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Author(s):

CMS Collaboration; Sirunyan, Albert M.; Backhaus, Malte; Bäni, Lukas; Berger, Pirmin; Bianchini, Lorenzo; Casal, Bruno; Dissertori, Günther; Dittmar, Michael; Donegà, Mauro; Dorfer, Christian; [Grab, Christophorus](#) ; Heidegger, Constantin; Hits, Dmitry; Hoss, Jan; Kasieczka, Gregor; Klijnsma, Thomas; Lustermann, Werner; Mangano, Boris; Marionneau, Matthieu; Meinhard, Maren T.; Meister, Daniel; Micheli, Francesco; Musella, Pasquale; Nessi-Tedaldi, Francesca; Pandolfi, Francesco; Pata, Joosep; Paus, Felicitas; Perrin, Gaël; Perrozzi, Luca; Quittnat, Milena; Reichmann, Michael; Sanz Becerra, Diego A.; Schönenberger, Myriam; Shchutska, Lesya; Tavoraro, Vittorio R.; Theofilatos, Konstantinos; Vesterbacka Olsson, Minna L.; [Wallny, Rainer](#) ; Zhu, De H.; et al.

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Measurement of prompt and nonprompt charmonium suppression in PbPb collisions at 5.02 TeV

CMS Collaboration*

CERN, 1211 Geneva 23, Switzerland

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Abstract The nuclear modification factors of J/ψ and $\psi(2S)$ mesons are measured in PbPb collisions at a centre-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. The analysis is based on PbPb and pp data samples collected by CMS at the LHC in 2015, corresponding to integrated luminosities of $464 \mu\text{b}^{-1}$ and 28pb^{-1} , respectively. The measurements are performed in the dimuon rapidity range of $|y| < 2.4$ as a function of centrality, rapidity, and transverse momentum (p_T) from $p_T = 3$ GeV/c in the most forward region and up to 50 GeV/c. Both prompt and nonprompt (coming from b hadron decays) J/ψ mesons are observed to be increasingly suppressed with centrality, with a magnitude similar to the one observed at $\sqrt{s_{NN}} = 2.76$ TeV for the two J/ψ meson components. No dependence on rapidity is observed for either prompt or nonprompt J/ψ mesons. An indication of a lower prompt J/ψ meson suppression at $p_T > 25$ GeV/c is seen with respect to that observed at intermediate p_T . The prompt $\psi(2S)$ meson yield is found to be more suppressed than that of the prompt J/ψ mesons in the entire p_T range.

1 Introduction

Quarkonium production in heavy ion collisions has a rich history. In their original article [1], Matsui and Satz proposed that Debye color screening of the heavy-quark potential in a hot medium prevents the production of J/ψ mesons (and this applies also to other heavy-quark bound states such as $\psi(2S)$, and $\Upsilon(1S)$ mesons [2]). Consequently, the suppression of quarkonium yields in heavy ion collisions, relative to those in pp collisions, has long been considered to be a sensitive probe of deconfinement and quark-gluon plasma formation. The J/ψ meson suppression observed in PbPb collisions at the CERN SPS [3] and AuAu collisions at the BNL RHIC [4] is compatible with this picture. Similarly, the disappearance of Υ resonances in PbPb collisions at the CERN LHC [5,6] is consistent with the Debye screening scenario.

When produced abundantly in a single heavy ion collision, uncorrelated heavy quarks may combine to form quarkonia states in the medium [7,8]. This additional source of quarkonium, commonly referred to as *recombination*, would enhance its production in heavy ion collisions, in contradistinction with the Debye screening scenario. Signs of this effect can be seen in the recent results from the ALICE Collaboration at the LHC [9,10], which measured a weaker J/ψ meson suppression than at RHIC [4,11], despite the higher medium energy density. Note that recombination is only expected to affect charmonium production at low transverse momenta (p_T), typically for values smaller than the charmonium mass ($p_T \lesssim m_\psi c$), where the number of charm quarks initially produced in the collision is the largest [8].

At large p_T , other mechanisms may contribute to charmonium suppression. Until recently, no quarkonium results were available at high p_T , because of kinematic constraints at the SPS and too low counting rates at RHIC. At the LHC, a strong J/ψ suppression has been measured up to $p_T = 30$ GeV/c by the CMS Collaboration [12] in PbPb collisions at a centre-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 2.76$ TeV. Results at 5.02 TeV have also been reported, up to $p_T = 10$ GeV/c, by the ALICE Collaboration [10]. According to Refs. [13,14], quarkonium suppression by Debye screening may occur even at high p_T . At the same time, when $p_T \gg m_\psi c$, heavy quarkonium is likely to be produced by parton fragmentation, hence it should rather be sensitive to the parton energy loss in the quark-gluon plasma. The similarity of J/ψ meson suppression with the quenching of jets, light hadrons, and D mesons supports this picture [12,15,16].

At the LHC, the inclusive J/ψ meson yield also contains a significant *nonprompt* contribution coming from b hadron decays [17–19]. The nonprompt J/ψ component should reflect medium effects on b hadron production in heavy ion collisions, such as b quark energy loss. Measuring both prompt and nonprompt J/ψ meson production in PbPb collisions thus offers the opportunity to study both hidden charm and open beauty production in the same data sample.

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

In this paper we report on a new measurement of the prompt and nonprompt J/ψ and $\psi(2S)$ nuclear modification factors (R_{AA}) using PbPb data, collected at the end of 2015 with the CMS experiment at $\sqrt{s_{NN}} = 5.02$ TeV. The analysis is performed via the dimuon decay channel. The results are compared to those obtained at 2.76 TeV [12]. The larger integrated luminosities allow for more precise and more differential measurements of R_{AA} , as functions of centrality, rapidity (y), and p_T up to 50 GeV/c.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the coverage provided by the barrel and endcap detectors. Muons are measured in the pseudorapidity range $|\eta| < 2.4$ in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. The hadron forward (HF) calorimeters use steel as an absorber and quartz fibres as the sensitive material. The two HF calorimeters are located 11.2 m from the interaction region, one on each side, and together they provide coverage in the range $2.9 < |\eta| < 5.2$. They also serve as luminosity monitors. Two beam pick-up timing detectors are located at 175 m on both sides of the interaction point, and provide information about the timing structure of the LHC beam. Events of interest are selected using a two-tiered trigger system [20]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events. 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 optimised for fast processing. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [21].

For pp data the vertices are reconstructed with a deterministic annealing vertex fitting algorithm using all of the fully reconstructed tracks [22]. The physics objects used to determine the primary vertex are defined based on a jet finding algorithm [23,24] applied to all charged tracks associated with the vertex, plus the corresponding associated missing transverse momentum. The reconstructed vertex with the largest value of summed physics object p_T^2 is taken to be the primary pp interaction vertex. In the case of PbPb data, a single primary vertex is reconstructed using a gap clustering algorithm [22], using pixel tracks only.

3 Data selection

3.1 Event selection

Hadronic collisions are selected offline using information from the HF calorimeters. In order to select PbPb collisions, at least three towers with energy deposits above 3 GeV are required in each of the HF calorimeters, both at forward and backward rapidities. A primary vertex reconstructed with at least two tracks is also required. In addition, a filter on the compatibility of the silicon pixel cluster width and the vertex position is applied [25]. The combined efficiency for this event selection, including the remaining non-hadronic contamination, is $(99 \pm 2)\%$. Values higher than 100% are possible, reflecting the possible presence of ultra-peripheral (i.e. non-hadronic) collisions in the selected event sample.

The PbPb sample is divided into bins of collision centrality, which is a measure of the degree of overlap of the colliding nuclei and is related to the number of participating nucleons (N_{part}). Centrality is defined as the percentile of the inelastic hadronic cross section corresponding to a HF energy deposit above a certain threshold [26]. The most central (highest HF energy deposit) and most peripheral (lowest HF energy deposit) centrality bins used in the analysis are 0–5% and 70–100% respectively. Variables related to the centrality, such as N_{part} and the nuclear overlap function (T_{AA}) [27], are estimated using a Glauber model simulation described in Ref. [28].

The pp and PbPb data sets correspond to integrated luminosities of 28.0 pb^{-1} and $464 \mu\text{b}^{-1}$, respectively. Both J/ψ and $\psi(2S)$ mesons are reconstructed using their dimuon decay channel. The dimuon events were selected online by the L1 trigger system, requiring two tracks in the muon detectors with no explicit momentum threshold, in coincidence with a bunch crossing identified by beam pick-up timing detectors. No additional selection was applied by the HLT. Because of the high rate of the most central dimuon events, a prescale was applied at the HLT level during part of the PbPb data taking: as a consequence only 79% of all the dimuon events were recorded, resulting in an effective luminosity of $368 \mu\text{b}^{-1}$. For peripheral events we were able to sample the entire integrated luminosity of $464 \mu\text{b}^{-1}$. This was done by adding an additional requirement that events be in the centrality range of 30–100% to the dimuon trigger. The prescaled data sample is used for the results integrated over centrality and those in the centrality range 0–30%, while for the results in the 30–100% range the data sample with $464 \mu\text{b}^{-1}$ was used instead. The results reported in this paper are unaffected by the small number of extra collisions potentially present in the collected events: the mean of the Poisson distribution of the number of collisions per bunch crossing (pileup), averaged over the full data sample, is approximately 0.9 for the pp data and less than 0.01 for PbPb collisions.

Simulated events are used to tune the muon selection criteria and the signal fitting parameters, as well as for acceptance and efficiency studies. These samples, produced using PYTHIA 8.212 [29], and decaying the b hadrons with EVTGEN 1.3.0 [30], are embedded in a realistic PbPb background event generated with HYDJET 1.9 [31] and propagated through the CMS detector with GEANT4 [32]. The prompt J/ψ is simulated unpolarised, a scenario in good agreement with pp measurements [33–35]. For nonprompt J/ψ , the polarisation is the one predicted by EVTGEN, roughly $\lambda_\theta = 0.4$. The resulting events are processed through the trigger emulation and the event reconstruction sequences. The assumptions made on the quarkonium polarisation affect the computation of the acceptance. Quantitative estimates of the possible effect evaluated for several polarisation scenarios can be found in Refs. [36,37]. While there are no measurements on quarkonium polarisations in PbPb collisions, a study in pp collisions as a function of the event activity [38] has not revealed significant changes. Therefore the effects of the J/ψ polarisation on the acceptance are not considered as systematic uncertainties.

3.2 Muon selection

The muon reconstruction algorithm starts by finding tracks in the muon detectors, which are then fitted together with tracks reconstructed in the silicon tracker. Kinematic selections are imposed to single muons so that their combined trigger, reconstruction and identification efficiency stays above 10%. These selections are: $p_T^\mu > 3.50$ GeV/c for $|\eta^\mu| < 1.2$ and $p_T^\mu > 1.89$ GeV/c for $2.1 < |\eta^\mu| < 2.4$, linearly interpolated in the intermediate $|\eta^\mu|$ region. The muons are required to match the ones selected by the dimuon trigger, and *soft* muon selection criteria are applied to *global muons* (i.e. muons reconstructed using the combined information of the tracker and muon detectors), as defined in Ref. [39]. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution for muons between 1 and 2% for a typical muon in this analysis [39]. In order to remove cosmic and in-flight decay muons, the transverse and longitudinal distances of approach to the measured vertex of the muons entering in the analysis are required to be less than 0.3 and 20 cm, respectively. The probability that the two muon tracks originate from a common vertex is required to be larger than 1%, lowering the background from b and c hadron semileptonic decays.

4 Signal extraction

Because of the long lifetime of b hadrons compared to that of J/ψ mesons, the separation of the prompt and nonprompt J/ψ components relies on the measurement of a

secondary $\mu^+\mu^-$ vertex displaced from the primary collision vertex. The J/ψ mesons originating from the decay of b hadrons can be resolved using the pseudo-proper decay length [40] $\ell_{J/\psi} = L_{xyz} m_{J/\psi} c / |p_{\mu\mu}|$, where L_{xyz} is the distance between the primary and dimuon vertices, $m_{J/\psi}$ is the Particle Data Group [41] world average value of the J/ψ meson mass (assumed for all dimuon candidates), and $p_{\mu\mu}$ is the dimuon momentum. Note that due to resolution effects and background dimuons the pseudo-proper decay length can take negative values. To measure the fraction of J/ψ mesons coming from b hadron decays (the so-called nonprompt fraction), the invariant mass spectrum of $\mu^+\mu^-$ pairs and their $\ell_{J/\psi}$ distribution are fitted using a two-dimensional (2D) extended unbinned maximum-likelihood fit. In order to obtain the parameters of the different components of the 2D probability density function (PDF), the invariant mass and the $\ell_{J/\psi}$ distributions are fitted sequentially prior to the final 2D fits, as explained below. These fits are performed for each p_T , rapidity and centrality bin of the analysis, and separately in pp and PbPb collisions.

The sum of two Crystal Ball functions [42], with different widths but common mean and tail parameters, is used to extract the nominal yield values from the pp and PbPb invariant mass distributions. The tail parameters, as well as the ratio of widths in the PbPb case, are fixed to the values obtained from simulation. The background is described by a polynomial function of order N , where N is the lowest value that provides a good description of the data, and is determined by performing a log-likelihood ratio test between polynomials of different orders, in each analysis bin, while keeping the tail and width ratio parameters fixed. The order of the polynomial is chosen in such a way that increasing the order does not significantly improve the quality of the fit. The typical order of the polynomial is 1 for most of the analysis bins. The invariant mass signal and background parameters are obtained in an initial fit of the invariant mass distribution only and then fixed on the 2D fits of mass and $\ell_{J/\psi}$ distributions, while the number of extracted J/ψ mesons and background dimuons are left as free parameters.

The prompt, nonprompt, and background components of the $\ell_{J/\psi}$ distributions are parameterised using collision data and Monte Carlo (MC) simulated events, and the signal and background contributions unfolded with the *sPlot* technique [43]. In the context of this analysis, this technique uses the invariant mass signal and background PDFs to discriminate signal from background in the $\ell_{J/\psi}$ distribution. The $\ell_{J/\psi}$ per-event uncertainty distributions of signal and background, provided by the reconstruction algorithm of primary and secondary vertices, are extracted from data and used as templates. The $\ell_{J/\psi}$ resolution is also obtained from the data by fitting the distribution of events with $\ell_{J/\psi} < 0$ with a combination of three Gaussian functions. The resolution varies event-by-event, so the per-event uncertainty is used as the

width of the Gaussian function that describes the core. To take into account the difference on the per-event uncertainty distributions of signal and background dimuons, the resolution PDF is multiplied by the per-event uncertainty distribution of signal and background dimuons separately. All the resolution parameters are fixed in the 2D fits. The b hadron decay length is allowed to float freely in the fit, and it is initialised to the value extracted by fitting the $\ell_{J/\psi}$ distribution of nonprompt J/ψ mesons from a MC sample with an exponential decay function, at generator level. The $\ell_{J/\psi}$ distribution of background dimuons is obtained from fits to the data, using an empirical combination of exponential functions. The parameters of the $\ell_{J/\psi}$ background distribution are also fixed in the 2D fits. Finally, the number of extracted J/ψ mesons, the number of background dimuons and the nonprompt fraction are extracted from the 2D fits. An example of a 2D fit of the invariant mass and pseudo-proper decay length for the PbPb data is shown in Fig. 1 for a representative analysis bin.

5 Acceptance and efficiency corrections

Correction factors are applied to all results to account for detector acceptance, trigger, reconstruction, and selection efficiencies of the $\mu^+\mu^-$ pairs. The corrections are derived from prompt and nonprompt J/ψ meson MC samples in pp and PbPb, and are evaluated in the same bins of p_T , centrality, and rapidity used in the R_{AA} and cross section analyses. The prompt and nonprompt J/ψ meson p_T distributions in bins of rapidity in MC samples are compared to those in data, and the ratios of data over MC are used to weight the MC J/ψ distributions to describe the data better. This weighting accounts for possible mis-modelling of J/ψ kinematics in MC. The acceptance in a given analysis bin is defined as the fraction of generated J/ψ mesons in that bin which decay into two muons entering the kinematic limits defined above, and reflects the geometrical coverage of the CMS detector. The value of the acceptance correction ranges from 4 to 70%, depending on the dimuon p_T , both for prompt and nonprompt J/ψ mesons in pp and PbPb collisions. The efficiency in a given analysis bin is defined as the ratio of the number of reconstructed J/ψ mesons in which both muons pass the analysis selection and the number of generated J/ψ mesons in which both muons pass the analysis selection. The efficiency correction depends on the dimuon p_T , rapidity and event centrality, and ranges from 20 to 75% (15 to 75%) for prompt (nonprompt) J/ψ mesons in PbPb data, and from 40 to 85% for both prompt and nonprompt J/ψ mesons in pp data. The efficiency is lower at low than at high p_T , and it decreases from mid to forward rapidity; it is also lower for central than peripheral events. The individual components of the efficiency (tracking recon-

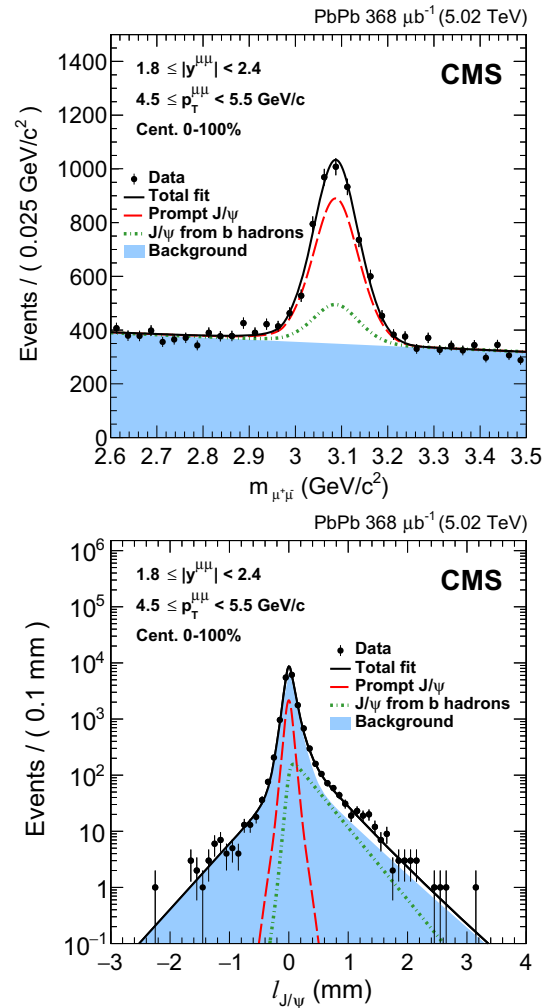


Fig. 1 Invariant mass spectrum of $\mu^+\mu^-$ pairs (upper) and pseudo-proper decay length distribution (lower) in PbPb collisions for $1.8 < |y| < 2.4$, $4.5 < p_T < 5.5$ GeV/c, for all centralities. The result of the fit described in the text is also shown

struction, standalone muon reconstruction, global muon fit, muon identification and selection, and triggering) are also measured using single muons from J/ψ meson decays in both simulated and collision data, using the *tag-and-probe* (T&P) technique [36,44]. The values obtained from data and simulation are seen to differ only for the muon trigger efficiency and the ratio of the data over simulated efficiencies is used as a correction factor for the efficiency. The correction factor for dimuons is at most 1.35 (1.38) for the pp (PbPb) efficiency in the $3 < p_T < 4.5$ GeV/c and forward rapidity bin, but the p_T and rapidity integrated value of the correction is about 1.03. The other T&P efficiency components are compatible, hence only used as a cross-check, as well as to estimate systematic uncertainties.

6 Systematic uncertainties

The systematic uncertainties in these measurements arise from the invariant mass signal and background fitting model assumptions, the parameterisation of the $\ell_{J/\psi}$ distribution, the acceptance and efficiency computation, and sample normalisation (integrated luminosity in pp data, counting of the equivalent number of minimum bias events in PbPb, and nuclear overlap function). These systematic uncertainties are derived separately for pp and PbPb results, and the total systematic uncertainty is computed as the quadratic sum of the partial terms.

The systematic uncertainty due to each component of the 2D fits is estimated from the difference between the nominal value and the result obtained with the variations of the different components mentioned below, in the extracted number of prompt and nonprompt J/ψ mesons, or nonprompt fraction separately. In the following, the typical uncertainty is given for the observable on which each source has the biggest impact.

In order to determine the uncertainty associated with the invariant mass fitting procedure, the signal and background PDFs are independently varied, in each analysis bin. For the uncertainty in the signal, the parameters that were fixed in the nominal fits are left free with a certain constraint. The constraint for each parameter is determined from fits to the data, by leaving only one of the parameters free, and it is chosen as the root mean square of the variations over the different analysis bins. A different signal shape is also used: a Crystal Ball function plus a Gaussian function, with the CB tail parameters, as well as the ratio of widths in the PbPb case, again fixed from MC. The dominant uncertainty comes from the variation of the signal shape, yielding values for the number of extracted nonprompt J/ψ mesons ranging from 0.1 to 2.9% (0.3–5.5%) in pp (PbPb) data. For the background model, the following changes are considered, while keeping the nominal signal shape. First, the log-likelihood ratio tests are done again with two variations of the threshold used to choose the order of the polynomial function in each analysis bin. Also the fitted mass range is varied. Finally, an exponential of a polynomial function is also used. The dominant uncertainty in the background model arises from the assumed shape (invariant mass range) in pp (PbPb) data. The corresponding uncertainty ranges from 0.1 to 2.1% (0.1–2.8%). The maximum difference of each of these variations, in each analysis bin and separately for the signal and the background, is taken as an independent systematic uncertainty.

For the $\ell_{J/\psi}$ distribution fitting procedure, four independent variations of the different components entering in the 2D fits are considered. For the $\ell_{J/\psi}$ uncertainty distribution, instead of using the distributions corresponding to signal and background, the total distribution is assumed. The contribution to the systematic uncertainty in the number of extracted

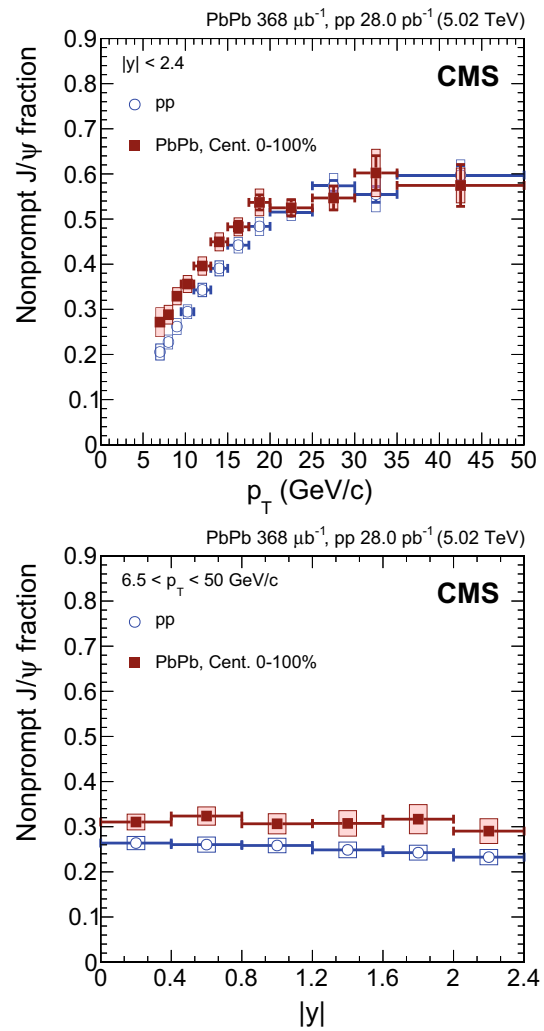


Fig. 2 Fraction of J/ψ mesons coming from the decay of b hadrons, i.e. nonprompt J/ψ meson fraction, as a function of dimuon p_T (upper) and rapidity (lower) for pp and PbPb collisions, for all centralities. The bars (boxes) represent statistical (systematic) point-by-point uncertainties

nonprompt J/ψ mesons ranges from 0.3 to 2% (0.3–9.5%) in pp (PbPb) data. The $\ell_{J/\psi}$ resolution obtained from prompt J/ψ meson MC is used instead of that evaluated from data. The corresponding uncertainty in the nonprompt fraction ranges from 1 to 5% (1–11%) in pp (PbPb) data. A nonprompt J/ψ meson MC template replaces the exponential decay function for the b hadron decay length. In this case, the contribution of this source to the systematic uncertainty in the nonprompt J/ψ yield ranges from 0.2 to 8% (0.2–20%) in pp (PbPb) data. A template of the $\ell_{J/\psi}$ distribution of background dimuons obtained from the data is used to describe the background, instead of the empirical combination of exponential functions. This variation has an impact on the nonprompt J/ψ yield ranging from 0.1 to 1.3% (0.2–22%) in pp (PbPb) data. Therefore the dominant sources of uncertainty in the $\ell_{J/\psi}$ fitting are the background parameterisation and the MC

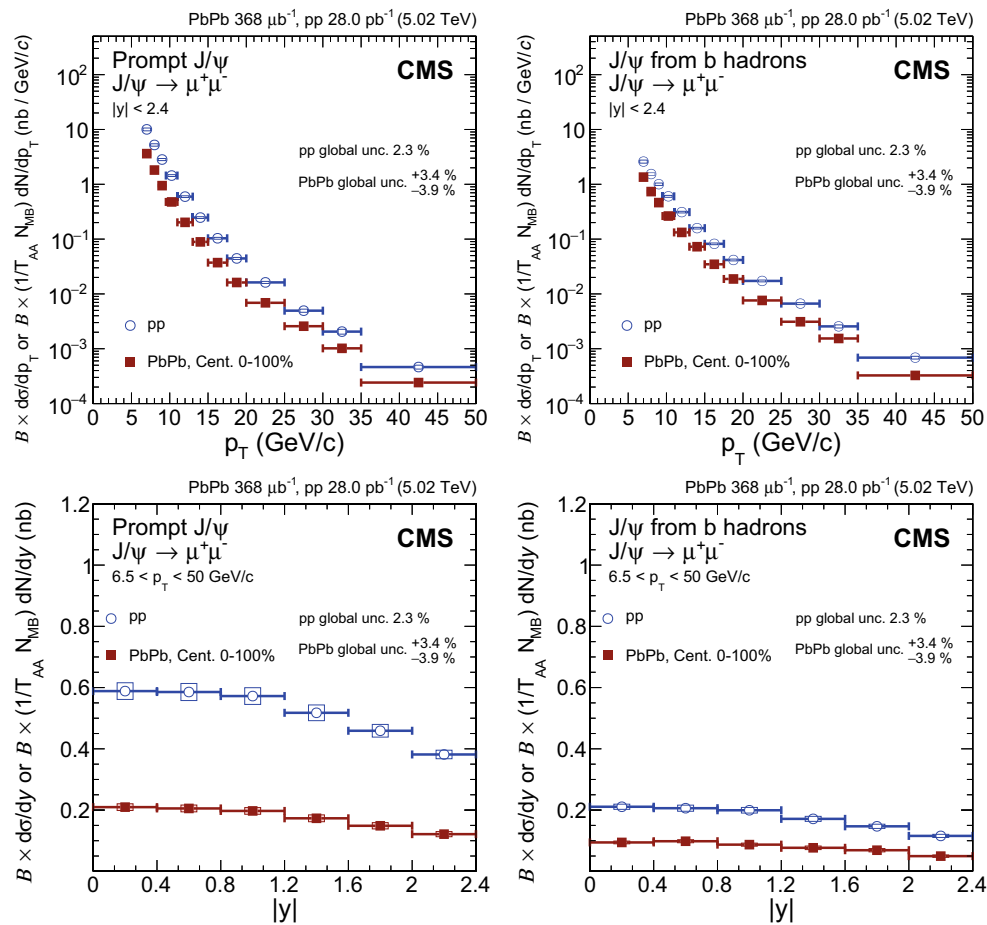


Fig. 3 Differential cross section of prompt J/ψ mesons (left) and J/ψ mesons from b hadrons (nonprompt J/ψ) (right) decaying into two muons as a function of dimuon p_T (upper) and rapidity (lower) in pp and PbPb collisions. The PbPb cross sections are normalised by T_{AA}

template for the nonprompt signal. They have an important impact on the nonprompt J/ψ meson yield, especially at the lowest p_T reached in this analysis for the most central events in PbPb collisions. The reason for this is that the background dimuons largely dominate over the nonprompt J/ψ signal.

The uncertainties in the acceptance and efficiency determination are evaluated with MC studies considering a broad range of p_T and angular spectra compatible with the pp and PbPb data within their uncertainties. These variations yield an uncertainty about 0.2% ($<1.7\%$) in pp (PbPb) collisions, both for prompt and nonprompt J/ψ acceptance and efficiency. The statistical uncertainty of the weighting of the MC distributions, reflecting the impact of the limited knowledge on the kinematic distribution of J/ψ mesons on the acceptance and efficiency corrections, is used as systematic uncertainty. This uncertainty is at most 6% (11%) in pp (PbPb) collisions at the largest p_T but it usually ranges from 1 to 3% in both collision systems. In addition, the systematic uncertainties in the T&P correction factors, arising from the limited

for direct comparison. The bars (boxes) represent statistical (systematic) point-by-point uncertainties, while global uncertainties are written on the plots

data sample available and from the procedure itself, are taken into account, covering all parts of the muon efficiency: inner tracking and muon reconstruction, identification, and triggering. The dominant uncertainty in the T&P correction factors arises from muon reconstruction and ranges from 2 to 10% for both collision systems.

The global uncertainty in the pp luminosity measurement is 2.3% [45]. The number of minimum bias events corresponding to our dimuon sample in PbPb (N_{MB}) comes from a simple event counting in the events selected by the Minimum Bias triggers, taking into account the trigger prescale. The corresponding uncertainty arises from the inefficiency of trigger and event selection, and is estimated to be 2%. Finally, the uncertainty in the T_{AA} is estimated by varying the Glauber model parameters within their uncertainty and taking into account the uncertainty on the trigger and event selection efficiency, and ranges from 3 to 16% from the most central to the most peripheral events used in this analysis.

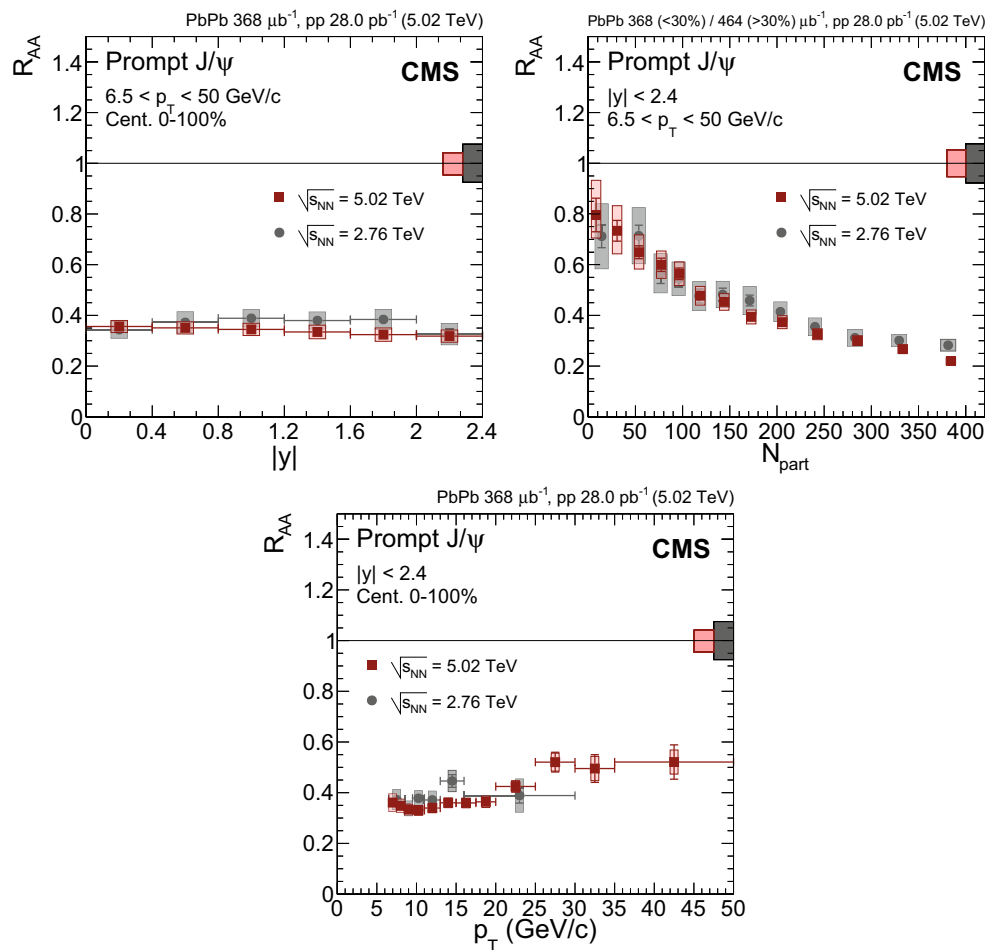


Fig. 4 Nuclear modification factor of prompt J/ψ mesons as a function of dimuon rapidity (upper left), N_{part} (upper right) and dimuon p_T (lower) at $\sqrt{s_{NN}} = 5.02$ TeV. For the results as a function of N_{part} the most central bin corresponds to 0–5%, and the most peripheral one

to 70–100%. Results obtained at 2.76 TeV are overlaid for comparison [12]. The bars (boxes) represent statistical (systematic) point-by-point uncertainties. The boxes plotted at $R_{AA} = 1$ indicate the size of the global relative uncertainties

7 Results

In this section, the results obtained for nonprompt J/ψ fractions, prompt and nonprompt J/ψ cross sections for each collision system, and nuclear modification factors R_{AA} are presented and discussed. In addition, a derivation of the $\psi(2S)$ R_{AA} is also presented and discussed. For all results plotted versus p_T or $|y|$, the abscissae of the points correspond to the centre of the respective bin, and the horizontal error bars reflect the width of the bin. The lower p_T thresholds in the different rapidity intervals reflect the detector acceptance. In the range $1.8 < |y| < 2.4$ J/ψ are measured down to 3 GeV/c, while for the bins with $|y| < 1.8$ they are measured down to 6.5 GeV/c. When plotted as a function of centrality, the abscissae are the average N_{part} values for minimum bias events within each centrality bin. The weighted average N_{part} values (weighted for the number of binary nucleon-nucleon collisions) correspond in most cases to the average

N_{part} values for minimum bias events, with the exception of the most peripheral bin (50–100%) where N_{part} changes from 22 to 43. The centrality binning used is 0–5–10–15–20–25–30–35–40–45–50–60–70–100% for the results in $|y| < 2.4$, and 0–10–20–30–40–50–100% for the results differential in rapidity.

7.1 Nonprompt J/ψ meson fractions

The nonprompt J/ψ meson fraction is defined as the proportion of measured J/ψ mesons coming from b hadron decays, corrected for acceptance and efficiency. It is presented in Fig. 2 for pp and PbPb collisions, as a function of p_T and rapidity, in the full $|y| < 2.4$ and $6.5 < p_T < 50 \text{ GeV}/c$ range. No significant rapidity dependence is observed, while there is a strong p_T dependence, from about 20% at low p_T to 60% at high p_T , reflecting the different p_T distributions

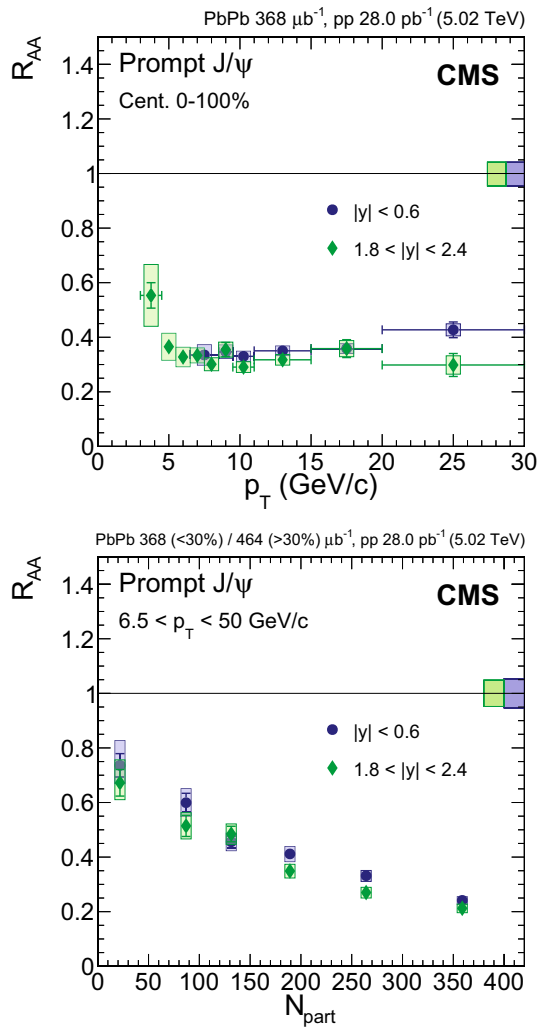


Fig. 5 Nuclear modification factor of prompt J/ψ meson as a function of dimuon p_T (upper) and N_{part} (lower), in the mid- and most forward rapidity intervals. For the results as a function of N_{part} the most central bin corresponds to 0–10%, and the most peripheral one to 50–100%. The bars (boxes) represent statistical (systematic) point-by-point uncertainties. The boxes plotted at $R_{AA} = 1$ indicate the size of the global relative uncertainties

of prompt and nonprompt J/ψ mesons, which highlights the necessity of separating the two contributions.

7.2 Prompt and nonprompt J/ψ meson cross sections in pp and PbPb collisions

The measurements of the prompt and nonprompt J/ψ cross sections can help to test the existing theoretical models of both quarkonium production and b hadron production. The cross sections are computed from the corrected yields,

$$\frac{d^2N}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \frac{N_{J/\psi}}{\mathcal{A} \epsilon}, \quad (1)$$

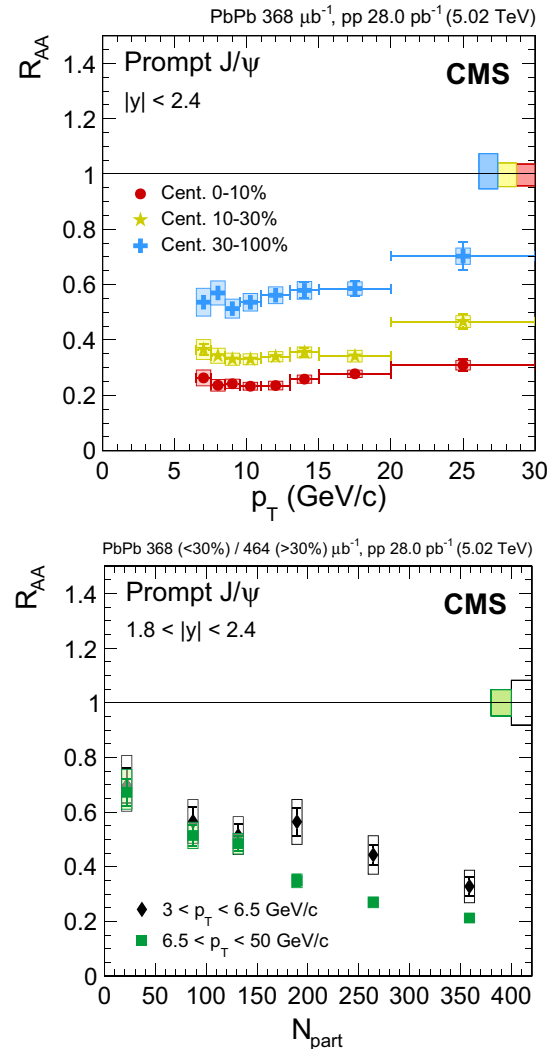


Fig. 6 Nuclear modification factor of prompt J/ψ mesons. Upper: as a function of dimuon p_T in three centrality bins. Lower: as a function of N_{part} at moderate and high p_T , in the forward $1.8 < |y| < 2.4$ range. For the results as a function of N_{part} the most central bin corresponds to 0–10%, and the most peripheral one to 50–100%. The bars (boxes) represent statistical (systematic) point-by-point uncertainties. The boxes plotted at $R_{AA} = 1$ indicate the size of the global relative uncertainties

where $N_{J/\psi}$ is the number of prompt or nonprompt J/ψ mesons, \mathcal{A} is the acceptance, ϵ is the efficiency, and Δp_T and Δy are the p_T and rapidity bin widths, respectively. To put the pp and PbPb data on a comparable scale, the corrected yields are normalised by the measured integrated luminosity for pp collisions ($\sigma = N/\mathcal{L}$), and by the product of the number of corresponding minimum bias events and the centrality-integrated nuclear overlap value for PbPb collisions ($N/(N_{MB} T_{AA})$). Global uncertainties (common to all measurements) arise from these normalisation factors and account for the integrated luminosity uncertainty in pp collisions ($\pm 2.3\%$) and the N_{MB} and T_{AA} uncertainty for PbPb collisions ($+3.4\%$, -3.9%), respectively.

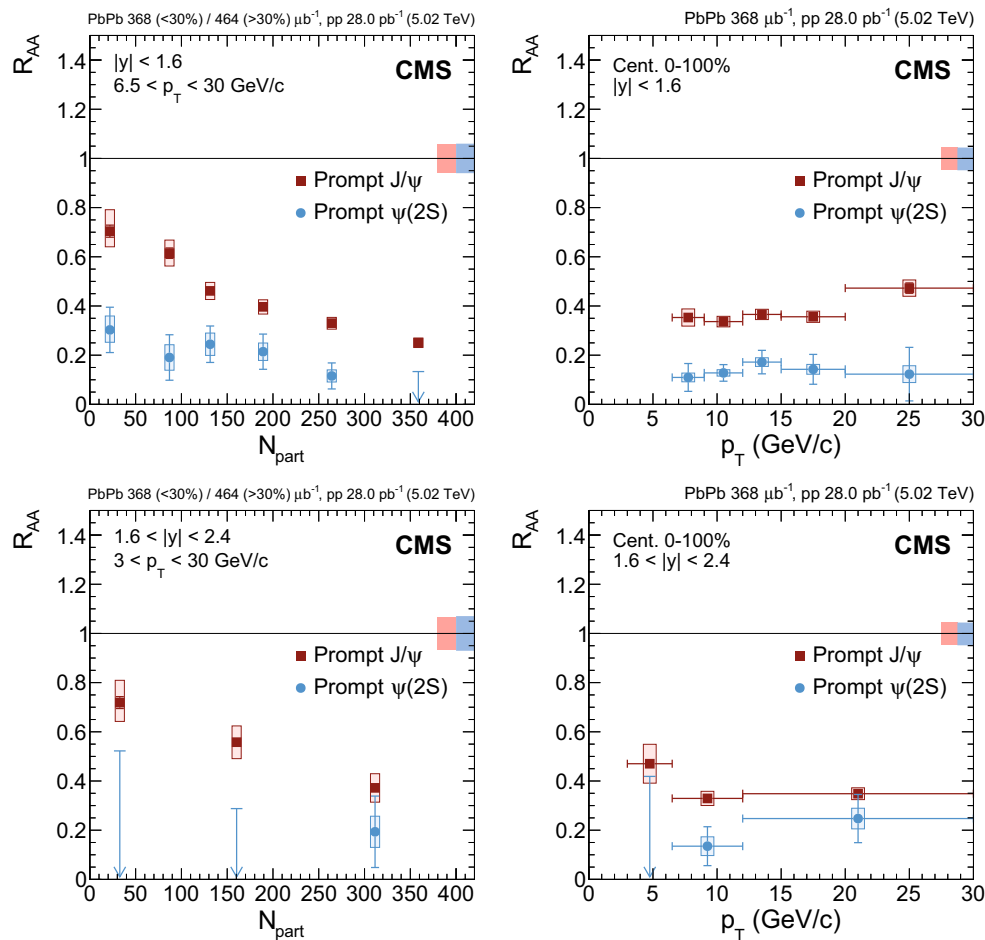


Fig. 7 Nuclear modification factor of prompt J/ψ and $\psi(2S)$ mesons as a function of N_{part} (left) and dimuon p_T (right), at central (upper, starting at $p_T = 6.5$ GeV/c) and forward (lower, starting at $p_T = 3.0$ GeV/c) rapidity. The vertical arrows represent 95% confidence intervals in the bins where the double ratio measurement is consistent with 0 (see text).

For the results as a function of N_{part} the most central bin corresponds to 0–10% (0–20%), and the most peripheral one to 50–100% (40–100%), for $|y| < 1.6$ ($1.6 < |y| < 2.4$). The bars (boxes) represent statistical (systematic) point-by-point uncertainties. The boxes plotted at $R_{AA} = 1$ indicate the size of the global relative uncertainties

The cross sections for the production of prompt and non-prompt J/ψ mesons that decay into two muons ($\mathcal{B}\sigma$, where \mathcal{B} is the branching ratio of J/ψ to dimuons) are reported as a function of p_T and rapidity in Fig. 3.

7.3 Prompt J/ψ meson nuclear modification factor

In order to compute the nuclear modification factor R_{AA} in a given bin of centrality (cent.), the above-mentioned PbPb and pp normalised cross sections are divided in the following way:

$$R_{AA} = \frac{N_{J/\psi}^{PbPb}(\text{cent.})}{N_{J/\psi}^{pp}} \times \frac{\mathcal{A}^{pp} \times \epsilon^{pp}}{\mathcal{A}^{PbPb} \epsilon^{PbPb}(\text{cent.})} \times \frac{\mathcal{L}^{pp}}{N_{MB} \langle T_{AA} \rangle (\text{cent. fraction})},$$

where the centrality fraction is the fraction of the inclusive inelastic cross section probed in the analysis bin. Global uncertainties (indicated as boxes in the plots at $R_{AA} = 1$) arise from the full pp statistical and systematic uncertainties and the PbPb N_{MB} uncertainty when binning as a function of the centrality; and from the integrated luminosity of the pp data, and the N_{MB} and T_{AA} uncertainties of the PbPb data, when binning as a function of rapidity or p_T .

In Fig. 4, the R_{AA} of prompt J/ψ mesons as a function of rapidity, N_{part} and p_T are shown, integrating in each case over the other two non-plotted variables. The results are compared to those obtained at $\sqrt{s_{NN}} = 2.76$ TeV [12], and they are found to be in good overall agreement. No strong rapidity dependence of the suppression is observed. As a function of centrality, the R_{AA} is suppressed even for the most peripheral bin (70–100%), with the suppression slowly increasing with N_{part} . The R_{AA} value for the most central events (0–5%) is

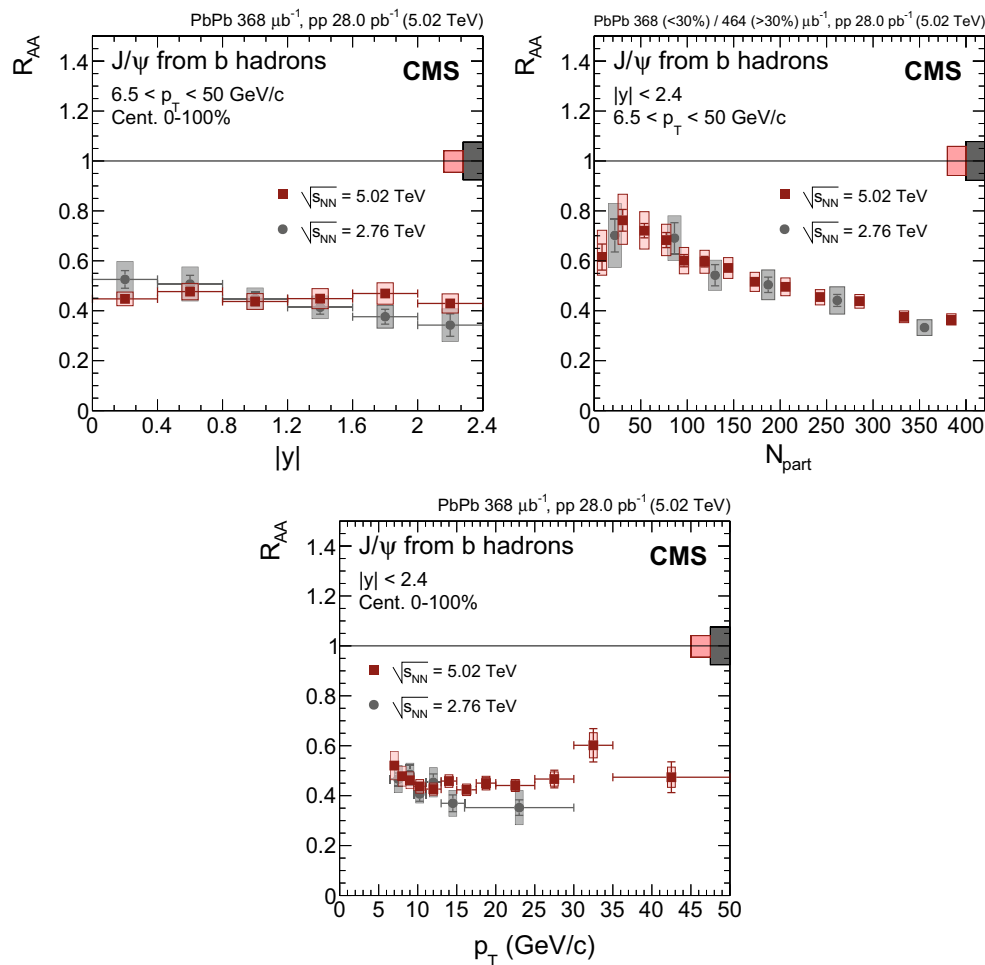


Fig. 8 Nuclear modification factor of J/ψ mesons from b hadrons (non-prompt J/ψ) as a function of dimuon rapidity (upper left), N_{part} (upper right) and dimuon p_T (lower) at $\sqrt{s_{NN}} = 5.02$ TeV. For the results as a function of N_{part} the most central bin corresponds to 0–5%, and the most

peripheral one to 70–100%. Results obtained at 2.76 TeV are overlaid for comparison [12]. The bars (boxes) represent statistical (systematic) point-by-point uncertainties. The boxes plotted at $R_{AA} = 1$ indicate the size of the global relative uncertainties

measured for $6.5 < p_T < 50$ GeV/c and $|y| < 2.4$ to be 0.219 ± 0.005 (stat) ± 0.013 (syst). As a function of p_T the R_{AA} is approximately constant in the range of 5–20 GeV/c, but an indication of less suppression at higher p_T is seen for the first time in quarkonia. Charged hadrons, for which the suppression is usually attributed to parton energy loss [16, 46], show a similar increase in R_{AA} at high p_T for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [27].

Double-differential studies are also performed. Figure 5 shows the p_T (upper) and centrality (lower) dependence of prompt J/ψ R_{AA} measured in the mid- and most forward rapidity intervals. A similar suppression pattern is observed for both rapidities. Figure 6 (upper) shows the dependence of R_{AA} as a function of p_T , for three centrality intervals. Although the mean level of suppression strongly depends on the sampled centrality range, the general trend of the p_T dependence appears similar in all three centrality ranges,

including the increase of R_{AA} at high p_T . Finally, Fig. 6 (lower) considers the rapidity interval $1.8 < |y| < 2.4$, where the acceptance goes down at lower p_T . The suppression is found to be similar in peripheral events at moderate ($3 < p_T < 6.5$ GeV/c) and high ($6.5 < p_T < 50$ GeV/c) transverse momentum ranges, but it is weaker for lower p_T in the most central region. This is also reflected in the first bin of the most forward measurement in Fig. 5 (upper). A similarly reduced suppression at low p_T is observed by the ALICE Collaboration, which is attributed to a regeneration contribution [9, 10].

7.4 Prompt $\psi(2S)$ meson nuclear modification factor

Having measured the prompt J/ψ R_{AA} , one can derive that of the $\psi(2S)$ meson by multiplying it by the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{\text{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{\text{pp}}$ of the relative modifi-

cation of the prompt $\psi(2S)$ and J/ψ meson yields from pp to PbPb collisions published in Ref. [47]. Since the $\psi(2S)$ yield suffers from lower statistics, the current J/ψ analysis is repeated using the wider bins of Ref. [47]. The centrality binning used is 0–10–20–30–40–50–100% for the results in $|y| < 1.6$, and 0–20–40–100% for the results in $1.6 < |y| < 2.4$. Since the statistical uncertainty in the $\psi(2S)$ largely dominates, the J/ψ uncertainties are propagated by considering them to be uncorrelated to the double ratio uncertainties.

The results are presented in Fig. 7 as a function of dimuon p_T and N_{part} , in two rapidity ranges of different p_T reach. In the bins where the double ratio is consistent with 0, 95% CL intervals on the prompt $\psi(2S)$ R_{AA} are derived using the Feldman–Cousins procedure [48]. The procedure to obtain the CL intervals is the same as in the double ratio measurement, incorporating the J/ψ R_{AA} statistical and systematic uncertainties as a nuisance parameter. It can be observed that the $\psi(2S)$ meson production is more suppressed than that of J/ψ mesons, in the entire measured range. The $\psi(2S)$ meson R_{AA} shows no clear dependence of the suppression with p_T , and hints of an increasing suppression with collision centrality. These results show that the $\psi(2S)$ mesons are more strongly affected by the medium created in PbPb collisions than the J/ψ mesons.

7.5 Nonprompt J/ψ meson nuclear modification factor

The procedure applied to derive the prompt J/ψ meson R_{AA} is applied to the nonprompt component. In Fig. 8, the R_{AA} of nonprompt J/ψ as a function of rapidity, centrality and p_T are shown, integrating in each case over the other two non-plotted variables. The results are compared to those obtained at $\sqrt{s_{NN}} = 2.76$ TeV [12]. A good overall agreement is found, although no rapidity dependence is observed in the present analysis, while the suppression was slowly increasing towards forward rapidities in the lower-energy measurement. A steady increase of the suppression is observed with increasing centrality of the collision. The R_{AA} for the most central events (0–5%) measured for $6.5 < p_T < 50$ GeV/c and $|y| < 2.4$ is 0.365 ± 0.009 (stat) ± 0.022 (syst).

As for the prompt production case, double-differential studies are also performed. Figure 9 shows the p_T (upper) and centrality (lower) dependence of nonprompt J/ψ meson R_{AA} measured in the mid- and most forward rapidity intervals. No strong rapidity dependence is observed, and a hint of a smaller suppression at low p_T is seen in the $1.8 < |y| < 2.4$ range. Figure 10 (upper) shows the dependence of R_{AA} as a function of p_T , for three centrality ranges. While the nonprompt J/ψ meson R_{AA} does not seem to depend on rapidity, the data indicates a larger p_T dependence in peripheral events. Finally, Fig. 10 (lower) shows, for $1.8 < |y| < 2.4$, R_{AA} as a function of N_{part} , for two p_T intervals. Hints of

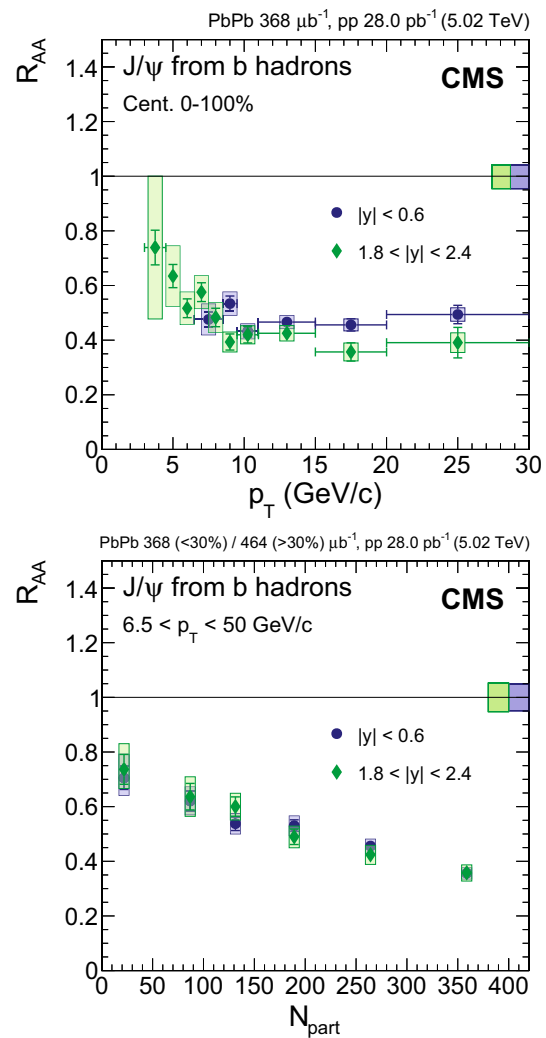


Fig. 9 Nuclear modification factor of J/ψ mesons from b hadrons (nonprompt J/ψ) as a function of dimuon p_T (upper) and in the mid- and most forward rapidity intervals. For the results as a function of N_{part} the most central bin corresponds to 0–10%, and the most peripheral one to 50–100%. The bars (boxes) represent statistical (systematic) point-by-point uncertainties. The boxes plotted at $R_{AA} = 1$ indicate the size of the global relative uncertainties

a stronger suppression are seen for $p_T > 6.5$ GeV/c at all centralities.

8 Conclusions

Prompt and nonprompt J/ψ meson production has been studied in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of rapidity, transverse momentum (p_T), and collision centrality, in different kinematic and centrality ranges. Three observables were measured: nonprompt J/ψ fractions, prompt and nonprompt J/ψ cross sections for each collision system, and nuclear modification factors R_{AA} . The R_{AA}

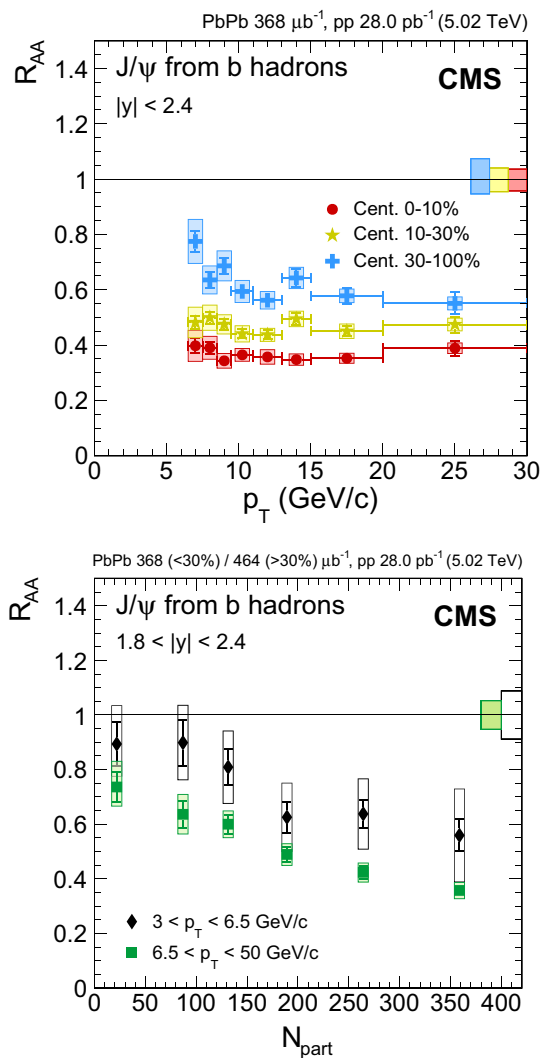


Fig. 10 Nuclear modification factor of J/ψ mesons from b hadrons (nonprompt J/ψ). Upper: as a function of dimuon p_T in three centrality bins. Lower: as a function of N_{part} at moderate and high p_T , in the forward $1.8 < |y| < 2.4$ range. For the results as a function of N_{part} the most central bin corresponds to 0–10%, and the most peripheral one to 50–100%. The bars (boxes) represent statistical (systematic) point-by-point uncertainties. The boxes plotted at $R_{AA} = 1$ indicate the size of the global relative uncertainties

results show a strong centrality dependence, with an increasing suppression for increasing centrality. For both prompt and nonprompt J/ψ mesons no significant dependence on rapidity is observed. An indication of less suppression in the lowest p_T range at forward rapidity is seen for both J/ψ components. Double-differential measurements show the same trend, and also suggest a stronger p_T dependence in peripheral events. An indication of less suppression of the prompt J/ψ meson at high p_T is seen with respect to that observed at intermediate p_T . The measurements are consistent with previous results at $\sqrt{s_{NN}} = 2.76$ TeV.

Combined with previous results for the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, the current R_{AA} values for J/ψ mesons are used to derive the prompt $\psi(2S)$ meson R_{AA} in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of p_T and collision centrality, in two different rapidity ranges. The results show that the $\psi(2S)$ is more suppressed than the J/ψ meson for all the kinematical ranges studied. No p_T dependence is observed within the current uncertainties. Hints of an increase in suppression with increasing collision centrality are also observed.

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CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

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

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

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

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

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

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

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

Universidade Estadual Paulista^a, Universidade Federal do ABC^b, São Paulo, Brazil

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

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

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

W. Fang⁵, X. Gao⁵, L. Yuan

Institute of High Energy Physics, Beijing, China

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

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

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

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

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

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

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P. M. Ribeiro Cipriano, T. Sculac

Faculty of Science, University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁶, T. Susa

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger⁷, M. Finger Jr.⁷

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

R. K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

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

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

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

Université de Strasbourg, CNRS, IPHC UMR 7178, 67000 Strasbourg, France

J.-L. Agram¹¹, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E. C. Chabert, N. Chanon, C. Collard, E. Conte¹¹, X. Coubez, J.-C. Fontaine¹¹, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I. B. Laktineh, M. Lethuillier, L. Mirabito, A. L. Pequegnot, S. Perries, A. Popov¹², V. Sordini, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹³

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁷

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

C. Autermann, L. Feld, M. K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, M. Teroerde, V. Zhukov¹²

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

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

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁴

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A. A. Bin Anuar, K. Borras¹⁵, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁶, J. Garay Garcia, A. Geiser, J. M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel¹⁷, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁷, R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, N. Stefaniuk, G. P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁴, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F. M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M. A. Harrendorf, F. Hartmann¹⁴, S. M. Heindl, U. Husemann, F. Kassel¹⁴, S. Kudella, H. Mildner, M. U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H. J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

K. Kousouris

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Giannelos, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F. A. Triantis, D. Tsitsonis

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

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G. I. Veres¹⁸

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath¹⁹, Á. Hunyadi, F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók¹⁸, P. Raics, Z. L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J. R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²¹, S. Bhowmik, P. Mal, K. Mandal, A. Nayak²², D. K. Sahoo²¹, N. Sahoo, S. K. Swain

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India

P. K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A. K. Mohanty¹⁴, P. K. Netrakanti, L. M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²³, G. Majumder, K. Mazumdar, T. Sarkar²³, N. Wickramage²⁴

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

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

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

S. Chenarani²⁵, E. Eskandari Tadavani, S. M. Etesami²⁵, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁶, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, F. Errico^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,14}, R. Venditti^a, P. Verwilligen^a

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

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F. R. Cavallo^a, S. S. Chhibra^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G. M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F. L. Navarria^{a,b}, A. Perrotta^a, A. M. Rossi^{a,b}, T. Rovelli^{a,b}, G. P. Siroli^{a,b}, N. Tosi^a

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

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

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

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,28}, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁴

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

V. Calvelli^{a,b}, F. Ferro^a, F. Ravera^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,14}, M. E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R. A. Manzoni^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, K. Pauwels^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b,29}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

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

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,14}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A. O. M. Iorio^{a,b}, W. A. Khan^a, L. Lista^a, S. Meola^{a,d,14}, P. Paolucci^{a,14}, C. Sciacca^{a,b}, F. Thyssen^a

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

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

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

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S. P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

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

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G. M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, R. Leonardi^{a,b}, E. Manoni^{a,b}, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

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

K. Androsov^a, P. Azzurri^{a,14}, G. Bagliesi^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M. A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, L. Giannini^{a,c}, A. Giassi^a, M. T. Grippo^{a,28}, F. Ligabue^{a,c}, T. Lomtadze^a, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,30}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P. G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b,14}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M. M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G. L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

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

S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

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

Chonbuk National University, Jeonju, Korea

A. Lee

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

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

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z. A. Ibrahim, M. A. B. Md Ali³¹, F. Mohamad Idris³², W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli

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

R. Reyes-Almanza, G. Ramirez-Sanchez, M. C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³³, R. I. Rabadan-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P. H. Butler

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Bunkowski, A. Byzuk³⁴, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

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

Joint Institute for Nuclear Research, Dubna, Russia

A. Baginyan, A. Golunov, I. Golutvin, V. Karjavin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev^{35,36}, V. V. Mitsyn, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, B. S. Yuldashev³⁷, A. Zarubin, V. Zhiltsov

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

Y. Ivanov, V. Kim³⁸, E. Kuznetsova³⁹, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev, A. Bylinkin³⁶

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

M. Chadeeva⁴⁰, P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁶, I. Dremin³⁶, M. Kirakosyan³⁶, A. Terkulov

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

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

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴¹, D. Shtol⁴¹, Y. Skovpen⁴¹

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

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

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

P. Adzic⁴², P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

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

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J. F. de Trocóniz, M. Missiroli

Universidad de Oviedo, Oviedo, Spain

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

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A. H. Ball, D. Barney, J. Bendavid, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁷, J. Kieseler, V. Knünz, A. Kornmayer, M. J. Kortelainen, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M. T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴³, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabaday, A. Racz, T. Reis,

G. Rolandi⁴⁴, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁵, A. Stakia, J. Stegeman, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsiros, V. Veckalns⁴⁶, M. Verweij, W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada⁴⁷, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S. A. Wiederkehr

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

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

Universität Zürich, Zurich, Switzerland

T. K. Aarrestad, C. Amsler⁴⁸, M. F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

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

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

M. N. Bakirci⁴⁹, A. Bat, F. Boran, S. Damarseekin, Z. S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵⁰, E. E. Kangal⁵¹, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut⁵², K. Ozdemir⁵³, S. Ozturk⁴⁹, D. Sunar Cerci⁵⁴, U. G. Tok, H. Topakli⁴⁹, S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

Physics Department, Middle East Technical University, Ankara, Turkey

G. Karapinar⁵⁵, K. Ocalan⁵⁶, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁷, O. Kaya⁵⁸, S. Tekten, E. A. Yetkin⁵⁹

Istanbul Technical University, Istanbul, Turkey

M. N. Agaras, S. Atay, A. Cakir, K. Cankocak, I. Köseoglu

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

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, UK

F. Ball, L. Beck, J. J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G. P. Heath, H. F. Heath, L. Kreczko, D. M. Newbold⁶⁰, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V. J. Smith

Rutherford Appleton Laboratory, Didcot, UK

A. Belyaev⁶¹, C. Brew, R. M. Brown, L. Calligaris, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams

Imperial College, London, UK

G. Auzinger, R. Bainbridge, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko⁵,

V. Palladino, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶², T. Virdee¹⁴, N. Wardle, D. Winterbottom, J. Wright, S. C. Zenz

Brunel University, Uxbridge, UK

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

Baylor University, Waco, USA

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

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, USA

J. G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, M. Tadel, A. Vartak, S. Wasserbaech⁶³, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

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

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, G. Bolla[†], K. Burkett, J. N. Butler, A. Canepa, G. B. Cerati, H. W. K. Cheung, F. Chlebana,

M. Cremonesi, J. Duarte, V. D. Elvira, J. Freeman, Z. Gece, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R. M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J. M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H. A. Weber, A. Whitbeck

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

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

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

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

The University of Iowa, Iowa City, USA

B. Bilki⁶⁴, W. Clarida, K. Dilsiz⁶⁵, S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁷, Y. Onel, F. Ozok⁶⁸, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

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

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

J. G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D. J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁵, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

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

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

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

Purdue University Northwest, Hammond, USA

T. Cheng, N. Parashar, J. Stupak

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, USA

R. Ciesielski, K. Goulianos, C. Mesropian

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

A. Agapitos, J. P. Chou, Y. Gershtein, T. A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

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

Texas A&M University, College Station, USA

O. Bouhali⁶⁹, A. Castaneda Hernandez⁶⁹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi,

J. Gilmore, T. Huang, T. Kamon⁷⁰, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K. A. Ulmer

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin-Madison, Madison, WI, USA

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

† Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 3: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 4: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 7: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 8: Also at Fayoum University, El-Fayoum, Egypt
- 9: Now at British University in Egypt, Cairo, Egypt
- 10: Now at Ain Shams University, Cairo, Egypt
- 11: Also at Université de Haute Alsace, Mulhouse, France
- 12: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 13: Also at Tbilisi State University, Tbilisi, Georgia
- 14: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 15: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 16: Also at University of Hamburg, Hamburg, Germany
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 21: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 22: Also at Institute of Physics, Bhubaneswar, India
- 23: Also at University of Visva-Bharati, Santiniketan, India
- 24: Also at University of Ruhuna, Matara, Sri Lanka
- 25: Also at Isfahan University of Technology, Isfahan, Iran
- 26: Also at Yazd University, Yazd, Iran
- 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
- 30: Also at Purdue University, West Lafayette, USA
- 31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

- 32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 35: Also at Institute for Nuclear Research, Moscow, Russia
- 36: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 37: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
- 38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 39: Also at University of Florida, Gainesville, USA
- 40: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 45: Also at National and Kapodistrian University of Athens, Athens, Greece
- 46: Also at Riga Technical University, Riga, Latvia
- 47: Also at Universität Zürich, Zurich, Switzerland
- 48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 49: Also at Gaziosmanpasa University, Tokat, Turkey
- 50: Also at Istanbul Aydin University, Istanbul, Turkey
- 51: Also at Mersin University, Mersin, Turkey
- 52: Also at Cag University, Mersin, Turkey
- 53: Also at Piri Reis University, Istanbul, Turkey
- 54: Also at Adiyaman University, Adiyaman, Turkey
- 55: Also at Izmir Institute of Technology, Izmir, Turkey
- 56: Also at Necmettin Erbakan University, Konya, Turkey
- 57: Also at Marmara University, Istanbul, Turkey
- 58: Also at Kafkas University, Kars, Turkey
- 59: Also at Istanbul Bilgi University, Istanbul, Turkey
- 60: Also at Rutherford Appleton Laboratory, Didcot, UK
- 61: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
- 62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 63: Also at Utah Valley University, Orem, USA
- 64: Also at Beykent University, Istanbul, Turkey
- 65: Also at Bingol University, Bingol, Turkey
- 66: Also at Erzincan University, Erzincan, Turkey
- 67: Also at Sinop University, Sinop, Turkey
- 68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 69: Also at Texas A&M University at Qatar, Doha, Qatar
- 70: Also at Kyungpook National University, Daegu, Korea