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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  $J/\psi$ ,  $\psi(2S)$ ,  $Y(1S)$ , 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 ( $\eta$ ) 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  $300 \text{ pb}^{-1}$  ( $1.61 \text{ nb}^{-1}$ ) [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  $\chi^2$  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%.

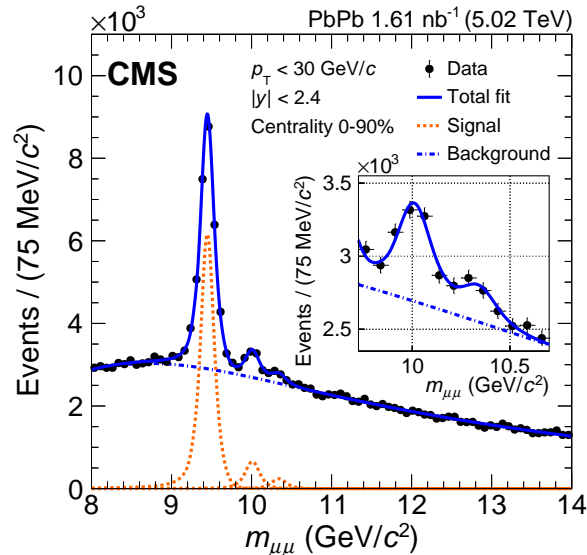


Figure 1: Dimuon invariant mass distribution in PbPb collisions, integrated over the full kinematic range  $p_T < 30 \text{ GeV}/c$  and  $|y| < 2.4$ . The solid curves show the result of the fit, whereas the orange dashed and blue dash-dotted curves represent the three  $Y$  states and the background, 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  $J/\psi$  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  $\sigma^{PP}$  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  $N_{\text{part}}$ ) 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  $0.115 \pm 0.008$  (stat)  $\pm 0.007$  (syst) and  $0.080 \pm 0.014$  (stat)  $\pm 0.012$  (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].

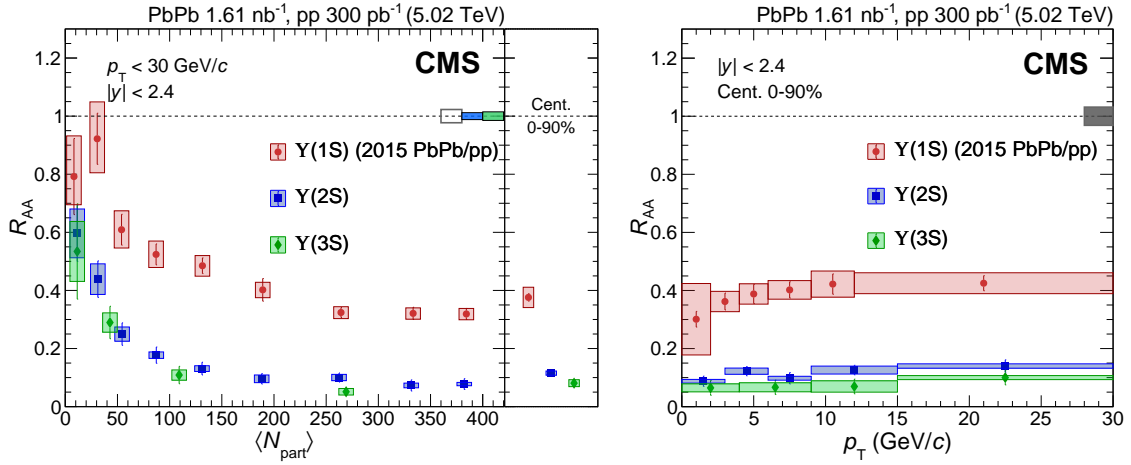


Figure 2: Measured  $R_{AA}$  for the Y states as functions of  $\langle N_{\text{part}} \rangle$  (left), showing also the 0–90% centrality interval, and of  $p_T$  (right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. In the left plot, the leftmost box at unity represents the pp luminosity and PbPb  $N_{\text{MB}}$  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  $N_{\text{MB}}$ . 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  $N_{\text{MB}}$  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

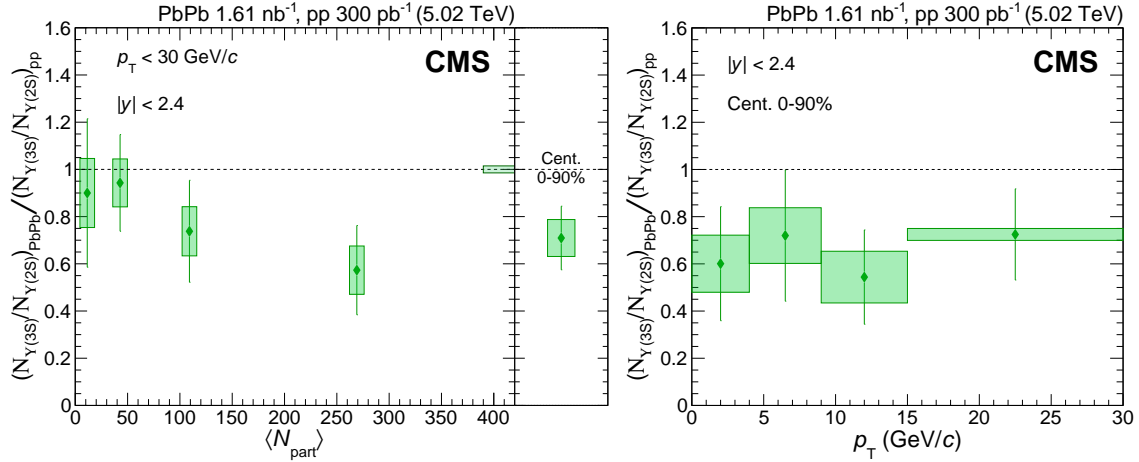


Figure 3: The double ratios of  $Y(3S)/Y(2S)$  as functions of  $\langle N_{\text{part}} \rangle$  (left), showing also the 0–90% centrality interval, and of  $p_T$  (right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity in the left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

- [1] T. Matsui and H. Satz, “ $J/\psi$  suppression by quark gluon plasma formation”, *Phys. Lett. B* **178** (1986) 416, doi:10.1016/0370-2693(86)91404-8.
- [2] F. Karsch, M. T. Mehr, and H. Satz, “Color screening and deconfinement for bound states of heavy quarks”, *Z. Phys. C* **37** (1988) 617, doi:10.1007/BF01549722.
- [3] D. Kharzeev and H. Satz, “Quarkonium interactions in hadronic matter”, *Phys. Lett. B* **334** (1994) 155, doi:10.1016/0370-2693(94)90604-1, arXiv:hep-ph/9405414.
- [4] M. Laine, O. Philipsen, P. Romatschke, and M. Tassler, “Real-time static potential in hot QCD”, *JHEP* **03** (2007) 054, doi:10.1088/1126-6708/2007/03/054, arXiv:hep-ph/0611300.
- [5] N. Brambilla, J. Ghiglieri, A. Vairo, and P. Petreczky, “Static quark antiquark pairs at finite temperature”, *Phys. Rev. D* **78** (2008) 014017, doi:10.1103/PhysRevD.78.014017, arXiv:0804.0993.
- [6] N. Brambilla et al., “Heavy quarkonium in a weakly coupled quark-gluon plasma below the melting temperature”, *JHEP* **09** (2010) 038, doi:10.1007/JHEP09(2010)038, arXiv:1007.4156.
- [7] J.-P. Blaizot, D. De Boni, P. Faccioli, and G. Garberoglio, “Heavy quark bound states in a quark-gluon plasma: Dissociation and recombination”, *Nucl. Phys. A* **946** (2016) 49, doi:10.1016/j.nuclphysa.2015.10.011, arXiv:1503.03857.
- [8] N. Brambilla et al., “Bottomonium production in heavy-ion collisions using quantum trajectories: Differential observables and momentum anisotropy”, *Phys. Rev. D* **104** (2021) 094049, doi:10.1103/PhysRevD.104.094049, arXiv:2107.06222.
- [9] X. Yao et al., “Coupled Boltzmann transport equations of heavy quarks and quarkonia in quark-gluon plasma”, *JHEP* **01** (2021) 046, doi:10.1007/JHEP01(2021)046, arXiv:2004.06746.
- [10] X. Du, M. He, and R. Rapp, “Color screening and regeneration of bottomonia in high-energy heavy-ion collisions”, *Phys. Rev. C* **96** (2017) 054901, doi:10.1103/PhysRevC.96.054901, arXiv:1706.08670.
- [11] A. Rothkopf, “Heavy quarkonium in extreme conditions”, *Phys. Rept.* **858** (2020) 1, doi:10.1016/j.physrep.2020.02.006, arXiv:1912.02253.
- [12] R. L. Thews, M. Schroedter, and J. Rafelski, “Enhanced  $J/\psi$  production in deconfined quark matter”, *Phys. Rev. C* **63** (2001) 054905, doi:10.1103/PhysRevC.63.054905, arXiv:hep-ph/0007323.
- [13] P. Braun-Munzinger and J. Stachel, “(Non)thermal aspects of charmonium production and a new look at  $J/\psi$  suppression”, *Phys. Lett. B* **490** (2000) 196, doi:10.1016/S0370-2693(00)00991-6, arXiv:nucl-th/0007059.

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- [14] N. Brambilla, M. A. Escobedo, J. Soto, and A. Vairo, “Quarkonium suppression in heavy ion collisions: an open quantum system approach”, *Phys. Rev. D* **96** (2017) 034021, doi:10.1103/PhysRevD.96.034021, arXiv:1612.07248.
- [15] A. Emerick, X. Zhao, and R. Rapp, “Bottomonia in the quark gluon plasma and their production at RHIC and LHC”, *Eur. Phys. J. A* **48** (2012) 72, doi:10.1140/epja/i2012-12072-y, arXiv:1111.6537.
- [16] A. Andronic et al., “Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy ion collisions”, *Eur. Phys. J. C* **76** (2016) 107, doi:10.1140/epjc/s10052-015-3819-5, arXiv:1506.03981.
- [17] NA50 Collaboration, “Anomalous  $J/\psi$  suppression in Pb-Pb interactions at 158 GeV/c per nucleon”, *Phys. Lett. B* **410** (1997) 337, doi:10.1016/S0370-2693(97)00915-5.
- [18] NA38 Collaboration, “ $J/\psi$ ,  $\psi'$  and Drell–Yan production in S-U interactions at 200 GeV per nucleon”, *Phys. Lett. B* **449** (1999) 128, doi:10.1016/S0370-2693(99)00057-X.
- [19] NA50 Collaboration, “Evidence for deconfinement of quarks and gluons from the  $J/\psi$  suppression pattern measured in Pb+Pb collisions at the CERN SPS”, *Phys. Lett. B* **477** (2000) 28, doi:10.1016/S0370-2693(00)00237-9.
- [20] NA60 Collaboration, “ $J/\psi$  production in indium-indium collisions at 158 GeV/nucleon”, *Phys. Rev. Lett.* **99** (2007) 132302, doi:10.1103/PhysRevLett.99.132302.
- [21] PHENIX Collaboration, “ $J/\psi$  suppression at forward rapidity in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV”, *Phys. Rev. C* **84** (2011) 054912, doi:10.1103/PhysRevC.84.054912, arXiv:1103.6269.
- [22] STAR Collaboration, “Measurement of inclusive  $J/\psi$  suppression in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV through the dimuon channel at STAR”, *Phys. Lett. B* **787** (2019) 134917, doi:10.1016/j.physletb.2019.134917, arXiv:1905.13669.
- [23] ALICE Collaboration, “Studies of  $J/\psi$  production at forward rapidity in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *JHEP* **02** (2019) 041, doi:10.1007/JHEP02(2020)041, arXiv:1909.03158.
- [24] ALICE Collaboration, “ $\psi(2S)$  suppression in Pb-Pb collisions at the LHC”, 2022. arXiv:2210.08893.
- [25] ATLAS Collaboration, “Prompt and non-prompt  $J/\psi$  and  $\psi(2S)$  suppression at high transverse momentum in 5.02 TeV Pb+Pb collisions with the ATLAS experiment”, *Eur. Phys. J. C* **78** (2018) 762, doi:10.1140/epjc/s10052-018-6219-9, arXiv:1805.04077.
- [26] CMS Collaboration, “Measurement of prompt and nonprompt charmonium suppression in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Eur. Phys. J. C* **78** (2018) 509, doi:10.1140/epjc/s10052-018-5950-6, arXiv:1712.08959.
- [27] CMS Collaboration, “Measurement of nuclear modification factors of  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Lett. B* **790** (2019) 270, doi:10.1016/j.physletb.2019.01.006, arXiv:1805.09215.

- [28] ALICE Collaboration, “Y production and nuclear modification at forward rapidity in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Lett. B* **822** (2021) 136579, doi:10.1016/j.physletb.2021.136579, arXiv:2011.05758.
- [29] ATLAS Collaboration, “Production of Y(nS) mesons in Pb+Pb and pp collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, 2022. arXiv:2205.03042.
- [30] STAR Collaboration, “Suppression of Y production in d+Au and Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV”, *Phys. Lett. B* **735** (2014) 127, doi:10.1016/j.physletb.2014.06.028, arXiv:1312.3675. [Erratum: doi:10.1016/j.physletb.2015.01.046].
- [31] STAR Collaboration, “Measurement of Sequential Y Suppression in Au+Au Collisions at  $\sqrt{s_{NN}} = 200$  GeV with the STAR Experiment”, *Phys. Rev. Lett.* **130** (2023) 112301, doi:10.1103/PhysRevLett.130.112301, arXiv:2207.06568.
- [32] PHENIX Collaboration, “Measurement of Y(1S + 2S + 3S) production in p + p and Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV”, *Phys. Rev. C* **91** (2015) 024913, doi:10.1103/PhysRevC.91.024913, arXiv:1404.2246.
- [33] D. d’Enterria and C. Loizides, “Progress in the Glauber Model at Collider Energies”, *Ann. Rev. Nucl. Part. Sci.* **71** (2021) 315, doi:10.1146/annurev-nucl-102419-060007, arXiv:2011.14909.
- [34] HEPData record for this analysis, 2023. doi:10.17182/hepdata.130959.
- [35] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [36] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [37] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [38] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [39] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [40] CMS Collaboration, “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *JINST* **10** (2015) P08010, doi:10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.
- [41] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
- [42] CMS Collaboration, “Observation and studies of jet quenching in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV”, *Phys. Rev. C* **84** (2011) 024906, doi:10.1103/PhysRevC.84.024906, arXiv:1102.1957.

- [43] CMS Collaboration, “Measurement of the azimuthal anisotropy of  $Y(1S)$  and  $Y(2S)$  mesons in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Lett. B* **819** (2021) 136385, doi:10.1016/j.physletb.2021.136385, arXiv:2006.07707.
- [44] CMS Collaboration, “Luminosity measurement in proton-proton collisions at 5.02 TeV in 2017 at CMS”, CMS Physics Analysis Summary CMS-PAS-LUM-19-001, 2021.
- [45] CMS Collaboration, “CMS luminosity measurement using nucleus-nucleus collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in 2018”, CMS Physics Analysis Summary CMS-PAS-LUM-18-001, 2022.
- [46] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [47] CMS Collaboration, “Charged-particle nuclear modification factors in PbPb and pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *JHEP* **04** (2017) 039, doi:10.1007/JHEP04(2017)039, arXiv:1611.01664.
- [48] CMS Collaboration, “Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid”, CMS Technical Proposal CERN-LHCC-2015-010, 2015.
- [49] CMS Collaboration, “Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at  $\sqrt{s} = 0.9$  and 2.36 TeV”, *JHEP* **02** (2010) 041, doi:10.1007/JHEP02(2010)041, arXiv:1002.0621.
- [50] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [51] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [52] CMS Collaboration, “Measurement of the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  polarizations in pp collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Rev. Lett.* **110** (2013) 081802, doi:10.1103/PhysRevLett.110.081802, arXiv:1209.2922.
- [53] CMS Collaboration, “ $Y(nS)$  polarizations versus particle multiplicity in pp collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Lett. B* **761** (2016) 31, doi:10.1016/j.physletb.2016.07.065, arXiv:1603.02913.
- [54] LHCb Collaboration, “Measurement of the  $Y$  polarizations in pp collisions at  $\sqrt{s} = 7$  and 8 TeV”, *JHEP* **12** (2017) 110, doi:10.1007/JHEP12(2017)110, arXiv:1709.01301.
- [55] ALICE Collaboration, “First measurement of quarkonium polarization in nuclear collisions at the LHC”, *Phys. Lett. B* **815** (2021) 136146, doi:10.1016/j.physletb.2021.136146, arXiv:2005.11128.
- [56] I. P. Lokhtin and A. M. Snigirev, “A model of jet quenching in ultrarelativistic heavy ion collisions and high- $p_T$  hadron spectra at RHIC”, *Eur. Phys. J. C* **45** (2006) 211, doi:10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.
- [57] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

- [58] H. Voss, A. Höcker, J. Stelzer, and F. Tegenfeldt, “TMVA, the toolkit for multivariate data analysis with ROOT”, in *XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT)*, p. 40. 2007. arXiv:physics/0703039. doi:10.22323/1.050.0040.
- [59] M. J. Oreglia, “A study of the reactions  $\psi' \rightarrow \gamma\gamma\psi$ ”. PhD thesis, Stanford University, 1980. SLAC Report R-236 p.184.
- [60] Particle Data Group, R. L. Workman et al., “Review of particle physics”, *Prog. Theor. Exp. Phys.* **2022** (2022) 083C01, doi:10.1093/ptep/ptac097.
- [61] H. Akaike, “A new look at the statistical model identification”, *IEEE Trans. Automat. Contr.* **19** (1974) 716, doi:10.1109/TAC.1974.1100705.
- [62] M. S. Barlett, “Tests of significance in factor analysis”, *Br. J. Stat. Psychol.* **3** (1950) 77, doi:10.1111/j.2044-8317.1950.tb00285.x.
- [63] CMS Collaboration, “Performance of the CMS muon trigger system in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **16** (2021) P07001, doi:10.1088/1748-0221/16/07/p07001, arXiv:2102.04790.
- [64] CMS Collaboration, “Fragmentation of jets containing a prompt  $J/\psi$  meson in PbPb and pp collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Lett. B* **825** (2022) 136842, doi:10.1016/j.physletb.2021.136842, arXiv:2106.13235.
- [65] C. Loizides, J. Kamin, and D. d’Enterria, “Improved Monte Carlo Glauber predictions at present and future nuclear colliders”, *Phys. Rev. C* **97** (2018) 054910, doi:10.1103/PhysRevC.97.054910, arXiv:1710.07098.
- [66] S. S. Wilks, “The large-sample distribution of the likelihood ratio for testing composite hypotheses”, *Annals Math. Statist.* **9** (1938) 60, doi:10.1214/aoms/1177732360.
- [67] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [68] P. D. Dauncey, M. Kenzie, N. Wardle, and G. J. Davies, “Handling uncertainties in background shapes : the discrete profiling method”, *JINST* **10** (2015) P04015, doi:10.1088/1748-0221/10/04/P04015, arXiv:1408.6865.
- [69] P. Faccioli and C. Lourenço, “The fate of quarkonia in heavy-ion collisions at LHC energies: a unified description of the sequential suppression patterns”, *Eur. Phys. J. C* **78** (2018) 731, doi:10.1140/epjc/s10052-018-6216-z, arXiv:1809.10488.
- [70] N. Brambilla et al., “Regeneration of bottomonia in an open quantum systems approach”, *Phys. Rev. D* **108** (2023) L011502, doi:10.1103/PhysRevD.108.L011502, arXiv:2302.11826.
- [71] E. G. Ferreira and J.-P. Lansberg, “Is bottomonium suppression in proton-nucleus and nucleus-nucleus collisions at LHC energies due to the same effects?”, *JHEP* **10** (2018) 094, doi:10.1007/JHEP10(2018)094, arXiv:1804.04474. [Erratum: doi:10.1007/JHEP03(2019)063].

- [72] G. Wolschin, “Bottomonium spectroscopy in the quark gluon plasma”, *Int. J. Mod. Phys. A* **35** (2020) 2030016, doi:10.1142/S0217751X20300161, arXiv:2010.05841.
- [73] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, “Decoding the phase structure of QCD via particle production at high energy”, *Nature* **561** (2018) 321, doi:10.1038/s41586-018-0491-6.
- [74] ALICE Collaboration, “Studies of  $J/\psi$  production at forward rapidity in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *JHEP* **02** (2020) 041, doi:10.1007/JHEP02(2020)041, arXiv:1909.03158.
- [75] CMS Collaboration, “Measurement of prompt and nonprompt charmonium suppression in PbPb collisions at 5.02 TeV”, *The European Physical Journal C* **78** (2018) 509, doi:10.1140/epjc/s10052-018-5950-6, arXiv:1712.08959.
- [76] H. Satz, “Colour deconfinement and quarkonium binding”, *J. Phys. G: Nucl. Part. Phys.* **32** (2006) R25, doi:10.1088/0954-3899/32/3/R01, arXiv:hep-ph/0512217.
- [77] CMS Collaboration, “Nuclear modification of  $Y$  states in pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Lett. B* **835** (2022) 137397, doi:10.1016/j.physletb.2022.137397, arXiv:2202.11807.

## A Supplemental material

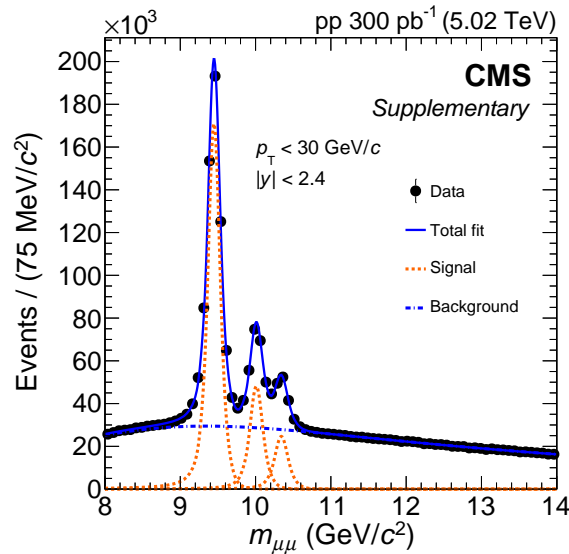


Figure A.1: Dimuon invariant mass distribution in pp collisions, integrated over the full kinematic range  $p_T < 30$  GeV/c and  $|y| < 2.4$ . The solid curves show the result of the fit, whereas the orange dashed and blue dash-dotted curves represent the three  $Y$  states and the background, respectively.

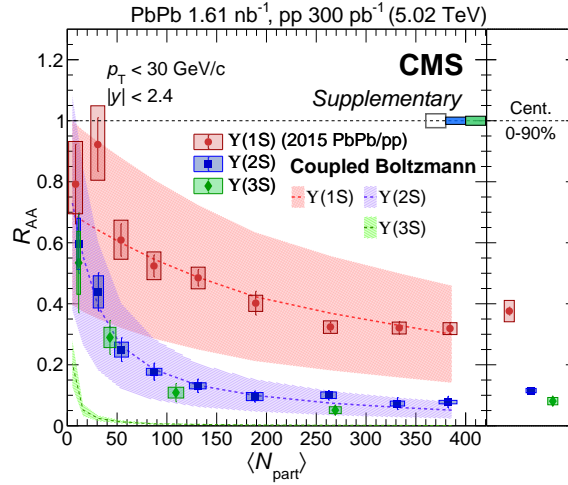


Figure A.2: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb  $N_{\text{MB}}$ , 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].

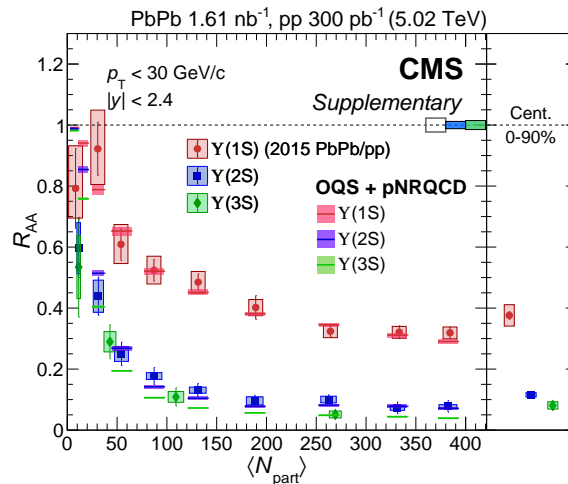


Figure A.3: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb  $N_{\text{MB}}$ , 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].

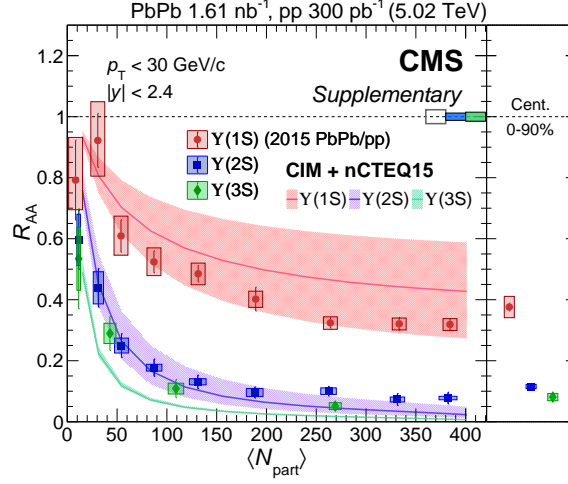


Figure A.4: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb  $N_{\text{MB}}$ , 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].

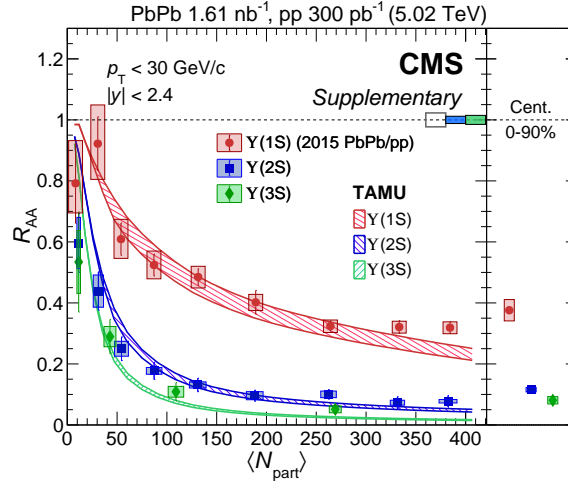


Figure A.5: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb  $N_{\text{MB}}$ , 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].



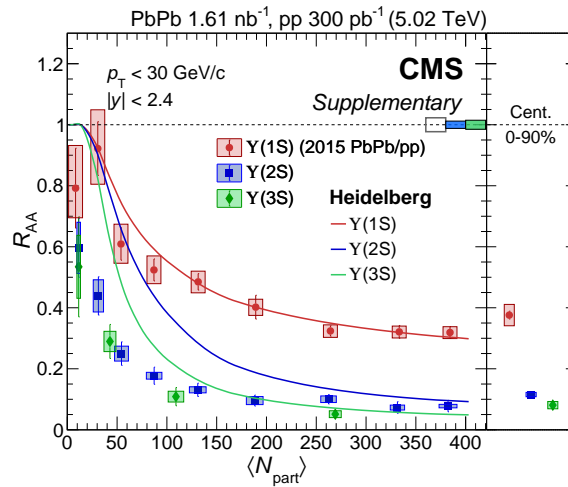


Figure A.6: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most 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].

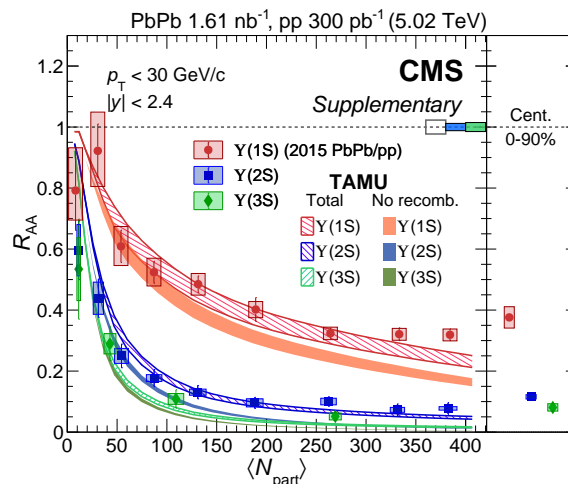


Figure A.7: Nuclear modification factors for the Y(1S), Y(2S), and Y(3S) mesons as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most 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.

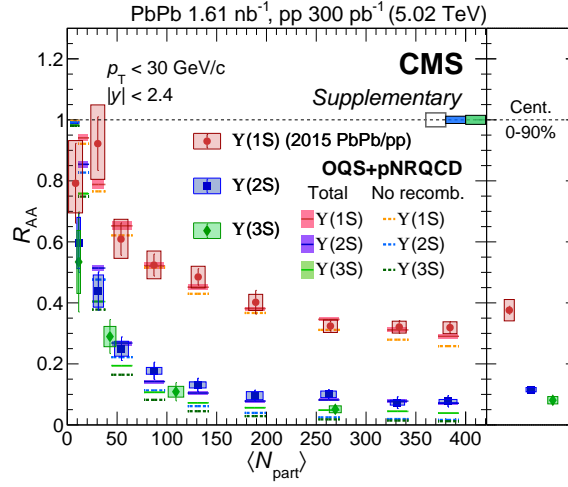


Figure A.8: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb  $N_{\text{MB}}$ , 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.

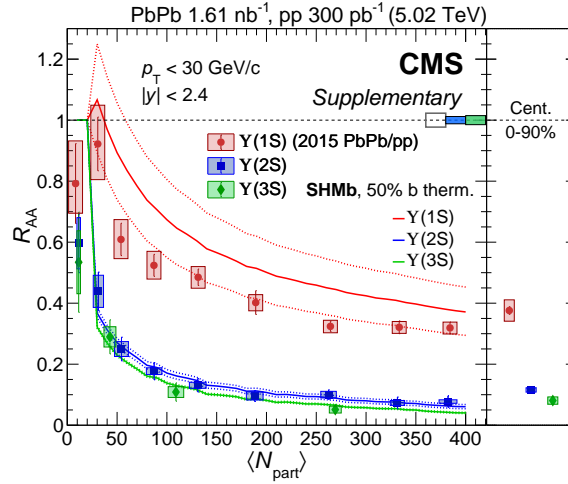


Figure A.9: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 2 left), including the centrality integrated bin. The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The left-most box at unity combines the uncertainties of pp luminosity and PbPb  $N_{\text{MB}}$ , 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.

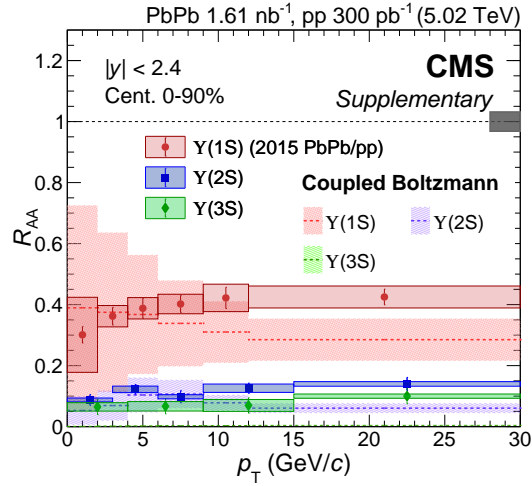


Figure A.10: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons as a function of  $p_T$  (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines 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].

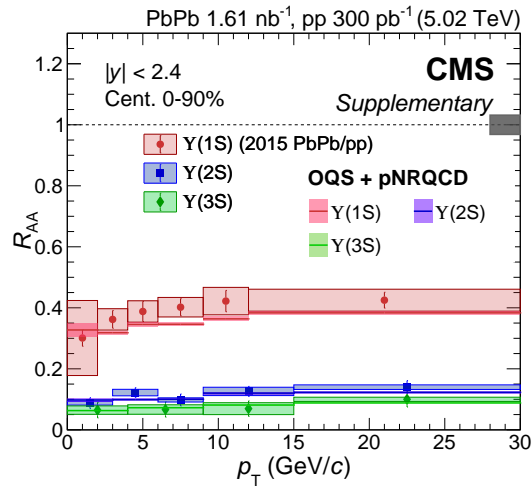


Figure A.11: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons as a function of  $p_T$  (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines 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].

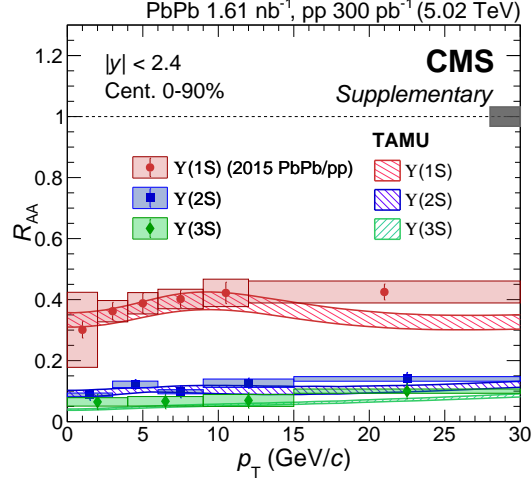


Figure A.12: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons as a function of  $p_T$  (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines 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].

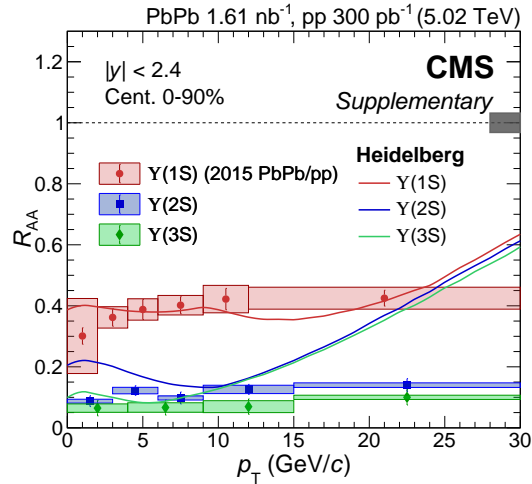


Figure A.13: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons as a function of  $p_T$  (from 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines uncertainties 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].

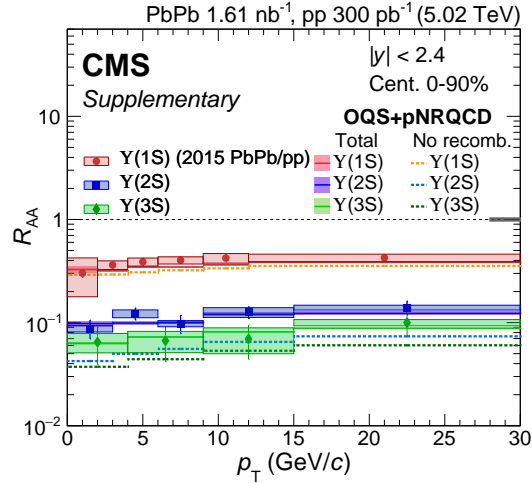


Figure A.14: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons as a function of  $p_T$  (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines 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.

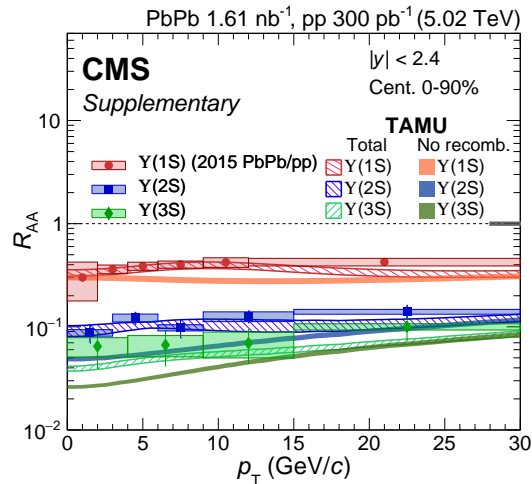


Figure A.15: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  mesons as a function of  $p_T$  (from Figure 2 right). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity represents the global uncertainty, which combines 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.

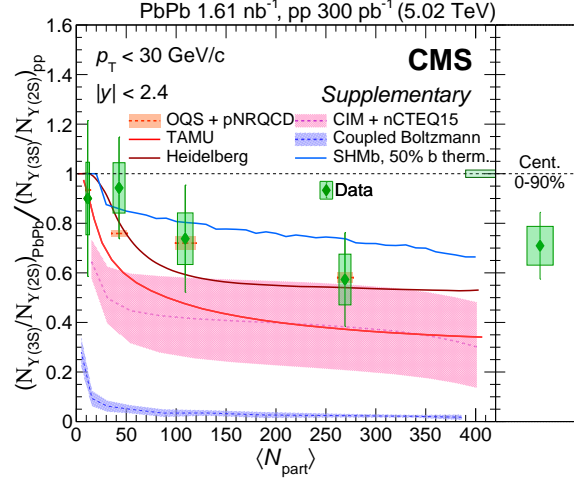


Figure A.16: The double ratio of  $Y(3S)/Y(2S)$  as functions of  $\langle N_{\text{part}} \rangle$  (from Figure 3 left). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The box at unity shows the combined systematic and statistical uncertainties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

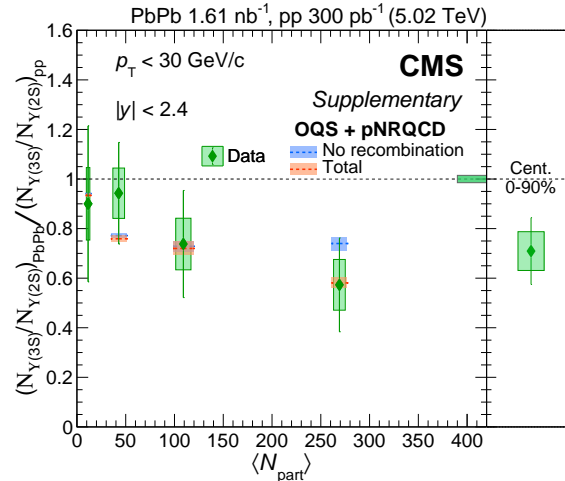


Figure A.17: The double ratio of  $Y(3S)/Y(2S)$  as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 3 left). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The box at unity shows the combined systematic and statistical uncertainties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

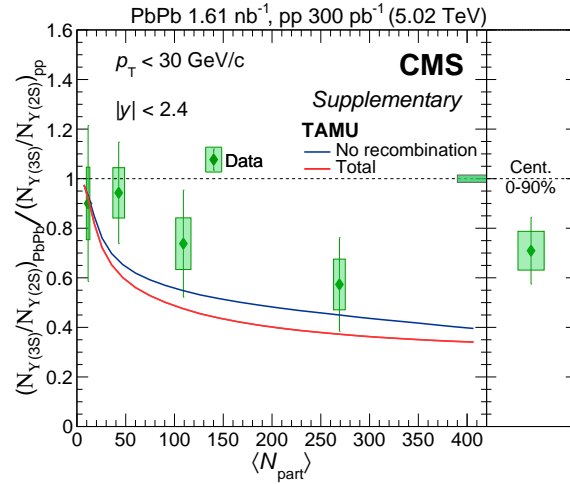


Figure A.18: The double ratio of  $Y(3S)/Y(2S)$  as a function of  $\langle N_{\text{part}} \rangle$  (from Figure 3 left). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The box at unity shows the combined systematic and statistical uncertainties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

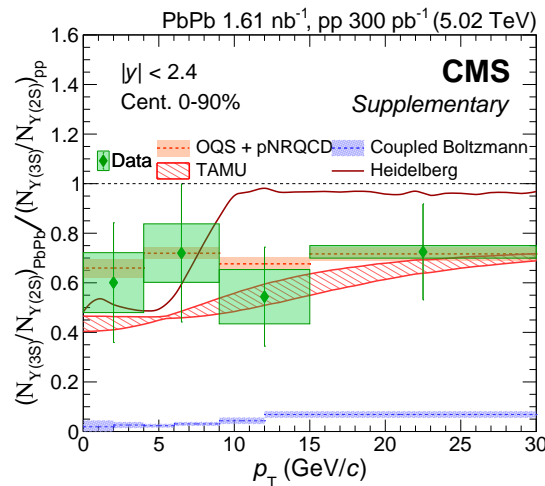


Figure A.19: The double ratio of  $Y(3S)/Y(2S)$  as a function of  $p_T$  (from Figure 3 right). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The bands and line represent calculations from Ref. [9, 10, 70, 72].

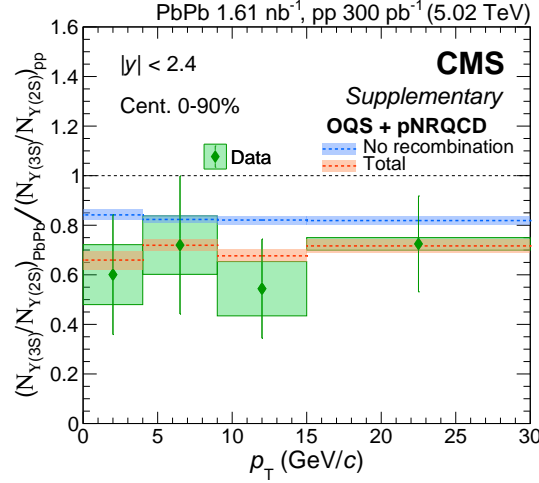


Figure A.20: The double ratio of  $Y(3S)/Y(2S)$  as a function of  $p_T$  (from Figure 3 right). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The orange and blue bands represent calculations from Ref. [70], with the latter showing the calculations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

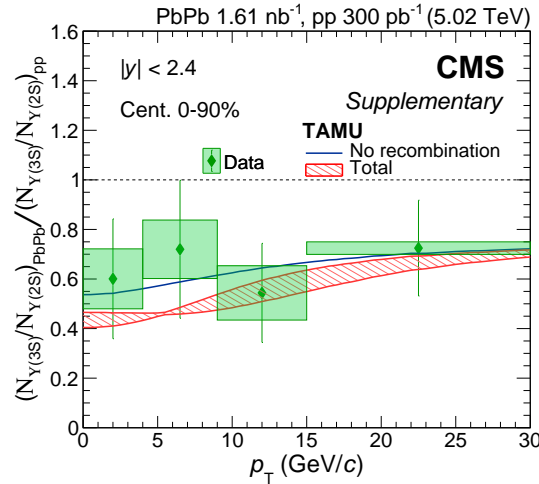


Figure A.21: The double ratio of  $Y(3S)/Y(2S)$  as a function of  $p_T$  (from Figure 3 right). The vertical lines correspond to statistical uncertainties, while the boxes are the systematic uncertainties. The red band and blue line represent calculations from Ref. [10], with the latter showing the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



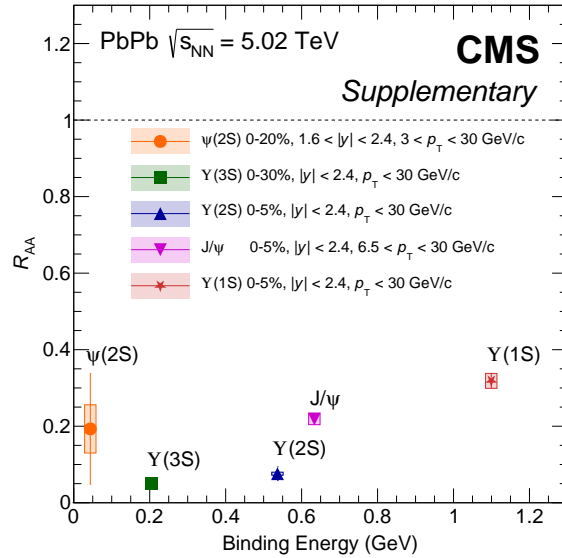


Figure A.22: The nuclear modification factors for various quarkonium mesons as a function of quarkonium binding energy at  $\sqrt{s_{NN}} = 5.02$  TeV. The  $R_{AA}$  values are taken from the data point with the most central collision bin, e.g., the values for the Y's correspond to the points of the 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/ $\psi$  and  $\psi(2S)$ ) are taken from Refs. [27] and [75], respectively.

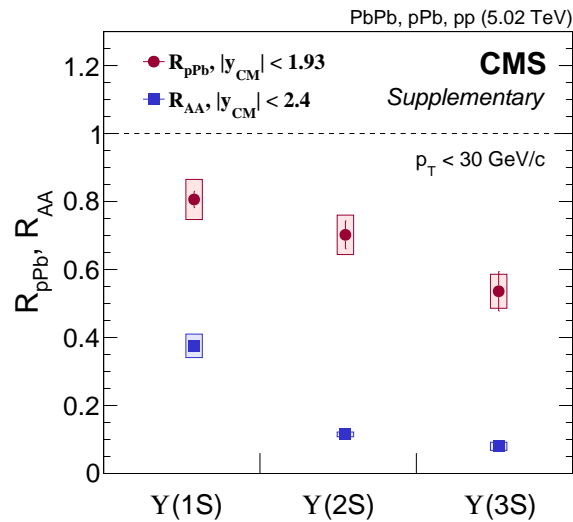


Figure A.23: The nuclear modification factors for Y(1S), Y(2S), and Y(3S) mesons in pPb and PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The error bars and boxes represent the statistical and systematic uncertainties, respectively. The Y(2S) and Y(3S) values are from the integrated bin in Figure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

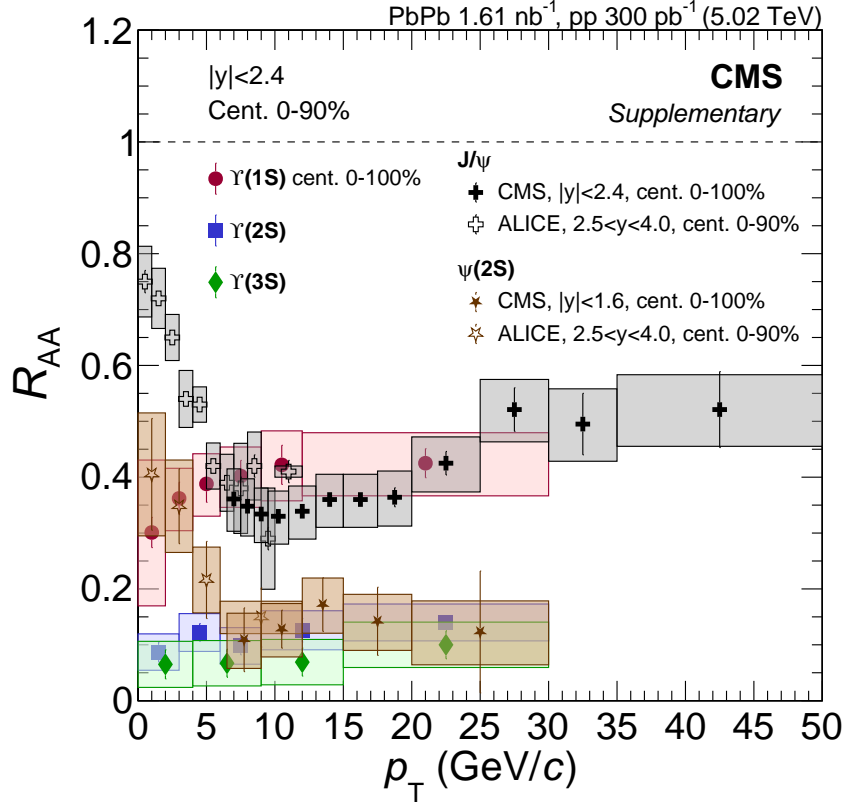


Figure A.24: Nuclear modification factors for the  $Y(1S)$ ,  $Y(2S)$ ,  $Y(3S)$ ,  $J/\psi$ , and  $\psi(2S)$  mesons as a function of  $p_T$ . The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. Results for the  $Y(1S)$  meson are taken from Ref. [27].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

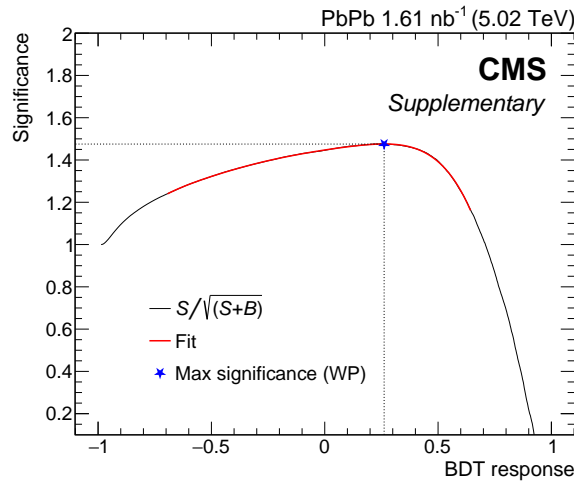


Figure A.25: The significance  $S/\sqrt{S+B}$  for  $Y$  mesons in PbPb collisions as a function of BDT score normalized to range between -1 and 1. The quantities  $S$  and  $B$  represent the yields of signal and background dimuons used for the BDT training, respectively. The working point (WP) is determined 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  $N_{\text{MB}}$ . 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  $N_{\text{MB}}$  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. Tumasyan<sup>1</sup> 













### 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. Jeitler<sup>2</sup> , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch, F.M. Pitters, J. Schieck<sup>2</sup> , R. Schöfbeck , D. Schwarz , S. Templ , W. Waltenberger , C.-E. Wulz<sup>2</sup> 













### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>3</sup> , T. Janssen , T. Kello<sup>4</sup>, 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. Lemaitre, 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. Chinellato<sup>5</sup>, E.M. Da Costa , G.G. Da Silveira<sup>6</sup> , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins<sup>7</sup> , 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 Araujo<sup>8</sup> , A. Vilela Pereira 







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


C.A. Bernardes<sup>6</sup> , 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. Javaid<sup>9</sup> , M. Mittal , L. Yuan 











**Department of Physics, Tsinghua University, Beijing, China**

M. Ahmad , G. Bauer<sup>10</sup>, Z. Hu , S. Lezki , K. Yi<sup>10,11</sup>

**Institute of High Energy Physics, Beijing, China**

G.M. Chen<sup>9</sup> , H.S. Chen<sup>9</sup> , M. Chen<sup>9</sup> , F. Iemmi , C.H. Jiang, A. Kapoor , H. Kou , H. Liao , Z.-A. Liu<sup>12</sup> , 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. Gao<sup>4</sup> , 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. Starodumov<sup>13</sup> , 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<sup>14,15</sup> , E. Salama<sup>16,17</sup> 

**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,  
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

























**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-Navarro<sup>18</sup> , 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 ,  
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

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

J.-L. Agram<sup>19</sup> , 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. Dozen<sup>20</sup> , 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. Toriashvili<sup>21</sup> , Z. Tsamalaidze<sup>13</sup> 









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

V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert ,  
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 Ahmad<sup>22</sup> , 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. Blekman<sup>23</sup> , K. Borrás<sup>24</sup> , 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. Gallo<sup>23</sup> , A. Geiser , A. Giraldi , G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari<sup>25</sup> , N.Z. Jomhari , B. Kaech , A. Kasem<sup>24</sup> , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka<sup>26</sup> , W. Lohmann<sup>27</sup> , 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<sup>28,24</sup> , V. Scheurer, S. Schnake<sup>24</sup> , P. Schütze , C. Schwanenberger<sup>23</sup> , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon<sup>†</sup> , M. Van De Klundert , F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann, L. Wiens<sup>24</sup> , 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. Kasieczka , 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. Savoie , 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. Hartmann<sup>29</sup> , 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. Gadallah<sup>30</sup> , S. Lökös<sup>31</sup> , P. Major , K. Mandal , G. Pásztor , A.J. Rádli<sup>32</sup> , O. Surányi , G.I. Veres 


**Wigner Research Centre for Physics, Budapest, Hungary**

M. Bartók<sup>33</sup> , G. Bencze, C. Hajdu , D. Horvath<sup>34,35</sup> , F. Sikler , V. Veszpremi 




**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni , S. Czellar, J. Karancsi<sup>33</sup> , J. Molnar, Z. Szillasi, D. Teyssier 


















**Institute of Physics, University of Debrecen, Debrecen, Hungary**

P. Raics, B. Ujvari<sup>36</sup> 

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

T. Csorgo<sup>32</sup> , F. Nemes<sup>32</sup> , T. Novak 









**Panjab University, Chandigarh, India**

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra<sup>37</sup> , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh<sup>38</sup> , 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. Barman<sup>39</sup> , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber<sup>40</sup> , M. Maity<sup>39</sup>, 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. Komaragiri<sup>41</sup> , D. Kumar<sup>41</sup> , A. Muham-mad , L. Panwar<sup>41</sup> , R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar , P.C. Tiwari<sup>41</sup> , S. Verma 

**Bhabha Atomic Research Centre, Mumbai, India**

K. Naskar<sup>42</sup> 

**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. Bahinipati<sup>43</sup> , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu<sup>44</sup> ,  
A. Nayak<sup>44</sup> , P. Saha , S.K. Swain, D. Vats<sup>44</sup> 





**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. Bakhshiansohi<sup>45</sup> , E. Khazaie , M. Zeinali<sup>46</sup> 

































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

S. Chenarani<sup>47</sup> , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























**University College Dublin, Dublin, Ireland**

M. Grunewald 

**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

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


















**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

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

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

S. Costa<sup>a,b,49</sup> , A. Di Mattia<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,49</sup> , C. Tuve<sup>a,b</sup> 

**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy**

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












**INFN Laboratori Nazionali di Frascati, Frascati, Italy**












L. Benussi , S. Bianco , S. Meola<sup>29</sup> , D. Piccolo 

**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**










M. Bozzo<sup>a,b</sup> , P. Chatagnon<sup>a</sup> , F. Ferro<sup>a</sup> , R. Mulargia<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> 

**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**
























A. Benaglia<sup>a</sup> , G. Boldrini<sup>a</sup> , F. Brivio<sup>a,b</sup> , F. Cetorelli<sup>a,b</sup> , F. De Guio<sup>a,b</sup> ,  
M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a,b</sup> 

M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup> , S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , D. Pedrini<sup>a</sup> , B.S. Pinolini<sup>a</sup>, S. Ragazzi<sup>a,b</sup> , N. Redaelli<sup>a</sup> , T. Tabarelli de Fatis<sup>a,b</sup> , D. Zuolo<sup>a,b</sup> 












**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Università G. Marconi<sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup> , F. Carnevali<sup>a,b</sup>, N. Cavallo<sup>a,c</sup> , A. De Iorio<sup>a,b</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,50</sup> , P. Paolucci<sup>a,29</sup> , B. Rossi<sup>a</sup> , C. Sciacca<sup>a,b</sup> 















**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**

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



































**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**

S. Abu Zeid<sup>a,17</sup> , C. Aimè<sup>a,b</sup> , A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a,b</sup> , D. Fiorina<sup>a,b</sup> , P. Montagna<sup>a,b</sup> , V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a</sup> , P. Vitulo<sup>a,b</sup> 




**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**

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






































**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy**

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





**INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy**

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














**INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**

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

**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup> , V. Candelise<sup>a,b</sup> , M. Casarsa<sup>a</sup> , F. Cossutti<sup>a</sup> , A. Da Rold<sup>a,b</sup> ,  
G. Della Ricca<sup>a,b</sup> , G. Sorrentino<sup>a,b</sup> 




**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. Hoh<sup>55</sup> , I. Yusuff<sup>55</sup> , 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 Cruz<sup>56</sup> , 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. Mijuskovic<sup>57</sup>, 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. Adzic<sup>58</sup> , M. Dordevic , P. Milenovic , J. Milosevic 













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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 ,  
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








**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 ,  
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



**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. Kailasapathy<sup>59</sup> , 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<sup>†</sup>,  
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. Fallavollita<sup>60</sup>,  
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. Sphicas<sup>61</sup> , A.G. Stahl Leitner ,  
S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsirou, J. Wanczyk<sup>62</sup> ,  
K.A. Wozniak , W.D. Zeuner
























**Paul Scherrer Institut, Villigen, Switzerland**

L. Caminada<sup>63</sup> , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram ,  
H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli<sup>63</sup> , L. Noehte<sup>63</sup> , T. Rohe 



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

T.K. Aarrestad , K. Androsov<sup>62</sup> , 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. Mascellani<sup>62</sup> , 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. Steggemann<sup>62</sup> , D. Valsecchi<sup>29</sup> , R. Wallny 











**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>64</sup> , 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. Jofre-  
hei , 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. Adloff<sup>65</sup>, 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. Dumanoglu<sup>66</sup> , E. Eskut ,  
Y. Guler<sup>67</sup> , E. Gurpinar Guler<sup>67</sup> , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu ,  
G. Onengut , K. Ozdemir<sup>68</sup> , A. Polatoz , A.E. Simsek , B. Tali<sup>69</sup> , U.G. Tok ,  
S. Turkcapar , E. Uslan , I.S. Zorbakir 

**Middle East Technical University, Physics Department, Ankara, Turkey**

G. Karapinar<sup>70</sup>, K. Ocalan<sup>71</sup> , M. Yalvac<sup>72</sup> 

**Bogazici University, Istanbul, Turkey**

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya<sup>73</sup> , O. Kaya<sup>74</sup> , S. Tekten<sup>75</sup> 


**Istanbul Technical University, Istanbul, Turkey**

A. Cakir , K. Cankocak<sup>66</sup> , Y. Komurcu , S. Sen<sup>66</sup> 


**Istanbul University, Istanbul, Turkey**

O. Aydilek , S. Cerci<sup>69</sup> , B. Hacisahinoglu , I. Hos<sup>76</sup> , B. Isildak<sup>77</sup> , B. Kaynak ,  
S. Ozkorucuklu , C. Simsek , D. Sunar Cerci<sup>69</sup> 
















**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. Stylianou<sup>78</sup> ,  
K. Walkingshaw Pass, R. White 




**Rutherford Appleton Laboratory, Didcot, United Kingdom**

A.H. Ball, K.W. Bell , A. Belyaev<sup>79</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill ,  
C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg<sup>80</sup> , 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. Chahal<sup>81</sup> , 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. Nash<sup>82</sup> , 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. Virdee<sup>29</sup> , 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. Rumerio<sup>83</sup> , 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. Coubez<sup>24</sup> , D. Cutts , M. Hadley , U. Heintz , J.M. Hogan<sup>84</sup> , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan , S. Sagir<sup>85</sup> , 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. Pena<sup>86</sup> , F. Ravera , A. Reinsvold Hall<sup>87</sup> , 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. Elkafrawy<sup>17</sup> , 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. Dilsiz<sup>88</sup> , L. Emediato , R.P. Gandrajula , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>89</sup> , J. Nachtman , O. Neogi, H. Ogul<sup>90</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>91</sup> 

**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**

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#### **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**

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**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. Zhang<sup>92</sup>,  
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. Karacheban<sup>27</sup> , 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. Bouhali<sup>93</sup> , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang ,  
T. Kamon<sup>94</sup> , 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. Blinov<sup>95</sup>, E. Boos , V. Borshch , D. Budkouski , V. Chekhovsky,  
R. Chistov<sup>95</sup> , A. Demiyarov , A. Dermenev , T. Dimova<sup>95</sup> , I. Dremin , V. Epshteyn ,  
A. Ershov , G. Gavrilov , V. Gavrilov , S. Gninenko , V. Golovtcov , N. Golubev ,  
I. Golutvin , I. Gorbunov , A. Gribushin , V. Ivanchenko , Y. Ivanov , V. Kachanov ,  
L. Kardapoltsev<sup>95</sup> , V. Karjavine , A. Karneyev , L. Khein, V. Kim<sup>95</sup> , M. Ki-  
rakosyan, D. Kirpichnikov , M. Kirsanov , O. Kodolova<sup>96</sup> , D. Konstantinov , V. Ko-  
renkov , V. Korotkikh, A. Kozyrev<sup>95</sup> , N. Krasnikov , E. Kuznetsova<sup>97</sup> , A. Lanev ,  
P. Levchenko , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov ,  
V. Matveev<sup>95</sup> , V. Murzin , A. Nikitenko<sup>98</sup> , S. Obraztsov , A. Oskin, I. Ovtin<sup>95</sup> ,  
V. Palichik , P. Parygin , V. Perelygin , S. Petrushanko , S. Polikarpov<sup>95</sup> , V. Popov,  
E. Popova , O. Radchenko<sup>95</sup> , M. Savina , V. Savrin , D. Selivanova , V. Shalaev ,  
S. Shmatov , S. Shulha , Y. Skovpen<sup>95</sup> , 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. Yuldashev<sup>99</sup>, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

<sup>1</sup>Also at Yerevan State University, Yerevan, Armenia

<sup>2</sup>Also at TU Wien, Vienna, Austria

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

<sup>4</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium

<sup>5</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil

<sup>6</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

<sup>7</sup>Also at UFMS, Nova Andradina, Brazil

<sup>8</sup>Also at The University of the State of Amazonas, Manaus, Brazil

<sup>9</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>10</sup>Also at Nanjing Normal University Department of Physics, Nanjing, China

<sup>11</sup>Now at The University of Iowa, Iowa City, Iowa, USA

<sup>12</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>13</sup>Also at an institute or an international laboratory covered by a cooperation agreement with CERN

<sup>14</sup>Also at Helwan University, Cairo, Egypt

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

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