

# Bottom quark energy loss and hadronization with $B^+$ and $B_s^0$ nuclear modification factors using pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration\*

## Abstract

The production cross sections of  $B_s^0$  and  $B^+$  mesons are reported in proton-proton (pp) collisions recorded by the CMS experiment at the CERN LHC with a center-of-mass energy of 5.02 TeV. The data sample corresponds to an integrated luminosity of  $302 \text{ pb}^{-1}$ . The cross sections are based on measurements of the  $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(1020)(K^+K^-)$  and  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$  decay channels. Results are presented in the transverse momentum ( $p_T$ ) range 7–50 GeV/ $c$  and the rapidity interval  $|y| < 2.4$  for the B mesons. The measured  $p_T$ -differential cross sections of  $B^+$  and  $B_s^0$  in pp collisions are well described by fixed-order plus next-to-leading logarithm perturbative quantum chromodynamics calculations. Using previous PbPb collision measurements at the same nucleon-nucleon center-of-mass energy, the nuclear modification factors,  $R_{AA}$ , of the B mesons are determined. For  $p_T > 10 \text{ GeV}/c$ , both mesons are found to be suppressed in PbPb collisions (with  $R_{AA}$  values significantly below unity), with less suppression observed for the  $B_s^0$  mesons. In this  $p_T$  range, the  $R_{AA}$  values for the  $B^+$  mesons are consistent with those for inclusive charged hadrons and  $D^0$  mesons. Below 10 GeV/ $c$ , both  $B^+$  and  $B_s^0$  are found to be less suppressed than either inclusive charged hadrons or  $D^0$  mesons, with the  $B_s^0$   $R_{AA}$  value consistent with unity. The  $R_{AA}$  values found for the  $B^+$  and  $B_s^0$  are compared to theoretical calculations, providing constraints on the mechanism of bottom quark energy loss and hadronization in the quark-gluon plasma, the hot and dense matter created in ultrarelativistic heavy ion collisions.

*Submitted to the Journal of High Energy Physics*



## 1 Introduction

Ultrarelativistic collisions of heavy ions create extreme temperatures and energy densities. As predicted by lattice quantum chromodynamics (QCD) calculations [1], such conditions produce a state of matter referred to as the quark-gluon plasma (QGP) [2, 3], in which the relevant degrees of freedom of the system can be described by the interactions of quarks and gluons [4]. Heavy quarks can be used as probes of the QGP [5–7]. The study of their interactions with the medium they traverse, which include both elastic collisions and medium-induced gluon radiation [8–11], provide insights into the transport properties of the QGP. While data relevant to the energy loss of heavy flavor quarks are available from RHIC and LHC experiments [5], comprehensive measurements sensitive to the influence of the QGP medium on the transport of flavor-identified heavy hadrons are crucial for a deeper understanding of the hadronization mechanism. Such measurements are needed to extract transport properties, including, e.g., the heavy quark diffusion constant [6, 7] and the jet quenching parameter [7].

For bottom quarks, in particular, there is significant theoretical uncertainty associated with how the presence of the QGP medium affects the hadronization process [12]. The QGP is known to have an abundant strangeness content [13–19] since its temperature is above the strange quark mass [20]. This abundance may enhance the production of  $B_s^0$  mesons in the QGP medium, relative to the non-strange  $B^+$  mesons, through a quark recombination process [21–24]. Studies of open-charm [25] and open-bottom [26] mesons in lead-lead (PbPb) collisions at a nucleon-nucleon (NN) center-of-mass energy of  $\sqrt{s_{\text{NN}}} = 5.02$  TeV at the LHC hint at an enhanced production of strange-charm and strange-bottom hadrons. Recently, this line of studies has been extended to heavier  $B_c$  [27] and exotic  $X(3872)$  [28] hadron production in PbPb collisions. Reference [29] presents a summary of previous CMS work on how the QGP medium affects particle production at the LHC, as well as a more general overview of the CMS heavy ion program.

Measurements comparing various flavors of bottom hadrons have the potential to yield new insights regarding the hadronization of heavy quarks. Such measurements are challenging because of the relatively small production cross sections, large and varied background sources, and detector resolution limitations. In this paper, we present a study of the production rates of the  $B^+$  and  $B_s^0$  mesons in proton-proton (pp) collisions at  $\sqrt{s} = 5.02$  TeV, using a data set corresponding to  $302 \pm 6 \text{ pb}^{-1}$  [30] recorded with the CMS detector at the LHC in 2017. The B mesons are reconstructed via the exclusive decay channels  $B_s^0 \rightarrow J/\psi \phi(1020)$  and  $B^+ \rightarrow J/\psi K^+$ , with  $J/\psi \rightarrow \mu^+ \mu^-$  and  $\phi(1020) \rightarrow K^+ K^-$ . The pp cross sections are presented as functions of the transverse momentum ( $p_T$ ) of the meson measured in the rapidity interval  $|y| < 2.4$  and are compared to fixed-order plus next-to-leading logarithm (FONLL) calculations [31–33]. The new results are complementary to B meson measurements in pp collisions at  $\sqrt{s} = 5.02, 7, 8,$  and  $13$  TeV [26, 34–49], in proton-lead collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  and  $8.16$  TeV [50, 51], and in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV [26, 34, 52]. The published PbPb results [52] for  $B^+$  and  $B_s^0$  mesons are used to calculate the respective nuclear modification factors  $R_{\text{AA}}$ , i.e., the meson yield ratio in nucleus-nucleus (AA) and pp interactions normalized by the number of inelastic NN collisions via the relation

$$R_{\text{AA}}(p_T) = \frac{1}{T_{\text{AA}}} \frac{dN_{\text{PbPb}}^{\text{B}^+, \text{B}_s^0}}{dp_T} \bigg/ \frac{d\sigma_{\text{PP}}^{\text{B}^+, \text{B}_s^0}}{dp_T}, \quad (1)$$

where  $T_{\text{AA}}$  is the average number of NN binary collisions per PbPb interaction divided by the NN total inelastic cross section, which can be interpreted as the NN-equivalent integrated luminosity per heavy ion collision [52]. The reported  $R_{\text{AA}}$  results are for collisions with 0–90% centrality, corresponding to the 90% of collisions having the largest overlap of the two

nuclei [10, 52]. Throughout this paper, unless otherwise specified, the  $y$  and  $p_T$  variables refer to the B mesons. All references to B mesons in the text also include the corresponding charge-conjugate state, although the quoted cross sections correspond to individual states i.e., the average of the two yields), as was done for the previous PbPb analysis [52]. Tabulated results are provided in the HEPData record for this analysis [53].

## 2 The CMS apparatus

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. The silicon tracker measures charged particles within the pseudorapidity range  $|\eta| < 3.0$ . During the LHC running period when the data used in this paper were recorded, the silicon tracker consisted of 1856 silicon pixel and 15 148 silicon strip detector modules. Details on the pixel detector can be found in Ref. [54]. For nonisolated particles of  $1 < p_T < 10 \text{ GeV}/c$  and  $|\eta| < 3.0$ , the track resolutions are typically 1.5% in  $p_T$  and 20–75  $\mu\text{m}$  in the transverse impact parameter [55]. Muons are measured in the range  $|\eta| < 2.4$ , with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The single-muon trigger efficiency exceeds 90% over the full  $\eta$  range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution, for muons with  $p_T < 100 \text{ GeV}/c$ , of 1% in the barrel and 3% in the endcaps. The  $p_T$  resolution in the barrel is better than 7% for muons with  $p_T < 1 \text{ TeV}/c$  [56]. The hadron forward (HF) calorimeters, situated 11.2 m from the interaction region on both sides, with the coverage in the range  $3.0 < |\eta| < 5.2$ , utilize steel for absorption and quartz fibers as sensitive material. Information from the HF is used for determining the centrality.

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4  $\mu\text{s}$  [57]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [58]. A detailed description of the CMS experiment and coordinate system can be found in Ref. [59].

## 3 Analysis method

### 3.1 Candidate reconstruction and selection

The pp collision events are collected with a first-level trigger requiring the presence of two muon candidates, with no explicit momentum threshold. A subsequent high-level trigger required one of the muon candidates to be reconstructed using information from both the muon detectors and the inner tracker, while only information from the muon detectors is required for the other muon candidate. The dimuon candidates are further required to have an invariant mass within  $1 < m_{\mu\mu} < 5 \text{ GeV}/c^2$ .

For the offline analysis, events must pass a set of selection criteria designed to reject non-collision events and to select only inelastic hadronic collisions [60, 61]. Events are required to have at least one reconstructed primary interaction vertex, formed by two or more tracks, with a distance from the center of the nominal interaction region of less than 25 cm along the

beam axis. The shapes of the clusters in the pixel detector must be compatible with those expected from particles produced in a pp collision [62]. To select inelastic hadronic collisions, the pp events are also required to have at least one tower in both of the HF detectors with an energy deposit of more than 4 GeV.

The signal is extracted following the same procedure as for the PbPb results [52], as will be described. The same kinematic constraints are applied for the pp and PbPb samples to select muon candidates. The muons are required to match the trigger-level muon candidates and to pass the *soft muon* selection criteria [63]. Two muons of opposite charge, with an invariant mass within  $\pm 150 \text{ MeV}/c^2$  of the world-average  $J/\psi$  meson mass [64], are selected to reconstruct a  $J/\psi$  candidate. All remaining tracks are considered kaon candidates with no attempt at particle ID. The  $\phi(1020)$  meson candidates are formed with a common-vertex constraint between two oppositely charged tracks with  $p_T > 500 \text{ MeV}/c$ . The resulting invariant mass, assuming the world-average charged-kaon mass [64] for each of the two tracks is required to lie within  $\pm 15 \text{ MeV}/c^2$  of the world-average  $\phi(1020)$  meson mass [64]. Muon pairs (from  $J/\psi$  meson decays) and  $\phi(1020)$  meson candidates are combined to form  $B_s^0$  meson candidates, requiring that they originate from a common vertex. Similarly, muon pairs are combined with a single charged particle, assuming the  $K^+$  mass, to form  $B^+$  candidates. Negative tracks are also included to account for the charge-conjugate state. The B meson candidates are reconstructed within a fiducial region of  $1.5 < |y| < 2.4$  for  $p_T < 10 \text{ GeV}/c$  and  $|y| < 2.4$  for  $p_T > 10 \text{ GeV}/c$ , which are the same regions as used in the PbPb analysis [52]. Muons from B decays at midrapidity have a reduced detector acceptance at low  $p_T$ , therefore fiducial regions have been chosen in a  $p_T$ -dependent way.

Several samples of Monte Carlo (MC) simulated events are used to evaluate background components, signal efficiencies, and detector acceptance corrections. The simulations include signal samples containing only the B meson decay channels being measured and background samples of other b hadron decay chains also involving  $J/\psi$  mesons. These signal and background simulated samples in pp collisions are generated with PYTHIA8 v230 [65], with underlying event tunes CP5 [66] (signal) and CUETP8M1 [67] (background), respectively. The resulting particles are propagated through a model of the CMS detector using the GEANT4 package [68]. The decay of the B mesons is modeled with EVTGEN 1.6.0 [69], and the final-state photon radiation is simulated with PHOTOS 2.0 [70]. Pileup interactions (the number of concurrent interactions in the same bunch crossing) are also simulated according to a mean pileup of 3.5 in the data set.

The final B candidate selection is determined via multivariate discriminators based on a boosted decision tree (BDT) [71]. The same discriminating variables are employed as in the PbPb data analysis. These include the  $\chi^2$  probability of the decay vertex (the probability for the muon tracks from the  $J/\psi$  meson decay and the other charged-hadron track(s) to originate from a common vertex), the distance from the primary to the B decay vertices (normalized by its uncertainty), the pointing angle (the angle between the line segment connecting the primary and decay vertices and the momentum vector of the B meson), the  $p_T$  of the daughter charged-hadron track(s), and the transverse and longitudinal track distances of closest approach to the primary vertex, normalized by their uncertainties. For the  $B_s^0$  meson, an additional selection variable is used: the absolute difference between the reconstructed  $\phi(1020)$  meson invariant mass and its nominal value. The BDT training is performed by employing the MC-simulated B signal samples, and background samples taken from data sidebands constructed using candidates with the invariant mass away from the B meson nominal mass,  $0.25 < |m_{B^+} - m_{B^+}^{\text{PDG}}| < 0.30 \text{ GeV}/c^2$  and  $0.20 < |m_{B_s^0} - m_{B_s^0}^{\text{PDG}}| < 0.30 \text{ GeV}/c^2$ , where  $m_{B^+}^{\text{PDG}} = 5279.32 (\pm 0.14) \text{ MeV}/c^2$

and  $m_{B_s^0}^{\text{PDG}} = 5366.89 (\pm 0.19) \text{ MeV}/c^2$  are the world-average masses given by the Particle Data Group (PDG) [64]. The signal samples are scaled to the expected number of B candidates calculated by the measured integrated luminosity and cross sections predicted by FONLL perturbative QCD calculations [33]. The BDT selection is individually optimized for each meson and  $p_T$  range to maximize the figure of merit  $S/\sqrt{S+B}$ . Here,  $S$  and  $B$  are the number of signal and background candidates, respectively, in the signal region after applying the selection criteria. The signal region is defined as  $|m_B - m_B^{\text{PDG}}| < 0.08 \text{ GeV}/c^2$ .

### 3.2 Differential cross sections

The raw B meson signal yields are extracted from data using an extended unbinned maximum likelihood fit to the invariant mass spectra, following the same procedure and fit functions as for the PbPb analysis [52]. The signal shape is modeled by a sum of two Gaussian functions, with parameters determined from the MC simulation, except for the common mean and the overall signal yield, which are free parameters of the fit. The fit also includes an additional free scaling parameter to account for a potential resolution difference between data and simulation. The combinatorial background, from uncorrelated combinations of  $J/\psi$  candidates with other particles, gives rise to a falling contribution in the invariant mass spectrum that is modeled by an exponential function.

Additional background sources can arise from possible contamination from other B hadron decays,  $B \rightarrow J/\psi X$ . The Cabibbo-suppressed decay  $B^+ \rightarrow J/\psi \pi^+$ , where the pion is incorrectly assigned the kaon mass, results in a small peaking structure in the signal region. It is modeled by the sum of two split normal distribution functions, with both the shape and the normalization (relative to the signal) being fixed in the fit to the data. Partially reconstructed decays lead to an accumulation of events in the low mass sideband that is also modeled from simulation and described by an error function. For the  $B_s^0$  meson, such misreconstructed and partially reconstructed background contributions are found to be negligible. Examples of the signal extraction from  $B^+$  and  $B_s^0$  invariant-mass distributions, corresponding to the lowest and highest  $p_T$  ranges, are shown in Fig. 1.

The differential cross section for B meson production in pp collisions is calculated in each  $p_T$  interval according to

$$\frac{d\sigma_{\text{pp}}}{dp_T} = \frac{1}{2} \frac{N_{\text{obs}}(p_T)}{\mathcal{B} \mathcal{L}} \frac{1}{\Delta p_T} \left\langle \frac{1}{\alpha(p_T, y) \epsilon(p_T, y)} \right\rangle, \quad (2)$$

where  $N_{\text{obs}}$  is the raw signal yield extracted in each  $p_T$  interval of width  $\Delta p_T$ ,  $\mathcal{B}$  is the branching fraction of the corresponding decay chain obtained from Ref. [64], and  $\mathcal{L}$  is the integrated luminosity. The factor  $\frac{1}{2}$  is to quote the production cross sections for particles, whereas the raw yields include both particles and antiparticles. The acceptance and efficiency factor,  $\langle 1/(\alpha(p_T, y)\epsilon(p_T, y)) \rangle$ , is obtained employing two-dimensional (2D), fine-grained maps of acceptance  $\alpha(p_T, y)$  and efficiency  $\epsilon(p_T, y)$ . The acceptance corresponds to the fraction of generated signal events passing the muon and kaon selection thresholds. The efficiency is determined as the fraction of accepted signal events that pass the complete analysis selection criteria, including losses resulting from inefficiencies in the event trigger. These maps are determined from MC-simulated samples of B meson signal events generated within the fiducial region in the analysis. The maps are used to determine the  $1/(\alpha\epsilon)$  value for each B candidate in data, based on the kinematics  $(p_T, y)$  of the candidates. The corresponding average  $\langle 1/(\alpha\epsilon) \rangle$  was obtained for the candidates within a  $\pm 80 \text{ MeV}/c^2$  window centered on the B meson's world-average mass. Combinatorial background can influence the 2D map-based correction factor and its impact is studied and included as a systematic uncertainty. The efficiency maps derived

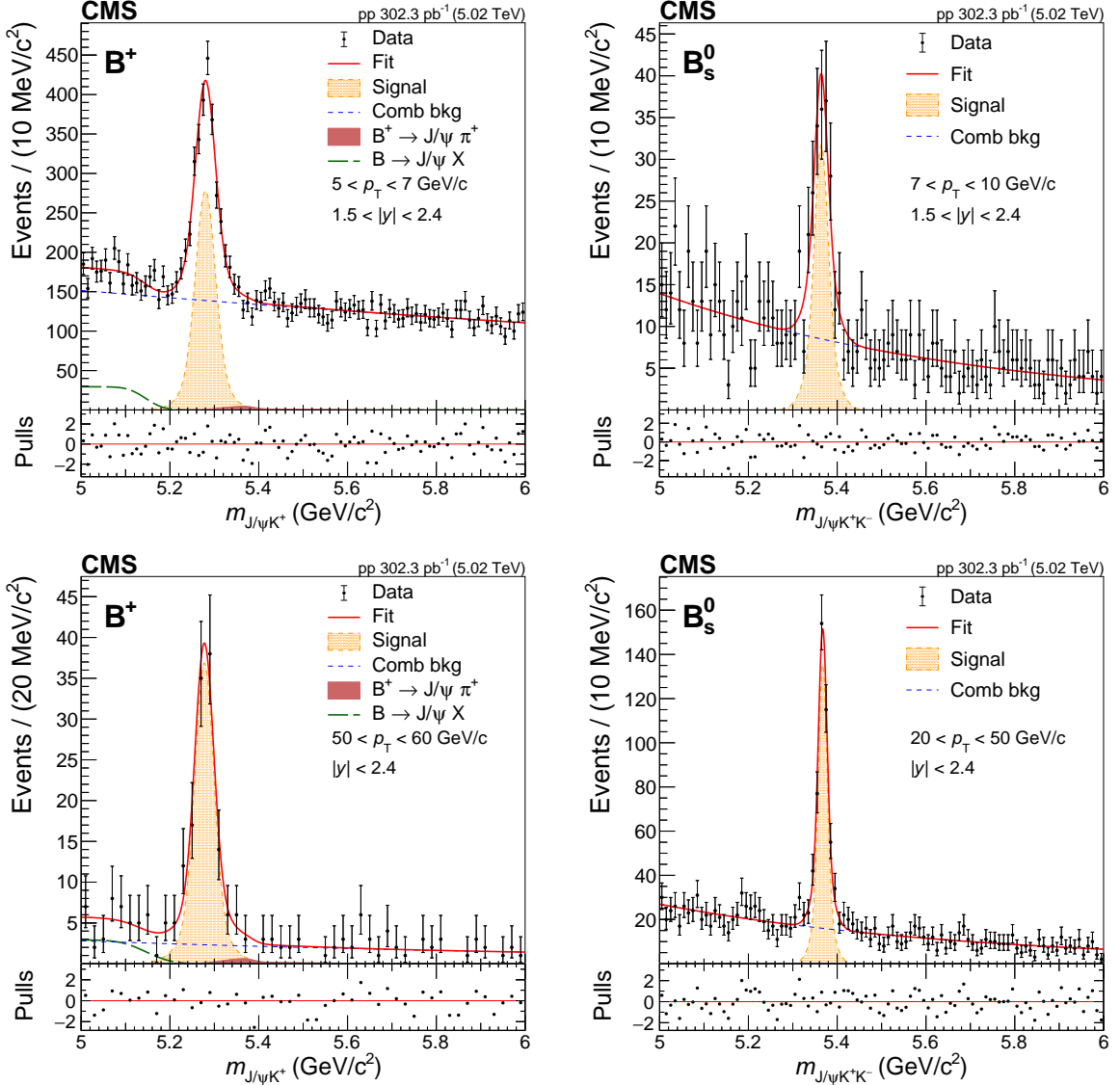


Figure 1: Invariant mass distributions of  $B^+$  (left) and  $B_s^0$  (right) candidates, for the lowest (upper) and highest (lower)  $p_T$  ranges in pp collisions at  $\sqrt{s} = 5.02$  TeV. The bottom section in each panel shows the pulls, calculated as the difference between the data points and the fit results, divided by the uncertainty in data.

from the simulation are corrected by data-to-simulation scale factors for the muon reconstruction and trigger efficiencies, obtained by applying the “tag-and-probe” method [72] using the  $J/\psi$  resonance.

## 4 Systematic uncertainties

The measured  $B^+$  and  $B_s^0$  cross sections in pp collisions are affected by several systematic uncertainties arising from the signal extraction, the efficiency and acceptance corrections, the associated branching fractions, and the integrated luminosity measurement.

The uncertainty in the raw yield extraction is evaluated by considering the following fitting model variations : (i) using a sum of three Gaussian functions with a common mean, (ii) using

a sum of a Gaussian function and a Crystal Ball function [73], (iii) fixing the double-Gaussian mean to its MC simulation value for the signal modeling instead of letting it be a free parameter, (iv) using low-order polynomials for describing the combinatorial background, and (v) changing the fitting range from 5–6 GeV/ $c^2$  to 5.19–6 GeV/ $c^2$  to minimize the  $B^+ \rightarrow J/\psi X$  component in the background modeling. For each  $p_T$  interval, we take the maximum of the percent difference between the varied and the nominal yield among (i)–(iii) as the signal uncertainty and (iv)–(v) as the background uncertainty. The signal and background uncertainties are added in quadrature as the systematic uncertainty in raw yield extraction.

The efficiency and acceptance determinations are affected by potential disagreements between data and simulation for the B meson selection efficiency, the track reconstruction efficiency, and the efficiency of the muon trigger, reconstruction, and identification. The systematic uncertainties associated with these effects are estimated as done for the PbPb analysis results [52]. To account for the potential discrepancy between data and simulation, the signal MC simulation is validated by inspecting the distributions of the discriminating variables listed in Section 3.1. For each  $p_T$  range, the signal distributions are extracted from the data employing the  $sPlot$  method [74], using the mass of the B meson candidates as a discriminating variable, and are also cross-checked with a simple sideband subtraction method. In particular, the  $sPlot$ -derived signal distributions for the BDT score are retrieved from the data, and the corresponding data-to-simulation ratios computed. These ratios are, in turn, used to re-weight the MC simulation, and the resulting deviation in the  $\langle 1/(\alpha \epsilon) \rangle$  factors are assigned as systematic uncertainties.

The systematic uncertainty associated with the combinatorial background and its influence on the 2D-map-based correction factor is studied by varying the B meson candidate mass window range by a factor of two. The resulting change in the correction factor is quoted as a systematic uncertainty, which varies from 0.2%–2.8% for  $B^+$  and from 0.3%–2.3% for  $B_s^0$  mesons. The MC simulation is weighted by the FONLL-to-PYTHIA ratios of  $p_T$  distributions, and the difference in the  $\langle 1/(\alpha \epsilon) \rangle$  factors are assigned as systematic uncertainties to estimate the potential impact of the assumed B meson  $p_T$  shape in MC. The uncertainty arising from the  $p_T$  shape is negligible. The uncertainty in the efficiency of the muon trigger, reconstruction, and identification is evaluated using the tag-and-probe method [72]. The systematic uncertainty in the muon efficiency has an insignificant effect on both the  $B^+$  and  $B_s^0$  meson results. The derived data-to-MC scale factors are employed to determine the nominal  $(\alpha \epsilon)$  2D maps, while the difference in the  $\langle 1/(\alpha \epsilon) \rangle$  factors between the scaled and original values are taken as the systematic uncertainty. The difference in the track reconstruction efficiency in data and simulation is estimated by comparing 3-prong and 5-prong  $D^*$  decays,  $D^* \rightarrow D^0(K\pi)\pi$  and  $D^* \rightarrow D^0(K\pi\pi\pi)\pi$  [75]. This difference results in a 2.4% uncertainty in the efficiency determination for each hadronic track, independent of  $p_T$ . We consider this uncertainty to be uncorrelated between tracks. In addition, the selections on track quality are tightened and loosened. These selections include the relative  $p_T$  uncertainty, the normalized  $\chi^2$  by the number of degrees of freedom, and the sum of the numbers of pixel and strip layer hits. The maximum resulting deviation of cross sections from the nominal values is quoted as a systematic uncertainty. The uncertainties associated with the branching fraction  $\mathcal{B}$  of the decay chains are obtained from Ref. [64].

The total systematic uncertainties in the cross sections are computed as the sum in quadrature of the different contributions mentioned above, which are summarized in Table 1 for the  $B^+$  and  $B_s^0$  cross sections. The systematic uncertainties resulting from the fitting model variation, the discrepancy between the MC simulation and the experimental results for the discriminating variables, the background contamination of the efficiency, the muon efficiency, the track selection, and the integrated luminosity for pp and PbPb are taken as independent and added in quadrature as the systematic uncertainty in the nuclear modification factors. On the other



hand, for the  $R_{AA}$  calculations, the branching fractions are common to the pp and PbPb systems and, consequently, do not impact the results. The track reconstruction efficiencies used for the two systems also have common elements, resulting in partial cancellation of the corresponding uncertainties when calculating the  $R_{AA}$  values. The global uncertainties in  $R_{AA}$  consist of the uncertainties in  $T_{AA}$ , the number of minimum bias events, and the integrated luminosity in pp collisions.

Table 1: Summary of systematic uncertainties (in %) for the  $B^+$  (upper table) and  $B_s^0$  (lower one) meson cross section as a function of  $p_T$ . The systematic uncertainties in luminosity and branching fractions are global uncertainties that are applied equally to all  $p_T$  ranges.

Source	$B^+$ $p_T$ (GeV/c)							
	5–7	7–10	10–15	15–20	20–30	30–50	50–60	20–50
Fitting model variation	2.1	1.4	3.2	1.1	0.69	1.8	2.4	0.57
Data-to-simulation discrepancy	4.7	7.2	7.2	0.98	0.87	0.92	0.83	0.84
Bkg. contamination: efficiency	1.5	2.8	0.84	0.41	0.46	0.18	1.1	0.41
Muon efficiency	0.47	0.45	0.37	0.36	0.43	0.64	0.64	0.47
Hadron tracking efficiency	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Track selection	1.8	0.31	0.43	0.37	0.27	0.052	1.6	0.24
Sum	6.2	8.3	8.3	2.9	2.7	3.2	4.1	2.7
Integrated luminosity				1.9				
Branching fractions				2.9				
Sum (global systematic unc.)				3.5				

Source	$B_s^0$ $p_T$ (GeV/c)			
	7–10	10–15	15–20	20–50
Fitting model variation	3.6	2.0	2.9	3.2
Data-to-simulation discrepancy	3.7	1.9	1.7	1.5
Bkg. contamination: efficiency	1.1	2.3	0.28	0.38
Muon efficiency	0.46	0.38	0.35	0.45
Hadron tracking efficiency	4.8	4.8	4.8	4.8
Track selection	0.65	0.2	2.7	0.78
Sum	7.2	6.0	6.5	6.0
Integrated luminosity				1.9
Branching fractions				7.5
Sum (global systematic unc.)				7.7

## 5 Results

The  $p_T$ -differential production cross sections of  $B^+$  and  $B_s^0$  mesons are presented in Fig. 2. The results are compared to the cross sections obtained from FONLL calculations [33], which are obtained by scaling the FONLL total b quark production [31–33] by the world-average production fractions of  $B^+$  ( $B_s^0$ ) of 40.2 (10.5)% [64]. The calculated FONLL reference spectra are consistent with the pp spectra measured for both the  $B^+$  and  $B_s^0$  mesons within the quoted uncertainties. With smaller experimental uncertainties, these measurements are useful for constraining the b-quark fragmentation functions.

The nuclear modification factors of  $B^+$  and  $B_s^0$ , determined according to Eq. (1), are shown in Fig. 3 as a functions of  $p_T$ . For the  $B^+$  meson a strong suppression is observed in PbPb collisions (with  $R_{AA}$  values significantly below unity). In the range  $7 < p_T < 50$  GeV/c,  $R_{AA}$

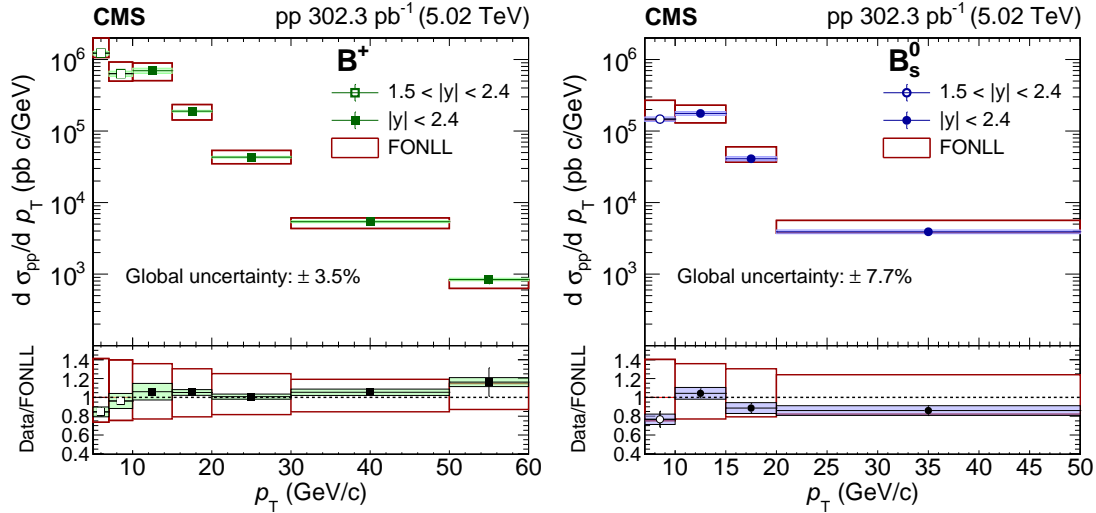


Figure 2: The  $p_T$ -differential cross sections of  $B^+$  (left) and  $B_s^0$  (right) mesons in pp collisions at  $\sqrt{s} = 5.02$  TeV. The vertical bars (shaded boxes) correspond to statistical (systematic) uncertainties. The horizontal bars reflect the bin widths. The global systematic uncertainty includes uncertainties in the integrated luminosity and the external branching fractions. The comparison with the calculation from FONLL (open boxes) is also shown. The lower panels show that the measured cross sections deviate from the FONLL calculations by less than 20%, and the two are consistent within uncertainty.

varies from 0.3 to 0.6. For the  $B_s^0$  meson, the central value is found to be larger than 1 (i.e., a production enhancement) in the range  $7 < p_T < 10 \text{ GeV/c}$ , although the large uncertainty suggests that it is also consistent with the  $R_{AA}$  values at higher  $p_T$ . In the range  $10 < p_T < 50 \text{ GeV/c}$  the  $R_{AA}$  values are also smaller than unity, but larger than those found for the  $B^+$  meson. This observation, together with the trend of  $B_s^0$  production enhancement observed over higher  $p_T$  ranges, suggests that recombination may play an important role in the production of  $B_s^0$  mesons, especially at low  $p_T$ , although reduced uncertainties for the PbPb results are needed to establish this effect.

The  $p_T$  dependence of the  $B^+$   $R_{AA}$  values are compared to the predictions of three types of models: (a) two perturbative QCD-based models that include both collisional and radiative energy loss (DREENA-A [77, 78] and CUJET3.0 [79–81]); (b) a transport model based on a Langevin equation featuring collisional energy loss and heavy quark diffusion in the medium (TAMU [24, 76]), with the spatial diffusion coefficient  $D_s$  characterizing the long-wavelength limit of heavy-flavor transport [6], and (c) a model based on the anti-de-Sitter/conformal field theory correspondence, that includes thermal fluctuations in the energy loss for heavy quarks in a strongly coupled plasma (AdS/CFT HH) [82, 83]. The AdS/CFT HH calculation is provided for two settings of the diffusion coefficient  $D$  of the heavy-quark propagation through the medium, either dependent on or independent of the quark momentum. Apart from the interactions between heavy quarks and the medium, the set of the (nuclear) parton distribution functions used for the initial heavy-quark  $p_T$  distributions are also different between these models. Furthermore, the difference includes the modeling of the PbPb medium (hydrodynamically [24, 79] or via a Glauber model [77, 78]) and the energy loss sources (partonic only [24, 79] or also hadronic [24]).

The TAMU model, which does not include radiative energy loss, overpredicts the observed  $B^+$   $R_{AA}$  values over the available  $p_T > 10 \text{ GeV/c}$  range, where the radiative energy loss is expected to play a more significant role. The perturbative QCD-based models CUJET3.0 and DREENA-A

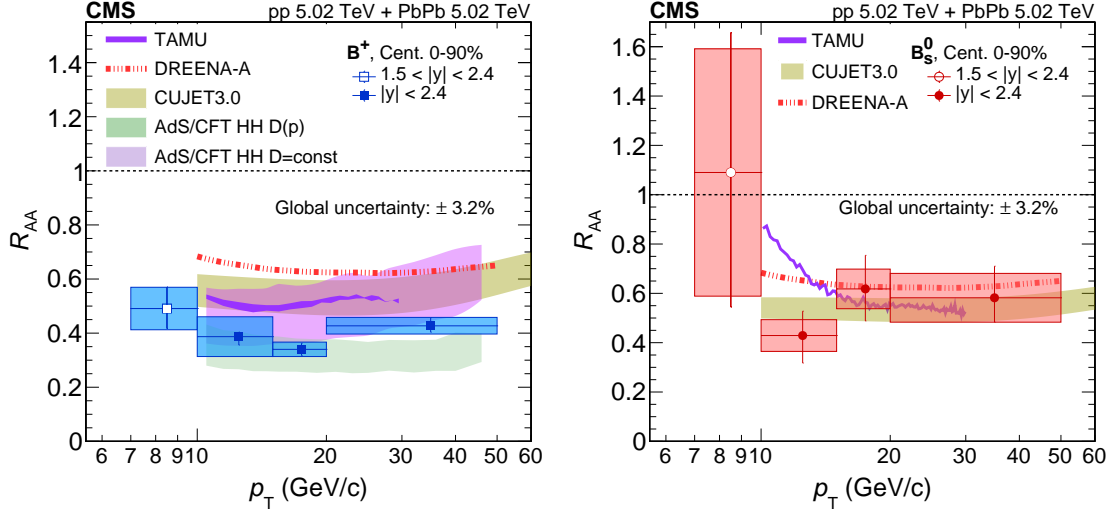


Figure 3: The  $p_T$  dependence of the nuclear modification factor of  $B^+$  (left) and  $B_s^0$  (right) mesons using PbPb and pp collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The horizontal bars reflect the bin widths and not uncertainties. The global systematic uncertainty includes the uncertainties in the integrated luminosity,  $T_{AA}$ , and the number of minimum bias events [52]. For the  $B^+$  meson, four theoretical calculations are also shown for comparison: TAMU [24, 76], DREENA-A [77, 78], CUJET3.0 [79–81], and AdS/CFT HH [82, 83] with the diffusion coefficient either dependent or independent of the quark momentum. For the  $B_s^0$  meson, three theoretical calculations are shown for comparison: TAMU [24, 76], DREENA-A [77, 78], and CUJET3.0 [79–81]. The line width of the theoretical calculation from Refs. [24, 76] indicates the uncertainty in the total b quark coalescence probability (no shadowing is applied). The rapidity range is  $|y| < 2.4$  for all the theoretical predictions and, therefore, these predictions can only be compared to the measurements in the range of  $p_T > 10$  GeV/c.

both predict slightly weaker suppression than TAMU, despite the inclusion of radiative energy loss, with DREENA-A predicting the least suppression in the  $10 < p_T < 15$  GeV/c range. The AdS/CFT HH calculation with the diffusion coefficient dependent on the quark momentum has the broadest agreement with the data, although it slightly underestimates the  $R_{AA}$  value in the highest  $p_T$  range. The  $R_{AA}$  values are compatible with the lower-end values predicted by AdS/CFT HH calculation with the diffusion coefficient independent of the quark momentum. The experimental  $R_{AA}$  value for the highest  $p_T$  range falls between the two AdS/CFT HH model predictions.

Given that the experimental uncertainties are smaller than the uncertainties of the theoretical calculations from CUJET3.0 and AdS/CFT HH, the current results could be used to optimize parameter settings in such models (e.g., the parton-medium coupling parameters in the AdS/CFT HH model) and constrain the relevance of collisional and radiative processes in the b quark energy loss [84, 85]. The  $B_s^0$   $R_{AA}$  result is compared to DREENA-A, TAMU, and CUJET3.0. The difference between TAMU and CUJET3.0 below  $p_T = 15$  GeV/c reflects the contribution from recombination processes, which are included in the TAMU model, but are not present in the CUJET3.0 model. Given the current statistical and systematic uncertainties, these three theoretical predictions are roughly compatible with the measurement.

The  $B^+$  and  $B_s^0$   $R_{AA}$  are compared in Fig. 4 to the CMS measurements of the  $R_{AA}$  of  $B_c$  mesons [27],  $D^0$  mesons [86], and charged particles [60] performed at the same energy and in either the same

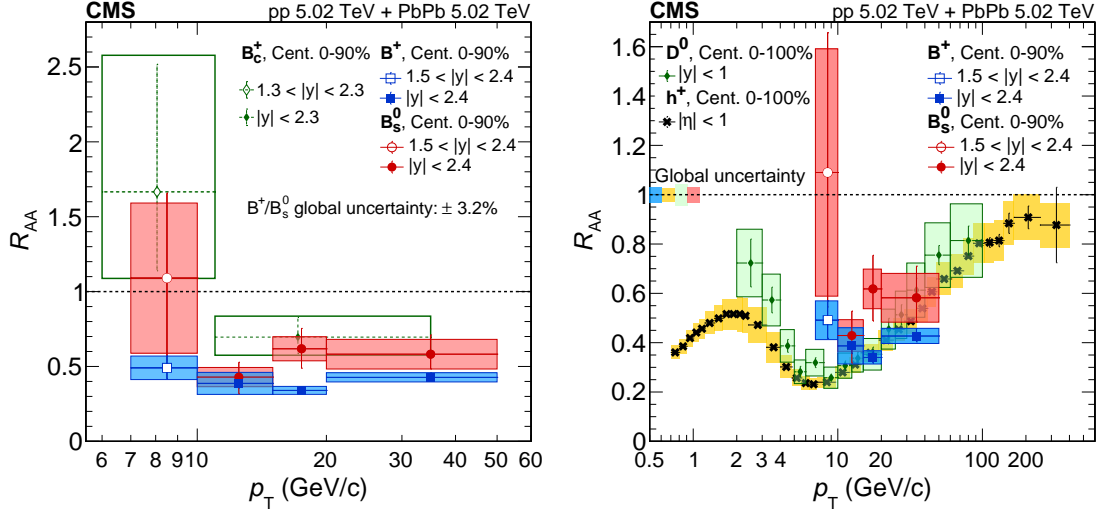


Figure 4: Comparison of the nuclear modification factor as a function of  $p_T$  of  $B^+$  and  $B_s^0$  mesons with  $B_c$  mesons [27] (left) as well as with  $D^0$  mesons [86] and inclusive charged hadrons [60] (right) in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The horizontal bars reflect the bin widths. The global systematic uncertainties, written in text on the left plot and depicted in shaded boxes around  $R_{AA} = 1$  on the right plot, comprise the uncertainties in  $T_{AA}$ , the number of minimum-bias events, and the luminosity in pp collisions. The dashed lines and the open boxes in the  $B_c$  data (left plot) represent bin-to-bin-uncorrelated and total uncertainties, respectively.

(0–90%) or a similar (0–100%) centrality range. For the heavy  $B_c$  mesons, the rapidity is similarly limited to the forward region at low  $p_T$ , and for the lighter charged particles and  $D^0$  mesons the measurement is performed at mid-rapidity. The  $R_{AA}$  value for  $B_c$  mesons in the  $7 < p_T < 50$  GeV/c range is higher than that for  $B^+$  mesons, with  $B_s^0$  values falling in between. For  $B^+$  mesons, the  $R_{AA}$  values are consistent with those of charged particles and  $D^0$  mesons for  $p_T > 10$  GeV/c. At lower  $p_T$ , a reduced level of suppression is observed, which is in line with expectations based on the quark mass dependence of parton energy loss [7, 87].

## 6 Summary

In summary, the differential cross sections of  $B^+$  and  $B_s^0$  mesons as functions of transverse momentum ( $p_T$ ) in proton-proton (pp) collisions at a center-of-mass energy of 5.02 TeV have been measured with the CMS detector at the LHC. The mesons were reconstructed via the exclusive decay channels  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$  and  $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(1020)(K^+K^-)$  in the  $p_T$  intervals of 5–60 and 7–50 GeV/c for  $B^+$  and  $B_s^0$ , respectively. The measured  $p_T$ -differential cross sections of  $B^+$  and  $B_s^0$  mesons in pp collisions are well-described by fixed-order plus next-to-leading logarithm calculations.

The nuclear modification factors ( $R_{AA}$ ) are obtained from these differential cross sections and the corresponding measurements in lead-lead collisions. The  $R_{AA}$  of  $B_s^0$  and  $B^+$  mesons are significantly lower than unity for  $p_T > 10$  GeV/c, while at lower  $p_T$  the  $B_s^0$  meson results hint at having larger  $R_{AA}$  values than found for  $B^+$  mesons. The  $R_{AA}$  data for  $B^+$  and  $B_s^0$  mesons are compared to theoretical calculations, providing constraints for the mechanisms of bottom quark energy loss and hadronization in the quark-gluon plasma. The results are also compared to experimental  $R_{AA}$  values for charm and light-flavor hadrons. The  $B^+$  meson  $R_{AA}$  values are compatible with those found for generic charged hadrons and  $D^0$  mesons in the  $p_T$  range from

10 to 30 GeV/c, while the  $R_{AA}$  values from 7 to 10 GeV/c are consistent with expectations based on the quark mass dependence of parton energy loss.

## Acknowledgments

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 centers and personnel of the Worldwide LHC Computing Grid and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and

the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

## References

- [1] F. Karsch and E. Laermann, “Thermodynamics and in-medium hadron properties from lattice QCD”, in *Quark-Gluon Plasma III*, R. Hwa (ed.). 2003. arXiv:hep-lat/0305025.
- [2] É. V. Shuryak, “Theory of hadronic plasma”, *Sov. Phys. JETP* **47** (1978) 212.
- [3] J. C. Collins and M. J. Perry, “Superdense matter: neutrons or asymptotically free quarks?”, *Phys. Rev. Lett.* **34** (1975) 1353, doi:10.1103/PhysRevLett.34.1353.
- [4] W. Busza, K. Rajagopal, and W. van der Schee, “Heavy ion collisions: the big picture, and the big questions”, *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 339, doi:10.1146/annurev-nucl-101917-020852, arXiv:1802.04801.
- [5] A. Andronic et al., “Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions”, *Eur. Phys. J. C* **76** (2016) 107, doi:10.1140/epjc/s10052-015-3819-5, arXiv:1506.03981.
- [6] X. Dong, Y.-J. Lee, and R. Rapp, “Open heavy-flavor production in heavy-ion collisions”, *Ann. Rev. Nucl. Part. Sci.* **69** (2019) 417, doi:10.1146/annurev-nucl-101918-023806, arXiv:1903.07709.
- [7] L. Apolinário, Y.-J. Lee, and M. Winn, “Heavy quarks and jets as probes of the QGP”, *Prog. Part. Nucl. Phys.* **127** (2022) 103990, doi:10.1016/j.pnpnp.2022.103990, arXiv:2203.16352.
- [8] J. D. Bjorken, “Energy loss of energetic partons in quark-gluon plasma: possible extinction of high  $p_T$  jets in hadron-hadron collisions”, Fermilab pub, 1982.
- [9] R. Baier, D. Schiff, and B. G. Zakharov, “Energy loss in perturbative QCD”, *Ann. Rev. Nucl. Part. Sci.* **50** (2000) 37, doi:10.1146/annurev.nucl.50.1.37, arXiv:hep-ph/0002198.
- [10] CMS Collaboration, “Observation and studies of jet quenching in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV”, *Phys. Rev. C* **84** (2011) 024906, doi:10.1103/PhysRevC.84.024906, arXiv:1102.1957.
- [11] ATLAS Collaboration, “Observation of a centrality-dependent dijet asymmetry in lead-lead collisions at  $\sqrt{s_{NN}} = 2.76$  TeV with the ATLAS detector at the LHC”, *Phys. Rev. Lett.* **105** (2010) 252303, doi:10.1103/PhysRevLett.105.252303, arXiv:1011.6182.
- [12] A. Beraudo et al., “Extraction of heavy-flavor transport coefficients in QCD matter”, *Nucl. Phys. A* **979** (2018) 21, doi:10.1016/j.nuclphysa.2018.09.002, arXiv:1803.03824.

- [13] ALICE Collaboration, “ $K_S^0$  and  $\Lambda$  production in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV”, *Phys. Rev. Lett.* **111** (2013) 222301, doi:10.1103/PhysRevLett.111.222301, arXiv:1307.5530.
- [14] STAR Collaboration, “Strangeness enhancement in Cu+Cu and Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV”, *Phys. Rev. Lett.* **108** (2012) 072301, doi:10.1103/PhysRevLett.108.072301, arXiv:1107.2955.
- [15] STAR Collaboration, “Energy and system size dependence of  $\phi$  meson production in Cu+Cu and Au+Au collisions”, *Phys. Lett. B* **673** (2009) 183, doi:10.1016/j.physletb.2009.02.037, arXiv:0810.4979.
- [16] BRAHMS Collaboration, “Kaon and pion production in central Au+Au collisions at  $\sqrt{s_{NN}} = 62.4$  GeV”, *Phys. Lett. B* **687** (2010) 36, doi:10.1016/j.physletb.2010.02.078, arXiv:0911.2586.
- [17] STAR Collaboration, “Collision energy dependence of moments of net-kaon multiplicity distributions at RHIC”, *Phys. Lett. B* **785** (2018) 551, doi:10.1016/j.physletb.2018.07.066, arXiv:1709.00773.
- [18] PHENIX Collaboration, “ $\phi$  meson production in the forward/backward rapidity region in Cu+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV”, *Phys. Rev. C* **93** (2016) 024904, doi:10.1103/PhysRevC.93.024904, arXiv:1509.06337.
- [19] ALICE Collaboration, “Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions”, *Nature Phys.* **13** (2017) 535, doi:10.1038/nphys4111, arXiv:1606.07424.
- [20] J. Rafelski and B. Müller, “Strangeness production in the quark-gluon plasma”, *Phys. Rev. Lett.* **48** (1982) 1066, doi:10.1103/PhysRevLett.48.1066, arXiv:nucl-th/0312100v2.
- [21] D. Molnar and S. A. Voloshin, “Elliptic flow at large transverse momenta from quark coalescence”, *Phys. Rev. Lett.* **91** (2003) 092301, doi:10.1103/PhysRevLett.91.092301, arXiv:nucl-th/0302014.
- [22] V. Greco, C. M. Ko, and P. Levai, “Parton coalescence at RHIC”, *Phys. Rev. C* **68** (2003) 034904, doi:10.1103/PhysRevC.68.034904, arXiv:nucl-th/0305024.
- [23] V. Greco, C. M. Ko, and R. Rapp, “Quark coalescence for charmed mesons in ultrarelativistic heavy ion collisions”, *Phys. Lett. B* **595** (2004) 202, doi:10.1016/j.physletb.2004.06.064, arXiv:nucl-th/0312100.
- [24] M. He, R. J. Fries, and R. Rapp, “Heavy flavor at the large hadron collider in a strong coupling approach”, *Phys. Lett. B* **735** (2014) 445, doi:10.1016/j.physletb.2014.05.050, arXiv:1401.3817.
- [25] ALICE Collaboration, “Measurement of  $D^0$ ,  $D^+$ ,  $D^{*+}$  and  $D_s^+$  production in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *JHEP* **10** (2018) 174, doi:10.1007/JHEP10(2018)174, arXiv:1804.09083.
- [26] CMS Collaboration, “Measurement of  $B_s^0$  meson production in pp and PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Lett. B* **796** (2019) 168, doi:10.1016/j.physletb.2019.07.014, arXiv:1810.03022.

- 
- [27] CMS Collaboration, “Observation of the  $B_c$  meson in PbPb and pp collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and measurement of its nuclear modification factor”, *Phys. Rev. Lett.* **128** (2022) 252301, doi:10.1103/PhysRevLett.128.252301, arXiv:2201.02659.
- [28] CMS Collaboration, “Evidence for  $X(3872)$  in PbPb collisions and studies of its prompt production at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Rev. Lett.* **128** (2022) 032001, doi:10.1103/PhysRevLett.128.032001, arXiv:2102.13048.
- [29] CMS Collaboration, “Overview of high-density QCD studies with the CMS experiment at the LHC”, **5**, 2024. arXiv:2405.10785.
- [30] CMS Collaboration, “Luminosity measurement in proton-proton collisions at 5.02 TeV in 2017 at CMS”, CMS Physics Analysis Summary CMS-PAS-LUM-19-001, 2021.
- [31] M. Cacciari, M. Greco, and P. Nason, “The  $p_T$  spectrum in heavy-flavour hadroproduction”, *JHEP* **05** (1998) 007, doi:10.1088/1126-6708/1998/05/007, arXiv:hep-ph/9803400.
- [32] M. Cacciari and P. Nason, “Charm cross sections for the Tevatron Run II”, *JHEP* **09** (2003) 006, doi:10.1088/1126-6708/2003/09/006, arXiv:hep-ph/0306212.
- [33] M. Cacciari et al., “Theoretical predictions for charm and bottom production at the LHC”, *JHEP* **10** (2012) 137, doi:10.1007/JHEP10(2012)137, arXiv:1205.6344.
- [34] CMS Collaboration, “Measurement of the  $B^\pm$  meson nuclear modification factor in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Rev. Lett.* **119** (2017) 152301, doi:10.1103/PhysRevLett.119.152301, arXiv:1705.04727.
- [35] CMS Collaboration, “Measurement of the  $B^+$  production cross section in pp collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Rev. Lett.* **106** (2011) 112001, doi:10.1103/PhysRevLett.106.112001, arXiv:1101.0131.
- [36] CMS Collaboration, “Measurement of the  $B_s^0$  production cross section in pp collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Rev. Lett.* **106** (2011) 252001, doi:10.1103/PhysRevLett.106.252001, arXiv:1104.2892.
- [37] CMS Collaboration, “Measurement of the  $B_s^0$  production cross section with  $B_s^0 \rightarrow J/\psi\phi$  decays in pp collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Rev. D* **84** (2011) 052008, doi:10.1103/PhysRevD.84.052008, arXiv:1106.4048.
- [38] ATLAS Collaboration, “Measurement of the differential cross-section of  $B^+$  meson production in pp collisions at  $\sqrt{s} = 7$  TeV at ATLAS”, *JHEP* **10** (2013) 042, doi:10.1007/JHEP10(2013)042, arXiv:1307.0126.
- [39] LHCb Collaboration, “Measurement of the  $B^\pm$  production cross-section in pp collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **04** (2012) 093, doi:10.1007/JHEP04(2012)093, arXiv:1202.4812.
- [40] LHCb Collaboration, “Measurement of B meson production cross-sections in proton-proton collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **08** (2013) 117, doi:10.1007/JHEP08(2013)117, arXiv:1306.3663.
- [41] LHCb Collaboration, “Measurement of  $b$ -hadron production fractions in 7 TeV pp collisions”, *Phys. Rev. D* **85** (2012) 032008, doi:10.1103/PhysRevD.85.032008, arXiv:1111.2357.



- [42] LHCb Collaboration, “Measurements of  $B_c^+$  production and mass with the  $B_c^+ \rightarrow J/\psi \pi^+$  decay”, *Phys. Rev. Lett.* **109** (2012) 232001, doi:10.1103/PhysRevLett.109.232001, arXiv:1209.5634.
- [43] CMS Collaboration, “Measurement of the ratio of the production cross sections times branching fractions of  $B_c^\pm \rightarrow J/\psi \pi^\pm$  and  $B^\pm \rightarrow J/\psi K^\pm$  and  $\mathcal{B}(B_c^\pm \rightarrow J/\psi \pi^\pm \pi^\pm \pi^\mp)/\mathcal{B}(B_c^\pm \rightarrow J/\psi \pi^\pm)$  in pp collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **01** (2015) 063, doi:10.1007/JHEP01(2015)063, arXiv:1410.5729.
- [44] LHCb Collaboration, “Study of the production of  $\Lambda_b^0$  and  $\bar{B}^0$  hadrons in pp collisions and first measurement of the  $\Lambda_b^0 \rightarrow J/\psi p K^-$  branching fraction”, *Chin. Phys. C* **40** (2016) 011001, doi:10.1088/1674-1137/40/1/011001, arXiv:1509.00292.
- [45] LHCb Collaboration, “Measurement of  $B_c^+$  production in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *Phys. Rev. Lett.* **114** (2015) 132001, doi:10.1103/PhysRevLett.114.132001, arXiv:1411.2943.
- [46] ATLAS Collaboration, “Measurement of the relative  $B_c^\pm/B^\pm$  production cross section with the ATLAS detector at  $\sqrt{s} = 8$  TeV”, *Phys. Rev. D* **104** (2021) 012010, doi:10.1103/PhysRevD.104.012010, arXiv:1912.02672.
- [47] CMS Collaboration, “Measurement of the total and differential inclusive  $B^+$  hadron cross sections in pp collisions at  $\sqrt{s} = 13$  TeV”, *Phys. Lett. B* **771** (2017) 435, doi:10.1016/j.physletb.2017.05.074, arXiv:1609.00873.
- [48] LHCb Collaboration, “Measurement of the  $B^\pm$  production cross-section in pp collisions at  $\sqrt{s} = 7$  and 13 TeV”, *JHEP* **12** (2017) 026, doi:10.1007/JHEP12(2017)026, arXiv:1710.04921.
- [49] LHCb Collaboration, “Measurement of the  $B_c^-$  meson production fraction and asymmetry in 7 and 13 TeV pp collisions”, *Phys. Rev. D* **100** (2019) 112006, doi:10.1103/PhysRevD.100.112006, arXiv:1910.13404.
- [50] CMS Collaboration, “Study of B meson production in pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV using exclusive hadronic decays”, *Phys. Rev. Lett.* **116** (2016) 032301, doi:10.1103/PhysRevLett.116.032301, arXiv:1508.06678.
- [51] LHCb Collaboration, “Measurement of  $B^+$ ,  $B_s^0$  and  $\Lambda_b^0$  production in pPb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV”, *Phys. Rev. D* **99** (2019) 052011, doi:10.1103/PhysRevD.99.052011, arXiv:1902.05599.
- [52] CMS Collaboration, “Observation of  $B_s^0$  mesons and measurement of the  $B_s^0/B^+$  yield ratio in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Lett. B* **829** (2022) 137062, doi:10.1016/j.physletb.2022.137062, arXiv:2109.01908.
- [53] “HEPData record for this analysis”, 2024. doi:10.17182/hepdata.152831.
- [54] Tracker Group of the CMS Collaboration, “The CMS phase-1 pixel detector upgrade”, *JINST* **16** (2021) P02027, doi:10.1088/1748-0221/16/02/P02027, arXiv:2012.14304.
- [55] CMS Collaboration, “Track impact parameter resolution for the full pseudorapidity coverage in the 2017 dataset with the CMS phase-1 pixel detector”, CMS Detector Performance Note CMS-DP-2020-049, 2020.

- 
- [56] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [57] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [58] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [59] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [60] CMS Collaboration, “Charged-particle nuclear modification factors in PbPb and pPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV”, *JHEP* **04** (2017) 039, doi:10.1007/JHEP04(2017)039, arXiv:1611.01664.
- [61] CMS Collaboration, “Study of jet quenching with isolated-photon+jet correlations in PbPb and pp collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV”, *Phys. Lett. B* **785** (2018) 14, doi:10.1016/j.physletb.2018.07.061, arXiv:1711.09738.
- [62] CMS Collaboration, “Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at  $\sqrt{s} = 0.9$  and 2.36 TeV”, *JHEP* **02** (2010) 041, doi:10.1007/JHEP02(2010)041, arXiv:1002.0621.
- [63] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV”, *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
- [64] Particle Data Group, “Review of Particle Physics”, *Prog. Theo. Expt. Phys.* **2022** (2022) doi:10.1093/ptep/ptac097.
- [65] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [66] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [67] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [68] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [69] D. J. Lange, “The EvtGen particle decay simulation package”, *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.
- [70] E. Barberio, B. van Eijk, and Z. Was, “PHOTOS: A universal Monte Carlo for QED radiative corrections in decays”, *Comput. Phys. Commun.* **66** (1991) 115, doi:10.1016/0010-4655(91)90012-A.

- [71] A. Hocker et al., “TMVA–Toolkit for Multivariate Data Analysis with ROOT: Users guide”, Technical Report CERN-OPEN-2007-007, 2007. arXiv:physics/0703039.
- [72] CMS Collaboration, “Upsilon production cross-section in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$ ”, *Phys. Rev. D* **83** (2011) 112004, doi:10.1103/PhysRevD.83.112004, arXiv:1012.5545.
- [73] M. J. Oreglia, “A Study of the Reactions  $\psi' \rightarrow \gamma\gamma\psi$ ”. PhD thesis, Stanford University, 1980. Appendix D.
- [74] M. Pivk and F. R. Le Diberder, “*sPlot*: a statistical tool to unfold data distributions”, *Nucl. Instrum. Meth. A* **555** (2005) 356, doi:10.1016/j.nima.2005.08.106, arXiv:physics/0402083.
- [75] CMS Collaboration, “Tracking POG results for pion efficiency with the  $D^*$  meson using data from 2016 and 2017”, CMS Detector Performance Note CMS-DP-2018-050, 2018.
- [76] M. He, R. J. Fries, and R. Rapp, “Heavy-quark diffusion and hadronization in quark-gluon plasma”, *Phys. Rev. C* **86** (2012) 014903, doi:10.1103/PhysRevC.86.014903, arXiv:1106.6006.
- [77] D. Zigic et al., “Importance of higher harmonics and  $v_4$  puzzle in quark-gluon plasma tomography”, *Phys. Rev. C* **106** (2022) 044909, doi:10.1103/PhysRevC.106.044909, arXiv:2208.09886.
- [78] D. Zigic et al., “DREENA–A framework as a QGP tomography tool”, *Front. Phys.* **10** (2022) 957019, doi:10.3389/fphy.2022.957019, arXiv:2110.01544.
- [79] J. Xu, J. Liao, and M. Gyulassy, “Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0”, *JHEP* **02** (2016) 169, doi:10.1007/JHEP02(2016)169, arXiv:1508.00552.
- [80] J. Xu, J. Liao, and M. Gyulassy, “Consistency of perfect fluidity and jet quenching in semi-quark-gluon monopole plasmas”, *Chin. Phys. Lett.* **32** (2015) 092501, doi:10.1088/0256-307X/32/9/092501, arXiv:1411.3673.
- [81] J. Xu, A. Buzzatti, and M. Gyulassy, “Azimuthal jet flavor tomography with CUJET2.0 of nuclear collisions at RHIC and LHC”, *JHEP* **08** (2014) 063, doi:10.1007/JHEP08(2014)063, arXiv:1402.2956.
- [82] W. A. Horowitz, “Fluctuating heavy quark energy loss in a strongly coupled quark-gluon plasma”, *Phys. Rev. D* **91** (2015) 085019, doi:10.1103/PhysRevD.91.085019, arXiv:1501.04693.
- [83] R. Hambrock and W. A. Horowitz, “AdS/CFT predictions for azimuthal and momentum correlations of  $b\bar{b}$  pairs in heavy ion collisions”, 2017. arXiv:1703.05845.
- [84] M. Rohmoser, P. B. Gossiaux, T. Gousset, and J. Aichelin, “Constraining in-medium heavy-quark energy-loss mechanisms via angular correlations between heavy and light mesons”, *J. Phys. Conf. Ser.* **779** (2017) 012032, doi:10.1088/1742-6596/779/1/012032, arXiv:1611.01854.
- [85] S. Cao, G.-Y. Qin, and S. A. Bass, “Heavy flavor dynamics in QGP and hadron gas”, *Nucl. Phys. A* **931** (2014) 569, doi:10.1016/j.nuclphysa.2014.09.011, arXiv:1408.0503v1.



















- [86] CMS Collaboration, "Nuclear modification factor of  $D^0$  mesons in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV", *Phys. Lett. B* **782** (2018) 474,  
doi:10.1016/j.physletb.2018.05.074, arXiv:1708.04962.
- [87] Y. L. Dokshitzer, V. A. Khoze, and S. I. Troian, "On specific QCD properties of heavy quark fragmentation ('dead cone')", *J. Phys. G* **17** (1991) 1602,  
doi:10.1088/0954-3899/17/10/023.

## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan<sup>1</sup> 













### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P.S. Hussain , M. Jeitler<sup>2</sup> , N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck<sup>2</sup> , R. Schöfbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz<sup>2</sup> 

















### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>3</sup> , T. Janssen , P. Van Mechelen 













### Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat<sup>4</sup> , G.P. Van Onsem , S. Van Putte , D. Vannerom 















### Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, G. De Lentdecker , H. Evard , L. Favart , P. Giannelos , J. Jaramillo , A. Khalilzadeh, F.A. Khan , K. Lee , M. Mahdavihorrani , A. Malara , S. Paredes , M.A. Shahzad, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 










### Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , Y. Hong , J. Knolle , L. Lambrecht , D. Marckx , K. Mota Amarilo , A. Samalan, K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 


















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

A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I.S. Donertas , A. Giammanco , A.O. Guzel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 










### Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , M. Alves Gallo Pereira , E. Coelho , G. Correia Silva , C. Hensel , T. Menezes De Oliveira , A. Moraes , P. Rebello Teles , M. Soeiro, A. Vilela Pereira<sup>5</sup> 

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

W.L. Aldá Júnior , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato<sup>6</sup>, E.M. Da Costa , G.G. Da Silveira<sup>7</sup> , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, M. Macedo , J. Martins<sup>8</sup> , C. Mora Herrera , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel 

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



C.A. Bernardes<sup>7</sup> , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , I. Maitto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 

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



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

### University of Sofia, Sofia, Bulgaria

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


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


**Beihang University, Beijing, China**  
T. Cheng , T. Javaid , L. Yuan 

**Department of Physics, Tsinghua University, Beijing, China**  
Z. Hu , Z. Liang, J. Liu, K. Yi<sup>9,10</sup> 

**Institute of High Energy Physics, Beijing, China**  
G.M. Chen<sup>11</sup> , H.S. Chen<sup>11</sup> , M. Chen<sup>11</sup> , F. Iemmi , C.H. Jiang, A. Kapoor<sup>12</sup> ,  
H. Liao , Z.-A. Liu<sup>13</sup> , R. Sharma<sup>14</sup> , J.N. Song<sup>13</sup>, J. Tao , C. Wang<sup>11</sup>, J. Wang , Z. Wang<sup>11</sup>,  
H. Zhang , J. Zhao 


**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**  
A. Agapitos , Y. Ban , S. Deng , B. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao,  
S. Qian, S.J. Qian , X. Qin, X. Sun , D. Wang , H. Yang, L. Zhang , Y. Zhao, C. Zhou 

**Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China**  
S. Yang 

**Sun Yat-Sen University, Guangzhou, China**  
Z. You 

**University of Science and Technology of China, Hefei, China**  
K. Jaffel , N. Lu 





**Nanjing Normal University, Nanjing, China**  
G. Bauer<sup>15</sup>, B. Li, J. Zhang 



**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**  
X. Gao<sup>16</sup> 

**Zhejiang University, Hangzhou, Zhejiang, China**  
Z. Lin , C. Lu , M. Xiao 

**Universidad de Los Andes, Bogota, Colombia**  
C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga , J.A. Reyes Vega

**Universidad de Antioquia, Medellin, Colombia**  
F. Ramirez , C. Rendón, M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez 

**University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**  
D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac 




**University of Split, Faculty of Science, Split, Croatia**  
M. Kovac , A. Petkovic, T. Sculac 

**Institute Rudjer Boskovic, Zagreb, Croatia**  
P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovic, S. Mishra ,  
A. Starodumov<sup>17</sup> , T. Susa 

**University of Cyprus, Nicosia, Cyprus**

A. Attikis , K. Christoforou , A. Hadjiagapiou, C. Leonidou , J. Mousa , C. Nicolaou, L. Paizanos, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

**Charles University, Prague, Czech Republic**

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

**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**

Y. Assran<sup>18,19</sup>, B. El-mahdy, S. Elgammal<sup>19</sup>

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

M.A. Mahmoud , Y. Mohammed 
















**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

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

**Department of Physics, University of Helsinki, Helsinki, Finland**

H. Kirschenmann , K. Osterberg , M. Voutilainen 



















**Helsinki Institute of Physics, Helsinki, Finland**

S. Bharthuar , N. Bin Norjoharuddeen , E. Brücken , F. Garcia , P. Inkaew , K.T.S. Kallonen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , J. Tuominiemi 



























**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

P. Luukka , H. Petrow 


















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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic , J. Malcles , F. Orlandi , L. Portales , A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro<sup>20</sup> , P. Simkina , M. Titov , M. Tornago 

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

F. Beaudette , P. Busson , A. Cappati , C. Charlot , M. Chiusi , F. Damas , O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , M. Nguyen , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , L. Urda Gómez , E. Vernazza , A. Zabi , A. Zghiche 






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













J.-L. Agram<sup>21</sup> , J. Andrea , D. Apparú , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet , G. Saha , M.A. Sessini , P. Van Hove , P. Vaucelle 

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

A. Di Florio 

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

D. Amram, S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo 

P. Depasse , C. Dozen<sup>22</sup> , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , E. Jourd'huy, I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao 





























### Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze<sup>17</sup> , I. Lomidze , Z. Tsamalaidze<sup>17</sup> 









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

V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , D. Pérez Adán , N. Röwert , M. Teroerde 






























































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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo<sup>23</sup> , S. Wiedenbeck , S. Zaleski



































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

C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 















### Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , S. Bhattacharya , F. Blekman<sup>24</sup> , K. Borrás<sup>25</sup> , A. Campbell , A. Cardini , C. Cheng, F. Colombina , S. Consuegra Rodríguez , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo<sup>24</sup> , A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka<sup>26</sup> , W. Lohmann<sup>27</sup> , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham<sup>28,25</sup> , S. Schnake<sup>25</sup> , P. Schütze , C. Schwanenberger<sup>24</sup> , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens<sup>25</sup> , C. Wissing , Y. Yang , A. Zimmermann Castro Santos 























### University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg, M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , C.c. Kuo, V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , B. Raciti , M. Rieger , D. Savoieu , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf 

### Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann<sup>29</sup> , R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link,








A. Lintuluoto , B. Maier , S. Maier , S. Mitra , M. Mornile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer , S. Wieland , F. Wittig, R. Wolf , X. Zuo 

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

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Papadopoulos<sup>29</sup>, A. Stakia 

**National and Kapodistrian University of Athens, Athens, Greece**

P. Kontaxakis , G. Melachroinos, Z. Painesis , I. Papavergou , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 






**National Technical University of Athens, Athens, Greece**

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos , E. Siamarkou, G. Tsiopolitis , A. Zacharopoulou

**University of Ioánnina, Ioánnina, Greece**

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

**HUN-REN Wigner Research Centre for Physics, Budapest, Hungary**

C. Hajdu , D. Horvath<sup>30,31</sup> , K. Márton, A.J. Rádl<sup>32</sup> , F. Sikler , V. Veszpremi 

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

M. Csanád , K. Farkas , A. Fehérkuti<sup>33</sup> , M.M.A. Gadallah<sup>34</sup> , Á. Kadlecik , P. Major , G. Pásztor , G.I. Veres 

**Faculty of Informatics, University of Debrecen, Debrecen, Hungary**

B. Ujvari , G. Zilizi 















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

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

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

F. Nemes<sup>33</sup> , T. Novak 

**Panjab University, Chandigarh, India**

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra<sup>35</sup> , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , K. Sandeep , T. Sheokand, J.B. Singh , A. Singla 
















**University of Delhi, Delhi, India**

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


**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

S. Baradia , S. Barman<sup>36</sup> , S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar










**Indian Institute of Technology Madras, Madras, India**

M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , G. Dash , P. Jana , P. Kalbhor , S. Kamble , J.R. Komaragiri<sup>37</sup> , D. Kumar<sup>37</sup> , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , R.K. Singh, P. Verma, S. Verma , A. Vijay












**Tata Institute of Fundamental Research-A, Mumbai, India**

S. Dugad, G.B. Mohanty , B. Parida , M. Shelake, P. Suryadevara











**Tata Institute of Fundamental Research-B, Mumbai, India**

A. Bala , S. Banerjee , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 

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

S. Bahinipati<sup>38</sup> , C. Kar , D. Maity<sup>39</sup> , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu<sup>39</sup> , K. Naskar<sup>39</sup> , A. Nayak<sup>39</sup> , S. Nayak, K. Pal, P. Sadangi, S.K. Swain , S. Varghese<sup>39</sup> , D. Vats<sup>39</sup> 





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

S. Acharya<sup>40</sup> , A. Alpana , S. Dube , B. Gomber<sup>40</sup> , P. Hazarika , B. Kansal , A. Laha , B. Sahu<sup>40</sup> , S. Sharma , K.Y. Vaish 

**Isfahan University of Technology, Isfahan, Iran**

H. Bakhshiansohi<sup>41</sup> , A. Jafari<sup>42</sup> , M. Zeinali<sup>43</sup> 































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

S. Bashiri, S. Chenarani<sup>44</sup> , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie<sup>45</sup> , M. Mohammadi Najafabadi , S. Tizchang<sup>46</sup> 































**University College Dublin, Dublin, Ireland**

M. Felcini , M. Grunewald 






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

M. Abbrescia<sup>a,b</sup> , A. Colaleo<sup>a,b</sup> , D. Creanza<sup>a,c</sup> , B. D'Anzi<sup>a,b</sup> , N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , W. Elmetenawee<sup>a,b,47</sup> , L. Fiore<sup>a</sup> , G. Iaselli<sup>a,c</sup> , L. Longo<sup>a</sup> , M. Louka<sup>a,b</sup>, G. Maggi<sup>a,c</sup> , M. Maggi<sup>a</sup> , I. Margjeka<sup>a</sup> , V. Mastrapasqua<sup>a,b</sup> , S. My<sup>a,b</sup> , S. Nuzzo<sup>a,b</sup> , A. Pellicchia<sup>a,b</sup> , A. Pompili<sup>a,b</sup> , G. Pugliese<sup>a,c</sup> , R. Radogna<sup>a,b</sup> , D. Ramos<sup>a</sup> , A. Ranieri<sup>a</sup> , L. Silvestris<sup>a</sup> , F.M. Simone<sup>a,c</sup> , Ü. Sözbilir<sup>a</sup> , A. Stamerra<sup>a,b</sup> , D. Troiano<sup>a,b</sup> , R. Venditti<sup>a,b</sup> , P. Verwilligen<sup>a</sup> , A. Zaza<sup>a,b</sup> 


















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

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

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
































































































































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






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

P. Assiouras<sup>a</sup> , G. Barbagli<sup>a</sup> , G. Bardelli<sup>a,b</sup> , B. Camaiani<sup>a,b</sup> , A. Cassese<sup>a</sup> , R. Ceccarelli<sup>a</sup> , V. Ciulli<sup>a,b</sup> , C. Civinini<sup>a</sup> , R. D'Alessandro<sup>a,b</sup> , E. Focardi<sup>a,b</sup> , T. Kello<sup>a</sup>, G. Latino<sup>a,b</sup> , P. Lenzi<sup>a,b</sup> , M. Lizzo<sup>a</sup> , M. Meschini<sup>a</sup> , S. Paoletti<sup>a</sup> , A. Papanastassiou<sup>a,b</sup>, G. Sguazzoni<sup>a</sup> , L. Viliani<sup>a</sup> 







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

L. Benussi , S. Bianco , S. Meola<sup>50</sup> , D. Piccolo 

**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**P. Chatagnon<sup>a</sup> , F. Ferro<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> **INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**A. Benaglia<sup>a</sup> , G. Boldrini<sup>a,b</sup> , F. Brivio<sup>a</sup> , F. Cetorelli<sup>a,b</sup> , F. De Guio<sup>a,b</sup> , M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , R. Gerosa<sup>a,b</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a</sup> , M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup> , S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , S. Palluotto<sup>a,b</sup> , D. Pedrini<sup>a</sup> , A. Perego<sup>a,b</sup> , B.S. Pinolini<sup>a</sup>, G. Pizzati<sup>a,b</sup>, S. Ragazzi<sup>a,b</sup> , T. Tabarelli de Fatis<sup>a,b</sup> **INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Scuola Superiore Meridionale (SSM)<sup>d</sup>, Napoli, Italy**S. Buontempo<sup>a</sup> , A. Cagnotta<sup>a,b</sup> , F. Carnevali<sup>a,b</sup>, N. Cavallo<sup>a,c</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,51</sup> , P. Paolucci<sup>a,29</sup> , B. Rossi<sup>a</sup> **INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**R. Ardino<sup>a</sup> , P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,52</sup> , M. Benettoni<sup>a</sup> , A. Bergnoli<sup>a</sup> , D. Bisello<sup>a,b</sup> , P. Bortignon<sup>a</sup> , G. Bortolato<sup>a,b</sup>, A. Bragagnolo<sup>a,b</sup> , A.C.M. Bulla<sup>a</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a</sup> , F. Gasparini<sup>a,b</sup> , U. Gasparini<sup>a,b</sup> , E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , M. Migliorini<sup>a,b</sup> , J. Pazzini<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup> , F. Simonetto<sup>a,b</sup> , M. Tosi<sup>a,b</sup> , A. Triossi<sup>a,b</sup> , S. Ventura<sup>a</sup> , M. Zanetti<sup>a,b</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> **INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**C. Aimè<sup>a</sup> , A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a</sup> , D. Fiorina<sup>a</sup> , P. Montagna<sup>a,b</sup> , V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a,b</sup> , P. Vitulo<sup>a,b</sup> **INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**S. Ajmal<sup>a,b</sup> , M.E. Ascioti<sup>a,b</sup>, G.M. Bilei<sup>a</sup> , C. Carrivale<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , M. Magherini<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,53</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> **INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy**C.A. Alexe<sup>a,c</sup> , P. Asenov<sup>a,b</sup> , P. Azzurri<sup>a</sup> , G. Bagliesi<sup>a</sup> , R. Bhattacharya<sup>a</sup> , L. Bianchini<sup>a,b</sup> , T. Boccali<sup>a</sup> , E. Bossini<sup>a</sup> , D. Bruschini<sup>a,c</sup> , R. Castaldi<sup>a</sup> , M.A. Ciocci<sup>a,b</sup> , M. Cipriani<sup>a,b</sup> , V. D'Amante<sup>a,d</sup> , R. Dell'Orso<sup>a</sup> , S. Donato<sup>a</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , A.C. Marini<sup>a</sup> , D. Matos Figueiredo<sup>a</sup> , A. Messineo<sup>a,b</sup> , M. Musich<sup>a,b</sup> , F. Palla<sup>a</sup> , A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a</sup> , T. Sarkar<sup>a</sup> , A. Scribano<sup>a</sup> , P. Spagnolo<sup>a</sup> , R. Tenchini<sup>a</sup> , G. Tonelli<sup>a,b</sup> , N. Turini<sup>a,d</sup> , F. Vaselli<sup>a,c</sup> , A. Venturi<sup>a</sup> , P.G. Verdini<sup>a</sup> **INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy**C. Baldenegro Barrera<sup>a,b</sup> , P. Barria<sup>a</sup> , C. Basile<sup>a,b</sup> , M. Campana<sup>a,b</sup> , F. Cavallari<sup>a</sup> , L. Cunqueiro Mendez<sup>a,b</sup> , D. Del Re<sup>a,b</sup> , E. Di Marco<sup>a,b</sup> , M. Diemoz<sup>a</sup> , F. Errico<sup>a,b</sup> , E. Longo<sup>a,b</sup> , J. Mijuskovic<sup>a,b</sup> , G. Organtini<sup>a,b</sup> , F. Pandolfi<sup>a</sup> , R. Paramatti<sup>a,b</sup> , C. Quaranta<sup>a,b</sup> , S. Rahatlou<sup>a,b</sup> , C. Rovelli<sup>a</sup> , F. Santanastasio<sup>a,b</sup> , L. Soffi<sup>a</sup> **INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**N. Amapane<sup>a,b</sup> , R. Arcidiacono<sup>a,c</sup> , S. Argiro<sup>a,b</sup> , M. Arneodo<sup>a,c</sup> , N. Bartosik<sup>a</sup> , R. Bellan<sup>a,b</sup> , A. Bellora<sup>a,b</sup> , C. Biino<sup>a</sup> , C. Borca<sup>a,b</sup> , N. Cartiglia<sup>a</sup> , M. Costa<sup>a,b</sup> 

R. Covarelli<sup>a,b</sup> , N. Demaria<sup>a</sup> , L. Finco<sup>a</sup> , M. Grippo<sup>a,b</sup> , B. Kiani<sup>a,b</sup> , F. Legger<sup>a</sup> ,  
 F. Luongo<sup>a,b</sup> , C. Mariotti<sup>a</sup> , L. Markovic<sup>a,b</sup> , S. Maselli<sup>a</sup> , A. Mecca<sup>a,b</sup> , L. Menzio<sup>a,b</sup>,  
 P. Meridiani<sup>a</sup> , E. Migliore<sup>a,b</sup> , M. Monteno<sup>a</sup> , R. Mulargia<sup>a</sup> , M.M. Obertino<sup>a,b</sup> ,  
 G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<sup>a</sup> , M. Pelliccioni<sup>a</sup> , M. Ruspa<sup>a,c</sup> ,  
 F. Siviero<sup>a,b</sup> , V. Sola<sup>a,b</sup> , A. Solano<sup>a,b</sup> , A. Staiano<sup>a</sup> , C. Tarricone<sup>a,b</sup> , D. Trocino<sup>a</sup> ,  
 G. Umoret<sup>a,b</sup> , R. White<sup>a,b</sup> 


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

S. Belforte<sup>a</sup> , V. Candelise<sup>a,b</sup> , M. Casarsa<sup>a</sup> , F. Cossutti<sup>a</sup> , K. De Leo<sup>a</sup> ,  
 G. Della Ricca<sup>a,b</sup> 

**Kyungpook National University, Daegu, Korea**

S. Dogra , J. Hong , C. Huh , B. Kim , J. Kim, D. Lee, H. Lee, S.W. Lee , C.S. Moon ,  
 Y.D. Oh , M.S. Ryu , S. Sekmen , B. Tae, Y.C. Yang 

**Department of Mathematics and Physics - GWNNU, Gangneung, Korea**

M.S. Kim 

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

G. Bak , P. Gwak , H. Kim , D.H. Moon 

**Hanyang University, Seoul, Korea**

E. Asilar , J. Choi , D. Kim , T.J. Kim , J.A. Merlin, Y. Ryou

**Korea University, Seoul, Korea**

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

**Kyung Hee University, Department of Physics, Seoul, Korea**

J. Goh , S. Yang 








**Sejong University, Seoul, Korea**

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



**Seoul National University, Seoul, Korea**

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

**University of Seoul, Seoul, Korea**

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

**Yonsei University, Department of Physics, Seoul, Korea**

S. Ha , H.D. Yoo 


**Sungkyunkwan University, Suwon, Korea**

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

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







































T. Beyrouthy, Y. Gharbia

**Kuwait University - College of Science - Department of Physics, Safat, Kuwait**

F. Alazemi 





























**Riga Technical University, Riga, Latvia**

K. Dreimanis , A. Gaile , G. Pikurs, A. Potrebko , M. Seidel , D. Sidiropoulos Kontos

**University of Latvia (LU), Riga, Latvia**N.R. Strautnieks **Vilnius University, Vilnius, Lithuania**M. Ambrozas , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis **National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**I. Yusuff<sup>54</sup> , Z. Zolkapli**Universidad de Sonora (UNISON), Hermosillo, Mexico**J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo **Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-De La Cruz<sup>55</sup> , R. Lopez-Fernandez , J. Mejia Guisao , C.A. Mondragon Herrera, A. Sánchez Hernández **Universidad Iberoamericana, Mexico City, Mexico**C. Oropeza Barrera , D.L. Ramirez Guadarrama, M. Ramírez García **Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**I. Bautista , I. Pedraza , H.A. Salazar Ibarquen , C. Uribe Estrada **University of Montenegro, Podgorica, Montenegro**I. Bubanja , N. Raicevic **University of Canterbury, Christchurch, New Zealand**P.H. Butler **National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, H.R. Hoorani , W.A. Khan **AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**V. Avati, L. Grzanka , M. Malawski **National Centre for Nuclear Research, Swierk, Poland**H. Bialkowska , M. Bluj , M. Górski , M. Kazana , M. Szleper , P. Zalewski **Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski , A. Muhammad **Warsaw University of Technology, Warsaw, Poland**K. Pozniak , W. Zabolotny **Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo , T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , H. Legoinha , N. Leonardo , G.B. Marozzo, T. Niknejad , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff**Faculty of Physics, University of Belgrade, Belgrade, Serbia**P. Adzic , P. Milenovic **VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**

M. Dordevic , J. Milosevic , L. Nadderd , V. Rekovic















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

J. Alcaraz Maestre , Cristina F. Bedoya , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , E. Martin Viscasillas , D. Moran , C.M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , S. Sánchez Navas , J. Sastre , J. Vazquez Escobar 




















**Universidad Autónoma de Madrid, Madrid, Spain**

J.F. de Trocóniz 


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

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

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

S. Bhowmik , S. Blanco Fernández , J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasaosa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , L. Scodellaro , I. Vila , J.M. Vizan Garcia 
























**University of Colombo, Colombo, Sri Lanka**

B. Kailasapathy<sup>56</sup> , D.D.C. Wickramarathna 



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

W.G.D. Dharmaratna<sup>57</sup> , K. Liyanage , N. Perera 

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**






































D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler , D. Barney , A. Bermúdez Martínez , M. Bianco , A.A. Bin Anuar , A. Bocci , C. Botta , E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , G. Franzoni , W. Funk , S. Giani , D. Gigi , K. Gill , F. Glege , J. Hegeman , J.K. Heikkilä , B. Huber , V. Innocente , T. James , P. Janot , O. Kaluzinska , O. Karacheban<sup>27</sup> , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , M. Matthewman , A. Mehta , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli , F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , H. Qu , D. Rabadý , B. Ribeiro Lopes , M. Rovere , H. Sakulin , S. Sanchez Cruz , S. Scarfi , C. Schwick , M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas<sup>58</sup> , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter , J. Wanczyk<sup>59</sup> , J. Wang , S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**




















T. Bevilacqua<sup>60</sup> , L. Caminada<sup>60</sup> , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli<sup>60</sup> , L. Noehte<sup>60</sup> 

T. Rohe 




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

T.K. Aarrestad , K. Androsov<sup>59</sup> , M. Backhaus , G. Bonomelli, A. Calandri , C. Cazaniga , K. Datta , P. De Bryas Dexmiers D'archiac<sup>59</sup> , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer , T.G. Harte, D. Hits , W. Luster mann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese , C. Martin Perez , A. Mascellani<sup>59</sup> , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , R. Seidita , J. Steggemann<sup>59</sup> , A. Tarabini , D. Valsecchi , R. Wallny 












**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>61</sup> , P. Bärtschi , M.F. Canelli , K. Cormier , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liehti , A. Macchiolo , P. Meiring , F. Meng , U. Molinatti , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr, F. Stäger , R. Tramontano 

**National Central University, Chung-Li, Taiwan**

C. Adloff<sup>62</sup>, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari<sup>37</sup> , S.S. Yu 



















**National Taiwan University (NTU), Taipei, Taiwan**

L. Ceard, K.F. Chen , P.s. Chen, Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, H.y. Wu, E. Yazgan 


**High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand**

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , F. Dolek , I. Dumanoglu<sup>63</sup> , E. Eskut , Y. Guler<sup>64</sup> , E. Gurpinar Guler<sup>64</sup> , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir<sup>65</sup> , A. Polatoz , B. Tali<sup>66</sup> , U.G. Tok , S. Turkcapar , E. Us lan , I.S. Zorbakir 






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

G. Sokmen, M. Yalvac<sup>67</sup> 

**Bogazici University, Istanbul, Turkey**

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya<sup>68</sup> , O. Kaya<sup>69</sup> , S. Tekten<sup>70</sup> 

**Istanbul Technical University, Istanbul, Turkey**

A. Cakir , K. Cankocak<sup>63,71</sup> , G.G. Dincer<sup>63</sup> , Y. Komurcu , S. Sen<sup>72</sup> 

**Istanbul University, Istanbul, Turkey**

O. Aydilek<sup>73</sup> , B. Hacisahinoglu , I. Hos<sup>74</sup> , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez 

**Yildiz Technical University, Istanbul, Turkey**

S. Cerci<sup>66</sup> , B. Isildak<sup>75</sup> , D. Sunar Cerci , T. Yetkin 


















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

A. Boyaryntsev , B. Grynyov 

























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

L. Levchuk 














































#### **University of Bristol, Bristol, United Kingdom**

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw , S. Seif El Nasr-Storey , V.J. Smith , N. Stylianou<sup>76</sup> , K. Walkingshaw Pass






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

A.H. Ball , K.W. Bell , A. Belyaev<sup>77</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis , K. Harder , S. Harper , J. Linacre , K. Manolopoulos , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh , C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 

#### **Imperial College, London, United Kingdom**

I. Andreou , R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller , V. Cacchio , C.A. Carrillo Montoya , G.S. Chahal<sup>78</sup> , D. Colling , J.S. Dancu , I. Das , P. Dauncey , G. Davies , J. Davies , M. Della Negra , S. Fayer , G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard , G. Iles , M. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , S. Mallios , M. Mieskolainen , J. Nash<sup>79</sup> , M. Pesaresi , P.B. Pradeep , B.C. Radburn-Smith , A. Richards , A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage , T. Virdee<sup>29</sup> , M. Vojinovic , N. Wardle , D. Winterbottom 







#### **Brunel University, Uxbridge, United Kingdom**

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












#### **Baylor University, Waco, Texas, USA**

S. Abdullin , A. Brinkerhoff , E. Collins , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 





















#### **Catholic University of America, Washington, DC, USA**

R. Bartek , A. Dominguez , C. Huerta Escamilla , A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 





















#### **The University of Alabama, Tuscaloosa, Alabama, USA**

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson , C.U. Perez , P. Rumerio<sup>80</sup> , E. Usai , R. Yi 

#### **Boston University, Boston, Massachusetts, USA**

A. Akpinar , C. Cosby , G. De Castro , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain , I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 

#### **Brown University, Providence, Rhode Island, USA**

G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , J.M. Hogan<sup>81</sup> , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , M. Narain<sup>†</sup> , N. Per-  
van , T. Russell , S. Sagir<sup>82</sup> , F. Simpson , M. Stamenkovic , N. Venkatasubramanian , X. Yan 





#### **University of California, Davis, Davis, California, USA**

S. Abbott , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral 



G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , Y. Yao , S. Yoo , F. Zhang 

























#### University of California, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

#### University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si 

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

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
















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

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , S. Wang , D. Zhang















#### California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 
















#### Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 

































































#### University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 



















#### Cornell University, Ithaca, New York, USA

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














#### Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>83</sup> , F. Ravera , A. Reinsvold Hall<sup>84</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 






**University of Florida, Gainesville, Florida, USA**

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 
























**Florida State University, Tallahassee, Florida, USA**

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Habibullah , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang











**Florida Institute of Technology, Melbourne, Florida, USA**

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy<sup>85</sup> , M. Hohlmann , M. Rahmani, E. Yanes












**University of Illinois Chicago, Chicago, Illinois, USA**

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 
























**The University of Iowa, Iowa City, Iowa, USA**

M. Alhusseini , D. Blend, K. Dilsiz<sup>86</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>87</sup> , O. Neogi, H. Ogul<sup>88</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>89</sup> 









**Johns Hopkins University, Baltimore, Maryland, USA**

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 
















**The University of Kansas, Lawrence, Kansas, USA**

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu<sup>90</sup> , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson 























**Kansas State University, Manhattan, Kansas, USA**

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 

**University of Maryland, College Park, Maryland, USA**

A. Baden , A. Belloni , J. Bistany-riebman, Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, L. Wang 













**Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**

J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. Mcginn, A. Novak , M.I. Park , C. Paus , C. Roland , G. Roland , S. Rothman , T.A. Sheng, G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang 











**University of Minnesota, Minneapolis, Minnesota, USA**

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , M. Revering , R. Rusack , R. Saradhy , N. Strobbe 

















#### **University of Nebraska-Lincoln, Lincoln, Nebraska, USA**

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado , W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 







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

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos , A. Kharchilava , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams , P. Young 





















#### **Northeastern University, Boston, Massachusetts, USA**

G. Alverson , E. Barberis , J. Bonilla , J. Dervan, Y. Haddad , Y. Han , A. Krishna , J. Li , M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , D. Wood 









#### **Northwestern University, Evanston, Illinois, USA**

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , Y. Miao , D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco


















#### **University of Notre Dame, Notre Dame, Indiana, USA**

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth , K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore , Y. Musienko<sup>17</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 

#### **The Ohio State University, Columbus, Ohio, USA**

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


















#### **Princeton University, Princeton, New Jersey, USA**

H. Bouchamaoui , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , A. Shevelev , D. Stickland , C. Tully 




#### **University of Puerto Rico, Mayaguez, Puerto Rico, USA**

S. Malik 



#### **Purdue University, West Lafayette, Indiana, USA**

A.S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A.W. Jung , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , V. Scheurer, J.F. Schulte , M. Stojanovic , J. Thieman , A. K. Viridi , F. Wang , W. Xie 






#### **Purdue University Northwest, Hammond, Indiana, USA**

J. Dolen , N. Parashar , A. Pathak 

#### **Rice University, Houston, Texas, USA**





















D. Acosta , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , W. Li , J. Lin , O. Miguel Colin , B.P. Padley , R. Redjimi, J. Rotter , E. Yigitbasi , Y. Zhang 

#### **University of Rochester, Rochester, New York, USA**

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido 

O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin<sup>91</sup> , E. Popova<sup>91</sup> , R. Taus 















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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo, K. Nash, J. Reichert , H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 

**University of Tennessee, Knoxville, Tennessee, USA**

D. Ally , A.G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A.R. Kanuganti , N. Karunarathna , L. Lee , E. Nibigira , S. Spanier 












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

D. Aebi , M. Ahmad , T. Akhter , O. Bouhali<sup>92</sup> , R. Eusebi , J. Gilmore , T. Huang , T. Kamon<sup>93</sup> , H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov 







**Texas Tech University, Lubbock, Texas, USA**

N. Akchurin , J. Damgov , N. Gogate , V. Hegde , A. Hussain , Y. Kazhykarim, K. Lamichhane , S.W. Lee , A. Mankel , T. Peltola , I. Volobouev 

**Vanderbilt University, Nashville, Tennessee, USA**

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 























**University of Virginia, Charlottesville, Virginia, USA**

B. Cardwell , B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Neu 

**Wayne State University, Detroit, Michigan, USA**


S. Bhattacharya , P.E. Karchin 

**University of Wisconsin - Madison, Madison, Wisconsin, USA**

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

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

S. Afanasiev , V. Alexakhin , D. Budkouski , I. Golutvin<sup>†</sup> , I. Gorbunov , V. Karjavine , V. Korenkov , A. Lanev , A. Malakhov , V. Matveev<sup>94</sup> , V. Palichik , V. Perelygin , M. Savina , V. Shalaev , S. Shmatov , S. Shulha , V. Smirnov , O. Teryaev , N. Voytishin , B.S. Yuldashev<sup>95</sup>, A. Zarubin , I. Zhizhin , G. Gavrillov , V. Golovtsov , Y. Ivanov , V. Kim<sup>94</sup> , P. Levchenko<sup>96</sup> , V. Murzin , V. Oreshkin , D. Sosnov , V. Sulimov , L. Uvarov , A. Vorobyev<sup>†</sup>, Yu. Andreev , A. Dermenev , S. Gninenko , N. Golubev , A. Karneyeu , D. Kirpichnikov , M. Kirsanov , N. Krasnikov , I. Tlisova , A. Toropin , T. Aushev , V. Gavrillov , N. Lychkovskaya , A. Nikitenko<sup>97,98</sup> , V. Popov , A. Zhokin , R. Chistov<sup>94</sup> , M. Danilov<sup>94</sup> , S. Polikarpov<sup>94</sup> , V. Andreev , M. Azarkin , M. Kirakosyan, A. Terkulov , E. Boos , A. Demijanov , A. Ershov , A. Gribushin , L. Khein, O. Kodolova<sup>98</sup> , V. Korotkikh, S. Obraztsov , S. Petrushanko , V. Savrin , A. Snigirev , I. Vardanyan , V. Blinov<sup>94</sup>, T. Dimova<sup>94</sup> , A. Kozyrev<sup>94</sup> , O. Radchenko<sup>94</sup> , Y. Skovpen<sup>94</sup> , V. Kachanov , D. Konstantinov , S. Slabospitskii , A. Uzunian , A. Babaev , V. Borshch , D. Druzhkin<sup>99</sup> 

**Authors affiliated with an institute formerly covered by a cooperation agreement with CERN**V. Chekhovsky, V. Makarenko 

†: Deceased

<sup>1</sup>Also at Yerevan State University, Yerevan, Armenia<sup>2</sup>Also at TU Wien, Vienna, Austria<sup>3</sup>Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt<sup>4</sup>Also at Ghent University, Ghent, Belgium<sup>5</sup>Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil<sup>6</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil<sup>7</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil<sup>8</sup>Also at UFMS, Nova Andradina, Brazil<sup>9</sup>Also at Nanjing Normal University, Nanjing, China<sup>10</sup>Now at The University of Iowa, Iowa City, Iowa, USA<sup>11</sup>Also at University of Chinese Academy of Sciences, Beijing, China<sup>12</sup>Also at China Center of Advanced Science and Technology, Beijing, China<sup>13</sup>Also at University of Chinese Academy of Sciences, Beijing, China<sup>14</sup>Also at China Spallation Neutron Source, Guangdong, China<sup>15</sup>Now at Henan Normal University, Xinxiang, China<sup>16</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium<sup>17</sup>Also at an institute or an international laboratory covered by a cooperation agreement with CERN<sup>18</sup>Also at Suez University, Suez, Egypt<sup>19</sup>Now at British University in Egypt, Cairo, Egypt<sup>20</sup>Also at Purdue University, West Lafayette, Indiana, USA<sup>21</sup>Also at Université de Haute Alsace, Mulhouse, France<sup>22</sup>Also at Istinye University, Istanbul, Turkey<sup>23</sup>Also at The University of the State of Amazonas, Manaus, Brazil<sup>24</sup>Also at University of Hamburg, Hamburg, Germany<sup>25</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany<sup>26</sup>Also at Bergische University Wuppertal (BUW), Wuppertal, Germany<sup>27</sup>Also at Brandenburg University of Technology, Cottbus, Germany<sup>28</sup>Also at Forschungszentrum Jülich, Juelich, Germany<sup>29</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland<sup>30</sup>Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary<sup>31</sup>Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania<sup>32</sup>Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary<sup>33</sup>Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary<sup>34</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt<sup>35</sup>Also at Punjab Agricultural University, Ludhiana, India<sup>36</sup>Also at University of Visva-Bharati, Santiniketan, India<sup>37</sup>Also at Indian Institute of Science (IISc), Bangalore, India<sup>38</sup>Also at IIT Bhubaneswar, Bhubaneswar, India<sup>39</sup>Also at Institute of Physics, Bhubaneswar, India<sup>40</sup>Also at University of Hyderabad, Hyderabad, India<sup>41</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany<sup>42</sup>Also at Isfahan University of Technology, Isfahan, Iran<sup>43</sup>Also at Sharif University of Technology, Tehran, Iran

- <sup>44</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>45</sup>Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- <sup>46</sup>Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- <sup>47</sup>Also at Helwan University, Cairo, Egypt
- <sup>48</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>49</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>50</sup>Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>51</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>52</sup>Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- <sup>53</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>54</sup>Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- <sup>55</sup>Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- <sup>56</sup>Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- <sup>57</sup>Also at Saegis Campus, Nugegoda, Sri Lanka
- <sup>58</sup>Also at National and Kapodistrian University of Athens, Athens, Greece
- <sup>59</sup>Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- <sup>60</sup>Also at Universität Zürich, Zurich, Switzerland
- <sup>61</sup>Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- <sup>62</sup>Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- <sup>63</sup>Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- <sup>64</sup>Also at Konya Technical University, Konya, Turkey
- <sup>65</sup>Also at Izmir Bakircay University, Izmir, Turkey
- <sup>66</sup>Also at Adiyaman University, Adiyaman, Turkey
- <sup>67</sup>Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- <sup>68</sup>Also at Marmara University, Istanbul, Turkey
- <sup>69</sup>Also at Milli Savunma University, Istanbul, Turkey
- <sup>70</sup>Also at Kafkas University, Kars, Turkey
- <sup>71</sup>Now at Istanbul Okan University, Istanbul, Turkey
- <sup>72</sup>Also at Hacettepe University, Ankara, Turkey
- <sup>73</sup>Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- <sup>74</sup>Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- <sup>75</sup>Also at Yildiz Technical University, Istanbul, Turkey
- <sup>76</sup>Also at Vrije Universiteit Brussel, Brussel, Belgium
- <sup>77</sup>Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- <sup>78</sup>Also at IPPP Durham University, Durham, United Kingdom
- <sup>79</sup>Also at Monash University, Faculty of Science, Clayton, Australia
- <sup>80</sup>Also at Università di Torino, Torino, Italy
- <sup>81</sup>Also at Bethel University, St. Paul, Minnesota, USA
- <sup>82</sup>Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- <sup>83</sup>Also at California Institute of Technology, Pasadena, California, USA
- <sup>84</sup>Also at United States Naval Academy, Annapolis, Maryland, USA
- <sup>85</sup>Also at Ain Shams University, Cairo, Egypt
- <sup>86</sup>Also at Bingol University, Bingol, Turkey

<sup>87</sup>Also at Georgian Technical University, Tbilisi, Georgia

<sup>88</sup>Also at Sinop University, Sinop, Turkey

<sup>89</sup>Also at Erciyes University, Kayseri, Turkey

<sup>90</sup>Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

<sup>91</sup>Now at another institute or international laboratory covered by a cooperation agreement with CERN

<sup>92</sup>Also at Texas A&M University at Qatar, Doha, Qatar

<sup>93</sup>Also at Kyungpook National University, Daegu, Korea

<sup>94</sup>Also at another institute or international laboratory covered by a cooperation agreement with CERN

<sup>95</sup>Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

<sup>96</sup>Also at Northeastern University, Boston, Massachusetts, USA

<sup>97</sup>Also at Imperial College, London, United Kingdom

<sup>98</sup>Now at Yerevan Physics Institute, Yerevan, Armenia

<sup>99</sup>Also at Universiteit Antwerpen, Antwerpen, Belgium