Physics Letters B 782 (2018) 474–496

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 16 August 2017
Received in revised form 19 April 2018
Accepted 28 May 2018
Available online 31 May 2018
Editor: M. Doser

Keywords:
Physics
Suppression
Quark gluon plasma
Shadowing
D-meson
Open heavy-flavour

ABSTRACT

The transverse momentum (p_T) spectrum of prompt D^0 mesons and their antiparticles has been measured via the hadronic decay channels $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$ in pp and PbPb collisions at a centre-of-mass energy of 5.02 TeV per nucleon pair with the CMS detector at the LHC. The measurement is performed in the D^0 meson p_T range of 2–100 GeV/c and in the rapidity range of $|y| < 1$. The pp (PbPb) dataset used for this analysis corresponds to an integrated luminosity of 27.4 pb^{-1} (530 μb^{-1}). The measured D^0 meson p_T spectrum in pp collisions is well described by perturbative QCD calculations. The nuclear modification factor, comparing D^0 meson yields in PbPb and pp collisions, was extracted for both minimum-bias and the 10% most central PbPb interactions. For central events, the D^0 meson yield in the PbPb collisions is suppressed by a factor of 5–6 compared to the pp reference in the p_T range of 6–10 GeV/c. For D^0 mesons in the high-p_T range of 60–100 GeV/c, a significantly smaller suppression is observed. The results are also compared to theoretical calculations.

© 2018 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

1. Introduction

Relativistic heavy ion collisions allow the study of quantum chromodynamics (QCD) at high energy density and temperature. Lattice QCD calculations predict that under such extreme conditions a transition to a strongly interacting and deconfined medium, called the quark-gluon plasma (QGP), occurs [1–3]. Heavy quarks are effective probes to study the properties of the deconfined medium created in heavy ion collisions. These quarks are mostly produced in primary hard QCD scatterings with a production timescale that is shorter than the formation time of the QGP [4]. During their propagation through the medium, heavy quarks lose energy via radiative and collisional interactions with the medium constituents. Quarks are expected to lose less energy than gluons as a consequence of their smaller colour factor. In addition, the so-called "dead-cone effect" is expected to reduce small-angle gluon radiation of heavy quarks when compared to both gluons and light quarks [5–7]. Energy loss can be studied using the nuclear modification factor (R_{AA}), defined as the ratio of the PbPb yield to the pp cross-section scaled by the nuclear overlap function [8]. Precise measurements of the R_{AA} of particles containing both light and heavy quarks can thus provide important tests of QCD predictions at extreme densities and temperatures and in particular allow one to test the expected flavour dependence of the energy loss processes. The comparison to theoretical calculations is fundamental in order to claim any evidence of flavour dependence of the energy loss mechanisms since sizeable discrepancies in the R_{AA} of light and heavy particles can arise as a consequence of the different transverse momentum spectra and fragmentation functions of beauty, charm, and light quarks and gluons.

Evidence of open charm suppression at the CERN LHC was observed by the ALICE Collaboration using the R_{AA} of promptly produced D mesons (D^0, D^+, D^{*+} mesons and their conjugates) at mid-rapidity ($|y| < 0.5$) at a nucleon–nucleon centre-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV. The measurement was performed as a function of centrality (i.e. the degree of overlap of the two colliding nuclei) and transverse momentum ($1 < p_T < 36$ GeV/c) [9,10]. A maximum suppression by a factor of 5–6 with respect to the pp reference was observed for the 10% most central collisions at p_T of about 10 GeV/c. A suppression by a factor of about 3 was measured at the highest p_T range studied, from 25 to 35 GeV/c. The D meson R_{AA} was found to be consistent with that for all charged particles for p_T from 6 to 36 GeV/c. For lower p_T, the D meson R_{AA} was observed to be slightly higher than the charged-particle R_{AA}, although still compatible within the uncertainties [11,12]. At RHIC, the R_{AA} of D^0 mesons for the 10% most central AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV was measured by the STAR Collaboration in the rapidity range of $|y| < 1$ [13]. A suppression by a factor of 2–3 for

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

https://doi.org/10.1016/j.physletb.2018.05.074
0370-2693/© 2018 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

p_T larger than 3 GeV/c was seen. This suggests that a significant energy loss of charm quarks in the hot medium also occurs at RHIC energies. A first indication of a sizeable difference in the R_{AA} of B and D mesons was observed when comparing the ALICE D meson R_{AA} with the nonprompt J/ψ meson (i.e. from b-hadron decays) R_{AA} measurement performed by the CMS Collaboration in PbPb collisions at the same energy and collision centrality [14]. The R_{AA} of nonprompt J/ψ mesons in the p_T range 6.5–30 GeV/c was indeed found to be significantly larger than the R_{AA} of D mesons in the 8–16 GeV/c p_T region for central events. The D^0 p_T range was chosen to give a similar median p_T value to that of the parent b hadrons decaying to J/ψ particles [9]. Several measurements were also performed to address the relevance of cold nuclear matter effects for the suppression observed for heavy-flavour particles. Indeed, these phenomena can affect the yield of such particles, independently of the presence of a deconfined partonic medium. For instance, modifications of the parton distribution functions (PDFs) in the nucleus with respect to nucleon PDFs [15–17] could change the production rate of heavy-flavour particles. To evaluate the relevance of these effects, the production of prompt D mesons was measured in pPb collisions at mid-rapidity at 5.02 TeV by the ALICE Collaboration [18]. The nuclear modification factor in pPb collisions (R_{pA}) was found to be consistent within the 15–20% uncertainties with unity for p_T from 2 to 24 GeV/c. This suggests that the suppression of D mesons observed in PbPb collisions cannot be explained in terms of initial-state effects but is mostly due to strong final-state effects induced by the QGP. A similar conclusion was obtained from the study of the R_{pA} of B mesons in pPb collisions at 5.02 TeV, where values consistent with unity within the uncertainties were found for p_T from 10 to 60 GeV/c [19].

In this Letter, the production of prompt D^0 mesons in PbPb collisions at 5.02 TeV is measured for the first time up to a p_T of 100 GeV/c, allowing one to study the properties of the in-medium energy loss in a new kinematic regime. The D^0 meson and its antiparticle are reconstructed in the central rapidity region ($|y| < 1$) of the CMS detector via the hadronic decay channels $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$. The production cross section and yields in pp and PbPb collisions, respectively, and the R_{AA} of prompt D^0 mesons are presented as a function of their p_T. The R_{AA} is reported for two centrality intervals: in the inclusive sample (0–100%), and in one corresponding to the most overlapping 10% of the collisions.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon tracker which measures charged particles within the pseudorapidity range $|\eta| < 2.5$, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). The ECAL consists of more than 75 000 lead tungstate crystals, and is partitioned into a barrel region ($|\eta| < 1.48$) and two endcaps extending out to $|\eta| = 3.0$. The HCAL consists of sampling calorimeters composed of brass and scintillator plates, covering $|\eta| < 3.0$. Iron hadron forward (HF) calorimeters, with quartz fibres read out by photomultipliers, extend the calorimeter coverage out to $|\eta| = 5.2$. A detailed description of the CMS experiment can be found in Ref. [20].

3. Event selection and Monte Carlo samples

The pp (PbPb) dataset used for this analysis corresponds to an integrated luminosity of 27.4 pb^{-1} (530 μb^{-1}). The D^0 meson production is measured from p_T of 2 up to 20 GeV/c using large samples of minimum-bias (MB) events (≈2.5 billion pp events and ≈300 million PbPb events). Minimum-bias events were selected online using the information from the HF calorimeters and the beam pickup monitors. For measuring the D^0 meson production above 20 GeV/c, dedicated high-level trigger (HLT) algorithms were designed to identify online events with a D^0 candidate. Since events with a high-p_T D^0 meson are expected to leave large energy deposits in HCAL, HLT algorithms were run on events preselected by jet triggers in the level-1 (L1) calorimeter trigger system. In PbPb collisions, the D^0 triggers with p_T threshold below 40 GeV/c were run on events passing the L1 MB trigger selection. While the MB and lower-threshold triggers had to be prescaled because of the high instantaneous luminosity of the LHC, the highest threshold trigger used in the analysis ($p_T > 60\,(50)$ GeV/c for PbPb (pp) data taken) was always unprescaled. The efficiency of the HLT algorithms was evaluated in data, and modelled by a linear function of D^0 p_T. The efficiency was found to be about 100 (90)% in pp (PbPb) collisions for events passing the corresponding L1 selection.

For the offline analysis, events have to pass a set of selection criteria designed to reject events from background processes (beam-gas collisions and beam scraping events) as described in Ref. [21]. In order to select hadronic collisions, both pp and PbPb events are required to have at least one reconstructed primary interaction vertex with a distance from the centre of the nominal interaction region of less than 15 cm along the beam axis. In addition, in PbPb collisions the shapes of the clusters in the pixel detector have to be compatible with those expected from particles produced by a PbPb collision [22]. The PbPb collision events are also required to have at least three towers in each of the HF detectors with energy deposits of more than 3 GeV per tower. The combined efficiency for this event selection, and the remaining nonhadronic contamination, is (99 ± 2)%. Selection efficiencies higher than 100% are possible, reflecting the possible presence of ultraperipheral (nonhadronic) collisions in the selected event sample. The collision centrality is determined from the total transverse energy deposition in both the HF calorimeters. Collision centrality bins are given in percentage ranges of the total inelastic hadronic cross section, with the 0–10% bin corresponding to the 10% of collisions having the largest overlap of the two nuclei.

Several Monte Carlo (MC) simulated event samples are used to evaluate background components, signal efficiencies, and detector acceptance corrections. The events produced include both prompt and nonprompt (from b hadron decays) D^0 meson events. Proton–proton collisions are generated with PYTHIA 8 v212 [23] tune CUETP8M1 [24] and propagated through the CMS detector using the GEANT4 package [25]. The D^0 mesons are decayed with EVTGEN 1.3.0 [26], and final-state photon radiation in the D^0 decays is simulated with PHOTOS 2.0 [27]. For the PbPb MC samples, each PYTHIA 8 event is embedded into a PbPb collision event generated with HYDJET 1.8 [28], which is tuned to reproduce global event properties such as the charged-hadron p_T spectrum and particle multiplicity.

4. Signal extraction

The D^0 candidates are reconstructed by combining pairs of oppositely charged particle tracks with an invariant mass within 0.2 GeV/c^2 of the world-average D^0 mass [29]. Each track is required to have $p_T > 1$ GeV/c in order to reduce the combinatorial background. For high-p_T D^0 mesons (above 20 GeV/c) in PbPb data, the single track cut is raised to $p_T > 8.5$ GeV/c to account for the selection ($p_T > 8$ GeV/c) performed at the HLT. All tracks are also required to be within $|\eta| < 1.5$. For each pair of selected tracks, two D^0 candidates are created by assuming that one of the particles has the mass of the pion while the other has the mass of the kaon, and vice-versa. The D^0 mesons are required to be within

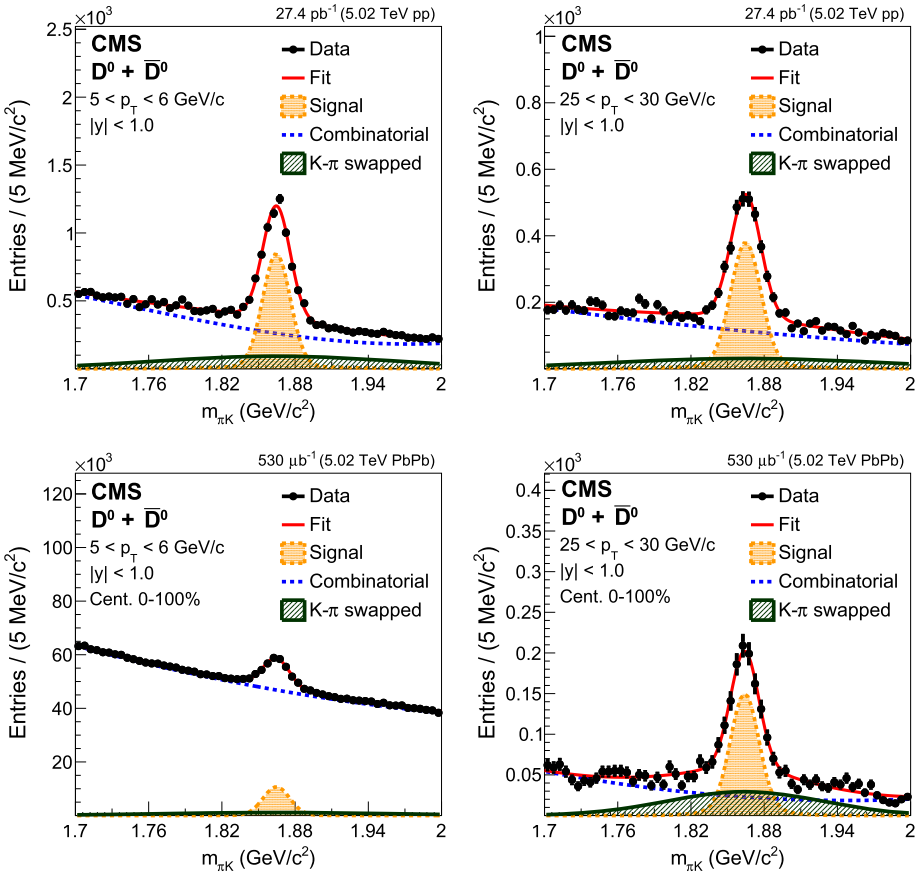


Fig. 1. Examples of D^0 candidate invariant mass distributions in pp (top) and PbPb (bottom) collisions at 5.02 TeV . (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

$|y| < 1$, optimised in conjunction to the track pseudorapidity selection to give the best signal to background ratio over the whole range of D^0 p_T studied. In order to further reduce the combinatorial background, the D^0 candidates are selected based on three topological criteria: on the three-dimensional (3D) decay length L_{xyz} normalised to its uncertainty (required to be larger than 4–6), on the pointing angle θ_p (defined as the angle between the total momentum vector of the tracks and the vector connecting the primary and the secondary vertices and required to be smaller than 0.12), and on the χ^2 probability, divided by the number of degrees of freedom, of the D^0 vertex fit (required to be larger than 0.025–0.05). The selection is optimised in each p_T bin using a multivariate technique [30] in order to maximise the statistical significance of the D^0 meson signals.

The D^0 meson yields in each p_T interval are extracted with a binned maximum-likelihood fit to the invariant mass distributions in the range $1.7 < m_{\pi K} < 2.0\,\text{GeV}/c^2$. Several examples of D^0 candidate invariant mass distributions are shown in Fig. 1 for pp (top) and PbPb (bottom) collisions. The combinatorial background, originating from random pairs of tracks not produced by a D^0 meson decay, is modelled by a third-order polynomial. The signal shape was found to be best modelled over the entire p_T range measured by two Gaussian functions with the same mean but different widths. An additional Gaussian function is used to describe the invariant mass shape of D^0 candidates with incorrect mass assignment from the exchange of the pion and kaon designations. The widths of the Gaussian functions that describe the D^0 signal shape and the shape of the D^0 candidates with swapped mass assignment are free parameters in the fit. Also, the ratio between the yields of the signal and of the D^0 candidates with swapped mass assignments is fixed to the value extracted from simulation.

The D^0 p_T-differential cross section in each p_T interval in pp collisions is defined as:

$$\left.\frac{d\sigma_{pp}}{dp_T}\right|_{|y|<1} = \frac{1}{2}\frac{1}{\Delta p_T}\frac{1}{\mathcal{B}\,\mathcal{L}}\left.\frac{f_{\text{prompt}}\,N_{pp}}{(\alpha\,\epsilon)_{\text{prompt}}\,\beta_{\text{prescale}}\,\epsilon_{\text{trigger}}}\right|_{|y|<1}, \quad (1)$$

where Δp_T is the width of the p_T interval, $\mathcal{B}$ is the branching fraction of the decay chain, $\mathcal{L}$ is the integrated luminosity, $(\alpha\,\epsilon)_{\text{prompt}}$ represents the correction for acceptance and efficiency and N_{pp} is the yield of D^0 and $\overline{D}^0$ mesons extracted in each p_T interval. In both pp and PbPb cases, the value of α_{prompt} ranges from about 0.3 at 2–3 GeV/c to about 100% at 60–100 GeV/c. The value of ϵ_{prompt} ranges for PbPb (pp) from about 0.02 (0.03) at 2–3 GeV/c to about 0.4 (0.6) at 60–100 GeV/c. The factor 1/2 accounts for the fact that the cross section is given for the average of particles and antiparticles. The raw yields N_{pp} are corrected in order to account for the average prescale factor β_{prescale} and the efficiency $\epsilon_{\text{trigger}}$ of the trigger that was used to select events in that specific p_T interval. The factor f_{prompt} is the fraction of D^0 mesons that comes directly from c quark fragmentation and is measured using control samples in data by exploiting the difference in the distributions of a quantity found by multiplying the 3D D^0 decay length L_{xyz} by the sine of the pointing angle $\sin(\theta_p)$ of prompt and nonprompt D^0 mesons. In particular, the value of f_{prompt} (typically in the range 0.8–0.9) is measured in each p_T interval by fitting the distribution of $L_{xyz}\sin(\theta_p)$ using the prompt and nonprompt shapes obtained from MC simulation.

The D^0 p_T-differential production yield in each p_T interval in PbPb collisions is defined as:

$$\left.\frac{1}{T_{AA}}\frac{dN_{PbPb}}{dp_T}\right|_{|y|<1} = \frac{1}{T_{AA}}\frac{1}{2}\frac{1}{\Delta p_T}\frac{1}{\mathcal{B}\,N_{MB}}\left.\frac{f_{prompt}\,N_{PbPb}}{(\alpha\,\epsilon)_{prompt}\,\beta_{prescale}\,\epsilon_{trigger}}\right|_{|y|<1}, \quad (2)$$

where N_{MB} is the number of MB events used for the analysis and T_{AA} is the nuclear overlap function [8], which is equal to the number of nucleon–nucleon (NN) binary collisions divided by the NN cross section and can be interpreted as the NN-equivalent integrated luminosity per heavy ion collision. The values of T_{AA} are $5.61\,mb^{-1}$ for inclusive PbPb collisions and $23.2\,mb^{-1}$ for central events [21]. The other terms were defined analogously to Eq. (1).

5. Systematic uncertainties

The yields are affected by several sources of systematic uncertainties arising from the signal extraction, acceptance and efficiency corrections, branching fraction, and integrated luminosity determination. The uncertainty in the raw yield extraction (1.6–8.2% for pp and 1.3–17.5% for PbPb data, with the highest value at low-p_T, which is the region with the smallest signal to background ratio) is evaluated by repeating the fit procedure using different background fit functions and by forcing the widths of the Gaussian functions that describe the signal to be equal to the values extracted in simulations to account for possible differences in the signal resolution in data and in MC. In the background variation study, an exponential plus a second-order polynomial function was considered instead of the first order polynomial one, which is used as default. The final uncertainty in the raw yield extraction is defined as the sum in quadrature of the relative differences of the signal variation and the maximum of all the background variations.

The systematic uncertainty due to the selection of the D^0 meson candidates (0.5–3.6% for pp and 2.7–8.1% for PbPb data, with the highest value at low-p_T) is estimated by considering the differences between MC and data in the reduction of the D^0 yields obtained by applying each of the D^0 selection variables described in Sec. 4. The study was performed by varying one selection at a time, in a range that allowed a robust signal extraction procedure and by considering the maximum relative discrepancy in the yield reduction between data and MC. The total uncertainty was the quadratic sum of the maximum relative discrepancy obtained by varying each of the three selection variables separately.

The uncertainty due to the D^0 trigger efficiency (1% for pp and 2% for PbPb data) is evaluated as the statistical uncertainty in the zeroth-order coefficient of the linear function used to describe the plateau of the efficiency distribution. The systematic uncertainty in the hadron tracking efficiency (4.0% for pp and 6.0–6.5% for PbPb data) is estimated from a comparison of two- and four-body D^0 meson decays in data and simulated samples [31].

To evaluate the systematic uncertainty in the prompt D^0 meson fraction, the width of the $L_{xyz}\sin(\theta_p)$ MC prompt and nonprompt templates are varied in a range that covers the observed differences between the data and MC values. The systematic uncertainty (10% for both pp and PbPb data) was obtained in each p_T bin as the difference between the f_{prompt} value extracted from the variation that gives the best χ^2 fit to data and the nominal f_{prompt} value. To evaluate this uncertainty for the R_{AA} measurement, the widths of the template distributions are varied simultaneously in pp and PbPb. The systematic uncertainty on the f_{prompt} correction was evaluated as the spread of the ratios of f_{prompt} in PbPb and pp to account for partial cancellations of the systematic effects in the two analyses.

The uncertainty related to the simulated p_T shape (smaller than 0.5% for both pp and PbPb data) is evaluated by reweighting the simulated D^0 meson p_T distribution according to the p_T shape obtained from a fixed-order plus next-to-leading logarithmic (FONLL) prediction [32].

The systematic uncertainty in the cross section measurement is computed as the sum in quadrature of the different contributions mentioned above. The global uncertainty in the pp measurement (2.5%) is the sum in quadrature of the systematic uncertainty in the integrated luminosity (2.3% [33]) and in the branching fraction $\mathcal{B}$ (1.0% [29]). The global uncertainty in the PbPb measurement (+3.6%, −4.1% for the centrality range 0–100% and +2.9%, −3.7% for 0–10%) is the sum in quadrature of the uncertainties in the MB selection efficiency (2%), in the branching fraction (1.0%) and in the T_{AA} (+2.8%, −3.4% for the centrality range 0–100% and +1.9%, −3.0% for 0–10%). For the R_{AA} results, no cancellation of uncertainties is assumed between the pp and PbPb results.

6. Results

The p_T-differential production cross section in pp collisions measured in the interval $|y| < 1$ is presented in the left panel of Fig. 2. The result is compared to the prediction of FONLL and a general-mass variable flavour number scheme (GM-VFNS) [34–36] calculation. The CMS measurement lies close to the upper bound of the FONLL prediction and the lower bound of the GM-VFNS calculation. The D^0 p_T-differential production yields divided by the nuclear overlap functions T_{AA} in PbPb collisions in the 0–100% and 0–10% centrality ranges are presented in the right panel of Fig. 2 and compared to the same pp cross section shown in the left panel.

The nuclear modification factor, R_{AA} is computed as:

$$R_{AA} = \frac{1}{T_{AA}}\frac{dN_{PbPb}}{dp_T}\Big/\frac{d\sigma_{pp}}{dp_T}. \quad (3)$$

The R_{AA} in the centrality range 0–100% is shown in the left panel of Fig. 3 as a function of p_T. The R_{AA} shows a suppression of a factor 3 to 4 at p_T of 6–8 GeV/c. At higher p_T, the suppression factor decreases to a value of about 1.3 in the p_T range 60–100 GeV/c. The R_{AA} for the centrality range 0–10% is presented in the right panel of Fig. 3. The D^0 R_{AA} in central events shows a hint of stronger suppression if compared to the inclusive R_{AA} result for $p_T > 5$ GeV/c. In this comparison, the large overlap between the two results has to be considered. Indeed, roughly 40% of the D^0 candidates used in the measurement in the centrality range 0–100% are also included in the 0–10% result.

The results are also compared to calculations of four types of models: (a) two perturbative QCD-based models that include both collisional and radiative energy loss, (M. Djordjevic [37] and CUJET 3.0 [38–40]) and one that includes radiative energy loss only (I. Vitev [41,42]), (b) a transport model based on a Langevin equation that includes collisional energy loss and heavy-quark diffusion in the medium (S. Cao et al. [43,44]), (c) a microscopic off-shell transport model based on a Boltzmann approach that includes collisional energy loss only (PHSD [45,46]), and (d) a model based on the anti-de Sitter/conformal field theory (AdS/CFT) correspondence, that includes thermal fluctuations in the energy loss for heavy quarks in a strongly coupled plasma [47]. The AdS/CFT calculation is provided for two settings of the diffusion coefficient D of the heavy quark propagation through the medium: dependent on, and independent of the quark momentum. For D^0 meson $p_T > 40$ GeV/c, the perturbative QCD-based models describe the suppression in both centrality ranges within the uncertainties, although the trend suggested by these predictions is typically lower than that in the experimental data. The model based

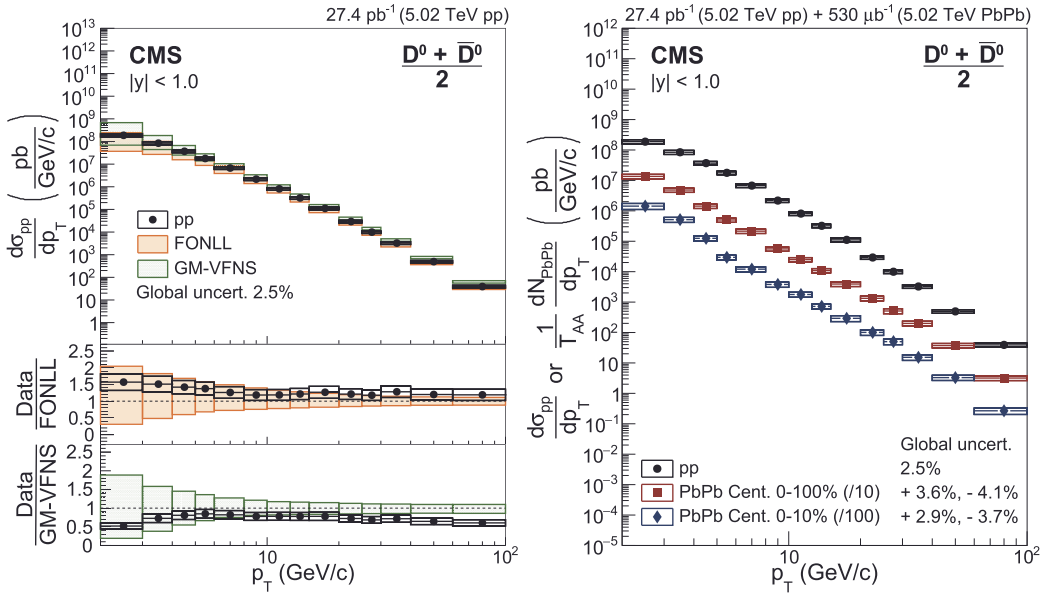


Fig. 2. (left) The p_T-differential production cross section of D^0 mesons in pp collisions at $\sqrt{s} = 5.02$ TeV. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty, listed in the legend and not included in the point-to-point uncertainties, comprises the uncertainties in the integrated luminosity measurement and the D^0 meson $\mathcal{B}$. Results are compared to FONLL [32] and GM-VFNS [34–36] calculations. (right) The p_T-differential production yields of D^0 mesons divided by the nuclear overlap functions T_{AA} for PbPb collisions in the 0–100% (red) and 0–10% (blue) centrality ranges compared to the same pp cross sections shown in the left panel (black).

on a Langevin approach describes the measurement well in the centrality range 0–100%, while it predicts slightly too much suppression for central events. The AdS/CFT calculations describe well both the 0–100% and the 0–10% measurements. In the intermediate p_T region ($10 < p_T < 40$ GeV/c), all the theoretical calculations describe well the R_{AA} results in both centrality intervals. For $p_T < 10$ GeV/c, the PHSD prediction that includes shadowing can reproduce the measurement in the 0–100% centrality region accurately, while the Langevin calculation predicts significantly more suppression than seen in data for both centrality ranges. In the same low-p_T region, the AdS/CFT calculation lies at the lower limit of the experimental uncertainties for both 0–10% and 0–100% measurements.

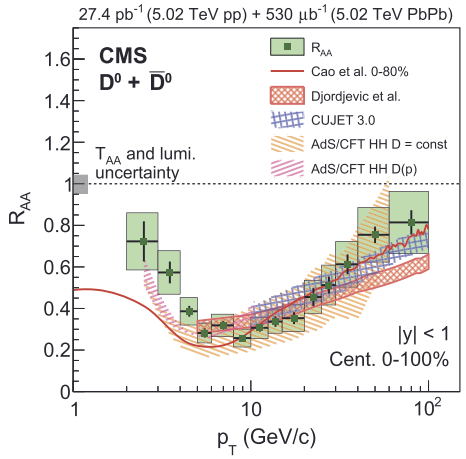
The D^0 R_{AA} measured in the centrality range 0–100% is compared in the top panel of Fig. 4 to the CMS measurements of the R_{AA} of charged particles [21], $B^{\pm}$ mesons [48] and nonprompt J/ψ meson [49] performed at the same energy and in the same centrality range. The systematic uncertainties between the R_{AA} measurement of the D^0 mesons, and of the light and beauty particles, are almost completely uncorrelated. The only common contribution comes from the systematic uncertainty of one track (4%), which is however negligible when compared to the total uncertainties. The D^0 meson R_{AA} values are consistent with those of charged particles for $p_T > 4$ GeV/c. For lower p_T, a somewhat smaller suppression for D^0 mesons is observed. The R_{AA} of the $B^{\pm}$ mesons, measured in the p_T range 7–50 GeV/c and the rapidity range of $|y| < 2.4$, is also consistent with the D^0 meson measurement within the experimental uncertainties. The R_{AA} of nonprompt J/ψ, which was found to have almost no rapidity dependence [49], is shown here measured in the p_T ranges 6.5–50 GeV/c in $|y| < 2.4$, and 3–6.5 GeV/c in $1.8 < |y| < 2.4$. Its R_{AA} is found to be higher than the D^0 meson R_{AA} in almost the entire p_T range. The D^0 meson R_{AA} in the centrality range 0–10% is compared in Fig. 4 to the charged-particle R_{AA}. As observed for 0–100% PbPb events, the two results are consistent within uncertainties for $p_T > 4$ GeV/c and a somewhat smaller suppression for charmed mesons is observed at lower p_T.

7. Summary

In this Letter, the transverse momentum (p_T) spectra of prompt D^0 mesons in pp and PbPb collisions and the D^0 meson nuclear modification factor (R_{AA}) in the central rapidity region ($|y| < 1$) at $\sqrt{s_{NN}} = 5.02$ TeV from CMS are presented. The R_{AA} of prompt D^0 mesons is measured as a function of their p_T from 2 to 100 GeV/c in two centrality ranges, inclusive and 10% most central. The D^0 meson yield is found to be strongly suppressed in PbPb collisions when compared to the measured pp reference data scaled by the number of binary nucleon–nucleon collisions. These measurements are consistent with the R_{AA} of charged hadrons in both centrality intervals for $p_T > 4$ GeV/c. A hint of a smaller suppression of D^0 R_{AA} with respect to charged particle R_{AA} is observed for $p_T < 4$ GeV/c. The D^0 R_{AA} was found to be compatible with the $B^{\pm}$ R_{AA} in the intermediate p_T region and significantly lower than the nonprompt J/ψ meson R_{AA} for $p_T < 10$ GeV/c. Comparisons to different theoretical models show that the general trend of the R_{AA} is qualitatively reproduced at high p_T. Comparisons to different theoretical models show that the general trend of the R_{AA} is qualitatively reproduced at high p_T, while quantitative agreement for all centrality and p_T selections is yet to be attained.

Acknowledgements

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



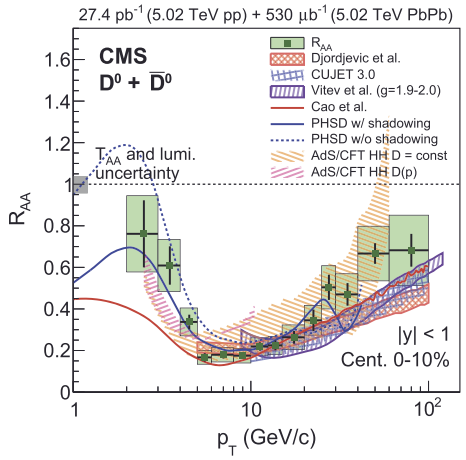
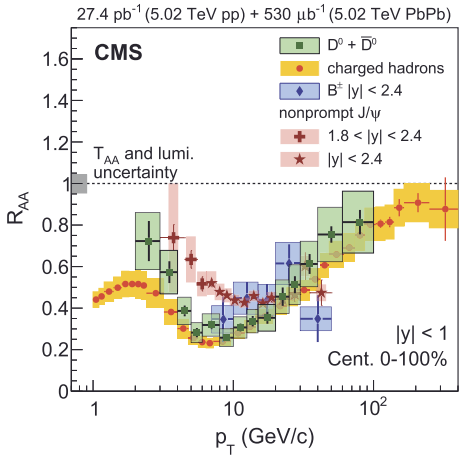


Fig. 3. R_{AA} as a function of p_T in the centrality range 0–100% (top) and 0–10% (bottom). The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty, represented as a grey box at $R_{AA} = 1$, comprises the uncertainties in the integrated luminosity measurement and T_{AA} value. The D^0 R_{AA} values are also compared to calculations from various theoretical models [37–47].



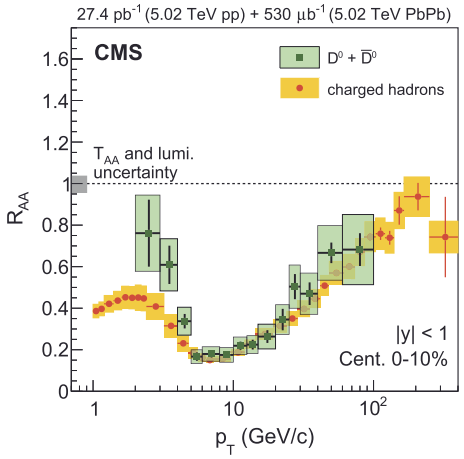


Fig. 4. (top) Nuclear modification factor R_{AA} as a function of p_T in the centrality range 0–100% (green squares) compared to the R_{AA} of charged particles (red circles) [21], $B^{\pm}$ mesons (blue triangles) [48] and nonprompt J/ψ meson (purple crosses and stars) [49] in the same centrality range at 5.02 TeV. (bottom) Nuclear modification factor R_{AA} as a function of p_T in the centrality range 0–10% (green squares) compared to the R_{AA} of charged particles (red circles) [21] in the same centrality range.

(Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEP Center, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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

References

[1] É.V. Shuryak, Theory of hadron plasma, Sov. Phys. JETP 47 (1978) 212, http://www.jetp.ac.ru/cgi-bin/e/index/e/47/2/p212?a=list.

[2] J.C. Collins, M.J. Perry, Superdense matter: neutrons or asymptotically free quarks? Phys. Rev. Lett. 34 (1975) 1353, https://doi.org/10.1103/PhysRevLett.34.1353.

[3] F. Karsch, E. Laermann, Thermodynamics and in-medium hadron properties from lattice QCD, in: R. Hwa (Ed.), Quark-Gluon Plasma III, 2003, arXiv:hep-lat/0305025.

[4] F.-M. Liu, S.-X. Liu, Quark-gluon plasma formation time and direct photons from heavy ion collisions, Phys. Rev. C 89 (2014) 034906, https://doi.org/10.1103/PhysRevC.89.034906.

[5] Y.L. Dokshitzer, D.E. Kharzeev, Heavy quark colorimetry of QCD matter, Phys. Lett. B 519 (2001) 199, https://doi.org/10.1016/S0370-2693(01)01130-3, arXiv:hep-ph/0106202.

[6] N. Armesto, C.A. Salgado, U.A. Wiedemann, Medium induced gluon radiation off massive quarks fills the dead cone, Phys. Rev. D 69 (2004) 114003, https://doi.org/10.1103/Armesto:2003jh, arXiv:hep-ph/0312106.

[7] A. Andronic, et al., Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions, Eur. Phys. J. C 76 (2016) 107, https://doi.org/10.1140/epjc/s10052-015-3819-5, arXiv:1506.03981.

[8] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Glauber modeling in high energy nuclear collisions, Annu. Rev. Nucl. Part. Sci. 57 (2007) 205, https://doi.org/10.1146/annurev.nucl.57.090506.123020, arXiv:nucl-ex/0701025.

[9] ALICE Collaboration, Centrality dependence of high-p_T D meson suppression in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, J. High Energy Phys. 11 (2015) 205, https://doi.org/10.1007/JHEP11(2015)205, arXiv:1506.06604, Erratum: https://doi.org/10.1007/JHEP06(2017)032.

[10] ALICE Collaboration, Transverse momentum dependence of D-meson production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, J. High Energy Phys. 03 (2016) 081, https://doi.org/10.1007/JHEP03(2016)081, arXiv:1509.06888.

[11] ALICE Collaboration, Production of charged pions, kaons and protons at large transverse momenta in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Lett. B 736 (2014) 196, https://doi.org/10.1016/j.physletb.2014.07.011, arXiv:1401.1250.

[12] ALICE Collaboration, Centrality dependence of charged particle production at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Lett. B 720 (2013) 52, https://doi.org/10.1016/j.physletb.2013.01.051, arXiv:1208.2711.

[13] L. Adamczyk, et al., STAR, Observation of D^0 meson nuclear modifications in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. Lett. 113 (2014) 142301, https://doi.org/10.1103/PhysRevLett.113.142301, arXiv:1404.6185.

[14] CMS Collaboration, Suppression and azimuthal anisotropy of prompt and non-prompt J/ψ production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Eur. Phys. J. C 77 (2017) 252, https://doi.org/10.1140/epjc/s10052-017-4781-1, arXiv:1610.00613.

[15] K.J. Eskola, H. Paukkunen, C.A. Salgado, EPS09 — a new generation of NLO and LO nuclear parton distribution functions, J. High Energy Phys. 04 (2009) 065, https://doi.org/10.1088/1126-6708/2009/04/065, arXiv:0902.4154.

[16] D. de Florian, R. Sassot, Nuclear parton distributions at next to leading order, Phys. Rev. D 69 (2004) 074028, https://doi.org/10.1103/PhysRevD.69.074028, arXiv:hep-ph/0311227.

[17] L. Frankfurt, V. Guzey, M. Strikman, Leading twist nuclear shadowing phenomena in hard processes with nuclei, Phys. Rep. 512 (2012) 255, https://doi.org/10.1016/j.physrep.2011.12.002, arXiv:1106.2091.

[18] ALICE Collaboration, Measurement of prompt D-meson production in $p - Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Rev. Lett. 113 (2014) 232301, https://doi.org/10.1103/PhysRevLett.113.232301, arXiv:1405.3452.

[19] CMS Collaboration, Study of B meson production in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using exclusive hadronic decays, Phys. Rev. Lett. 116 (2016) 032301, https://doi.org/10.1103/PhysRevLett.116.032301, arXiv:1508.06678.

[20] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.

[21] CMS Collaboration, Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, J. High Energy Phys. 04 (2017) 039, https://doi.org/10.1007/JHEP04(2017)039, arXiv:1611.01664.

[22] CMS Collaboration, Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV, J. High Energy Phys. 02 (2010) 041, https://doi.org/10.1007/JHEP02(2010)041, arXiv:1002.0621.

[23] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[24] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C 76 (2016) 155, https://doi.org/10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[25] S. Agostinelli, et al., GEANT4, GEANT4 — a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.

[26] D.J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods A 462 (2001) 152, https://doi.org/10.1016/S0168-9002(01)00089-4.

[27] E. Barberio, B. van Eijk, Z. Was, Photos – a universal Monte Carlo for QED radiative corrections in decays, Comput. Phys. Commun. 66 (1991) 115, https://doi.org/10.1016/0010-4655(91)90012-A.

[28] I.P. Lokhtin, A.M. Snigirev, A model of jet quenching in ultrarelativistic heavy ion collisions and high-p_T hadron spectra at RHIC, Eur. Phys. J. C 45 (2006) 211, https://doi.org/10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.

[29] Particle Data Group, C. Patrignani, et al., Review of particle physics, Chin. Phys. C 40 (2016) 100001, https://doi.org/10.1088/1674-1137/40/10/100001.

[30] H. Voss, A. Höcker, J. Stelzer, 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), 2007, p. 40, http://pos.sissa.it/archive/conferences/050/040/ACAT_040.pdf, arXiv:physics/0703039.

[31] CMS Collaboration, Measurement of Tracking Efficiency, CMS Physics Analysis Summary CMS-PAS-TRK-10-002, 2010, https://cds.cern.ch/record/1279139.

[32] M. Cacciari, M. Greco, P. Nason, The p_T spectrum in heavy flavor hadroproduction, J. High Energy Phys. 05 (1998) 007, https://doi.org/10.1088/1126-6708/1998/05/007, arXiv:hep-ph/9803400.

[33] CMS Collaboration, CMS Luminosity Calibration for the pp Reference Run at $\sqrt{s} = 5.02$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-16-001, 2016, https://cds.cern.ch/record/2235781.

[34] B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, Inclusive $D^{*\pm}$ production in $p\bar{p}$ collisions with massive charm quarks, Phys. Rev. D 71 (2005) 014018, https://doi.org/10.1103/PhysRevD.71.014018, arXiv:hep-ph/0410289.

[35] B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, Collinear subtractions in hadroproduction of heavy quarks, Eur. Phys. J. C 41 (2005) 199, https://doi.org/10.1140/epjc/s2005-02200-7, arXiv:hep-ph/0502194.

[36] B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, Inclusive charmed-meson production at the CERN LHC, Eur. Phys. J. C 72 (2012) 2082, https://doi.org/10.1140/epjc/s10052-012-2082-2, arXiv:1202.0439.

[37] M. Djordjevic, M. Djordjevic, Predictions of heavy-flavor suppression at 5.1 TeV Pb+Pb collisions at the CERN Large Hadron Collider, Phys. Rev. C 92 (2015) 024918, https://doi.org/10.1103/PhysRevC.92.024918, arXiv:1505.04316.

[38] J. Xu, J. Liao, M. Gyulassy, Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0, J. High Energy Phys. 02 (2016) 169, https://doi.org/10.1007/JHEP02(2016)169, arXiv:1508.00552.

[39] J. Xu, A. Buzzatti, M. Gyulassy, Azimuthal jet flavor tomography with CUJET2.0 of nuclear collisions at RHIC and LHC, J. High Energy Phys. 08 (2014) 063, https://doi.org/10.1007/JHEP08(2014)063, arXiv:1402.2956.

[40] J. Xu, J. Liao, M. Gyulassy, Consistency of perfect fluidity and jet quenching in semi-quark-gluon monopole plasmas, Chin. Phys. Lett. 32 (2015) 092501, https://doi.org/10.1088/0256-307X/32/9/092501, arXiv:1411.3673.

[41] Z.-B. Kang, R. Lashof-Regas, G. Ovanesyan, P. Saad, I. Vitev, Jet quenching phenomenology from soft-collinear effective theory with Glauber gluons, Phys. Rev. Lett. 114 (2015) 092002, https://doi.org/10.1103/PhysRevLett.114.092002, arXiv:1405.2612.

[42] Y.-T. Chien, A. Emerman, Z.-B. Kang, G. Ovanesyan, I. Vitev, Jet quenching from QCD evolution, Phys. Rev. D 93 (2016) 074030, https://doi.org/10.1103/PhysRevD.93.074030, arXiv:1509.02936.

[43] S. Cao, T. Luo, G.-Y. Qin, X.-N. Wang, Linearized Boltzmann transport model for jet propagation in the quark-gluon plasma: heavy quark evolution, Phys. Rev. C 94 (2016) 014909, https://doi.org/10.1103/PhysRevC.94.014909, arXiv:1605.06447.

[44] S. Cao, T. Luo, G.-Y. Qin, X.-N. Wang, Heavy and light flavor jet quenching at RHIC and LHC energies, arXiv:1703.00822, 2017.

[45] T. Song, H. Berrehrah, D. Cabrera, J.M. Torres-Rincon, L. Tolos, W. Cassing, E. Bratkovskaya, Tomography of the quark-gluon-plasma by charm quarks, Phys. Rev. C 92 (2015) 014910, https://doi.org/10.1103/PhysRevC.92.014910, arXiv:1503.03039.

[46] T. Song, H. Berrehrah, D. Cabrera, W. Cassing, E. Bratkovskaya, Charm production in Pb + Pb collisions at energies available at the CERN Large Hadron Collider, Phys. Rev. C 93 (2016) 034906, https://doi.org/10.1103/PhysRevC.93.034906, arXiv:1512.00891.

[47] W.A. Horowitz, Fluctuating heavy quark energy loss in a strongly coupled quark-gluon plasma, Phys. Rev. D 91 (2015) 085019, https://doi.org/10.1103/PhysRevD.91.085019, arXiv:1501.04693.

[48] CMS Collaboration, Measurement of the $B^{+/-}$ meson nuclear modification factor in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Rev. Lett. 119 (2017) 152301, https://doi.org/10.1103/PhysRevLett.119.152301, arXiv:1705.04727.

[49] CMS Collaboration, Measurement of prompt and nonprompt charmonium suppression in PbPb collisions at 5.02 TeV, Eur. Phys. J. C (2017), arXiv:1712.08959, submitted for publication.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth [1], V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler [1], A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck [1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz [1], M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

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

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang [2]

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

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

N. Beliy

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [3], A. Custódio, E.M. Da Costa, G.G. Da Silveira [4], 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, A. Santoro, A. Sznajder, E.J. Tonelli Manganote [3], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

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

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

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

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

University of Sofia, Sofia, Bulgaria

W. Fang [5], X. Gao [5]

Beihang University, Beijing, China

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

Institute of High Energy Physics, Beijing, China

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

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

Universidad de Los Andes, Bogota, Colombia

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

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov [6], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger [7], M. Finger Jr. [7]

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran [8,9], M.A. Mahmoud [10,9], A. Mahrous [11]

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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

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

A. Abdulsalam, 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, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

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

J.-L. Agram [12], J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte [12], X. Coubez, J.-C. Fontaine [12], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, 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. Popov [13], V. Sordini, M. Vander Donckt, S. Viret

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

T. Toriashvili [14]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [7]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage, V. Zhukov [13]

RWTH Aachen University, I. Physikalisches Institut, 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, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl [15]

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras [16], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo [17], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel [18], H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann [18], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

Deutsches Elektronen-Synchrotron, Hamburg, Germany

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, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo [15], 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, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann [15], S.M. Heindl, U. Husemann, F. Kassel [15], 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

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

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

National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

M. Csanad, N. Filipovic, G. Pasztor, G.I. Veres [19]

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

G. Bencze, C. Hajdu, D. Horvath [20], Á. Hunyadi, F. Sikler, V. Veszpremi, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók [19], P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati [22], S. Bhowmik, P. Mal, K. Mandal, A. Nayak [23], D.K. Sahoo [22], N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

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

Panjab University, Chandigarh, 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

University of Delhi, Delhi, 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, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty [15], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

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

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity [24], G. Majumder, K. Mazumdar, T. Sarkar [24], N. Wickramage [25]

Tata Institute of Fundamental Research-B, Mumbai, India

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

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

S. Chenarani [26], E. Eskandari Tadavani, S.M. Etesami [26], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi [27], F. Rezaei Hosseinabadi, B. Safarzadeh [28], M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], C. Calabria [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], F. Errico [a,b], L. Fiore [a], G. Iaselli [a,c], S. Lezki [a,b], G. Maggi [a,c], M. Maggi [a], G. Miniello [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], A. Ranieri [a], G. Selvaggi [a,b], A. Sharma [a], L. Silvestris [a,15], R. Venditti [a], P. Verwilligen [a]

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

G. Abbiendi [a], C. Battilana [a,b], D. Bonacorsi [a,b], 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]

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

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

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

G. Barbagli [a], K. Chatterjee [a,b], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], L. Russo [a,29], G. Sguazzoni [a], D. Strom [a], L. Viliani [a,b,15]

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

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli [a,b], F. Ferro [a], E. Robutti [a], S. Tosi [a,b]

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

A. Benaglia [a], L. Brianza [a,b], F. Brivio [a,b], V. Ciriolo [a,b], 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,30], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b]

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

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

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

P. Azzi [a,15], 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], P. De Castro Manzano [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], S. Lacaprara [a], P. Lujan, M. Margoni [a,b], A.T. Meneguzzo [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], S. Ventura [a], M. Zanetti [a,b], P. Zotto [a,b], G. Zumerle [a,b]

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

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

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

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

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

K. Androsov [a], P. Azzurri [a,15], G. Bagliesi [a], J. Bernardini [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,29], F. Ligabue [a,c], T. Lomtadze [a], E. Manca [a,c], G. Mandorli [a,c], L. Martini [a,b], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A. Savoy-Navarro [a,31], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

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

L. Barone [a,b], F. Cavallari [a], M. Cipriani [a,b], N. Daci [a], D. Del Re [a,b,15], E. Di Marco [a,b], M. Diemoz [a], S. Gelli [a,b], E. Longo [a,b], F. Margaroli [a,b], B. Marzocchi [a,b], P. Meridiani [a], G. Organtini [a,b], R. Paramatti [a,b], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], 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], F. Ravera [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], K. Shchelina [a,b], V. Sola [a], A. Solano [a,b], A. Staiano [a], P. Traczyk [a,b]

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

S. Belforte [a], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], A. Zanetti [a]

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

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

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

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

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

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

Hanyang University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

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

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali [32], F. Mohamad Idris [33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

R. Reyes-Almanza, G. Ramirez-Sanchez, M.C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [34], R.I. Rabadan-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

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

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev [36,37], V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

Y. Ivanov, V. Kim [38], E. Kuznetsova [39], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev, A. Bylinkin [37]

Moscow Institute of Physics and Technology, Moscow, Russia

R. Chistov [40], M. Danilov [40], P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

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

V. Andreev, M. Azarkin [37], I. Dremin [37], M. Kirakosyan [37], A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy [41], O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

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

V. Blinov [42], Y. Skovpen [42], D. Shtol [42]

Novosibirsk State University (NSU), Novosibirsk, Russia

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

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

P. Adzic [43], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

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

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

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, 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

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

D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, 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, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban [18], J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer [15], M.J. Kortelainen, M. Krammer [1], 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. Milenovic [44], F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi [45], M. Rovere,

H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas [46], A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns [47], M. Verweij, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

Paul Scherrer Institut, Villigen, Switzerland

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

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler [49], M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Takahashi, A. Zucchetta

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, 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

National Taiwan University (NTU), Taipei, Taiwan

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

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

F. Boran, S. Cerci [50], S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos [51], E.E. Kangal [52], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut [53], K. Ozdemir [54], D. Sunar Cerci [50], B. Tali [50], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Bilin, G. Karapinar [55], K. Ocalan [56], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya [57], O. Kaya [58], S. Tekten, E.A. Yetkin [59]

Bogazici University, Istanbul, Turkey

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

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold [60], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

A. Belyaev [61], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

G. Auzinger, R. Bainbridge, 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. Nikitenko [6], 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 Acosta [62], T. Virdee [15], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington DC, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [63], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

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

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

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla [†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, 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, S. Maruyama, 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

Fermi National Accelerator Laboratory, Batavia, USA

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

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

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

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

B. Bilki [64], W. Clarida, K. Dilsiz [65], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya [66], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul [67], Y. Onel, F. Ozok [68], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

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

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

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

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, D. Wood

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko [36], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

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

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M.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, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, N. Parashar, J. Stupak

Purdue University Northwest, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

R. Ciesielski, K. Goulianos, C. Mesropian

The Rockefeller University, New York, USA

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

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

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

University of Tennessee, Knoxville, USA

O. Bouhali [69], A. Castaneda Hernandez [69], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [70], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

Wayne State University, Detroit, 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, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin–Madison, Madison, WI, USA

† Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[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 Suez University, Suez, Egypt.
[9] Now at British University in Egypt, Cairo, Egypt.
[10] Also at Fayoum University, El-Fayoum, Egypt.
[11] Now at Helwan University, Cairo, Egypt.
[12] Also at Université de Haute Alsace, Mulhouse, France.
[13] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[14] Also at Tbilisi State University, Tbilisi, Georgia.
[15] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[16] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[17] Also at University of Hamburg, Hamburg, Germany.
[18] Also at Brandenburg University of Technology, Cottbus, Germany.
[19] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[20] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[21] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[22] Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
[23] Also at Institute of Physics, Bhubaneswar, India.
[24] Also at University of Visva-Bharati, Santiniketan, India.
[25] Also at University of Ruhuna, Matara, Sri Lanka.
[26] Also at Isfahan University of Technology, Isfahan, Iran.
[27] Also at Yazd University, Yazd, Iran.
[28] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[29] Also at Università degli Studi di Siena, Siena, Italy.
[30] Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy.
[31] Also at Purdue University, West Lafayette, USA.
[32] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[33] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[34] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

[35] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[36] Also at Institute for Nuclear Research, Moscow, Russia.
[37] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[38] Also at 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 INFN Sezione di Padova; Università di Padova; Università di Trento (Trento), Padova, Italy.
[42] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[43] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[44] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[45] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[46] Also at National and Kapodistrian University of Athens, Athens, Greece.
[47] Also at Riga Technical University, Riga, Latvia.
[48] Also at Universität Zürich, Zurich, Switzerland.
[49] Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
[50] Also at Adiyaman University, Adiyaman, Turkey.
[51] Also at Istanbul Aydin University, Istanbul, Turkey.
[52] Also at Mersin University, Mersin, Turkey.
[53] Also at Cag University, Mersin, Turkey.
[54] Also at Piri Reis University, Istanbul, 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, United Kingdom.
[61] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[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.