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Observation of the $Y(3S)$ meson and suppression of Y states in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration*

Abstract

The production of $Y(2S)$ and $Y(3S)$ mesons in lead-lead (PbPb) and proton-proton (pp) collisions is studied in their dimuon decay channel using the CMS detector at the LHC. The $Y(3S)$ meson is observed for the first time in PbPb collisions, with a significance above five standard deviations. The ratios of yields measured in PbPb and pp collisions are reported for both the $Y(2S)$ and $Y(3S)$ mesons, as functions of transverse momentum and PbPb collision centrality. These ratios, when appropriately scaled, are significantly less than unity, indicating a suppression of Y yields in PbPb collisions. This suppression increases from peripheral to central PbPb collisions. Furthermore, the suppression is stronger for $Y(3S)$ mesons compared to $Y(2S)$ mesons, extending the pattern of sequential suppression of quarkonium states in nuclear collisions previously seen for the J/ψ , $\psi(2S)$, $Y(1S)$, and $Y(2S)$ mesons.

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High-energy heavy ion collisions are useful to study the properties of the quark-gluon plasma (QGP), a strongly coupled medium of deconfined quarks and gluons. It has long been proposed that the yields of quarkonium states are suppressed because of interactions in the QGP [1–7]. These in-medium effects have been theoretically studied with calculations based on lattice quantum chromodynamics and effective field theories [8–11]. One of the fundamental aspects of these interactions with the medium is that the amount of suppression for different quarkonium states is expected to be stronger for those with smaller binding energies. On the other hand, quarkonia can also be produced by recombination processes [7–10, 12–15]. Studies of Y production are particularly interesting because the number of quark-antiquark pairs in a single lead-lead (PbPb) collision is much smaller for bottom than for charm quarks, so that the recombination of independently produced quarks and antiquarks can be neglected [16].

Experimentally, the dynamics of quarkonium production in heavy ion collisions are commonly studied using the nuclear modification factor (R_{AA}), which is defined as the ratio of particle yields in nucleus-nucleus (AA) collisions to those in proton-proton (pp) collisions scaled by the average number of binary nucleon-nucleon (NN) interactions in the AA events.

Measurements of R_{AA} have been performed at the SPS, RHIC, and LHC accelerators, both in the charmonium and bottomonium families [17–32]. For Y states, R_{AA} results have been reported by CMS [27], ALICE [28], and ATLAS [29] at the LHC, and by STAR [30, 31] and PHENIX [32] at RHIC. These results show a significant suppression of $Y(1S)$ mesons in heavy ion collisions, and $Y(2S)$ mesons are even more suppressed. For the $Y(3S)$ meson, only upper limits have been reported in AA collisions, by CMS [27].

In this Letter, the first observation of the $Y(3S)$ meson in PbPb collisions is reported. Nuclear modification factors for $Y(2S)$ and $Y(3S)$ mesons are found using PbPb and pp data collected with the CMS detector at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV in 2018 and 2017, respectively. The double ratios, obtained by dividing the $Y(3S)$ over $Y(2S)$ yield ratios in PbPb by those for pp collisions, are also reported. The Y states are identified using their decay into two oppositely charged muons. The results are presented as functions of PbPb collision centrality, as well as Y meson transverse momentum (p_T) in the rapidity range of $|y| < 2.4$. Centrality is related to the overlap of the two lead nuclei and is quantified as the percentage of the total inelastic nucleus-nucleus hadronic cross section, with 0% representing the largest overlap [33]. Tabulated results are provided in the HEPData record for this analysis [34].

The CMS apparatus [35] is a multipurpose, nearly hermetic detector, designed to trigger on [36, 37] and identify electrons, muons, photons, and hadrons [38–41]. A superconducting solenoid of 6 m internal diameter provides a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and strip tracker, a crystal electromagnetic calorimeter, and a brass-scintillator hadron calorimeter. The pseudorapidity (η) coverage of these calorimeters is extended by the forward hadron (HF) calorimeters, located at $3 < |\eta| < 5$. Muons are measured in the range $|\eta| < 2.4$ using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Events are filtered using a two-tiered trigger system [37]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors [36]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software. Centrality is determined using the sum of the total transverse energy deposited in both of the HF calorimeters [42].

The events are selected online using an L1 trigger requiring two muons in a single bunch crossing without explicit requirements on the muon momentum. Additional criteria on the single-muon quality and dimuon mass selection are applied at the HLT in PbPb collisions [43]. The collected pp (PbPb) sample corresponds to an integrated luminosity of 300 pb^{-1} (1.61 nb^{-1}) [44–

46].

In order to reject beam-gas interactions and nonhadronic collisions, an offline event selection is applied for pp and PbPb collisions [47]. For both systems, events are required to have at least one reconstructed primary vertex (PV), which is the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone [48]. In addition, more than 25% of the tracks have to pass a tight track-quality selection in pp collisions [41, 47]. For PbPb collisions, selections are applied on the silicon pixel detector cluster widths [47, 49] and on the HF information [43]. The reconstructed muons are selected using criteria that optimize the muon identification [43]. In addition, to ensure high reconstruction efficiency for Y mesons, the individual muons are required to have $p_T > 3.5 \text{ GeV}/c$ and $|\eta| < 2.4$.

Monte Carlo (MC) samples for each Y meson are simulated using the “CP5” tune [50] of PYTHIA 8.212 [51], with the assumption that they are produced unpolarized [52–55]. To reproduce the background environment in PbPb collisions, each PYTHIA Y event is embedded into a PbPb event simulated using HYDJET 1.9 [56]. The MC events are then weighted to match the measured Y p_T spectra for either pp or PbPb collisions [43]. A full simulation of the CMS detector using GEANT4 [57] is performed to determine the acceptance and reconstruction efficiency. The feed-down contributions, i.e., decays from heavier quarkonium states, are not considered in this analysis. The effect of such contributions on the kinematic distributions of the simulated Y states is, to a large extent, accounted for by the weighting procedure.

The dimuon invariant mass distribution is studied in the $8\text{--}14 \text{ GeV}/c^2$ region. To reduce the large amount of background in PbPb collisions, signal-enriched dimuon candidates are selected using boosted decision trees (BDTs), using the TMVA package [58]. For the BDT training, MC samples and dimuons from the invariant mass spectra in data except where the Y signals are present (i.e., $8.8\text{--}10.8 \text{ GeV}/c^2$) are used for the signal and background, respectively. In both cases, the dimuons must satisfy the selection criteria previously mentioned. The training variables for the BDT include: the χ^2 probability of the dimuon vertex fit; the distance of closest approach of the Y meson momentum vector relative to the PV; the distance between the PV and the dimuon vertex, both in three dimensions and projected onto the transverse plane; the pointing angle, defined as the angle between the line segment connecting the PV and decay vertex and the momentum vector of the reconstructed particle candidates, again in three dimensions and projected onto the transverse plane. To avoid potential biases, the algorithms and selections are optimized using a quarter of the PbPb data for dimuon $p_T < 30 \text{ GeV}/c$, $|y| < 2.4$, and centrality 0–90%. A threshold is set on the resulting BDT variable to maximize the signal significance, $S/\sqrt{S+B}$, where S and B represent the yields for signal and background, respectively.

The yields of the Y states are extracted by an extended unbinned maximum likelihood fit to the dimuon invariant mass distributions. The line shape of each Y state is modeled by a sum of three Crystal Ball (CB) functions [59], with common means and tail parameters but independent widths. The means and widths for the $Y(2S)$ and $Y(3S)$ are found by multiplying the fitted values of those for the $Y(1S)$ by the ratio of their world-average masses [60] over that for the $Y(1S)$. All other fit parameters, except the yields for the excited states, are fixed to those found for the ground state. The shape parameters of the signal fit model, with the exception of the $Y(1S)$ mean, are constrained by Gaussian probability density functions (pdfs), of means and widths determined, for each p_T bin, from the central values and uncertainties obtained from fits to the MC samples. The background of the mass distribution is modeled using three different functional forms: an error function multiplied by an exponential, a simple exponential, and a Chebyshev polynomial. An Akaike information criterion (AIC) test [61], which estimates the relative quality of each function, is performed to determine, for each kinematic

region, the nominal function for the background pdf. The order of the Chebyshev polynomial is chosen based on a log likelihood ratio test [62].

Figure 1 shows the dimuon invariant mass distribution in PbPb collisions, integrated over the full kinematic range, $p_T < 30 \text{ GeV}/c$ and $|y| < 2.4$, and centrality 0–90%.

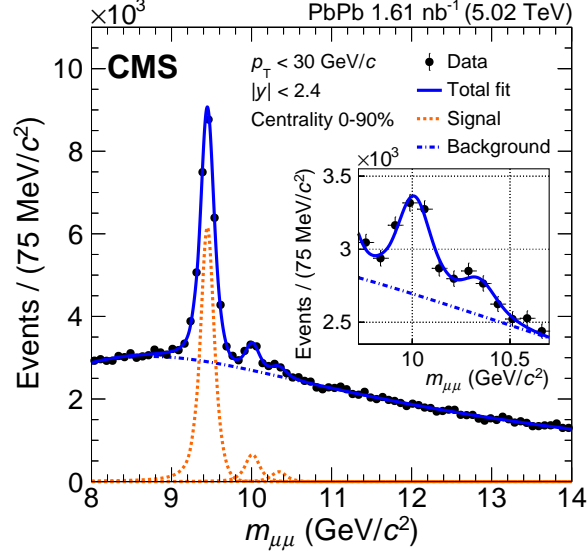


Figure 1: Dimuon invariant mass distribution in PbPb collisions, integrated over the full kinematic range $p_T < 30 \text{ GeV}/c$ and $|y| < 2.4$. The solid curves show the result of the fit, whereas the orange dashed and blue dash-dotted curves represent the three Y states and the background, respectively. The inset shows the region around the mass of the $Y(3S)$ meson.

Acceptance and efficiency correction factors are applied to the extracted number of Y mesons to compute the R_{AA} values. The acceptance is computed with simulated samples, as the fraction of generated Y mesons that decay to muons of $p_T^\mu > 3.5 \text{ GeV}/c$ and $|\eta^\mu| < 2.4$. The efficiency is also evaluated with simulated events, as the fraction of accepted dimuons that are reconstructed and pass the trigger and analysis selection criteria. To take into account possible differences between data and MC simulations, the individual components of the dimuon efficiency (reconstruction, identification, and triggering) are measured using single muons from J/ψ meson decays in both data and simulation, with the *tag-and-probe* (T&P) method [63]. The data over simulation ratios, for each of the three components, are applied as event-by-event weights to each dimuon. The acceptance and efficiency values for the full kinematic region are 40% (43%) and 37% (38%) for $Y(2S)$ ($Y(3S)$) in PbPb collisions.

The systematic uncertainties are analyzed for various sources and summarized in Table 1. For each source, the difference of the signal yields in the variation compared to the nominal is taken as the systematic uncertainty. Three sources are considered for the uncertainty in the signal extraction: choice of signal pdf parameters, choice of signal pdf, and choice of background pdf. For the parameterization of the signal pdf, the fit results using either the $Y(2S)$ or $Y(3S)$ MC samples are used to determine different values for the mean and width of the Gaussian function for each signal parameter. The signal pdf is modified from a sum of three CB functions to a sum of two CB functions and a Gaussian function. For the background pdf systematic study, functions rejected by the AIC test in the nominal background pdf determination, for each kinematic region, are used as alternatives.

The acceptance and efficiency uncertainties are evaluated by varying the p_T weights (used to

match the simulated and measured Y p_T spectra) by their fit uncertainties. The uncertainty on the T&P correction of the single muon efficiencies is propagated to the dimuon efficiencies.

For the PbPb analysis, additional uncertainties arise from the BDT training and centrality calibration. To evaluate the uncertainty reflecting the BDT training, the event samples used as signal or background are split in two. Each trained algorithm is applied to the other half of the samples and the average of the two BDT variable values is used as the nominal. Alternatively, the two individual values of each BDT variable are used and the largest difference of the corrected signal yields compared to the nominal is taken as the systematic uncertainty. The centrality calibration is varied by changing the boundaries of the centrality intervals [43] considering the inefficiency in the event selection.

The total uncertainty, dominated by the uncertainties from the BDT training and background pdf, is the quadratic sum of the uncertainties from all the different sources. In addition, global uncertainties reflect the integrated luminosity of the pp data set (1.9%) [44] and the number of minimum bias PbPb collision events (N_{MB}) sampled by the trigger (1.3%) [64]. The overlap function T_{AA} for each centrality interval is the average number of binary NN collisions per PbPb interaction divided by the inelastic NN cross section. Its uncertainty is estimated by varying the Glauber model parameters within their uncertainties [65] and is found to be in the range of 1.8–5.4%.

Table 1: Systematic uncertainties from various sources in pp and PbPb collisions listed in percentage. The global uncertainties described in the text are not included in the total uncertainties.

Source	Y(2S) (%)		Y(3S) (%)		Y(3S)/Y(2S) (%)	
	pp	PbPb	pp	PbPb	pp	PbPb
BDT selection	—	0.3–9.0	—	1.5–18.6	—	1.2–22.8
Background PDF	0.1–1.4	0.3–11.7	0.2–1.6	1.4–21.4	<0.5	0.6–17.6
Signal PDF	0.1–1.1	0.5–2.6	0.4–1.1	0.1–2.5	0.3–0.6	0.1–3.0
Signal parameter	0.1–1.2	0.0–3.8	0.1–1.6	0.3–3.7	0.05–1.4	0.1–0.9
Event selection	—	0.0–0.5	—	0.2–13.1	—	0.1–13.6
Correction factors	<0.1	<0.5	<0.1	<0.4	<2.0	
T&P	0.9–1.0	3.8–4.5	0.9–1.1	3.8–4.4	—	
Total uncertainty	1.0–1.8	3.9–13.5	1.1–2.2	6.0–22.2	0.4–1.5	4.1–23.8

The significance of the Y(3S) in PbPb collisions corresponds to 5.6 standard deviations, calculated using the fit likelihood ratio [66–68]. The nuclear modification factors are computed as

$$R_{AA}(p_T) = \frac{N_{AA}(p_T)}{\langle T_{AA} \rangle \sigma^{PP}(p_T)}, \quad (1)$$

where N_{AA} and σ^{PP} are the efficiency- and acceptance-corrected normalized yields in PbPb collisions and the pp cross sections, respectively, for Y mesons in a given kinematic range. The average value of T_{AA} computed in each centrality bin is denoted by $\langle T_{AA} \rangle$.

Figure 2 presents the R_{AA} values for Y(2S) and Y(3S), together with the previous measurements for the Y(1S) [27], as functions of Y meson p_T and PbPb collision centrality, with the latter represented using $\langle N_{part} \rangle$, the average number of participating nucleons in each of the centrality intervals [65]. The measurements as a function of p_T are reported in five intervals for the Y(2S), 0–3, 3–6, 6–9, 9–15, and 15–30 GeV/c, and four for the Y(3S), 0–4, 4–9, 9–15, and 15–30 GeV/c. The centrality intervals and the corresponding $\langle N_{part} \rangle$ values used for this analysis are listed in the HEPData record [34]. The results for the Y(1S) are taken from Ref. [27] because

the new data do not improve the statistical significance. Furthermore, the systematic uncertainties, which are dominant for the Y(1S) results, are found to not improve when including the BDT training.

A gradual decrease of R_{AA} is observed towards more central collisions (i.e., higher N_{part}) for both Y(2S) and Y(3S). On the other hand, no significant dependence on p_T is found for either of them. Both states are strongly suppressed in central PbPb collisions, as well as over the entire p_T region when averaged over centrality. Furthermore, the R_{AA} of the Y(3S) is smaller than that of the Y(2S), with values integrated over p_T and centrality 0–90% of 0.115 ± 0.008 (stat) ± 0.007 (syst) and 0.080 ± 0.014 (stat) ± 0.012 (syst) for the Y(2S) and Y(3S), respectively. These results indicate, much more clearly than the previous measurements [27–29], that the sequential suppression pattern of the bottomonium states follows the ordering of their binding energies [69].

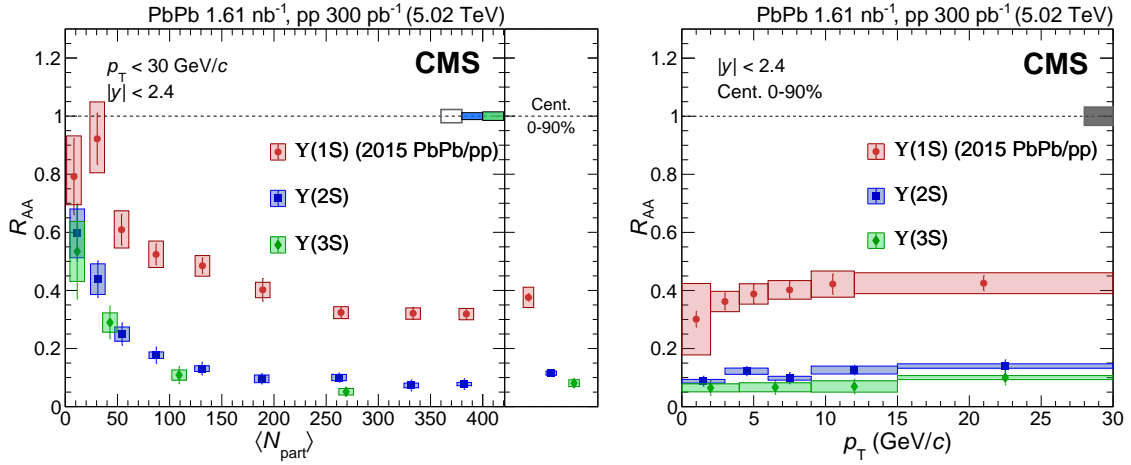


Figure 2: Measured R_{AA} for the Y states as functions of $\langle N_{\text{part}} \rangle$ (left), showing also the 0–90% centrality interval, and of p_T (right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. In the left plot, the leftmost box at unity represents the pp luminosity and PbPb N_{MB} combined uncertainties, whereas the second (third) box corresponds to the uncertainty on the Y(2S) (Y(3S)) pp yields. The box at unity in the right plot combines the uncertainties of T_{AA} , pp luminosity, and PbPb N_{MB} . The results for the Y(1S) are taken from Ref. [27] and are not affected by the boxes at unity.

Figure 3 shows, as functions of $\langle N_{\text{part}} \rangle$ and p_T , the Y(3S) to Y(2S) double ratios, obtained by dividing the Y(3S) over Y(2S) yield ratios in PbPb collisions by the corresponding ratios in pp collisions. The bins are identical to those used in the Y(3S) measurement. The uncertainties in the Y(3S)/Y(2S) ratios are computed by propagating the Y(2S) and Y(3S) uncertainties, taking into account their correlation, whereas the global uncertainties on T_{AA} , pp luminosity, and PbPb N_{MB} cancel out. The decreasing trend of the double ratios towards more central PbPb collisions indicates a stronger suppression for the Y(3S) than for the Y(2S), whereas no significant dependence on p_T is seen. Comparisons to various theoretical calculations [9, 10, 70–73] and previous experimental results [24, 74–77] can be found in Appendix A.

In summary, data from PbPb and pp collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV, collected with the CMS detector, were analyzed to measure the yields and nuclear modification factors, R_{AA} , of the Y(2S) and Y(3S) mesons. The Y(3S) meson is observed for the first time in PbPb collisions, with a significance above five standard deviations. Dividing the Y(3S) over Y(2S) yield ratios in PbPb by those in pp collisions gives the double ratios that quantify the relative modification of the two mesons. Results are shown as functions

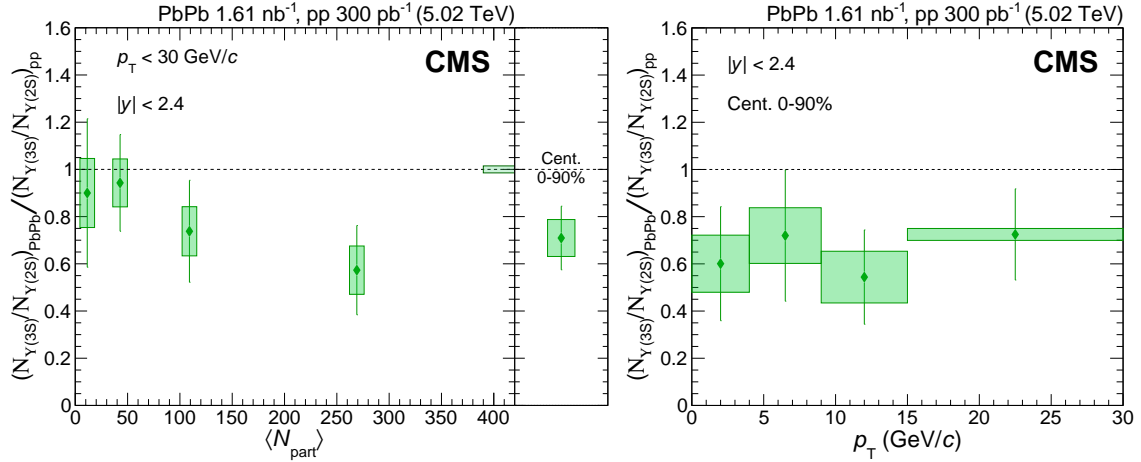


Figure 3: The double ratios of $Y(3S)/Y(2S)$ as functions of $\langle N_{\text{part}} \rangle$ (left), showing also the 0–90% centrality interval, and of p_T (right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity in the left plot shows the combined systematic and statistical uncertainties from pp data, which is common to all the points.

of Y transverse momentum and PbPb collision centrality. Both the $Y(2S)$ and $Y(3S)$ mesons are suppressed ($R_{AA} < 1$), with a stronger effect for the $Y(3S)$. The suppression increases for more central PbPb collisions, whereas no significant dependence on p_T is seen. The $Y(3S)$ over $Y(2S)$ double ratios show a gradual decrease towards more central PbPb collisions, indicating that the degree to which the suppression is stronger for the $Y(3S)$ meson increases for more central PbPb collisions. Combined with previous measurements, these results indicate that the strength of the suppression increases in the sequence $Y(1S)$, $Y(2S)$, and $Y(3S)$. These results provide new constraints on the understanding of the dynamics of quarkonium states in the QGP created in heavy ion collisions.

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A Supplemental material

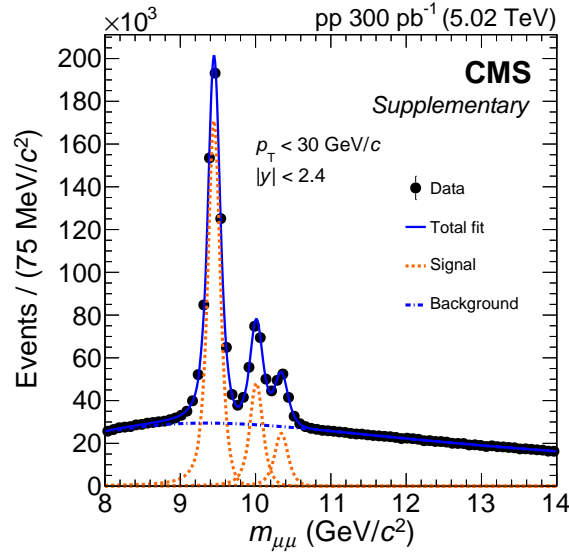


Figure A.1: Dimuon invariant mass distribution in pp collisions, integrated over the full kinematic range $p_T < 30$ GeV/c and $|y| < 2.4$. The solid curves show the result of the fit, whereas the orange dashed and blue dash-dotted curves represent the three Y states and the background, respectively.

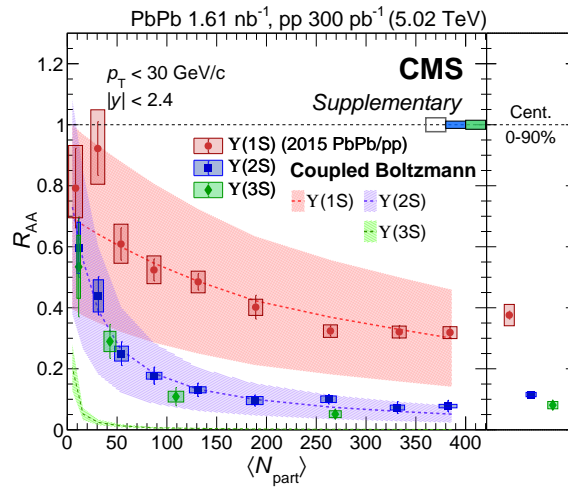


Figure A.2: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of $\langle N_{\text{part}} \rangle$ (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb N_{MB} , while the second (third) box corresponds to the uncertainty of pp yields for the Y(2S) (Y(3S)) state. Results for the Y(1S) meson are taken from Ref. [27]. The bands represent calculations from Ref. [9].

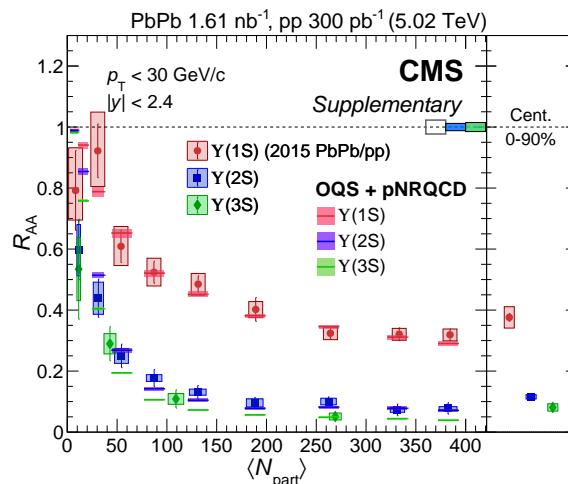


Figure A.3: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of $\langle N_{\text{part}} \rangle$ (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb N_{MB} , while the second (third) box corresponds to the uncertainty of pp yields for the Y(2S) (Y(3S)) state. Results for the Y(1S) meson are taken from Ref. [27]. The OQS + pNRQCD theory calculations are taken from Ref. [70].

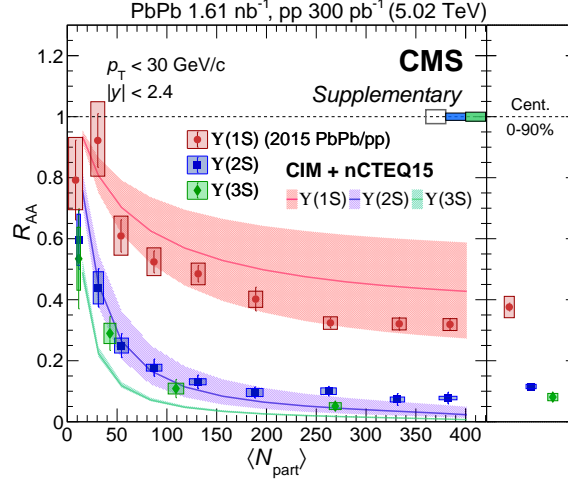


Figure A.4: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of $\langle N_{\text{part}} \rangle$ (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb N_{MB} , while the second (third) box corresponds to the uncertainty of pp yields for the Y(2S) (Y(3S)) state. Results for the Y(1S) meson are taken from Ref. [27]. The bands represent calculations from Ref. [71].

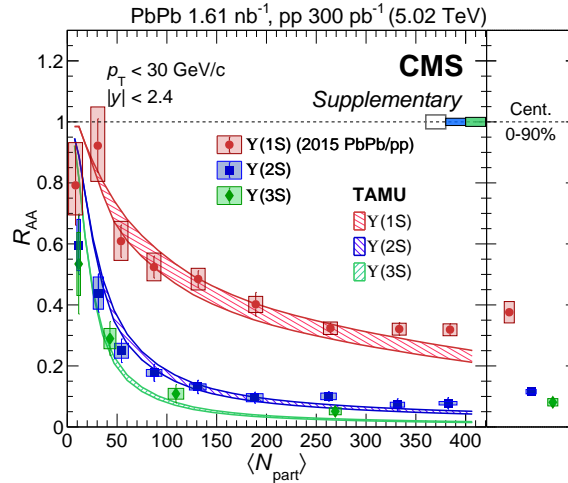


Figure A.5: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of $\langle N_{\text{part}} \rangle$ (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb N_{MB} , while the second (third) box corresponds to the uncertainty of pp yields for the Y(2S) (Y(3S)) state. Results for the Y(1S) meson are taken from Ref. [27]. The bands represent calculations from Ref. [10].

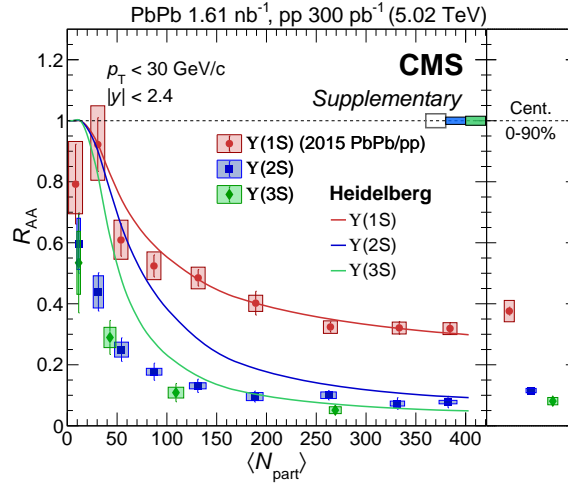


Figure A.6: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of $\langle N_{\text{part}} \rangle$ (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb N_{MB} , while the second (third) box corresponds to the uncertainty of pp yields for the Y(2S) (Y(3S)) state. Results for the Y(1S) meson are taken from Ref. [27]. The lines represent calculations from Ref. [72].

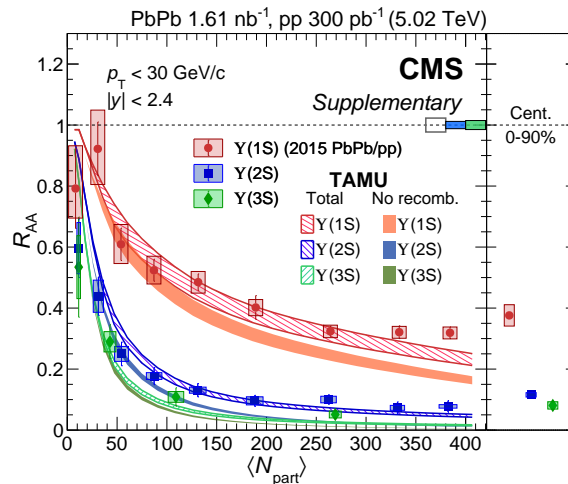


Figure A.7: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of $\langle N_{\text{part}} \rangle$ (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb N_{MB} , while the second (third) box corresponds to the uncertainty of pp yields for the Y(2S) (Y(3S)) state. Results for the Y(1S) meson are taken from Ref. [27]. The two type of bands represent calculations from Ref. [10], with the solid filled bands calculated without the recombination component.

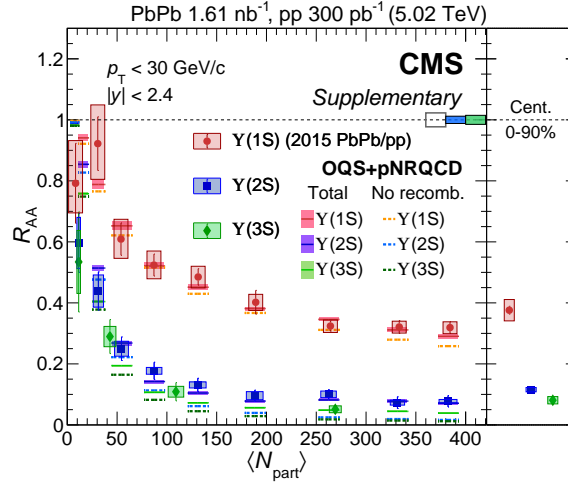


Figure A.8: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of $\langle N_{\text{part}} \rangle$ (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb N_{MB} , while the second (third) box corresponds to the uncertainty of pp yields for the Y(2S) (Y(3S)) state. Results for the Y(1S) meson are taken from Ref. [27]. The OQS + pNRQCD theory calculations are taken from Ref. [70], with the dashed one calculated without the recombination component.

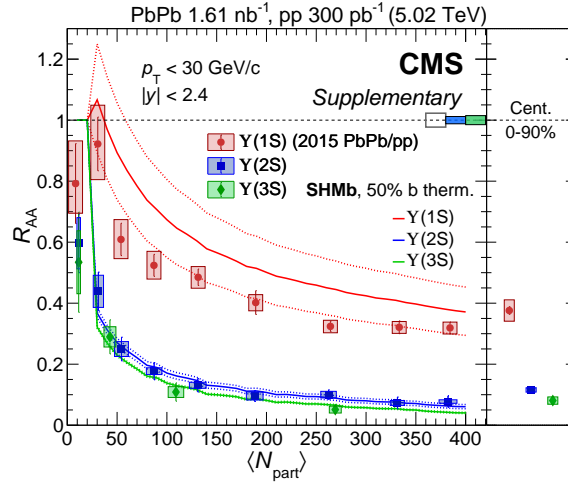


Figure A.9: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of $\langle N_{\text{part}} \rangle$ (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb N_{MB} , while the second (third) box corresponds to the uncertainty of pp yields for the Y(2S) (Y(3S)) state. Results for the Y(1S) meson are taken from Ref. [27]. The lines represent calculations from Ref. [73], with the solid line corresponding to 50% thermalization of the $b\bar{b}$ pairs and the upper and lower dashed lines representing the 20% uncertainty of the total $b\bar{b}$ cross section.

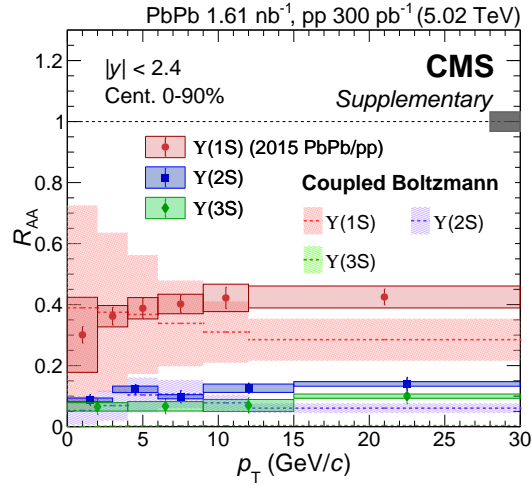


Figure A.10: Nuclear modification factors for the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons as a function of p_T (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines uncertainties from T_{AA} , pp luminosity, and PbPb N_{MB} . Results for the $Y(1S)$ meson are taken from Ref. [27]. The bands represent calculations from Ref. [9].

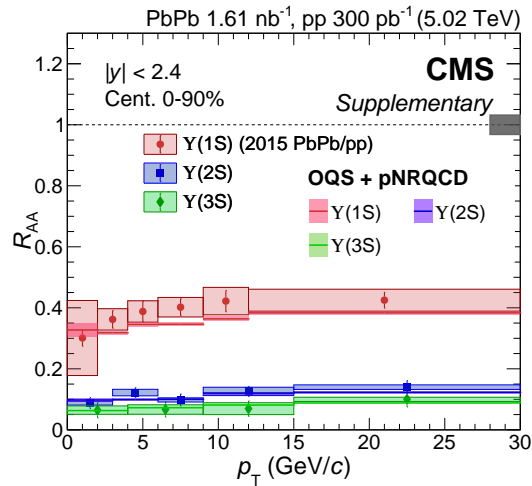


Figure A.11: Nuclear modification factors for the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons as a function of p_T (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines uncertainties from T_{AA} , pp luminosity, and PbPb N_{MB} . Results for the $Y(1S)$ meson are taken from Ref. [27]. The OQS + pNRQCD theory calculations are taken from Ref. [70].

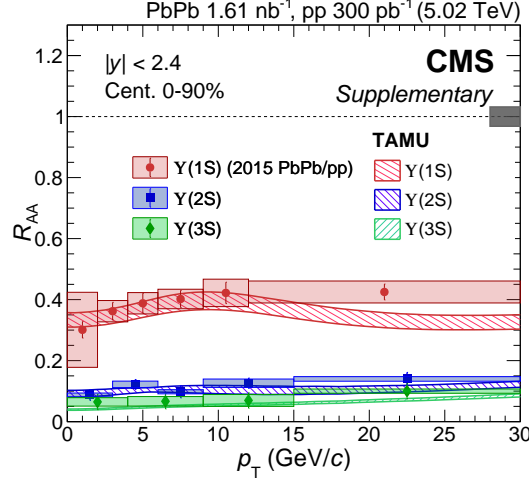


Figure A.12: Nuclear modification factors for the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons as a function of p_T (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines uncertainties from T_{AA} , pp luminosity, and PbPb N_{MB} . Results for the $Y(1S)$ meson are taken from Ref. [27]. The bands represent calculations from Ref. [10].

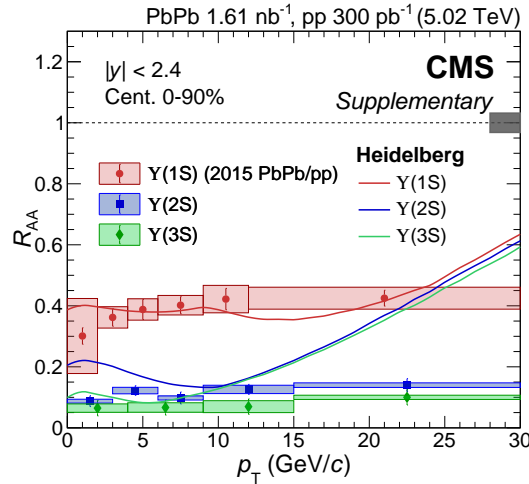


Figure A.13: Nuclear modification factors for the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons as a function of p_T (from 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines uncertainties from T_{AA} , pp luminosity, and PbPb N_{MB} . Results for the $Y(1S)$ meson are taken from Ref. [27]. The lines represent calculations from Ref. [72].

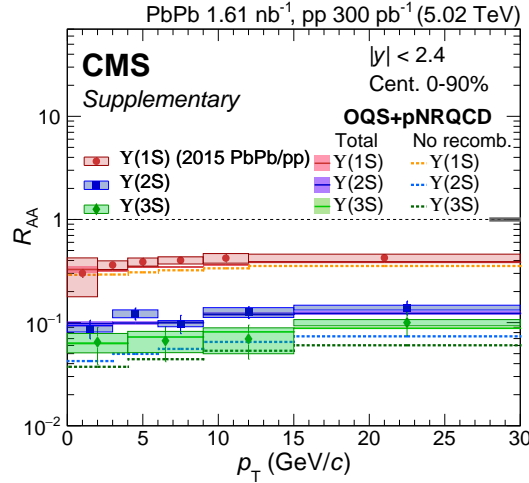


Figure A.14: Nuclear modification factors for the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons as a function of p_T (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines uncertainties from T_{AA} , pp luminosity, and PbPb N_{MB} . Results for the $Y(1S)$ meson are taken from Ref. [27]. The OQS + pNRQCD theory calculations are taken from Ref. [70], with the dashed one calculated without the recombination component.

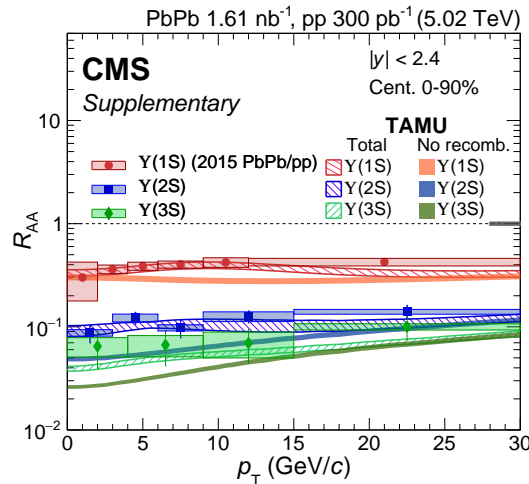


Figure A.15: Nuclear modification factors for the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons as a function of p_T (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines uncertainties from T_{AA} , pp luminosity, and PbPb N_{MB} . Results for the $Y(1S)$ meson are taken from Ref. [27]. The two type of bands represent calculations from Ref. [10], with the solid filled bands calculated without the recombination component.

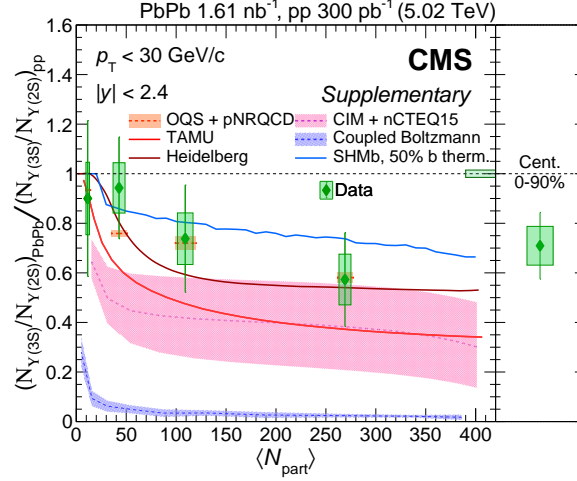


Figure A.16: The double ratio of $Y(3S)/Y(2S)$ as functions of $\langle N_{\text{part}} \rangle$ (from Figure 3 left). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The box at unity shows the combined systematic and statistical uncertainties from pp data. The six different types of lines and bands represent calculations from Ref. [9, 10, 70–73].

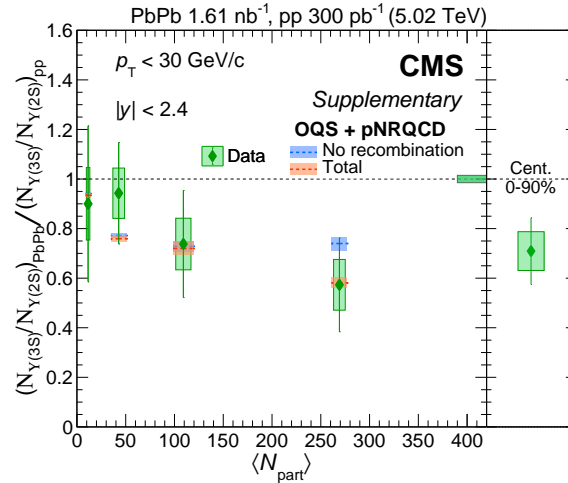


Figure A.17: The double ratio of $Y(3S)/Y(2S)$ as a function of $\langle N_{\text{part}} \rangle$ (from Figure 3 left). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The box at unity shows the combined systematic and statistical uncertainties from pp data. The orange and blue boxes represent calculations from Ref. [70], with the latter showing the calculations without the recombination component.

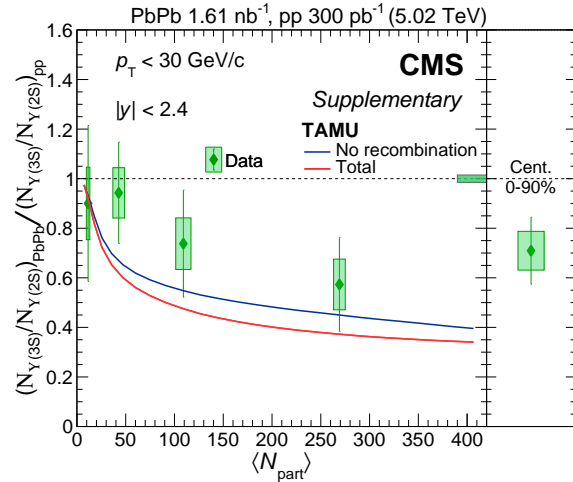


Figure A.18: The double ratio of $Y(3S)/Y(2S)$ as a function of $\langle N_{\text{part}} \rangle$ (from Figure 3 left). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The box at unity shows the combined systematic and statistical uncertainties from pp data. The red and blue lines represent calculations from Ref. [10], with the latter showing the calculations without the recombination component.

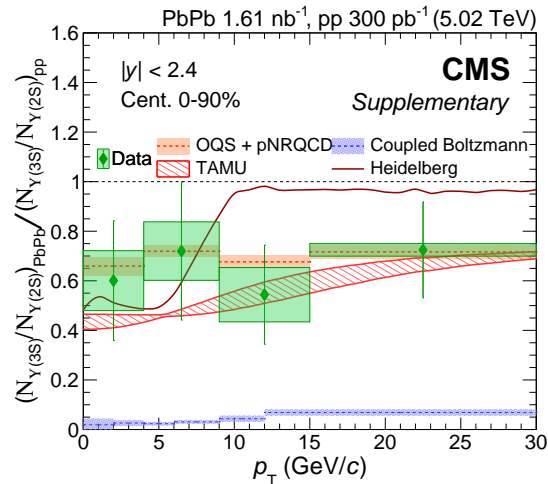


Figure A.19: The double ratio of $Y(3S)/Y(2S)$ as a function of p_T (from Figure 3 right). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The bands and line represent calculations from Ref. [9, 10, 70, 72].

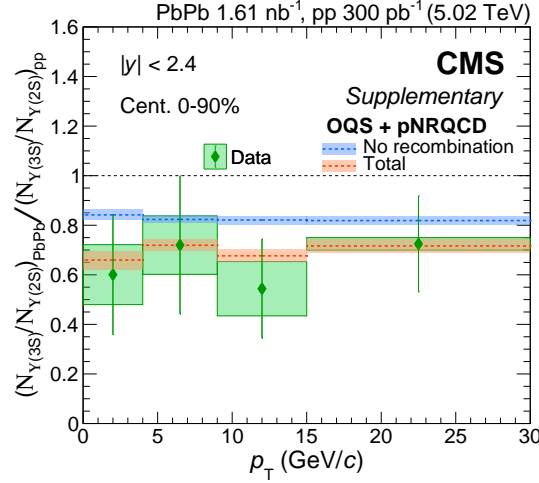


Figure A.20: The double ratio of $Y(3S)/Y(2S)$ as a function of p_T (from Figure 3 right). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The orange and blue bands represent calculations from Ref. [70], with the latter showing the calculations without the recombination component.

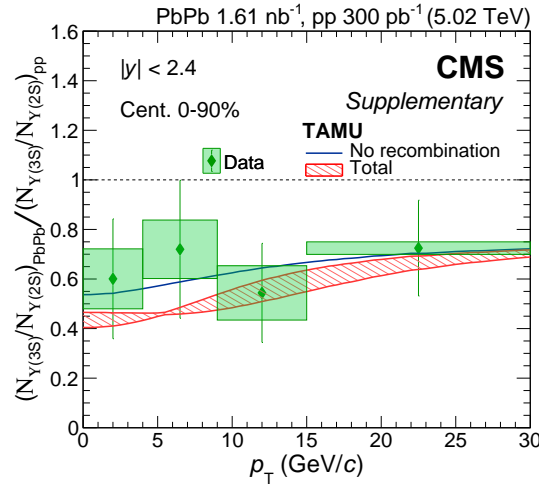


Figure A.21: The double ratio of $Y(3S)/Y(2S)$ as a function of p_T (from Figure 3 right). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The red band and blue line represent calculations from Ref. [10], with the latter showing the calculations without the recombination component.

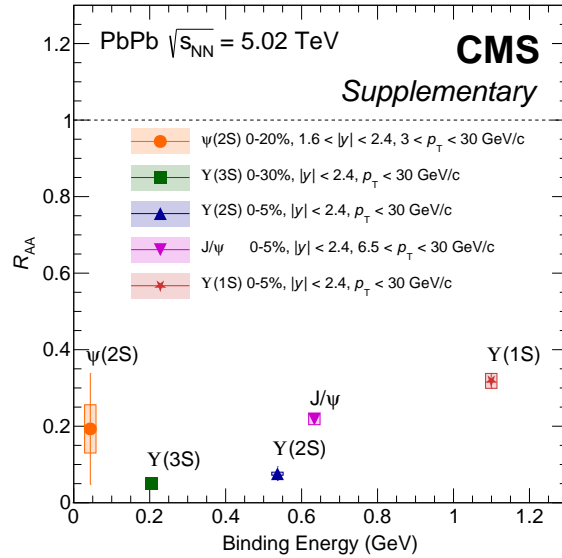


Figure A.22: The nuclear modification factors for various quarkonium mesons as a function of quarkonium binding energy at $\sqrt{s_{NN}} = 5.02$ TeV. The R_{AA} values are taken from the data point with the most central collision bin, e.g., the values for the Y's correspond to the points of the highest N_{part} in Figure 2 left. The values for the binding energy of each quarkonium state are taken from Ref. [76]. The error bars and boxes represent the statistical and systematic uncertainties, respectively. The results for the Y(1S) meson and charmonium states (J/ ψ and $\psi(2S)$) are taken from Refs. [27] and [75], respectively.

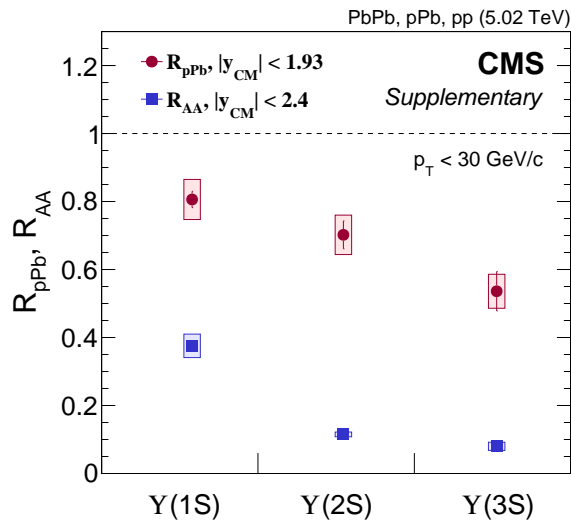


Figure A.23: The nuclear modification factors for Y(1S), Y(2S), and Y(3S) mesons in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The error bars and boxes represent the statistical and systematic uncertainties, respectively. The Y(2S) and Y(3S) values are from the integrated bin in Figure 2 left. The results for pPb collisions and the Y(1S) meson are taken from Refs. [77] and [27], respectively.

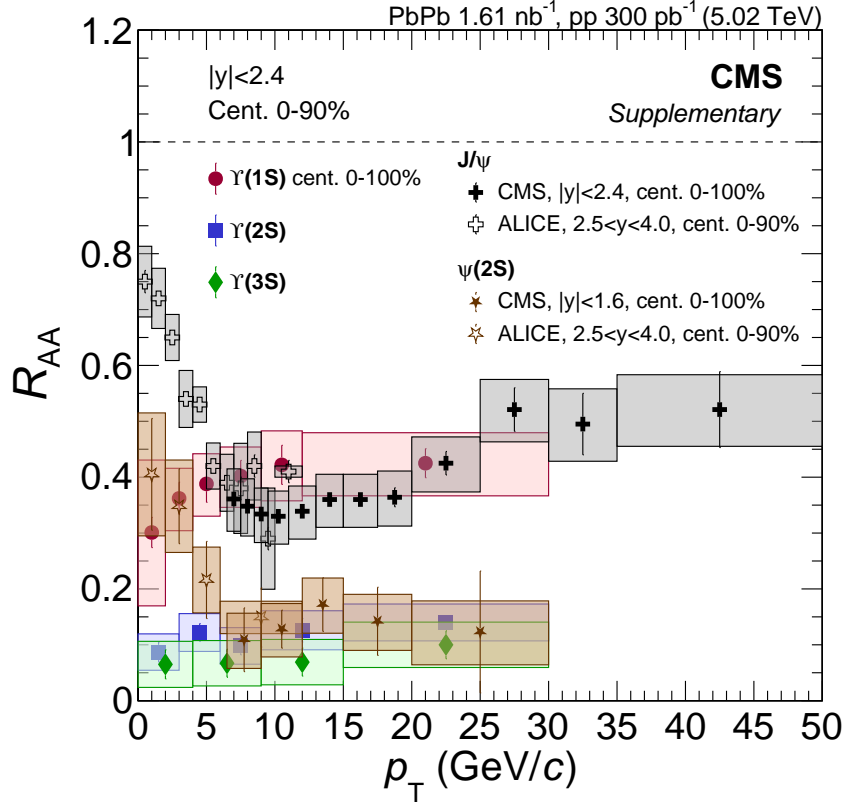


Figure A.24: Nuclear modification factors for the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, J/ψ , and $\psi(2S)$ mesons as a function of p_T . The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. Results for the $\Upsilon(1S)$ meson are taken from Ref. [27]. The open and full cross points are the results for J/ψ mesons from Refs. [74] and [75], respectively. Results for $\psi(2S)$ mesons are taken from Refs. [24] and [75] for the open and full star points, respectively.

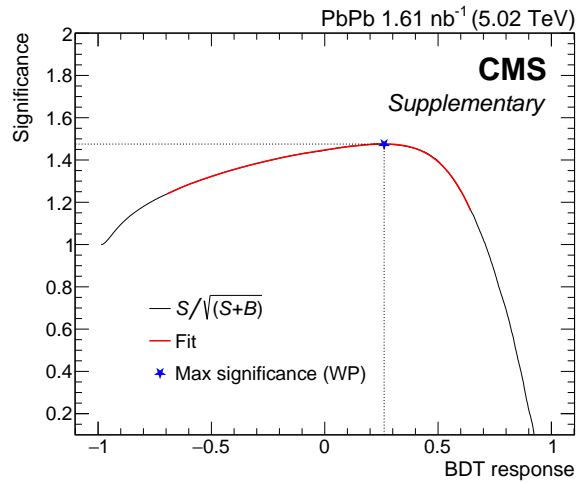


Figure A.25: The significance $S/\sqrt{S+B}$ for Υ mesons in PbPb collisions as a function of BDT score normalized to range between -1 and 1. The quantities S and B represent the yields of signal and background dimuons used for the BDT training, respectively. The working point (WP) is determined to be the BDT score that maximizes the significance using a parametric fit.

p_T range (GeV/c)	$\frac{1}{\langle T_{AA} \rangle} \frac{d^2 N^Y}{dp_T dy}$	Stat. Unc.	Syst. Unc.
0–3	2.98	0.60	0.22
3–6	5.51	0.72	0.48
6–9	2.72	0.54	0.19
9–15	1.17	0.15	0.13
15–30	0.15	0.02	0.01

Table A.1: Yields for $Y(2S)$ mesons in PbPb collisions in centrality 0–90% and $|y| < 2.4$, corrected for acceptance and efficiency, and normalized by the nuclear thickness function $\langle T_{AA} \rangle$ and the number of minimum bias events N_{MB} . The values for the yields and their uncertainties are in units of pb/ GeV/c.

Centrality	$\langle N_{part} \rangle$	$\frac{1}{\langle T_{AA} \rangle} \frac{d^2 N^Y}{dp_T dy}$	Stat. Unc.	Syst. Unc.
0–5%	382.30	1.02	0.25	0.08
5–10%	331.50	0.95	0.25	0.11
10–20%	262.30	1.31	0.20	0.14
20–30%	188.20	1.25	0.24	0.17
30–40%	131.00	1.71	0.29	0.13
40–50%	87.19	2.32	0.37	0.15
50–60%	54.42	3.27	0.51	0.32
60–70%	31.21	5.74	0.82	0.69
70–90%	11.43	7.80	1.26	1.10

Table A.2: Yields for $Y(2S)$ mesons in PbPb collisions in $p_T < 30$ GeV/c and $|y| < 2.4$, corrected for acceptance and efficiency, and normalized by the nuclear thickness function $\langle T_{AA} \rangle$ and the number of minimum bias events N_{MB} . The values for the yields and their uncertainties are in units of pb/ GeV/c.

p_T range (GeV/c)	$\frac{1}{\langle T_{AA} \rangle} \frac{d^2 N^Y}{dp_T dy}$	Stat. Unc.	Syst. Unc.
0–4	1.11	0.44	0.24
4–9	1.04	0.39	0.24
9–15	0.38	0.14	0.11
15–30	0.07	0.02	0.01

Table A.3: Yields for $Y(3S)$ mesons in PbPb collisions in centrality 0–90% and $|y| < 2.4$, corrected for acceptance and efficiency, and normalized by the nuclear thickness function $\langle T_{AA} \rangle$ and the number of minimum bias events N_{MB} . The values for the yields and their uncertainties are in units of pb/ GeV/c.

Centrality	$\langle N_{\text{part}} \rangle$	$\frac{1}{\langle T_{AA} \rangle} \frac{d^2 N^Y}{dp_T dy}$	Stat. Unc.	Syst. Unc.
0–30%	269.10	0.33	0.10	0.07
30–50%	109.10	0.70	0.19	0.11
50–70%	42.81	1.85	0.36	0.21
70–90%	11.43	3.42	1.05	0.68


Table A.4: Yields for $Y(3S)$ mesons in PbPb collisions in $p_T < 30 \text{ GeV}/c$ and $|y| < 2.4$, corrected for acceptance and efficiency, and normalized by the nuclear thickness function $\langle T_{AA} \rangle$ and the number of minimum bias events N_{MB} . The values for the yields and their uncertainties are in units of $\text{pb}/\text{GeV}/c$.

Centrality	$\frac{1}{\langle T_{AA} \rangle} \frac{d^2 N^Y}{dp_T dy}$	Stat. Unc.	Syst. Unc.
0–5%	15.20	0.89	+0.88 –0.95
5–10%	15.28	1.01	+0.89 –0.96
10–20%	15.40	0.82	+0.94 –1.00
20–30%	19.12	1.86	+1.22 –1.27
30–40%	23.06	1.29	+1.68 –1.71
40–50%	24.95	1.70	+2.18 –2.14
50–60%	28.96	2.51	+3.10 –3.00
60–70%	43.89	4.17	+6.04 –5.56
70–100%	37.69	6.21	+6.68 –4.61



















Table A.5: Yields for $Y(1S)$ mesons in PbPb collisions in $p_T < 30 \text{ GeV}/c$ and $|y| < 2.4$, corrected for acceptance and efficiency, and normalized by the nuclear thickness function $\langle T_{AA} \rangle$ and the number of minimum bias events N_{MB} from Ref. [27]. The values for the yields and their uncertainties are in units of $\text{pb}/\text{GeV}/c$.

B The CMS Collaboration




Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan¹ 













Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , P.S. Hussain , M. Jeitler² , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch, F.M. Pitters, J. Schieck² , R. Schöfbeck , D. Schwarz , S. Templ , W. Waltenberger , C.-E. Wulz² 











Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , T. Kello⁴, H. Rejeb Sfar, P. Van Mechelen 










Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck, D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux , G. De Lentdecker , L. Favart , D. Hohov , J. Jaramillo , K. Lee , M. Mahdavihorrani , I. Makarenko , A. Malara , S. Paredes , L. Pétré , N. Postiau, L. Thomas , M. Vanden Bemden, C. Vander Velde , P. Vanlaer 






Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach, M. Niedziela , C. Rendón, C. Roskas , A. Samalan, K. Skovpen , M. Tytgat , N. Van Den Bossche , B. Vermassen, L. Wezenbeek 






















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

A. Benecke , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaître, K. Mondal , A. Taliercio , T.T. Tran , P. Vischia , S. Wertz 








Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , A. Moraes , P. Rebello Teles 

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins⁷ , C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima , A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel , F. Torres Da Silva De Araujo⁸ , A. Vilela Pereira 

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil


C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 

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

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

University of Sofia, Sofia, Bulgaria




A. Dimitrov , T. Ivanov , L. Litov , B. Pavlov , P. Petkov , A. Petrov, E. Shumka 

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S.Thakur 

















Beihang University, Beijing, China

T. Cheng , T. Javaid⁹ , M. Mittal , L. Yuan 











Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer¹⁰, Z. Hu , S. Lezki , K. Yi^{10,11}

Institute of High Energy Physics, Beijing, China

G.M. Chen⁹ , H.S. Chen⁹ , M. Chen⁹ , F. Iemmi , C.H. Jiang, A. Kapoor , H. Kou ,
H. Liao , Z.-A. Liu¹² , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-
Wilsker , J. Wang , H. Zhang , J. Zhao 

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

A. Agapitos , Y. An , Y. Ban , C. Chen, A. Levin , C. Li , Q. Li , X. Lyu, Y. Mao,
S.J. Qian , X. Sun , D. Wang , J. Xiao , H. Yang

Sun Yat-Sen University, Guangzhou, China

M. Lu , Z. You 

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

X. Gao⁴ , D. Leggat, H. Okawa , Y. Zhang 

Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga 

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 








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

D. Giljanovic , N. Godinovic , D. Lelas , I. Puljak 

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac , T. Sculac 




Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra , M. Roguljic ,
A. Starodumov¹³ , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , M. Kolosova , S. Konstantinou , J. Mousa , C. Nicolaou,
F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

Charles University, Prague, Czech Republic

M. Finger , M. Finger Jr. , A. Kveton 

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala 

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 












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

A.A. Abdelalim^{14,15} , E. Salama^{16,17} 

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

M.A. Mahmoud , Y. Mohammed 


















National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik , T. Lange , S. Nandan ,
C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 



Department of Physics, University of Helsinki, Helsinki, Finland

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

















Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen,
T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti , L. Martikainen ,
M. Myllymäki , J. Ott , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi 





























Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow , T. Tuuva












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

C. Amendola , M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure,
F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , P. Jarry , V. Lohezic ,
J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁸ , P. Simkina ,
M. Titov 


















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

C. Baldenegro Barrera , F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati ,
C. Charlot , F. Damas , O. Davignon , B. Diab , G. Falmagne , B.A. Fontana Santos
Alves , S. Ghosh , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan ,
G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , R. Salerno , U. Sarkar ,
J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche 




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

J.-L. Agram¹⁹ , J. Andrea , D. Apparu , D. Bloch , G. Bourgatte , J.-M. Brom ,
E.C. Chabert , C. Collard , D. Darej, U. Goerlach , C. Grimault, A.-C. Le Bihan ,
P. Van Hove 







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

S. Beauceron , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi , D. Contardo ,
P. Depasse , C. Dozen²⁰ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch ,
G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, L. Torterotot ,
M. Vander Donckt , P. Verdier , S. Viret























Georgian Technical University, Tbilisi, Georgia

I. Lomidze , T. Toriashvili²¹ , Z. Tsamalaidze¹³ 


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

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M. Teroerde 




















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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , M. Erdmann , P. Fackeldey , D. Fasanella , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee , L. Mastrolorenzo, M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll , A. Novak , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , H. Reithler , A. Schmidt , S.C. Schuler, A. Sharma , L. Vigilante, S. Wiedenbeck , S. Zaleski























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

C. Dziwok , G. Flügge , W. Haj Ahmad²² , O. Hlushchenko, T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 




Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou , O. Behnke , A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , F. Blekman²³ , K. Borrás²⁴ , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , L. Didukh , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²³ , A. Geiser , A. Giraldi , G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari²⁵ , N.Z. Jomhari , B. Kaech , A. Kasem²⁴ , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²⁶ , W. Lohmann²⁷ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham^{28,24} , V. Scheurer, S. Schnake²⁴ , P. Schütze , C. Schwanenberger²³ , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon[†] , M. Van De Klundert , F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁴ , C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , M. Bonanomi , P. Connor , K. De Leo , M. Eich, K. El Morabit , F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , M. Hajheidari, J. Haller , A. Hinzmann , H.R. Jabusch , G. Kasioczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , A. Mehta , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , M. Rieger , O. Rieger, D. Savoiu , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf









Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann²⁹ , M. Horzela , U. Husemann , M. Klute , R. Koppenhöfer , S. Maier , S. Mitra , Th. Müller , M. Neukum, M. Oh , G. Quast , K. Rabbertz , J. Rauser, M. Schnepf, D. Seith, I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube , M. Wassmer , S. Wieland , R. Wolf , S. Wozniewski , S. Wunsch, X. Zuo




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

G. Anagnostou, P. Assiouras , G. Daskalakis , A. Kyriakis, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , A. Manousakis-Katsikakis , A. Panagiotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 

National Technical University of Athens, Athens, Greece

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






University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Gianneios , C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

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

M. Csanád , K. Farkas , M.M.A. Gadallah³⁰ , S. Lökös³¹ , P. Major , K. Mandal , G. Pásztor , A.J. Rádli³² , O. Surányi , G.I. Veres 


Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók³³ , G. Bencze, C. Hajdu , D. Horvath^{34,35} , F. Sikler , V. Veszpremi 




Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni , S. Czellar, J. Karancsi³³ , J. Molnar, Z. Szillasi, D. Teyssier 


















Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari³⁶ 

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

T. Csorgo³² , F. Nemes³² , T. Novak 









Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁷ , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh³⁸ , A. Singla , A. K. Viridi 














University of Delhi, Delhi, India

A. Ahmed , A. Bhardwaj , B.C. Choudhary , A. Kumar , M. Naimuddin , K. Ranjan , S. Saumya 


Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁹ , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber⁴⁰ , M. Maity³⁹, P. Palit , G. Saha , B. Sahu , S. Sarkar




Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , P. Kalbhor , J.R. Komaragiri⁴¹ , D. Kumar⁴¹ , A. Muham-mad , L. Panwar⁴¹ , R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar , P.C. Tiwari⁴¹ , S. Verma 

Bhabha Atomic Research Centre, Mumbai, India

K. Naskar⁴² 

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, I. Das , S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee , R. Chudasama , M. Guchait , S. Karmakar , S. Kumar , G. Majumder ,
K. Mazumdar , S. Mukherjee , A. Thachayath 




National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati⁴³ , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴⁴ ,
A. Nayak⁴⁴ , P. Saha , S.K. Swain, D. Vats⁴⁴ 





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

A. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma 


Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴⁵ , E. Khazaie , M. Zeinali⁴⁶ 

































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

S. Chenarani⁴⁷ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























University College Dublin, Dublin, Ireland

M. Grunewald 

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b} , R. Aly^{a,c,14} , C. Aruta^{a,b} , A. Colaleo^a , D. Creanza^{a,c} ,
N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,b} , W. Elmetenawee^{a,b} , F. Errico^{a,b} ,
L. Fiore^a , G. Iaselli^{a,c} , M. Ince^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} ,
V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} ,
G. Pugliese^{a,c} , R. Radogna^a , D. Ramos^a , A. Ranieri^a , G. Selvaggi^{a,b} ,
L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a ,
P. Verwilligen^a 


















INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borgonovi^a , L. Brigliadori^a,
R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} ,
G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , P. Giacomelli^a ,
L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,48} , L. Lunerti^{a,b} ,
S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} ,
A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Costa^{a,b,49} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,49} , C. Tuve^{a,b} 

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

G. Barbagli^a , G. Bardelli^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^{a,b} ,
V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , G. Latino^{a,b} ,
P. Lenzi^{a,b} , M. Lizzo^{a,b} , M. Meschini^a , S. Paoletti^a , R. Seidita^{a,b} , G. Sguazzoni^a ,
L. Viliani^a 












INFN Laboratori Nazionali di Frascati, Frascati, Italy













L. Benussi , S. Bianco , S. Meola²⁹ , D. Piccolo 

INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy


M. Bozzo^{a,b} , P. Chatagnon^a , F. Ferro^a , R. Mulargia^a , E. Robutti^a , S. Tosi^{a,b} 

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
























A. Benaglia^a , G. Boldrini^a , F. Brivio^{a,b} , F. Cetorelli^{a,b} , F. De Guio^{a,b} ,
M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^{a,b} 

M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , B.S. Pinolini^a, S. Ragazzi^{a,b} , N. Redaelli^a , T. Tabarelli de Fatis^{a,b} , D. Zuolo^{a,b} 












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

S. Buontempo^a , F. Carnevali^{a,b}, N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,50} , P. Paolucci^{a,29} , B. Rossi^a , C. Sciacca^{a,b} 















INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

N. Bacchetta^{a,51} , M. Biasotto^{a,52} , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , S. Fantinel^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , G. Grosso^a, L. Layer^{a,53}, E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , H. Yarar^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} 




































INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

S. Abu Zeid^{a,17} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^{a,b} , D. Fiorina^{a,b} , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^a , P. Vitulo^{a,b} 



INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

P. Asenov^{a,54} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , G. Mantovani^{a,b}, V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,54} , A. Piccinelli^{a,b} , M. Presilla^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 






































INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

P. Azzurri^a , G. Bagliesi^a , V. Bertacchi^{a,c} , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^{a,b} , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , M.R. Di Domenico^{a,d} , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , G. Mandorli^{a,c} , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , S. Parolia^{a,b} , G. Ramirez-Sanchez^{a,c} , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , N. Shafiei^{a,b} , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , A. Venturi^a , P.G. Verdini^a 





INFN Sezione di Roma^a, Sapienza Università di Roma^b, Roma, Italy

P. Barria^a , M. Campana^{a,b} , F. Cavallari^a , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , E. Longo^{a,b} , P. Meridiani^a , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a , R. Tramontano^{a,b} 














INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , C. Biino^a , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , M. Grippo^{a,b} , B. Kiani^{a,b} , F. Legger^a , C. Mariotti^a , S. Maselli^a , A. Mecca^{a,b} , E. Migliore^{a,b} , E. Monteil^{a,b} , M. Monteno^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , M. Ruspa^{a,c} , K. Shchelina^a , F. Siviero^{a,b} , V. Sola^a , A. Solano^{a,b} , D. Soldi^{a,b} , A. Staiano^a , M. Tornago^{a,b} , D. Trocino^a , G. Umoret^{a,b} , A. Vagnerini^{a,b} 

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , A. Da Rold^{a,b} ,
G. Della Ricca^{a,b} , G. Sorrentino^{a,b} 




Kyungpook National University, Daegu, Korea

S. Dogra , C. Huh , B. Kim , D.H. Kim , G.N. Kim , J. Kim, J. Lee , S.W. Lee ,
C.S. Moon , Y.D. Oh , S.I. Pak , M.S. Ryu , S. Sekmen , Y.C. Yang 

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

H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

E. Asilar , T.J. Kim , J. Park 

Korea University, Seoul, Korea

S. Choi , S. Han, B. Hong , K. Lee, K.S. Lee , S. Lee , J. Lim, J. Park, S.K. Park, J. Yoo 

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh 

Sejong University, Seoul, Korea

H. S. Kim , Y. Kim, S. Lee



Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi , S. Jeon , J. Kim , J.S. Kim, S. Ko , H. Kwon , H. Lee ,
S. Lee, B.H. Oh , S.B. Oh , H. Seo , U.K. Yang, I. Yoon 






University of Seoul, Seoul, Korea

W. Jang , D.Y. Kang, Y. Kang , D. Kim , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , J.A. Merlin,
I.C. Park , Y. Roh, D. Song, Watson, I.J. , S. Yang 


Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 




Sungkyunkwan University, Suwon, Korea

M. Choi , M.R. Kim , H. Lee, Y. Lee , Y. Lee , I. Yu 

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

T. Beyrouthy, Y. Maghrbi 




Riga Technical University, Riga, Latvia

K. Dreimanis , G. Pikurs, M. Seidel , V. Veckalns 







Vilnius University, Vilnius, Lithuania

M. Ambrozas , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius ,
G. Tamulaitis 

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

N. Bin Norjoharuddeen , S.Y. Hoh⁵⁵ , I. Yusuff⁵⁵ , Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez,
M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo 

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

G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz⁵⁶ , R. Lopez-Fernandez 

C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , F. Vazquez Valencia 








Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

University of Montenegro, Podgorica, Montenegro

I. Bubanja, J. Mijuskovic⁵⁷, N. Raicevic 








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

A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, M. Gul , H.R. Hoorani ,
W.A. Khan , M. Shoaib , M. Waqas 






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

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski 





























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

M. Araujo , P. Bargassa , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar ,
N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , J. Varela 


VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

P. Adzic⁵⁸ , M. Dordevic , P. Milenovic , J. Milosevic 













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

M. Aguilar-Benitez, J. Alcaraz Maestre , A. Álvarez Fernández , M. Barrio Luna, Cristina F. Bedoya , C.A. Carrillo Montoya , M. Cepeda , M. Cerrada , N. Colino ,
B. De La Cruz , A. Delgado Peris , D. Fernández Del Val , J.P. Fernández Ramos ,
J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez ,
M.I. Josa , J. León Holgado , D. Moran , C. Perez Dengra , A. Pérez-Calero Yzquierdo ,
J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas ,
J. Sastre , L. Urda Gómez , J. Vazquez Escobar , C. Willmott













Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain





B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , J.R. González Fernández , E. Palencia Cortezon , C. Ramón Álvarez ,
V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba 

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

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , C. Fernandez Madrazo , A. García Alonso, G. Gomez , C. Lasiosa García ,
C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas 

J. Piedra Gomez , C. Prieels, A. Ruiz-Jimeno , L. Scodellaro , I. Vila , J.M. Vizan Garcia 

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁵⁹ , D.U.J. Sonnadara , D.D.C. Wickramarathna 


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

W.G.D. Dharmaratna , K. Liyanage , N. Perera , N. Wickramage 
















CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , J. Alimena , E. Auffray , G. Auzinger , J. Baechler, P. Baillon[†], D. Barney , J. Bendavid , M. Bianco , B. Bilin , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury, M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont, F. Fallavollita⁶⁰, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , A. Lintuluoto , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabady , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas⁶¹ , A.G. Stahl Leitner , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsirou, J. Wanczyk⁶² , K.A. Wozniak , W.D. Zeuner

















Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶³ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶³ , L. Noehte⁶³ , T. Rohe 



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

T.K. Aarrestad , K. Androsov⁶² , M. Backhaus , P. Berger, A. Calandri , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani⁶² , F. Nessi-Tedaldi , J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini, D.A. Sanz Becerra , J. Steggemann⁶² , D. Valsecchi²⁹ , R. Wallny











Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁴ , P. Bäertschi , C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechi , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁵, C.M. Kuo, W. Lin, P.K. Rout , S.S. Yu 





















National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao , K.F. Chen , P.s. Chen, H. Cheng , W.-S. Hou , R. Khurana, G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , A. Psallidas, A. Steen , H.y. Wu, E. Yazgan , P.r. Yu

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

C. Asawatrangkuldee , N. Srimanobhas 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁶ , E. Eskut ,
Y. Guler⁶⁷ , E. Gurpinar Guler⁶⁷ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu ,
G. Onengut , K. Ozdemir⁶⁸ , A. Polatoz , A.E. Simsek , B. Tali⁶⁹ , U.G. Tok ,
S. Turkcapar , E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar⁷⁰, K. Ocalan⁷¹ , M. Yalvac⁷² 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷³ , O. Kaya⁷⁴ , S. Tekten⁷⁵ 


Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶⁶ , Y. Komurcu , S. Sen⁶⁶ 


Istanbul University, Istanbul, Turkey

O. Aydilek , S. Cerci⁶⁹ , B. Hacisahinoglu , I. Hos⁷⁶ , B. Isildak⁷⁷ , B. Kaynak ,
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








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

B. Grynyov 

















National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk 


































University of Bristol, Bristol, United Kingdom

D. Anthony , E. Bhal , J.J. Brooke , A. Bundock , E. Clement , D. Cussans ,
H. Flacher , M. Glowacki, J. Goldstein , G.P. Heath, H.F. Heath , L. Kreczko ,
B. Krikler , S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou⁷⁸ ,
K. Walkingshaw Pass, R. White 




Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁷⁹ , C. Brew , R.M. Brown , D.J.A. Cockerill ,
C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg⁸⁰ , J. Linacre ,
K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh,
C.H. Shepherd-Themistocleous , I.R. Tomalin, T. Williams 

Imperial College, London, United Kingdom







R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , S. Breeze, C.E. Brown , O. Buchmuller,
V. Cacchio, V. Cepaitis , G.S. Chahal⁸¹ , D. Colling , J.S. Dancu, P. Dauncey ,
G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi ,
A. Howard, G. Iles , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli ,
M. Mieskolainen , D.G. Monk , J. Nash⁸² , M. Pesaresi, B.C. Radburn-Smith ,
D.M. Raymond, A. Richards, A. Rose , E. Scott , C. Seez , A. Shtipliyski, R. Shukla ,
A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee²⁹ , M. Vojinovic ,
N. Wardle , S.N. Webb , D. Winterbottom

Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanu-

ganti , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , J. Wilson 

















Catholic University of America, Washington, DC, USA

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



















The University of Alabama, Tuscaloosa, Alabama, USA

S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio⁸³ , C. West 


















Boston University, Boston, Massachusetts, USA

A. Akpınar , A. Albert , D. Arcaro , C. Cosby , Z. Demiragli , C. Erice , E. Fontanesi , D. Gastler , S. May , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , S. Yuan 















Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez²⁴ , D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁴ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan , S. Sagir⁸⁵ , F. Simpson , E. Usai , W.Y. Wong , X. Yan , D. Yu , W. Zhang 










University of California, Davis, Davis, California, USA

J. Bonilla , C. Brainerd , R. Breedon , M. Calderon De La Barca Sanchez , M. Chertok , J. Conway , P.T. Cox , R. Erbacher , G. Haza , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , D. Pellett , B. Regnery , Y. Yao , F. Zhang 
























University of California, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , D. Hamilton , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , W.A. Nash , S. Regnard , D. Saltzberg , B. Stone , V. Valuev 























University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon , G. Hanson , G. Karapostoli , O.R. Long , N. Manganello , W. Si , S. Wimpenny 















University of California, San Diego, La Jolla, California, USA

J.G. Branson , P. Chang , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , M. Pieri , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 













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

N. Amin , C. Campagnari , M. Citron , G. Collura , A. Dorsett , V. Dutta , J. Incandela , M. Kilpatrick , J. Kim , A.J. Li , P. Masterson , H. Mei , M. Oshiro , M. Quinnan , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , P. Siddireddy , D. Stuart , S. Wang 













California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri , I. Dutta , A. Latorre , J.M. Lawhorn , N. Lu , J. Mao , H.B. Newman , T. Q. Nguyen , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 


















Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews , P. Bryant , T. Ferguson , A. Harilal , C. Liu , T. Mudholkar , S. Murthy , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 



University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hassani , G. Karathanasis , E. MacDonald, F. Marini , R. Patel, A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper 



















Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , D. Gadkari , S. Hogan , J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 









Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , K.F. Di Petrillo , J. Dickinson , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gece , L. Gray , D. Green, S. Grünendahl , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁶ , F. Ravera , A. Reinsvold Hall⁸⁷ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , H.A. Weber , I. Zoi







University of Florida, Gainesville, Florida, USA

P. Avery , D. Bourilkov , L. Cadamuro , V. Cherepanov , R.D. Field, D. Guerrero , M. Kim, E. Koenig , J. Konigsberg , A. Korytov , K.H. Lo, K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig , K. Shi , J. Wang , Z. Wu 



















Florida State University, Tallahassee, Florida, USA

T. Adams , A. Askew , R. Habibullah , V. Hagopian , T. Kolberg , G. Martinez, H. Prosper , C. Schiber, O. Viazlo , R. Yohay , J. Zhang













Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla , T. Elkafrawy¹⁷ , M. Hohmann , R. Kumar Verma , M. Rahmani, F. Yumiceva 












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

M.R. Adams , H. Becerril Gonzalez , R. Cavanaugh , S. Dittmer , O. Evdokimov , C.E. Gerber , D.J. Hofman , D. S. Lemos , A.H. Merrit , C. Mills , G. Oh , T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , X. Wang , Z. Ye , J. Yoo 







The University of Iowa, Iowa City, Iowa, USA


















M. Alhusseini , K. Dilsiz⁸⁸ , L. Emediato , R.P. Gandrajula , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁹ , J. Nachtman , O. Neogi, H. Ogul⁹⁰ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹¹ 

Johns Hopkins University, Baltimore, Maryland, USA






O. Amram , B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , S. Kyriacou , P. Maksimovic , J. Roskes , S. Sekhar , M. Swartz , T.Á. Vámi 

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers 

T. Isidori , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey, J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , J. Williams , G. Wilson 


















Kansas State University, Manhattan, Kansas, USA

B. Allmond , S. Duric, A. Ivanov , K. Kaadze , D. Kim, Y. Maravin , T. Mitchell, A. Modak, K. Nam, D. Roy 























Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 
















University of Maryland, College Park, Maryland, USA

E. Adams , A. Baden , O. Baron, A. Belloni , A. Bethani , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , L. Wang , K. Wong 

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

D. Abercrombie, W. Busza , I.A. Cali , Y. Chen , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, P. Harris, M. Hu , D. Kovalskyi , J. Krupa , Y.-J. Lee , K. Long , C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland , Z. Shi , G.S.F. Stephans , J. Wang, Z. Wang , B. Wyslouch , T. J. Yang 

University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, B. Crossman , A. Evans , J. Hiltbrand , Sh. Jain , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 




















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , M. Bryson, D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , R. Kamalieddin, I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow[†], W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 


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

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , A. Williams 





















Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , Y. Haddad , Y. Han , A. Krishna , J. Li , J. Lidrych , G. Madigan , B. Marzocchi , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , A. Tishelman-Charny , T. Wamorkar , B. Wang , A. Wisecarver , D. Wood 










Northwestern University, Evanston, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , A. Gilbert , K.A. Hahn , Y. Liu , N. Odell , M.H. Schmitt , M. Velasco



















University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko¹³ , R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, USA

B. Bylsma, M. Carrigan , L.S. Durkin , B. Francis , C. Hill , M. Joyce , A. Lesauvage , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 




















Princeton University, Princeton, New Jersey, USA

F.M. Addesa , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich , S. Higginbotham , A. Kalogeropoulos , G. Kopp , S. Kwan , D. Lange , D. Marlow , K. Mei , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , S. Norberg
















Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung , D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic , J. Thieman , F. Wang , R. Xiao , W. Xie 












Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar 


Rice University, Houston, Texas, USA

D. Acosta , A. Baty , T. Carnahan , M. Decaro, S. Dildick , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li , B.P. Padley , R. Redjimi, J. Rotter , W. Shi , S. Yang , E. Yigitbasi , L. Zhang⁹², Y. Zhang 

















University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , C. Fallon, T. Ferbel , M. Galanti, A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , E. Ranken , R. Taus , G.P. Van Onsem 

The Rockefeller University, New York, New York, USA

K. Goulianos 














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

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl , D. Jaroslowski , O. Karacheban²⁷ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, M. Osherson , H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier 







Texas A&M University, College Station, Texas, USA

O. Bouhali⁹³ , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁴ , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , V. Hegde , K. Lamichhane , S.W. Lee , T. Mengke, S. Muthumuni , T. Peltola , I. Volobouev , A. Whitbeck 

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , F. Romeo , P. Sheldon 

S. Tuo , J. Velkovska , J. Viinikainen 






















University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , A. Ledovsky ,
A. Li , C. Neu , C.E. Perez Lara , B. Tannenwald 

Wayne State University, Detroit, Michigan, USA

P.E. Karchin , N. Poudyal 

University of Wisconsin - Madison, Madison, Wisconsin, USA

S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni,
H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, A. Loeliger , R. Loveless ,
J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida ,
D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi ,
W. Vetens 

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev ,
A. Belyaev , V. Blinov⁹⁵, E. Boos , V. Borshch , D. Budkouski , V. Chekhovsky,
R. Chistov⁹⁵ , A. Demiyarov , A. Dermenev , T. Dimova⁹⁵ , I. Dremin , V. Epshteyn ,
A. Ershov , G. Gavrillov , V. Gavrillov , S. Gninenko , V. Golovtsov , N. Golubev ,
I. Golutvin , I. Gorbunov , A. Gribushin , V. Ivanchenko , Y. Ivanov , V. Kachanov ,
L. Kardapoltsev⁹⁵ , V. Karjavine , A. Karneyev , L. Khein, V. Kim⁹⁵ , M. Kirakosyan,
D. Kirpichnikov , M. Kirsanov , O. Kodolova⁹⁶ , D. Konstantinov , V. Koronkov ,
V. Korotkikh, A. Kozyrev⁹⁵ , N. Krasnikov , E. Kuznetsova⁹⁷ , A. Lanev ,
P. Levchenko , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov ,
V. Matveev⁹⁵ , V. Murzin , A. Nikitenko⁹⁸ , S. Obraztsov , A. Oskin, I. Ovtin⁹⁵ ,
V. Palichik , P. Parygin , V. Perelygin , S. Petrushanko , S. Polikarpov⁹⁵ , V. Popov,
E. Popova , O. Radchenko⁹⁵ , M. Savina , V. Savrin , D. Selivanova , V. Shalaev ,
S. Shmatov , S. Shulha , Y. Skovpen⁹⁵ , S. Slabospitskii , V. Smirnov , A. Snigirev ,
D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , I. Tlisova ,
M. Toms , A. Toropin , L. Uvarov , A. Uzunian , I. Vardanyan , E. Vlasov ,
A. Vorobyev, N. Voytishin , B.S. Yuldashev⁹⁹, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

⁴Also at Université Libre de Bruxelles, Bruxelles, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at The University of the State of Amazonas, Manaus, Brazil

⁹Also at University of Chinese Academy of Sciences, Beijing, China

¹⁰Also at Nanjing Normal University Department of Physics, Nanjing, China

¹¹Now at The University of Iowa, Iowa City, Iowa, USA

¹²Also at University of Chinese Academy of Sciences, Beijing, China

¹³Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁴Also at Helwan University, Cairo, Egypt

-
- ¹⁵Now at Zewail City of Science and Technology, Zewail, Egypt
- ¹⁶Also at British University in Egypt, Cairo, Egypt
- ¹⁷Now at Ain Shams University, Cairo, Egypt
- ¹⁸Also at Purdue University, West Lafayette, Indiana, USA
- ¹⁹Also at Université de Haute Alsace, Mulhouse, France
- ²⁰Also at Department of Physics, Tsinghua University, Beijing, China
- ²¹Also at Tbilisi State University, Tbilisi, Georgia
- ²²Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ²³Also at University of Hamburg, Hamburg, Germany
- ²⁴Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁵Also at Isfahan University of Technology, Isfahan, Iran
- ²⁶Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²⁷Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁸Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁹Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ³⁰Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³¹Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ³²Also at Wigner Research Centre for Physics, Budapest, Hungary
- ³³Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ³⁴Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³⁵Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³⁶Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ³⁷Also at Punjab Agricultural University, Ludhiana, India
- ³⁸Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ³⁹Also at University of Visva-Bharati, Santiniketan, India
- ⁴⁰Also at University of Hyderabad, Hyderabad, India
- ⁴¹Also at Indian Institute of Science (IISc), Bangalore, India
- ⁴²Also at Indian Institute of Technology (IIT), Mumbai, India
- ⁴³Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴⁴Also at Institute of Physics, Bhubaneswar, India
- ⁴⁵Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁶Also at Sharif University of Technology, Tehran, Iran
- ⁴⁷Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁸Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁹Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵⁰Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵¹Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵²Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
- ⁵³Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁶Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁷Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ⁵⁸Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- ⁵⁹Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁶⁰Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy

- ⁶¹Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶²Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶³Also at Universität Zürich, Zurich, Switzerland
- ⁶⁴Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁵Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁶Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁷Also at Konya Technical University, Konya, Turkey
- ⁶⁸Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁹Also at Adiyaman University, Adiyaman, Turkey
- ⁷⁰Also at Istanbul Gedik University, Istanbul, Turkey
- ⁷¹Also at Necmettin Erbakan University, Konya, Turkey
- ⁷²Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷³Also at Marmara University, Istanbul, Turkey
- ⁷⁴Also at Milli Savunma University, Istanbul, Turkey
- ⁷⁵Also at Kafkas University, Kars, Turkey
- ⁷⁶Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁷Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁸Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁹Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁸⁰Also at University of Bristol, Bristol, United Kingdom
- ⁸¹Also at IPPP Durham University, Durham, United Kingdom
- ⁸²Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸³Also at Università di Torino, Torino, Italy
- ⁸⁴Also at Bethel University, St. Paul, Minnesota, USA
- ⁸⁵Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁶Also at California Institute of Technology, Pasadena, California, USA
- ⁸⁷Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸⁸Also at Bingöl University, Bingöl, Turkey
- ⁸⁹Also at Georgian Technical University, Tbilisi, Georgia
- ⁹⁰Also at Sinop University, Sinop, Turkey
- ⁹¹Also at Erciyes University, Kayseri, Turkey
- ⁹²Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
- ⁹³Also at Texas A&M University at Qatar, Doha, Qatar
- ⁹⁴Also at Kyungpook National University, Daegu, Korea
- ⁹⁵Also at another institute or international laboratory covered by a cooperation agreement with CERN
- ⁹⁶Also at Yerevan Physics Institute, Yerevan, Armenia
- ⁹⁷Now at University of Florida, Gainesville, Florida, USA
- ⁹⁸Also at Imperial College, London, United Kingdom
- ⁹⁹Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan