a Universidade Estadual Paulista, São Paulo, Brazil

^b Universidade Federal do ABC, São Paulo, Brazil

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

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

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁵, X. Gao⁵, L. Yuan

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, J. Li, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang⁵

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

Y. Wang

Tsinghua University, Beijing, China

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, 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, B. Mesic, A. Starodumov⁶, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger⁷, M. Finger Jr.⁷

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

M.A. Mahmoud^{8,9}, Y. Mohammed⁸, E. Salama^{9,10}

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

S. Bhowmik, R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

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

A. Abdulsalam¹¹, C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

J.-L. Agram¹², J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, C. Collard, E. Conte¹², X. Coubez, F. Drouhin¹², J.-C. Fontaine¹², D. Gelé, U. Goerlach, M. Jansová, P. Juillot, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 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, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹³, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili¹⁴

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze⁷

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov¹³

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

A. Albert, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁵

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁷, J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel¹⁸, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann¹⁸, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁵, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁵, S.M. Heindl, U. Husemann, F. Kassel¹⁵, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Karlsruher Institut fuer Technologie Germany

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, I. Topsis-Giotis

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

G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Giannelios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradis, J. Strologas, F.A. Triantis, D. Tsiotis

University of Ioánnina, Ioánnina, Greece

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres¹⁹

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

G. Bencze, C. Hajdu, D. Horvath²⁰, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók¹⁹, P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²², P. Mal, K. Mandal, A. Nayak²³, D.K. Sahoo²², N. Sahoo, S.K. Swain

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

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, N. Dhingra, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, Ashok Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, Aashaq Shah, R. Sharma

University of Delhi, Delhi, India

R. Bhardwaj²⁴, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁴, D. Bhowmik, S. Dey, S. Dutt²⁴, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur²⁴

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁵, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, T. Sarkar²⁵, N. Wickramage²⁶

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁸, F. Rezaei Hosseinabadi, B. Safarzadeh²⁹, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, 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}, F. Errico^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, 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}, A. Sharma^a, L. Silvestris^{a,15}, R. Venditti^a, P. Verwilligen^a, G. Zito^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. Borghonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a,

L. Guiducci ^{a,b}, F. Iemmi, S. Marcellini ^a, G. Masetti ^a, A. Montanari ^a, F.L. Navarria ^{a,b}, A. Perrotta ^a, A.M. Rossi ^{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}, S. Costa ^{a,b}, A. Di Mattia ^a, F. Giordano ^{a,b}, R. Potenza ^{a,b}, A. Tricoli ^{a,b}, C. Tuve ^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli ^a, K. Chatterjee ^{a,b}, V. Ciulli ^{a,b}, C. Civinini ^a, R. D'Alessandro ^{a,b}, E. Focardi ^{a,b}, G. Latino, P. Lenzi ^{a,b}, M. Meschini ^a, S. Paoletti ^a, L. Russo ^{a,30}, G. Sguazzoni ^a, D. Strom ^a, L. Viliani ^a

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera ¹⁵

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli ^{a,b}, F. Ferro ^a, F. Ravera ^{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 ^b, L. Brianza ^{a,b}, F. Brivio ^{a,b}, V. Ciriolo ^{a,b,15}, M.E. Dinardo ^{a,b}, S. Fiorendi ^{a,b}, S. Gennai ^a, A. Ghezzi ^{a,b}, P. Govoni ^{a,b}, M. Malberti ^{a,b}, S. Malvezzi ^a, R.A. Manzoni ^{a,b}, D. Menasce ^a, L. Moroni ^a, M. Paganoni ^{a,b}, K. Pauwels ^{a,b}, D. Pedrini ^a, S. Pigazzini ^{a,b,31}, S. Ragazzi ^{a,b}, T. Tabarelli de Fatis ^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo ^a, N. Cavallo ^{a,c}, S. Di Guida ^{a,d,15}, F. Fabozzi ^{a,c}, F. Fienga ^{a,b}, A.O.M. Iorio ^{a,b}, W.A. Khan ^a, L. Lista ^a, S. Meola ^{a,d,15}, P. Paolucci ^{a,15}, C. Sciacca ^{a,b}, F. Thyssen ^a

^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, L. Benato ^{a,b}, D. Bisello ^{a,b}, A. Boletti ^{a,b}, A. Carvalho Antunes De Oliveira ^{a,b}, M. Dall'Osso ^{a,b}, P. De Castro Manzano ^a, T. Dorigo ^a, U. Dosselli ^a, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, A. Gozzelino ^a, S. Lacaprara ^a, P. Lujan, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, N. Pozzobon ^{a,b}, P. Ronchese ^{a,b}, R. Rossin ^{a,b}, F. Simonetto ^{a,b}, A. Tiko, E. Torassa ^a, S. Ventura ^a, M. Zanetti ^{a,b}, P. Zotto ^{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, A. Magnani ^a, 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,b}, P. Vitulo ^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

L. Alunni Solestizi ^{a,b}, M. Biasini ^{a,b}, G.M. Bilei ^a, C. Cecchi ^{a,b}, 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,15}, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^{a,30}, F. Ligabue^{a,c}, T. Lomtadze^a, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, 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

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{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}, C. Biino^a, N. Cartiglia^a, R. Castello^{a,b}, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, B. Kiani^{a,b}, 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}, 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. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{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, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, South Korea

H. Kim, D.H. Moon, G. Oh

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

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali³², F. Mohamad Idris³³, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

M.C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, G. Ramirez-Sanchez, I. Heredia-De La Cruz³⁴, R.I. Rabadan-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, 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

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁵, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucchio, J. Varela

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

A. Baginyan, A. Golunov, I. Golutvin, V. Karjavin, I. Kashunin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev^{36,37}, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, V. Trofimov, B.S. Yuldashev³⁸, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev, A. Bylinkin³⁷

Moscow Institute of Physics and Technology, Moscow, Russia

M. Chadeeva⁴¹, O. Markin, P. Parygin, D. Philippov, S. Polikarpov, V. Rusinov

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

V. Andreev, M. Azarkin³⁷, I. Dremin³⁷, M. Kirakosyan³⁷, S.V. Rusakov, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy⁴², O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

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

V. Blinov⁴³, D. Shtol⁴³, Y. Skovpen⁴³

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics of NRC 'Kurchatov Institute', Protvino, Russia

A. Babaev

National Research Tomsk Polytechnic University, Tomsk, Russia

P. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

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

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte,

A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁸, J. Kieseler, V. Knünz, A. Kornmayer, M.J. Kortelainen, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁵, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi⁴⁶, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁷, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Tsirou, V. Veckalns⁴⁸, M. Verweij, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl[†], L. Caminada⁴⁹, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, L. Bäni, P. Berger, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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

T.K. Aarrestad, C. Amsler⁵⁰, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

Universität Zürich, Zurich, Switzerland

V. Candelise, Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Arun Kumar, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, K. Kovitangoon, G. Singh, N. Srimanobhas

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

M.N. Bakirci⁵¹, A. Bat, F. Boran, S. Cerci⁵², S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵³, E.E. Kangal⁵⁴, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁵, B. Tali⁵², U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

G. Karapinar⁵⁶, K. Ocalan⁵⁷, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, S. Tekten, E.A. Yetkin⁶⁰

Bogazici University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu

Istanbul Technical 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

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶¹, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

A. Belyaev⁶², C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash⁶³, A. Nikitenko⁶, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁴, T. Virdee¹⁵, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington DC, USA

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

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁵, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, D. Taylor, K. Tos, M. Tripathi, S. Tuli, Z. Wang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Los Angeles, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁶, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

D. Anderson, A. Bornheim, J. Bunn, I. Dutta, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. Macdonald, T. Mulholland, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro⁶⁷, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck, W. Wu

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

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

B. Bilki⁶⁸, W. Clarida, K. Dilsiz⁶⁹, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁷⁰, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷¹, Y. Onel, F. Ozok⁷², A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁶, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, B. Liu, W. Luo, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, N. Parashar

Purdue University Northwest, Hammond, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

R. Ciesielski, K. Goulianos, C. Mesropian

The Rockefeller University, New York, USA

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur,

S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali⁷³, A. Castaneda Hernandez⁷³, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁴, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderov, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbbers, A. Lanaro, A. Levine, K. Long, R. Loveless, V. Rekovic, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

University of Wisconsin–Madison, Madison, WI, USA

† Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

³ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁴ Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

⁵ Also at Université Libre de Bruxelles, Bruxelles, Belgium.

⁶ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

⁷ Also at Joint Institute for Nuclear Research, Dubna, Russia.

⁸ Also at Fayoum University, El-Fayoum, Egypt.

⁹ Now at British University in Egypt, Cairo, Egypt.

¹⁰ Now at Ain Shams University, Cairo, Egypt.

¹¹ Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.

¹² Also at Université de Haute Alsace, Mulhouse, France.

¹³ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

¹⁴ Also at Tbilisi State University, Tbilisi, Georgia.

¹⁵ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

¹⁶ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

¹⁷ Also at University of Hamburg, Hamburg, Germany.

¹⁸ Also at Brandenburg University of Technology, Cottbus, Germany.

¹⁹ Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

²⁰ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

²¹ Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

²² Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

²³ Also at Institute of Physics, Bhubaneswar, India.

²⁴ Also at Shoolini University, Solan, India.

²⁵ Also at University of Visva-Bharati, Santiniketan, India.

²⁶ Also at University of Ruhuna, Matara, Sri Lanka.

- 27 Also at Isfahan University of Technology, Isfahan, Iran.
- 28 Also at Yazd University, Yazd, Iran.
- 29 Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- 30 Also at Università degli Studi di Siena, Siena, Italy.
- 31 Also at INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy.
- 32 Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- 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 Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
- 39 Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- 40 Also at University of Florida, Gainesville, USA.
- 41 Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- 42 Also at INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, 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 University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- 46 Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- 47 Also at National and Kapodistrian University of Athens, Athens, Greece.
- 48 Also at Riga Technical University, Riga, Latvia.
- 49 Also at Universität Zürich, Zurich, Switzerland.
- 50 Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
- 51 Also at Gaziosmanpasa University, Tokat, Turkey.
- 52 Also at Adiyaman University, Adiyaman, Turkey.
- 53 Also at Istanbul Aydin University, Istanbul, Turkey.
- 54 Also at Mersin University, Mersin, Turkey.
- 55 Also at Piri Reis University, Istanbul, Turkey.
- 56 Also at Izmir Institute of Technology, Izmir, Turkey.
- 57 Also at Necmettin Erbakan University, Konya, Turkey.
- 58 Also at Marmara University, Istanbul, Turkey.
- 59 Also at Kafkas University, Kars, Turkey.
- 60 Also at Istanbul Bilgi University, Istanbul, Turkey.
- 61 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- 62 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- 63 Also at Monash University, Faculty of Science, Clayton, Australia.
- 64 Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- 65 Also at Bethel University, St. Paul, USA.
- 66 Also at Utah Valley University, Orem, USA.
- 67 Also at Purdue University, West Lafayette, USA.
- 68 Also at Beykent University, Istanbul, Turkey.
- 69 Also at Bingol University, Bingol, Turkey.
- 70 Also at Erzincan University, Erzincan, Turkey.
- 71 Also at Sinop University, Sinop, Turkey.
- 72 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- 73 Also at Texas A&M University at Qatar, Doha, Qatar.
- 74 Also at Kyungpook National University, Daegu, Korea.