



# 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

The CMS Collaboration\*

CERN, Geneva, Switzerland



## ARTICLE INFO

### Article history:

Received 4 September 2021

Received in revised form 21 March 2022

Accepted 23 March 2022

Available online 4 April 2022

Editor: M. Doser

### Keywords:

CMS

Quark gluon plasma

Heavy flavor

B mesons

Hadronization

## ABSTRACT

The  $B_s^0$  and  $B^+$  production yields are measured in PbPb collisions at a center-of-mass energy per nucleon pair of 5.02 TeV. The data sample, collected with the CMS detector at the LHC, corresponds to an integrated luminosity of  $1.7 \text{ nb}^{-1}$ . The mesons are reconstructed in the exclusive decay channels  $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$  and  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ , in the transverse momentum range 7–50 GeV/ $c$  and absolute rapidity 0–2.4. The  $B_s^0$  meson is observed with a statistical significance in excess of five standard deviations for the first time in nucleus-nucleus collisions. The measurements are performed as functions of the transverse momentum of the B mesons and of the PbPb collision centrality. The ratio of production yields of  $B_s^0$  and  $B^+$  is measured and compared to theoretical models that include quark recombination effects.

© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.

## 1. Introduction

Relativistic heavy ion collisions allow the study of quantum chromodynamics (QCD) at high energy densities and temperatures. Under such conditions, a state in which quarks and gluons are the relevant degrees of freedom, the quark-gluon plasma (QGP) [1,2], is formed [3] as predicted by lattice QCD calculations [4]. Multiple probes are necessary for characterizing the properties of the QGP medium. Among these, heavy quarks, which are abundantly produced at the CERN LHC, have the potential of providing novel insights into QCD calculations, serving as probes of the QGP [5,6]. As they traverse the QGP, these hard-scattered partons lose energy by means of elastic collisions and medium-induced gluon radiation [7–10]. The study of parton energy loss can provide insights into the energy density and diffusion properties of the QGP. The full reconstruction of beauty and charm gives access to their four-momenta and allows the study of the flavor and mass dependences of such processes. Although heavy flavor data became available at BNL RHIC and at the LHC [5], there are still large theoretical uncertainties on the hadronization of heavy quarks in the presence of the QGP [11]. To extract the transport properties of the QGP using heavy quarks, an understanding of the hadronization mechanism is necessary.

An enhancement in the strangeness content of the medium formed in heavy ion collisions [12–18] is expected when the medium temperature lies above the strange quark mass [19]. Through a quark-recombination mechanism [20–23], a corresponding yield enhancement of hadrons containing strangeness is expected relative to corresponding hadrons that do not contain strange quarks. Hints of the presence of such recombination processes for heavy mesons containing strangeness were recently reported for open-charm [24] and open-beauty [25] mesons in lead-lead (PbPb) collisions at a nucleon-nucleon center-of-mass energy of  $\sqrt{s_{NN}} = 5.02$  TeV at the LHC.

The production of B mesons employing fully reconstructed decays was studied at the LHC in proton-proton (pp) collisions at center-of-mass energies,  $\sqrt{s}$ , of 7, 8 and 13 TeV [26–40] over wide transverse momentum ( $p_T$ ) and rapidity ( $y$ ) intervals, and in proton-lead (pPb) collisions at  $\sqrt{s_{NN}}$  of 5.02 and 8.16 TeV [41, 42]. In PbPb collisions, the CMS Collaboration reported results at  $\sqrt{s_{NN}} = 5.02$  TeV for the  $B^+$  [43] and  $B_s^0$  [25] mesons. In this Letter, we extend these results by employing the PbPb data set collected at the end of 2018, a sample larger by about a factor of three as compared to the first measurement with 2015 data, resulting in increased statistical precision and significance.

The  $B^+$  ( $u\bar{b}$ ) and  $B_s^0$  ( $s\bar{b}$ ) 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  $\phi(1020) \rightarrow K^+K^-$ . Throughout this Letter, unless otherwise specified, the  $y$  and  $p_T$  variables given are those of the B mesons, and charge-conjugate states are implied. The

\* E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).

production yields of the  $B_s^0$  and  $B^+$  mesons in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and their ratios are reported, using a data set corresponding to an integrated luminosity of  $1.7 \text{ nb}^{-1}$  collected by the CMS experiment. The measurements are performed as functions of the meson  $p_T$  and of the PbPb collision centrality, where the latter characterizes the degree of overlap of the two lead nuclei and is related to the temperature of the created medium.

## 2. Experimental apparatus and data sample

The central feature of the CMS detector is a superconducting solenoid, which provides a magnetic field of 3.8 T. Within the solenoid volume are a silicon tracker that measures charged particles in the pseudorapidity range  $|\eta| < 2.5$ , a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. For charged particles of  $1 < p_T < 10 \text{ GeV}/c$  and  $|\eta| < 1.4$ , the track resolutions are typically 1.5% in  $p_T$  and 25–90 (45–150)  $\mu\text{m}$  in the transverse (longitudinal) impact parameter [44]. 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 muon reconstruction algorithm starts by finding tracks in the muon detectors, which are then fitted together with tracks reconstructed in the silicon tracker to form *global muons*. Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution for muons with  $20 < p_T < 100 \text{ GeV}/c$  of 1.3–2.0% in the barrel and better than 6% in the endcaps. The hadron forward (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m away from the interaction point, one on each end, providing together coverage in the range  $3.0 < |\eta| < 5.2$ . In this analysis, the HF information is used to select PbPb collision events and to define their centrality class. Centrality, defined as the fraction of the total inelastic hadronic cross section with 0% representing collisions with the largest overlap of the two nuclei, is determined experimentally using the total energy in both HF calorimeters [45]. Events are filtered using a two-tiered trigger system [46]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events within a fixed time interval of less than 4  $\mu\text{s}$ . The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing. A detailed description of the CMS experiment and coordinate system can be found in Ref. [47].

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 decays also involving  $J/\psi$  mesons in the final state. Simulated proton-proton collisions are generated with PYTHIA8 v212 [48] tune CUETP8M1 [49] and propagated through the CMS detector model using the GEANT4 package [50]. The decay of the B mesons is modeled with EVTGEN1.3.0 [51], and final-state photon radiation is simulated with PHOTOS2.0 [52]. Each PYTHIA8 event is embedded into a simulated PbPb collision event generated with HYDJET1.8 [53], which is tuned to reproduce global event properties, such as the charged hadron  $p_T$  spectrum and particle multiplicity [54].

The PbPb collision events were collected with an L1 hardware trigger requiring the presence of two muon candidates, with no explicit momentum threshold, in coincidence with lead bunches crossing at the interaction point. At the HLT one of the muon candidates is reconstructed using information both from the muon detectors and the inner tracker, while only information from the muon detectors is required for the other muon candidate. The two muon candidates were required to have an invariant mass within

$1 < m_{\mu\mu} < 5 \text{ GeV}/c^2$ . For the offline analysis, events have to pass a set of selection criteria designed to reject events from background processes (beam-gas collisions), as described in Ref. [54]. 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 15 cm along the beam axis. The shapes of the clusters in the pixel detector must be compatible with those expected from particles produced by a PbPb collision [55]. In order to select inelastic hadronic collisions, the PbPb events are also required to have at least two towers in each of the HF detectors with energy deposits of more than 4 GeV per tower. Only events with centrality 0–90% are selected. Collision centrality bins are given in percentage ranges, with the 0–90% bin corresponding to the 90% of the collisions having the largest overlap of the two nuclei. The PbPb sample corresponds to an integrated luminosity of approximately  $1.7 \text{ nb}^{-1}$ . This value is indicative only, as the PbPb yield is normalized by the total number of minimum bias events sampled,  $N_{MB} = 11.8 \times 10^9$ .

## 3. Candidate selection and signal extraction

Muon candidates are selected within kinematic constraints that ensure that their reconstruction efficiency stays above 10%. These limits are  $p_T^\mu > 3.5 \text{ GeV}/c$  for  $|\eta^\mu| < 1.2$ ,  $p_T^\mu > 1.5 \text{ GeV}/c$  for  $2.1 < |\eta^\mu| < 2.4$ , and  $p_T^\mu > (5.47 - 1.89|\eta^\mu|) \text{ GeV}/c$  in the  $1.2 < |\eta^\mu| < 2.1$  region. The muons are also required to match the trigger-level muon candidates, and *soft muon* selection criteria are applied to *global muons* (i.e. muons reconstructed using the combined information of the tracker and muon detectors), as defined in Ref. [56]. Two muons of opposite charge, with an invariant mass within  $\pm 150 \text{ MeV}/c^2$  of the world-average  $J/\psi$  meson mass [57], are selected to reconstruct a  $J/\psi$  candidate, with a mass resolution of typically 15–30  $\text{MeV}/c^2$ , depending on the dimuon rapidity and  $p_T$ . The muon pairs are fitted with a common vertex constraint and are kept if the  $p$ -value of the  $\chi^2$  of the fit is greater than 1%, thus lowering the background from charm and beauty hadron semileptonic decays. Similarly, the  $\phi(1020)$  meson candidates are formed with a common vertex constraint between two oppositely charged particle tracks with  $p_T > 300 \text{ MeV}/c$ , both required to pass standard selection criteria described in Ref. [54]. The invariant mass, assuming the world-average charged kaon mass [57] for the two tracks, with a resolution of  $\sim 3.9 \text{ MeV}/c^2$ , is required to be within 15  $\text{MeV}/c^2$  of the world-average  $\phi(1020)$  meson mass [57].

The  $B_s^0$  ( $B^+$ ) meson candidates are constructed by combining a  $J/\psi$  candidate with a  $\phi(1020)$  (single track) candidate, and requiring that they originate from a common vertex. In the kinematic vertex fit to the dimuon plus two-track (single-track) system, the tracks are assigned the mass of the charged kaon, and the invariant mass of the muon pair is constrained to the nominal  $J/\psi$  meson mass [57]. The B candidate selection is performed via multivariate discriminators, based on a boosted decision tree (BDT) method [58]. The selection is optimized separately for each meson, as well as each individual bin of  $p_T$ . The discriminating variables employed 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 particle track(s) to originate from a common vertex), the decay length (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 cosine value of the angle between the B meson displacement and momentum in the transverse plane, the two-dimensional (2D) distance between the primary and decay vertices of their daughter tracks (normalized by their uncertainties), and the  $p_T$  of the daughter charged particle track(s). For the  $B_s^0$  meson, two additional selection variables are used: the distance along the  $z$ -direction between the primary vertex and the decay vertex

(normalized by its uncertainty), as well as the absolute difference between the reconstructed  $\phi(1020)$  meson invariant mass and its nominal value.

The BDT training is performed employing simulated B signal samples, and background samples taken from data sidebands (candidates with the invariant mass 0.15–0.35  $\text{GeV}/c^2$  away from the B meson nominal mass [57]). The signal samples are scaled to the number of B candidates predicted by fixed-order plus next-to-leading order logarithmic (FONLL) perturbative QCD calculations [59–61] for the integrated luminosity of the analyzed data sample. The background rejection achieved with the BDT selection is larger than 97%.

The raw B meson signal yields are extracted using an extended unbinned maximum likelihood fit to the invariant mass spectra. The signal shape is modeled by a sum of two Gaussian functions, with parameters determined from MC simulation, except for the common mean and the overall signal yield, which are free parameters of the fit. The combinatorial background, from uncorrelated combinations of  $J/\psi$  candidates with extra particles, gives rise to a falling contribution in the invariant mass spectrum that is modeled by an exponential function. An additional background source can arise from possible contamination from other b hadron decays. For the  $B^+$  spectrum, partially reconstructed B decays, such as  $B^0 \rightarrow J/\psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^-$ , lead to a heightened background in the invariant mass region below 5.2  $\text{GeV}/c^2$ . The decay  $B^+ \rightarrow J/\psi \pi^+$ , where the pion is misidentified as a kaon, results in a small peaking structure in the signal region. Such partially reconstructed and misreconstructed b hadron components are modeled from simulation, via an error function and a Gaussian function, respectively; both shapes and the normalization of the Gaussian function (relative to the signal) are fixed in the fit to the data. For the  $B_s^0$  meson case, such background contributions are found to be negligible, as a consequence of the tight selection on the mass of the  $\phi(1020)$  candidate. The results of the fits to the invariant mass distributions are shown in Fig. 1.

The statistical significance of the B meson signals is estimated from the ratio of likelihoods obtained by fitting the data with the full model and the background-only model. Using the standard asymptotic approximation for the likelihood [62], the estimate obtained for the  $B_s^0$  meson corresponds to approximately 16 standard deviations. The estimate is obtained with the nominal signal and background model described above, and verified with the model variations presented in Section 5. This is the first observation of the  $B_s^0$  signal in heavy ion collisions.

#### 4. Production yields

For each B meson, the production yield scaled by the overlap nuclear function,  $T_{AA}$  [63], and the number of minimum bias events,  $N_{MB}$ , is computed in each  $p_T$  interval, according to

$$\frac{1}{T_{AA}} \frac{dN}{dp_T} = \frac{1}{2 \mathcal{B} N_{MB} T_{AA}} \frac{N_{\text{obs}}(p_T)}{\Delta p_T} \left\langle \frac{1}{\alpha(p_T, y) \epsilon(p_T, y)} \right\rangle, \quad (1)$$

where  $N_{\text{obs}}$  denotes the raw signal yield, extracted in each  $p_T$  interval of width  $\Delta p_T$ . The factor 1/2 accounts for the fact that the raw yield is measured for particles and antiparticles added together while the production yield is given for one species only, and  $\mathcal{B}$  stands for the branching fraction of the corresponding decay chain. The factor  $T_{AA}$  is equal to the number of nucleon-nucleon (NN) binary collisions divided by the NN total inelastic cross section. The value of  $T_{AA}$  can be interpreted as the NN-equivalent integrated luminosity per heavy ion collision. The  $T_{AA}$  values for  $\sqrt{s_{NN}} = 5.02$  TeV PbPb collisions for the centrality intervals 0–30%, 30–90%, and 0–90% are, respectively,  $(15.4 \pm 0.3) \text{ mb}^{-1}$ ,  $(1.7 \pm 0.1) \text{ mb}^{-1}$ , and  $(6.3 \pm 0.1) \text{ mb}^{-1}$ , as estimated from a MC

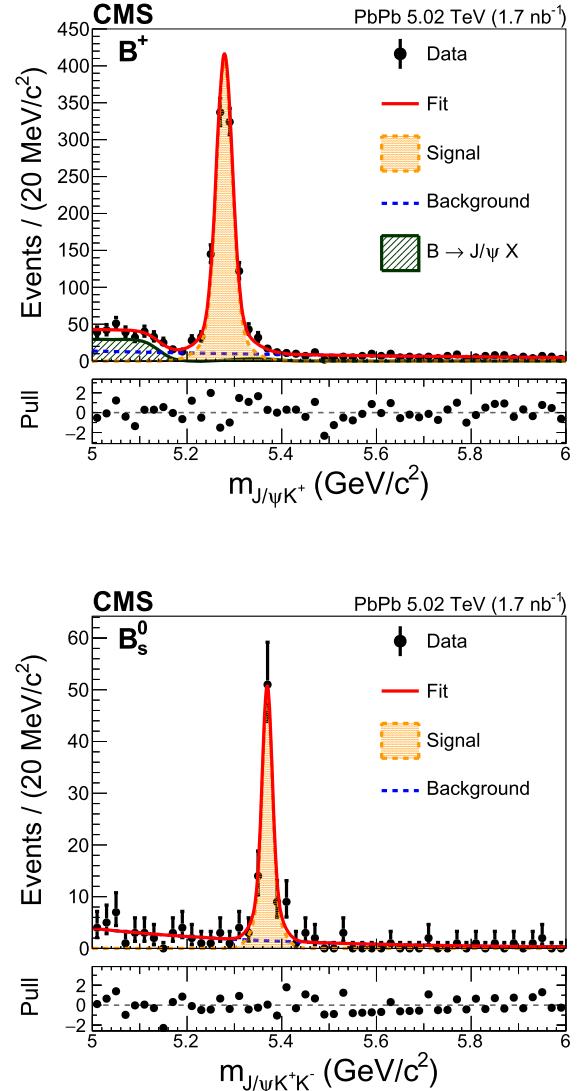


Fig. 1. Invariant mass distributions of  $B^+$  (upper) and  $B_s^0$  (lower) candidates, after the BDT selection, for event centrality in the range 0–90%. The lower panels show the pulls, obtained as the difference between the data points and the fit result, divided by the uncertainty in data.

Glauber model [63], implemented in the TGLAUBERM v3.2 software package [64]. The measurement is performed in a similar fashion as a function of the PbPb collision centrality. The centrality class is represented as the average number of participating nucleons,  $\langle N_{\text{part}} \rangle$ . This number, determined using the above Glauber model, is highly correlated with the impact parameter of the collision.

The acceptance and the efficiency factors, the last term in Eq. (1), are obtained employing 2D fine-grained maps of the acceptance  $\alpha(p_T, y)$  and the efficiency  $\epsilon(p_T, y)$ . These maps are determined, for each centrality region, from MC-simulated samples of B meson signal events, generated within the analysis fiducial region given by:  $|y| < 1.5$  and  $p_T > 10 \text{ GeV}/c$ ;  $1.5 < |y| < 2.4$  and  $7 < p_T < 50 \text{ GeV}/c$ . The acceptance corresponds to the fraction of generated events passing the muon and kaon selection thresholds specified in Section 3, while the efficiency is determined as the fraction of accepted events that pass the full analysis selection criteria, including the trigger. 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, and the corresponding average  $\langle 1/(\alpha\epsilon) \rangle$  obtained for the candidates within a 160  $\text{MeV}/c^2$  window centered on the B meson's world-average mass. The efficiency maps

derived from simulation are corrected by data/MC scale factors for the muon reconstruction and trigger efficiencies, obtained by applying the *tag-and-probe* method using the  $J/\psi$  resonance [65].

## 5. Systematic uncertainties

The  $T_{AA}$ -scaled yield measurements are affected by several sources of systematic uncertainties arising from the signal extraction, acceptance and efficiency,  $\mathcal{B}$ ,  $N_{MB}$ , and  $T_{AA}$  determinations.

The uncertainty from the signal and background modeling is evaluated by considering the following fit variations: (i) using low-order polynomials for describing the combinatorial background, (ii) using a sum of three Gaussian functions with a common mean for alternatively describing the signal, (iii) varying the widths of the signal double-Gaussian function by 10% (to account for possible mismatches in the mass resolution between simulation and data), and (iv) fixing the double-Gaussian mean to its MC simulation value. The maximum of the signal variations and the maximum of the background variations are added in quadrature as the systematic uncertainty from fit modeling.

The systematic uncertainties associated with the limited size of the MC simulation samples are obtained by recomputing the 2D fine-grained  $\alpha(p_T, y) \in (p_T, y)$  maps and the corresponding  $\langle 1/(\alpha\epsilon) \rangle$  averages over the data sample. The statistical uncertainties from the MC-derived product of acceptance and efficiency are propagated by generating 10000 2D maps (per bin in the differential measurement), where each entry is obtained by randomly sampling the  $\alpha\epsilon$  values from Gaussian distributions with widths given by the statistical uncertainty. The resulting systematic uncertainties are obtained as the width of the  $\langle 1/(\alpha\epsilon) \rangle$  distribution from the alternative 2D maps.

The efficiency and acceptance determinations, based on MC simulation, are further affected by potential disagreements between data and MC. The signal MC simulation is validated against data by inspecting the distributions of the variables employed in the selection. The signal distributions are extracted from the data employing the sPlot method [66], using the mass of the B meson candidates as 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/MC ratios formed. 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. This procedure is employed using the higher-yield channel, namely the  $B^+$ . For the  $B_s^0$  meson, the limited size of the data sample yields results that are compatible between data and simulation, within the statistical uncertainties. As such, the  $B^+$  channel is used as calibration mode for the  $B_s^0$  channel, and a procedure identical to that described above is applied to the  $B^+$  sample but using only tracking related variables. The systematic uncertainty for the  $B_s^0$  corresponds to that evaluated for the  $B^+$  and further taking the maximum of the deviation determined from tracking related variables to account for the presence of an extra track in the  $B_s^0$  channel.

The uncertainty in the efficiency of the muon trigger, reconstruction, and identification is evaluated using a tag-and-probe technique [65]. The derived data versus MC scale factors are employed in the determination of the nominal  $\alpha\epsilon$  2D maps, while the associated asymmetric uncertainties are propagated as the systematic uncertainty in the  $\langle 1/(\alpha\epsilon) \rangle$  factors. The difference in the track reconstruction efficiency in data and simulation is estimated by comparing 3-prong and 5-prong  $D^*$  decays,  $D^* \rightarrow K\pi\pi(\pi\pi)$  [54]. This results in 5 (10)% uncertainty in the efficiency determination for the  $B^+$  ( $B_s^0$ ) decay for involving one (two) kaon(s).

The determination of the  $\langle 1/(\alpha\epsilon) \rangle$  factors, for each analysis bin, involves averaging over the data. In order to reflect this statisti-

cal effect, the overall statistical uncertainty from the PbPb data is calculated using a bootstrap method [67], where data events are resampled 1000 times with replacement. The corrected yield is re-determined for each bootstrap sample, and the spread of its distribution is assigned as the statistical uncertainty.

Various consistency checks of the analysis procedure have been performed, which do not result in additional systematic uncertainties. The consistency of the fitting procedure was verified by generating and fitting pseudo-experiments using the likelihood model and parameters employed for fitting the data. The distributions of the pull (here defined as the difference between the generated and fitted parameter values divided by the uncertainty returned by the fit) show random behavior consistent with Gaussians of zero mean and unit width, which indicate the absence of bias in the fitting procedure. A consistency check was performed using MC simulation, where the signal yields are extracted with the fitting procedure and the acceptance and efficiency corrections applied, thus retrieving the generated yields. Potential biases in the acceptance and efficiency calculations associated with the shape of the B mesons kinematic distributions from simulation were probed by re-weighting the PYTHIA simulation according to varied  $p_T$  shapes and recomputing the factors  $\langle 1/(\alpha\epsilon) \rangle$ . Such deviations were found to be negligible. This confirmed independence from the MC simulation is expected in view of the fine-grained 2D  $\alpha\epsilon$  MC maps and the  $\langle 1/(\alpha\epsilon) \rangle$  averaging based on data, and further attests the robustness of the analysis procedure. The effect of background contamination in the averaging procedure was studied employing the sPlot method and was found to be negligible.

The systematic uncertainties in the Glauber model normalization factor ( $T_{AA}$ ) are derived from propagating the uncertainties in the event selection efficiency, and in the nuclear radius, skin depth, and minimum distance between nucleons in the Pb nucleus parameters of the Glauber model [54]. The uncertainties associated with the branching fraction of the decay chains  $\mathcal{B}$  are obtained from Ref. [57]. The  $\mathcal{B}$  factor is common to all bins in the production yield measurements, as is the case also of  $T_{AA}$  and  $N_{MB}$  in the  $p_T$ -differential results; the corresponding uncertainties are denoted global uncertainties.

The total systematic uncertainties in the  $T_{AA}$ -scaled yield measurement are computed as the sum in quadrature of the different contributions mentioned above, which are summarized in Tables 1 and 2.

## 6. Results

The differential  $T_{AA}$ -scaled yields for  $B_s^0$  and  $B^+$  mesons in PbPb collisions, Eq. (1), as a function of the meson  $p_T$  are presented in Fig. 2 (upper). On the horizontal scale, the abscissa of each data point is set to the mean value of the  $p_T$  distribution, after background subtraction via sPlot, while the bin ranges are represented by the boxes. In Fig. 2 (lower), the  $T_{AA}$ -scaled yields are presented for different PbPb event centrality ranges.

The ratio of production yields of the  $B_s^0$  and  $B^+$  mesons is formed as

$$R = \frac{N_{B_s^0}}{N_{B^+}} = \frac{N_{obs}^{B_s^0} \mathcal{B}^{B^+} \langle 1/(\alpha^{B_s^0} \epsilon^{B_s^0}) \rangle}{N_{obs}^{B^+} \mathcal{B}^{B_s^0} \langle 1/(\alpha^{B^+} \epsilon^{B^+}) \rangle}. \quad (2)$$

The terms  $T_{AA}$  and  $N_{MB}$ , that are common to the two meson samples, cancel in the ratio  $R$ . Correlated systematic uncertainties associated with the efficiency determination are partially reduced. For the tracking efficiency, a 5% uncertainty is assigned because of the different number of hadron tracks in the two decays. Muon efficiency uncertainties from the tag-and-probe method are determined by varying coherently the efficiency factors in the numerator and denominator within the corresponding uncertainties. For



**Table 1**

Summary of systematic uncertainties in the  $T_{AA}$ -scaled yield measurements for  $B^+$  and  $B_s^0$  mesons, in four  $p_T$  ranges. The measurements are performed in the B meson kinematic region  $|y| < 2.4$  and centrality range 0–90%. The relative uncertainty values are shown in percentage.

B meson $p_T$ (GeV/c)	$B^+$				$B_s^0$			
	7–10	10–15	15–20	20–50	7–10	10–15	15–20	20–50
Muon efficiency	+7.2	+4.3	+3.8	+3.9	+8.9	+6.0	+3.7	+3.9
	–6.3	–3.9	–3.5	–3.6	–7.5	–5.2	–3.5	–3.6
Data/MC agreement	4.2	15	3.0	1.7	35	5.6	4.7	10
MC sample size	9.1	3.2	1.9	1.4	27	6.3	3.1	3.2
Fit modeling	4.5	2.7	2.8	2.6	1.2	3.8	1.8	6.4
Tracking efficiency	5.0	5.0	5.0	5.0	10	10	10	10
$T_{AA}$			2.2				2.2	
$N_{MB}$			1.3				1.3	
Branching fraction			2.9				7.5	
Total	+15	+17	+8.7	+8.2	+47	+17	+15	+18
	–14	–17	–8.5	–8.0	–47	–17	–14	–18

**Table 2**

Summary of systematic uncertainties in the  $T_{AA}$ -scaled yield measurements for  $B^+$  and  $B_s^0$  mesons, in three centrality ranges. The measurements are performed in the B meson kinematic region given by  $10 < p_T < 50$  GeV/c and  $|y| < 2.4$ . The relative uncertainty values are shown in percentage.

Centrality class	$B^+$			$B_s^0$		
	0–30%	30–90%	0–90%	0–30%	30–90%	0–90%
Muon efficiency	+4.2	+4.1	+4.2	+5.5	+4.6	+5.3
	–3.8	–3.8	–3.8	–4.9	–4.2	–4.7
Data/MC agreement	13	8.0	12	3.1	3.7	3.2
MC sample size	3.2	2.2	2.4	6.6	2.3	4.4
Fit modeling	2.5	2.8	2.6	2.5	3.2	2.3
Tracking efficiency	5.0	5.0	5.0	10	10	10
$T_{AA}$	2.0	3.6	2.2	2.0	3.6	2.2
$N_{MB}$		1.3			1.3	
Branching fraction		2.9			7.5	
Total	+16	+12	+15	+16	+15	+15
	–15	–12	–15	–16	–15	–15

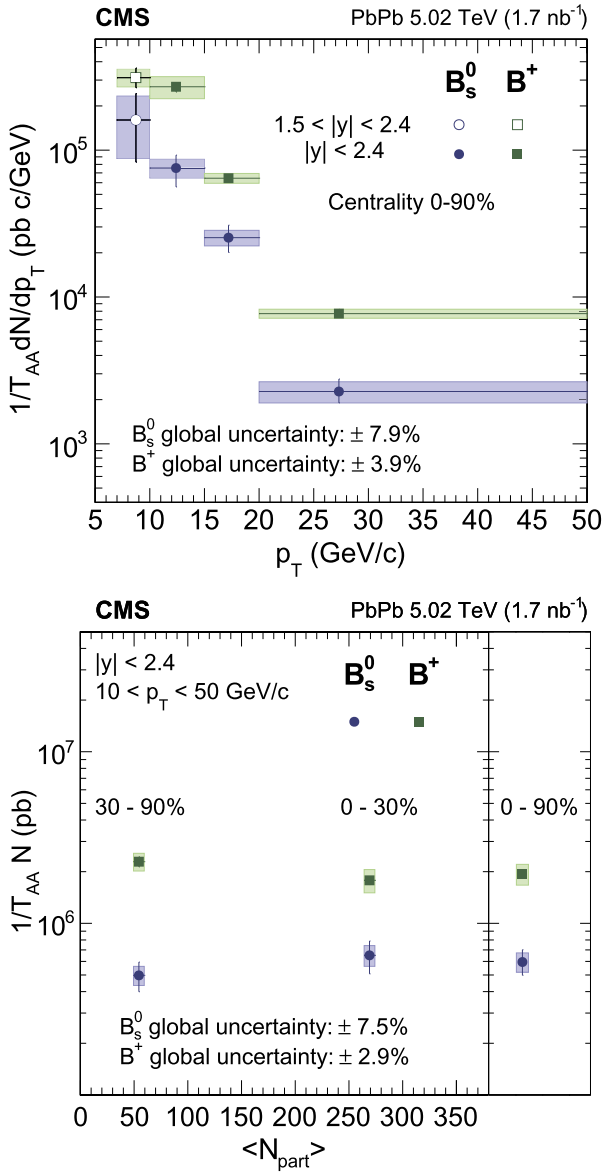
the determination of the uncertainties related to data/MC comparisons, an identical procedure to that used for the production yield is employed, but utilizing only tracking related variables, using the  $B^+$  channel. The dominant uncertainty arises from data/MC agreement and the limited MC sample size. The  $R$  ratio results are shown in Fig. 3 as functions of the mesons'  $p_T$  (upper) and event centrality (lower).

The  $p_T$  dependence of the ratio  $R$  is compared to a transport model (TAMU) based on a Langevin equation that includes collisional energy loss and heavy quark diffusion in the medium [23] and an advanced Langevin hydrodynamic model with both heavy quark elastic and inelastic energy loss [68]. Both predictions account for recombination contributions to the  $B_s^0$  meson yields, which are expected to be more significant at low  $p_T$ . Predictions from a quark combination model with the equal-velocity combination (EVC) approximation [69] are also shown for both PbPb and pp collisions. The ratio of the  $B_s^0$  and  $B^+$  yields in pp collisions has been determined by LHCb [70], at different collision energies, for B mesons within  $0.5 < p_T < 40$  GeV/c and  $2 < \eta < 5$ . While no rapidity dependence of the ratio has been found, a decrease with  $p_T$  and an increase with collision energy have been reported [70,71]. While the  $B_s^0$  to  $B^+$  meson yield ratios obtained in charmonium decay channels cannot be directly compared with those measured in  $e^+e^-$  collisions at LEP [72], earlier LHCb measurements [32,73,74] in pp collisions in other hadronic decay channels are compatible with the LEP results. The lack of sizable strangeness enhancement in the  $B_s^0$  meson hadronization in pp collisions, evident from the above agreement, makes pp collisions a robust baseline for comparison with our PbPb results. In Fig. 3, the pp results at 7 TeV by LHCb [70] are scaled by the same ratio of

branching fractions [57] as used in Eq. (2). The results are compatible with both the model predictions for PbPb collisions and the pp reference results. However, no significant  $p_T$  dependence can be established with the precision allowed by the current data. The results, while compatible, tend to lie systematically above the pp reference data. While the central value of  $R$  in the more central bin lies above that of the more peripheral bin, the results are compatible within the combined statistical and systematic uncertainty. These results are compatible with the ratio of nuclear modification factors,  $R_{AA}$ , reported earlier by the CMS Collaboration [25], albeit with reduced statistical uncertainties.

## 7. Summary

The  $B_s^0$  and  $B^+$  mesons are studied with the CMS detector at the LHC via the reconstruction of the exclusive hadronic decay channels  $B_s^0 \rightarrow J/\psi\phi(1020) \rightarrow \mu^+\mu^-K^+K^-$  and  $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+\mu^-K^+$ . The measurements are performed within the B mesons' fiducial region given by transverse momentum  $p_T > 10$  GeV/c for rapidity  $|y| < 1.5$  and  $7 < p_T < 50$  GeV/c for  $1.5 < |y| < 2.4$ . The first observation of the  $B_s^0$  meson in nucleus-nucleus collisions, with a statistical significance well surpassing five standard deviations, is attained. The production yields of  $B_s^0$  and  $B^+$  mesons, scaled by the nuclear overlap function  $T_{AA}$  and the number of minimum bias events  $N_{MB}$ , in lead-lead (PbPb) collisions at a center-of-mass energy of 5.02 TeV per nucleon pair are presented as functions of the meson  $p_T$  and, for the first time, of the event centrality. These results extend, and are compatible with, those previously reported by the CMS Collaboration [25,43], and are based on a three-fold larger PbPb data sample. The ratio of production

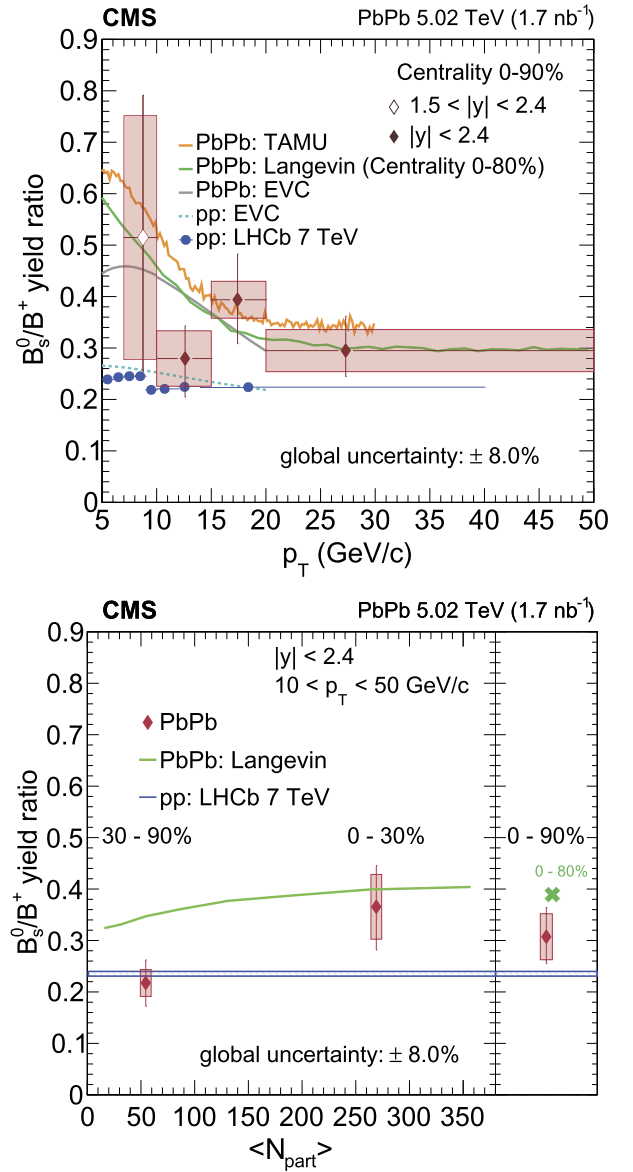


**Fig. 2.** The acceptance- and efficiency-corrected yields for the  $B^+$  and  $B_s^0$  mesons, scaled by  $T_{AA}$  and  $N_{MB}$  in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The results are shown as a function of the meson  $p_T$  (upper), and of the event centrality (lower), where the rightmost panel indicates the centrality-integrated result. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty comprises the uncertainties in  $T_{AA}$ ,  $N_{MB}$ ,  $\mathcal{B}$  (upper) and  $\mathcal{B}$  (lower).

yields of the two mesons in PbPb collisions is determined and it is found to be statistically compatible with the corresponding ratio in proton-proton (pp) collisions. The further investigation of possible hints of an enhancement of the ratio in PbPb, relative to pp collisions, will benefit from more precise PbPb and pp reference data taken at the same collision energy per nucleon. The larger PbPb data sets that should be accumulated in upcoming high-luminosity LHC heavy ion runs will provide greater precision and could help to further characterize the mechanisms of beauty hadronization in heavy ion collisions.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



**Fig. 3.** The ratio of  $B_s^0$  and  $B^+$  meson production yields, as a function of  $p_T$  (upper) and a function of collision centrality (lower). The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty on the yields ratio corresponds to the decay branching fractions  $\mathcal{B}$ . Predictions from a Langevin hydrodynamic model [68] and (upper panel only) from the TAMU transport model [23] and the EVC quark combination model [69] for pp (cyan, dashed) and PbPb (gray) collisions are overlaid. The yield ratio measured by LHCb in pp collisions at 7 TeV [70], scaled by the branching fraction ratio [57], is also displayed (shown in blue, as function of  $p_T$  on the upper panel, and the average value on the lower panel, where the double-line width denotes the uncertainty).

#### Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid and other centres 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: 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); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NK-FIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the 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; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 – GRK2497; the Lendület ("Momentum") Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFI research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Science and Higher Education and the National Science Center, contracts Opus 2014/15/B/ST2/03998 and 2015/19/B/ST2/02861 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education of the Russian Federation, project no. 14.W03.31.0026 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Stavros Niarchos Foundation (Greece); the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

## References

- [1] J.C. Collins, M.J. Perry, Superdense matter: neutrons or asymptotically free quarks?, *Phys. Rev. Lett.* 34 (1975) 1353, <https://doi.org/10.1103/PhysRevLett.34.1353>.
- [2] É.V. Shuryak, Theory of hadronic plasma, *Sov. Phys. JETP* 47 (1978) 212, <http://www.jetp.ras.ru/cgi-bin/e/index/e/47/2/p212?a=list>.
- [3] W. Busza, K. Rajagopal, W. van der Schee, Heavy ion collisions: the big picture, and the big questions, *Annu. Rev. Nucl. Part. Sci.* 68 (2018) 339, <https://doi.org/10.1146/annurev-nucl-101917-020852>, arXiv:1802.04801.
- [4] F. Karsch, E. Laermann, Thermodynamics and in-medium hadron properties from lattice QCD, in: R. Hwa (Ed.), *Quark-Gluon Plasma III*, 2003, arXiv:hep-lat/0305025.
- [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, <https://doi.org/10.1140/epjc/s10052-015-3819-5>, arXiv:1506.03981.
- [6] X. Dong, Y.-J. Lee, R. Rapp, Open heavy-flavor production in heavy-ion collisions, *Annu. Rev. Nucl. Part. Sci.* 69 (2019) 417, <https://doi.org/10.1146/annurev-nucl-101918-023806>, arXiv:1903.07709.
- [7] 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 82-059-THY*, <http://lss.fnal.gov/archive/1982/pub/Pub-82-059-T.pdf>, 1982.
- [8] R. Baier, D. Schiff, B.G. Zakharov, Energy loss in perturbative QCD, *Annu. Rev. Nucl. Part. Sci.* 50 (2000) 37, <https://doi.org/10.1146/annurev-nucl.50.1.37>, arXiv:hep-ph/0002198.
- [9] CMS Collaboration, Observation and studies of jet quenching in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, *Phys. Rev. C* 84 (2011) 024906, <https://doi.org/10.1103/PhysRevC.84.024906>, arXiv:1102.1957.
- [10] 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, <https://doi.org/10.1103/PhysRevLett.105.252303>, arXiv:1011.6182.
- [11] A. Beraudo, et al., Extraction of heavy-flavor transport coefficients in QCD matter, *Nucl. Phys. A* 979 (2018) 21, <https://doi.org/10.1016/j.nuclphysa.2018.09.002>, arXiv:1803.03824.
- [12] ALICE Collaboration,  $K_S^0$  and  $\Lambda$  production in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, *Phys. Rev. Lett.* 111 (2013) 222301, <https://doi.org/10.1103/PhysRevLett.111.222301>, arXiv:1307.5530.
- [13] G. Agakishiev, et al., STAR, Strangeness enhancement in Cu+Cu and Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, *Phys. Rev. Lett.* 108 (2012) 072301, <https://doi.org/10.1103/PhysRevLett.108.072301>, arXiv:1107.2955.
- [14] B.I. Abelev, et al., STAR, Energy and system size dependence of  $\phi$  meson production in Cu+Cu and Au+Au collisions, *Phys. Lett. B* 673 (2009) 183, <https://doi.org/10.1016/j.physletb.2009.02.037>, arXiv:0810.4979.
- [15] I.C. Arsene, et al., BRAHMS, Kaon and pion production in central Au+Au collisions at  $\sqrt{s_{NN}} = 62.4$  GeV, *Phys. Lett. B* 687 (2010) 36, <https://doi.org/10.1016/j.physletb.2010.02.078>, arXiv:0911.2586.
- [16] L. Adamczyk, et al., STAR, Collision energy dependence of moments of net-kaon multiplicity distributions at RHIC, *Phys. Lett. B* 785 (2018) 551, <https://doi.org/10.1016/j.physletb.2018.07.066>, arXiv:1709.00773.
- [17] A. Adare, et al., PHENIX,  $\phi$  meson production in the forward/backward rapidity region in Cu + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, *Phys. Rev. C* 93 (2016) 024904, <https://doi.org/10.1103/PhysRevC.93.024904>, arXiv:1509.06337.
- [18] ALICE Collaboration, Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions, *Nat. Phys.* 13 (2017) 535, <https://doi.org/10.1038/nphys4111>, arXiv:1606.07424.
- [19] J. Rafelski, B. Müller, Strangeness production in the quark-gluon plasma, *Phys. Rev. Lett.* 48 (1982) 1066, <https://doi.org/10.1103/PhysRevLett.48.1066>, Erratum, <https://doi.org/10.1103/PhysRevLett.56.2334>.
- [20] D. Molnar, S.A. Voloshin, Elliptic flow at large transverse momenta from quark coalescence, *Phys. Rev. Lett.* 91 (2003) 092301, <https://doi.org/10.1103/PhysRevLett.91.092301>, arXiv:nucl-th/0302014.
- [21] V. Greco, C.M. Ko, P. Levai, Parton coalescence at RHIC, *Phys. Rev. C* 68 (2003) 034904, <https://doi.org/10.1103/PhysRevC.68.034904>, arXiv:nucl-th/0305024.
- [22] V. Greco, C.M. Ko, R. Rapp, Quark coalescence for charmed mesons in ultrarelativistic heavy ion collisions, *Phys. Lett. B* 595 (2004) 202, <https://doi.org/10.1016/j.physletb.2004.06.064>, arXiv:nucl-th/0312100.
- [23] M. He, R.J. Fries, R. Rapp, Heavy flavor at the large hadron collider in a strong coupling approach, *Phys. Lett. B* 735 (2014) 445, <https://doi.org/10.1016/j.physletb.2014.05.050>, arXiv:1401.3817.
- [24] ALICE Collaboration, Measurement of  $D^0$ ,  $D^+$ ,  $D^{*0}$  and  $D_s^+$  production in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *J. High Energy Phys.* 10 (2018) 174, [https://doi.org/10.1007/JHEP10\(2018\)174](https://doi.org/10.1007/JHEP10(2018)174), arXiv:1804.09083.
- [25] 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, <https://doi.org/10.1016/j.physletb.2019.07.014>, arXiv:1810.03022.
- [26] CMS Collaboration, Measurement of the  $B^+$  production cross section in pp collisions at  $\sqrt{s} = 7$  TeV, *Phys. Rev. Lett.* 106 (2011) 112001, <https://doi.org/10.1103/PhysRevLett.106.112001>, arXiv:1101.0131.
- [27] 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, <https://doi.org/10.1103/PhysRevLett.106.252001>, arXiv:1104.2892.
- [28] 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, <https://doi.org/10.1103/PhysRevD.84.052008>, arXiv:1106.4048.
- [29] ATLAS Collaboration, Measurement of the differential cross-section of  $B^+$  meson production in pp collisions at  $\sqrt{s} = 7$  TeV at ATLAS, *J. High Energy Phys.* 10 (2013) 042, [https://doi.org/10.1007/JHEP10\(2013\)042](https://doi.org/10.1007/JHEP10(2013)042), arXiv:1307.0126.
- [30] LHCb Collaboration, Measurement of the  $B^\pm$  production cross-section in pp collisions at  $\sqrt{s} = 7$  TeV, *J. High Energy Phys.* 04 (2012) 093, [https://doi.org/10.1007/JHEP04\(2012\)093](https://doi.org/10.1007/JHEP04(2012)093), arXiv:1202.4812.

- [31] LHCb Collaboration, Measurement of B meson production cross-sections in proton-proton collisions at  $\sqrt{s} = 7$  TeV, *J. High Energy Phys.* 08 (2013) 117, [https://doi.org/10.1007/JHEP08\(2013\)117](https://doi.org/10.1007/JHEP08(2013)117), arXiv:1306.3663.
- [32] LHCb Collaboration, Measurement of *b*-hadron production fractions in 7 TeV pp collisions, *Phys. Rev. D* 85 (2012) 032008, <https://doi.org/10.1103/PhysRevD.85.032008>, arXiv:1111.2357.
- [33] LHCb Collaboration, Measurements of  $B_c^+$  production and mass with the  $B_c^+ \rightarrow J/\psi\pi^+$  decay, *Phys. Rev. Lett.* 109 (2012) 232001, <https://doi.org/10.1103/PhysRevLett.109.232001>, arXiv:1209.5634.
- [34] 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  $\mathcal{B}(B_c^{\pm} \rightarrow J/\psi\pi^{\pm}\pi^{\mp})/\mathcal{B}(B_c^{\pm} \rightarrow J/\psi\pi^{\pm})$  in pp collisions at  $\sqrt{s} = 7$  TeV, *J. High Energy Phys.* 01 (2015) 063, [https://doi.org/10.1007/JHEP01\(2015\)063](https://doi.org/10.1007/JHEP01(2015)063), arXiv:1410.5729.
- [35] 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, <https://doi.org/10.1088/1674-1137/40/1/011001>, arXiv:1509.00292.
- [36] LHCb Collaboration, Measurement of  $B_c^+$  production in proton-proton collisions at  $\sqrt{s} = 8$  TeV, *Phys. Rev. Lett.* 114 (2015) 132001, <https://doi.org/10.1103/PhysRevLett.114.132001>, arXiv:1411.2943.
- [37] 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, <https://doi.org/10.1103/PhysRevD.104.012010>, arXiv:1912.02672.
- [38] 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, <https://doi.org/10.1016/j.physletb.2017.05.074>, arXiv:1609.00873.
- [39] LHCb Collaboration, Measurement of the  $B^{\pm}$  production cross-section in pp collisions at  $\sqrt{s} = 7$  and 13 TeV, *J. High Energy Phys.* 12 (2017) 026, [https://doi.org/10.1007/JHEP12\(2017\)026](https://doi.org/10.1007/JHEP12(2017)026), arXiv:1710.04921.
- [40] LHCb Collaboration, Measurement of the  $B_c^-$  meson production fraction and asymmetry in 7 and 13 TeVpp collisions, *Phys. Rev. D* 100 (2019) 112006, <https://doi.org/10.1103/PhysRevD.100.112006>, arXiv:1910.13404.
- [41] 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, <https://doi.org/10.1103/PhysRevLett.116.032301>, arXiv:1508.06678.
- [42] 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, <https://doi.org/10.1103/PhysRevD.99.052011>, arXiv:1902.05599.
- [43] CMS Collaboration, Measurement of the  $B^+$  meson nuclear modification factor in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Rev. Lett.* 119 (2017) 152301, <https://doi.org/10.1103/PhysRevLett.119.152301>, arXiv:1705.04727.
- [44] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* 9 (2014) P10009, <https://doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [45] CMS Collaboration, Dependence on pseudorapidity and centrality of charged hadron production in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, *J. High Energy Phys.* 08 (2011) 141, [https://doi.org/10.1007/JHEP08\(2011\)141](https://doi.org/10.1007/JHEP08(2011)141), arXiv:1107.4800.
- [46] CMS Collaboration, The CMS trigger system, *J. Instrum.* 12 (2017) P01020, <https://doi.org/10.1088/1748-0221/12/01/P01020>, arXiv:1609.02366.
- [47] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [48] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA8.2, *Comput. Phys. Commun.* 191 (2015) 159, <https://doi.org/10.1016/j.cpc.2015.01.024>, arXiv:1410.3012.
- [49] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, *Eur. Phys. J. C* 76 (2016) 155, <https://doi.org/10.1140/epjc/s10052-016-3988-x>, arXiv:1512.00815.
- [50] J. Allison, et al., Recent developments in GEANT4, *Nucl. Instrum. Methods A* 835 (2016) 186, <https://doi.org/10.1016/j.nima.2016.06.125>.
- [51] D.J. Lange, The EVTGEN particle decay simulation package, *Nucl. Instrum. Methods A* 462 (2001) 152, [https://doi.org/10.1016/S0168-9002\(01\)00089-4](https://doi.org/10.1016/S0168-9002(01)00089-4).
- [52] E. Barberio, B. van Eijk, Z. Was, PHOTOS: a universal Monte Carlo for QED radiative corrections in decays, *Comput. Phys. Commun.* 66 (1991) 115, [https://doi.org/10.1016/0010-4655\(91\)90012-A](https://doi.org/10.1016/0010-4655(91)90012-A).
- [53] I.P. Lokhtin, A.M. Snigirev, A model of jet quenching in ultrarelativistic heavy ion collisions and high- $p_T$  hadron spectra at RHIC, *Eur. Phys. J. C* 45 (2006) 211, <https://doi.org/10.1140/epjc/s2005-02426-3>, arXiv:hep-ph/0506189.
- [54] CMS Collaboration, Charged-particle nuclear modification factors in PbPb and pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *J. High Energy Phys.* 04 (2017) 039, [https://doi.org/10.1007/JHEP04\(2017\)039](https://doi.org/10.1007/JHEP04(2017)039), arXiv:1611.01664.
- [55] CMS Collaboration, Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at  $\sqrt{s} = 0.9$  and 2.76 TeV, *J. High Energy Phys.* 02 (2010) 041, [https://doi.org/10.1007/JHEP02\(2010\)041](https://doi.org/10.1007/JHEP02(2010)041), arXiv:1002.0621.
- [56] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV, *J. Instrum.* 7 (2012) P10002, <https://doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.
- [57] M. Tanabashi, et al., Particle Data Group, Review of particle physics, *Phys. Rev. D* 98 (2018) 030001, <https://doi.org/10.1103/PhysRevD.98.030001>.
- [58] H. Voss, A. Höcker, J. Stelzer, F. Tegenfeldt, TMVA – the toolkit for multivariate data analysis, in: XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT), 2009, p. 40, [http://pos.sissa.it/archive/conferences/050/040/ACAT\\_040.pdf](http://pos.sissa.it/archive/conferences/050/040/ACAT_040.pdf), arXiv:physics/0703039.
- [59] M. Cacciari, M. Greco, P. Nason, The  $p_T$  spectrum in heavy-flavour hadroproduction, *J. High Energy Phys.* 05 (1998) 007, <https://doi.org/10.1088/1126-6708/1998/05/007>, arXiv:hep-ph/9803400.
- [60] M. Cacciari, P. Nason, Charm cross sections for the Tevatron Run II, *J. High Energy Phys.* 09 (2003) 006, <https://doi.org/10.1088/1126-6708/2003/09/006>, arXiv:hep-ph/0306212.
- [61] M. Cacciari, S. Frixione, N. Houdeau, M.L. Mangano, P. Nason, G. Ridolfi, Theoretical predictions for charm and bottom production at the LHC, *J. High Energy Phys.* 10 (2012) 137, [https://doi.org/10.1007/JHEP10\(2012\)137](https://doi.org/10.1007/JHEP10(2012)137), arXiv:1205.6344.
- [62] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* 71 (2011) 1554, <https://doi.org/10.1140/epjc/s10052-011-1554-0>, arXiv:1007.1727, Erratum, <https://doi.org/10.1140/epjc/s10052-013-2501-z>.
- [63] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Glauber modeling in high-energy nuclear collisions, *Annu. Rev. Nucl. Part. Sci.* 57 (2007) 205, <https://doi.org/10.1146/annurev.nucl.57.090506.123020>, arXiv:nucl-ex/0701025.
- [64] C. Loizides, J. Kamin, D. d'Enterria, Improved Monte Carlo Glauber predictions at present and future nuclear colliders, *Phys. Rev. C* 97 (2018) 054910, <https://doi.org/10.1103/PhysRevC.97.054910>, arXiv:1710.07098, Erratum, <https://doi.org/10.1103/PhysRevC.99.019901>.
- [65] CMS Collaboration, Upsilon production cross-section in pp collisions at  $\sqrt{s} = 7$  TeV, *Phys. Rev. D* 83 (2011) 112004, <https://doi.org/10.1103/PhysRevD.83.112004>, arXiv:1012.5545.
- [66] M. Pivk, F.R. Le Diberder, sPlot: a statistical tool to unfold data distributions, *Nucl. Instrum. Methods A* 555 (2005) 356, <https://doi.org/10.1016/j.nima.2005.08.106>, arXiv:physics/0402083.
- [67] B. Efron, Bootstrap methods: another look at the jackknife, *Ann. Stat.* 7 (1979) 1, <https://doi.org/10.1214/aos/1176344552>.
- [68] S. Cao, K.-J. Sun, S.-Q. Li, S.Y.F. Liu, W.-J. Xing, G.-Y. Qin, C.-M. Ko, Charmed hadron chemistry in relativistic heavy-ion collisions, *Phys. Lett. B* 807 (2020) 133561, <https://doi.org/10.1016/j.physletb.2020.133561>, arXiv:1911.00456.
- [69] J. Song, H.-h. Li, F.-l. Shao, New feature of low  $p_T$  charm quark hadronization in pp collisions at  $\sqrt{s} = 2.76$  TeV, *Eur. Phys. J. C* 78 (2018) 344, <https://doi.org/10.1140/epjc/s10052-018-5817-x>, arXiv:1801.09402.
- [70] LHCb Collaboration, Measurement of  $f_s/f_u$  variation with proton-proton collision energy and B-meson kinematics, *Phys. Rev. Lett.* 124 (2020) 122002, <https://doi.org/10.1103/PhysRevLett.124.122002>, arXiv:1910.09934.
- [71] LHCb Collaboration, Precise measurement of the  $f_s/f_d$  ratio of fragmentation fractions and of  $B_s^0$  decay branching fractions, *Phys. Rev. D* 104 (2021) 032005, <https://doi.org/10.1103/PhysRevD.104.032005>, arXiv:2103.06810.
- [72] Y.S. Amhis, et al., HFLAV, Averages of b-hadron, c-hadron, and  $\tau$ -lepton properties as of 2018, *Eur. Phys. J. C* 81 (2021) 226, <https://doi.org/10.1140/epjc/s10052-020-8156-7>, arXiv:1909.12524.
- [73] LHCb Collaboration, Measurement of the fragmentation fraction ratio  $f_s/f_d$  and its dependence on B meson kinematics, *J. High Energy Phys.* 04 (2013) 001, [https://doi.org/10.1007/JHEP04\(2013\)001](https://doi.org/10.1007/JHEP04(2013)001), arXiv:1301.5286.
- [74] LHCb Collaboration, Measurement of b hadron fractions in 13 TeV pp collisions, *Phys. Rev. D* 100 (2019) 031102, <https://doi.org/10.1103/PhysRevD.100.031102>, arXiv:1902.06794.

## The CMS Collaboration

### A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia



W. Adam, F. Ambroggi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth<sup>1</sup>, M. Jeitler<sup>1</sup>, N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck<sup>1</sup>, R. Schöffbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz<sup>1</sup>, M. Zarucki

*Institut für Hochenergiephysik, Vienna, Austria*

V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

*Institute for Nuclear Problems, Minsk, Belarus*

M.R. Darwish<sup>2</sup>, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello<sup>3</sup>, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

*Universiteit Antwerpen, Antwerpen, Belgium*

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskiy, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

*Vrije Universiteit Brussel, Brussel, Belgium*

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

*Université Libre de Bruxelles, Bruxelles, Belgium*

T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov<sup>4</sup>, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

*Ghent University, Ghent, Belgium*

G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliencio, M. Teklishyn, P. Vischia, S. Wuyckens, J. Zobec

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

G.A. Alves, C. Hensel, A. Moraes

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

W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. Brandao Malbouisson, W. Carvalho, J. Chinellato<sup>5</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>6</sup>, D. De Jesus Damiao, S. Fonseca De Souza, J. Martins<sup>7</sup>, D. Matos Figueiredo, M. Medina Jaime<sup>8</sup>, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, E.J. Tonelli Manganote<sup>5</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

C.A. Bernardes<sup>a,b</sup>, L. Calligaris<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>a,b</sup>, D.S. Lemos<sup>a</sup>, P.G. Mercadante<sup>a,b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

<sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil*

<sup>b</sup> *Universidade Federal do ABC, São Paulo, Brazil*

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

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

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

*University of Sofia, Sofia, Bulgaria*

W. Fang<sup>3</sup>, Q. Guo, H. Wang, L. Yuan

Beihang University, Beijing, China

M. Ahmad, Z. Hu, Y. Wang

Department of Physics, Tsinghua University, China

E. Chapon, G.M. Chen<sup>9</sup>, H.S. Chen<sup>9</sup>, M. Chen, A. Kapoor, D. Leggat, H. Liao, Z. Liu, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang<sup>9</sup>, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

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

Z. You

Sun Yat-Sen University, Guangzhou, China

X. Gao<sup>3</sup>

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

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

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

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov<sup>10</sup>, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger<sup>11</sup>, M. Finger Jr.<sup>11</sup>, A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

S. Elgammal<sup>12</sup>, A. Ellithi Kamel<sup>13</sup>, A. Mohamed<sup>14</sup>

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

M.A. Mahmoud, Y. Mohammed<sup>15</sup>

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

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

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

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

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

E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

*Helsinki Institute of Physics, Helsinki, Finland*

P. Luukka, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro<sup>16</sup>, M. Titov, G.B. Yu

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

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

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

J.-L. Agram<sup>17</sup>, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine<sup>17</sup>, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

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

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

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

T. Toriashvili<sup>18</sup>, Z. Tsamalaidze<sup>11</sup>

*Georgian Technical University, Tbilisi, Georgia*

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

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

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad<sup>19</sup>, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl<sup>20</sup>, T. Ziemons

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras<sup>21</sup>, V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, L.I. Estevez Banos, E. Gallo<sup>22</sup>, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari<sup>23</sup>, N.Z. Jomhari, H. Jung, A. Kasem<sup>21</sup>, M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann<sup>24</sup>, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otariid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebick

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

*University of Hamburg, Hamburg, Germany*

M. Baselga, S. Baur, J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann<sup>20</sup>, C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov<sup>25</sup>, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniowski

*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

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

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

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

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsiapolitis, A. Zacharopoulou

*National Technical University of Athens, Athens, Greece*

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strologas

*University of Ioánnina, Ioánnina, Greece*

M. Bartók<sup>26</sup>, R. Chudasama, M. Csanad, M.M.A. Gadallah<sup>27</sup>, S. Lökös<sup>28</sup>, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath<sup>29</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>†</sup>

*Wigner Research Centre for Physics, Budapest, Hungary*

S. Czellar, J. Karancsi<sup>26</sup>, J. Molnar, Z. Szillasi, D. Teyssier

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*



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

*Institute of Physics, University of Debrecen, Germany*

T. Csorgo, F. Nemes, T. Novak

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

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

*Indian Institute of Science (IISc), Bangalore, India*

S. Bahinipati<sup>30</sup>, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak<sup>31</sup>,  
D.K. Sahoo<sup>30</sup>, N. Sur, S.K. Swain

*National Institute of Science Education and Research, HBNI, Bhubaneswar, India*

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra<sup>32</sup>, R. Gupta, A. Kaur, S. Kaur, P. Kumari,  
M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi

*Panjab University, Chandigarh, India*

A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin,  
P. Priyanka, K. Ranjan, A. Shah

*University of Delhi, Delhi, India*

M. Bharti<sup>33</sup>, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber<sup>34</sup>, M. Maity<sup>35</sup>,  
S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh<sup>33</sup>, S. Thakur<sup>33</sup>

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

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

*Indian Institute of Technology Madras, Madras, India*

D. Dutta, V. Kumar, K. Naskar<sup>36</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, G.B. Mohanty, U. Sarkar

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

S. Banerjee, S. Bhattacharya, S. Chatterjee, M. Guchait, S. Karmakar, S. Kumar, G. Majumder,  
K. Mazumdar, S. Mukherjee, D. Roy, N. Sahoo

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

S. Dube, B. Kansal, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

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

H. Bakhshiansohi<sup>37</sup>

*Isfahan University of Technology, Isfahan, Iran*

S. Chenarani<sup>38</sup>, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Felcini, M. Grunewald

*University College Dublin, Dublin, Ireland*

M. Abbrescia<sup>a,b</sup>, R. Aly<sup>a,b,39</sup>, C. Aruta<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>,  
A. Di Florio<sup>a,b</sup>, A. Di Pilato<sup>a,b</sup>, W. Elmetenawee<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, M. Gul<sup>a</sup>, G. Iaselli<sup>a,c</sup>,

M. Ince<sup>a,b</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, I. Margjeka<sup>a,b</sup>, V. Mastrapasqua<sup>a,b</sup>, J.A. Merlin<sup>a</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, F.M. Simone<sup>a,b</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, T. Diotallevi<sup>a,b</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, E. Fontanesi<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, L. Giommi<sup>a,b</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, F. Iemmi<sup>a,b</sup>, S. Lo Meo<sup>a,40</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo<sup>a,b,41</sup>, S. Costa<sup>a,b,41</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,41</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

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

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

A. Benaglia<sup>a</sup>, A. Beschi<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, F. Cettorelli<sup>a,b</sup>, V. Ciriolo<sup>a,b,20</sup>, F. De Guio<sup>a,b</sup>, M.E. Dinardo<sup>a,b</sup>, P. Dini<sup>a</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, L. Guzzi<sup>a,b</sup>, M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup>, D. Menasce<sup>a</sup>, F. Monti<sup>a,b</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>, D. Valsecchi<sup>a,b,20</sup>, D. Zuolo<sup>a,b</sup>

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

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, A. De Iorio<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Lista<sup>a,b</sup>, S. Meola<sup>a,d,20</sup>, P. Paolucci<sup>a,20</sup>, B. Rossi<sup>a</sup>, C. Sciacca<sup>a,b</sup>, E. Voevodina<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli "Federico II", Napoli, Italy

<sup>c</sup> Università della Basilicata, Potenza, Italy

<sup>d</sup> Università G. Marconi, Roma, Italy

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, A. Bragagnolo<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, S.Y. Hoh<sup>a,b</sup>, L. Layer<sup>a,42</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Presilla<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, G. Strong<sup>a</sup>, A. Tiko<sup>a</sup>, M. Tosi<sup>a,b</sup>, H. Yarar<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento, Trento, Italy

C. Aime<sup>a,b</sup>, A. Braghieri<sup>a</sup>, S. Calzaferri<sup>a,b</sup>, D. Fiorina<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>

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

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

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

K. Androsov <sup>a</sup>, P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, V. Bertacchi <sup>a,c</sup>, L. Bianchini <sup>a</sup>, T. Boccali <sup>a</sup>, R. Castaldi <sup>a</sup>,  
M.A. Ciocci <sup>a,b</sup>, R. Dell'Orso <sup>a</sup>, M.R. Di Domenico <sup>a,d</sup>, S. Donato <sup>a</sup>, L. Giannini <sup>a,c</sup>, A. Giassi <sup>a</sup>, M.T. Grippo <sup>a</sup>,  
F. Ligabue <sup>a,c</sup>, E. Manca <sup>a,c</sup>, G. Mandorli <sup>a,c</sup>, A. Messineo <sup>a,b</sup>, F. Palla <sup>a</sup>, G. Ramirez-Sanchez <sup>a,c</sup>, A. Rizzi <sup>a,b</sup>,  
G. Rolandi <sup>a,c</sup>, S. Roy Chowdhury <sup>a,c</sup>, A. Scribano <sup>a</sup>, N. Shafiei <sup>a,b</sup>, P. Spagnolo <sup>a</sup>, R. Tenchini <sup>a</sup>, G. Tonelli <sup>a,b</sup>,  
N. Turini <sup>a,d</sup>, A. Venturi <sup>a</sup>, P.G. Verdini <sup>a</sup>

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

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

<sup>a</sup> INFN Sezione di Roma, Rome, Italy<sup>b</sup> Sapienza Università di Roma, Rome, 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>, A. Cappati <sup>a,b</sup>, N. Cartiglia <sup>a</sup>, S. Cometti <sup>a</sup>, M. Costa <sup>a,b</sup>, R. Covarelli <sup>a,b</sup>, N. Demaria <sup>a</sup>, B. Kiani <sup>a,b</sup>,  
F. Legger <sup>a</sup>, C. Mariotti <sup>a</sup>, S. Maselli <sup>a</sup>, E. Migliore <sup>a,b</sup>, V. Monaco <sup>a,b</sup>, E. Monteil <sup>a,b</sup>, M. Monteno <sup>a</sup>,  
M.M. Obertino <sup>a,b</sup>, G. Ortona <sup>a</sup>, L. Pacher <sup>a,b</sup>, N. Pastrone <sup>a</sup>, M. Pelliccioni <sup>a</sup>, G.L. Pinna Angioni <sup>a,b</sup>,  
M. Ruspa <sup>a,c</sup>, R. Salvatico <sup>a,b</sup>, F. Siviero <sup>a,b</sup>, V. Sola <sup>a</sup>, A. Solano <sup>a,b</sup>, D. Soldi <sup>a,b</sup>, A. Staiano <sup>a</sup>, D. Trocino <sup>a,b</sup>

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

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

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

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

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon

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

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Korea University, Seoul, Republic of Korea

J. Goh, A. Gurtu

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

H.S. Kim, Y. Kim

Sejong University, Seoul, Republic of Korea

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

*Seoul National University, Seoul, Republic of Korea*

D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

*University of Seoul, Seoul, Republic of Korea*

H.D. Yoo

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

Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

*Sungkyunkwan University, Suwon, Republic of Korea*

Y. Maghrbi

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

V. Veckalns<sup>43</sup>

*Riga Technical University, Latvia*

A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

*Vilnius University, Vilnius, Lithuania*

W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

*Universidad de Sonora (UNISON), Hermosillo, Mexico*

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>44</sup>, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

*Universidad Iberoamericana, Mexico City, Mexico*

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

*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

A. Morelos Pineda

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

J. Mijuskovic<sup>4</sup>, N. Raicevic

*University of Montenegro, Podgorica, Montenegro*

D. Krofcheck

*University of Auckland, Auckland, New Zealand*

S. Bheesette, P.H. Butler

*University of Canterbury, Christchurch, New Zealand*

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

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



V. Avati, L. Grzanka, M. Malawski

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

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szeleper, P. Traczyk, P. Zalewski

*National Centre for Nuclear Research, Swierk, Poland*

K. Bunkowski, A. Byszuk<sup>45</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

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

M. Araujo, P. Bargassa, D. Bastos, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, J. Silva, O. Toldaiev, J. Varela

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev<sup>46,47</sup>, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev<sup>48</sup>, A. Zarubin, I. Zhizhin

*Joint Institute for Nuclear Research, Dubna, Russia*

G. Gavrilo, V. Golovtsov, Y. Ivanov, V. Kim<sup>49</sup>, E. Kuznetsova<sup>50</sup>, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov<sup>†</sup>, A. Toropin

*Institute for Nuclear Research, Moscow, Russia*

V. Epshteyn, V. Gavrilo, N. Lychkovskaya, A. Nikitenko<sup>51</sup>, V. Popov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

*Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia*

T. Aushev

*Moscow Institute of Physics and Technology, Moscow, Russia*

R. Chistov<sup>52</sup>, M. Danilov<sup>53</sup>, A. Oskin, P. Parygin, S. Polikarpov<sup>53</sup>

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

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

*P.N. Lebedev Physical Institute, Moscow, Russia*

A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy<sup>54</sup>, O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

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

V. Blinov<sup>55</sup>, T. Dimova<sup>55</sup>, L. Kardapoltsev<sup>55</sup>, I. Ovtin<sup>55</sup>, Y. Skovpen<sup>55</sup>

*Novosibirsk State University (NSU), Novosibirsk, Russia*

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

*Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia*

A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh

*National Research Tomsk Polytechnic University, Tomsk, Russia*

V. Borchsh, V. Ivanchenko, E. Tcherniaev

*Tomsk State University, Tomsk, Russia*

P. Adzic<sup>56</sup>, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic

*University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia*

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, A. García Alonso, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, L. Urda Gómez, C. Willmott

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

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

*Universidad Autónoma de Madrid, Madrid, Spain*

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizán Garcia

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

M.K. Jayananda, B. Kailasapathy<sup>57</sup>, D.U.J. Sonnadara, D.D.C. Wickramaratna

*University of Colombo, Colombo, Sri Lanka*

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

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

T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita<sup>58</sup>, D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, D. Gulhan, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleo<sup>20</sup>, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabaday, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas<sup>59</sup>, J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsiros, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

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

L. Caminada<sup>60</sup>, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

*Paul Scherrer Institut, Villigen, Switzerland*

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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

C. Amsler<sup>61</sup>, C. Botta, D. Brzhechko, M.F. Canelli, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

*Universität Zürich, Zurich, Switzerland*

C. Adloff<sup>62</sup>, C.M. Kuo, W. Lin, A. Roy, T. Sarkar<sup>35</sup>, S.S. Yu

*National Central University, Chung-Li, Taiwan*

L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan

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

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

M.N. Bakirci<sup>63</sup>, F. Boran, S. Damarseckin<sup>64</sup>, Z.S. Demiroglu, F. Dolek, C. Dozen<sup>65</sup>, I. Dumanoglu<sup>66</sup>, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler<sup>67</sup>, I. Hos<sup>68</sup>, C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir<sup>69</sup>, A. Polatoz, A.E. Simsek, U.G. Tok, H. Topakli<sup>70</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak<sup>71</sup>, G. Karapinar<sup>72</sup>, K. Ocalan<sup>73</sup>, M. Yalvac<sup>74</sup>

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

I.O. Atakisi, E. Gülmez, M. Kaya<sup>75</sup>, O. Kaya<sup>76</sup>, Ö. Özçelik, S. Tekten<sup>77</sup>, E.A. Yetkin<sup>78</sup>

*Bogazici University, Istanbul, Turkey*

A. Cakir, K. Cankocak<sup>66</sup>, Y. Komurcu, S. Sen<sup>79</sup>

*Istanbul Technical University, Istanbul, Turkey*

F. Aydogmus Sen, S. Cerci<sup>80</sup>, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci<sup>80</sup>

*Istanbul University, Istanbul, Turkey*

B. Grynyov

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

L. Levchuk

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

E. Bhal, S. Bologna, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>81</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal<sup>82</sup>, D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash<sup>83</sup>, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee<sup>20</sup>, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

*Imperial College, London, United Kingdom*

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

*Brunel University, Uxbridge, United Kingdom*

A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson

*Baylor University, Waco, USA*

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

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

A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

*The University of Alabama, Tuscaloosa, USA*

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, S. Yuan, D. Zou

*Boston University, Boston, USA*

G. Benelli, B. Burkle, X. Coubez<sup>21</sup>, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan<sup>84</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir<sup>85</sup>, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

*Brown University, Providence, USA*

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko<sup>†</sup>, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

*University of California, Davis, Davis, USA*

M. Bachtis, R. Cousins, A. Dasgupta, D. Hamilton, J. Hauser, M. Ignatenko, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

*University of California, Los Angeles, USA*

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganeli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

*University of California, Riverside, Riverside, USA*

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

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



N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

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

D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

*California Institute of Technology, Pasadena, USA*

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

*University of Colorado Boulder, Boulder, USA*

J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

*Cornell University, Ithaca, USA*

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena<sup>86</sup>, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

*University of Florida, Gainesville, USA*

T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

*Florida State University, Tallahassee, USA*

M.M. Baarmand, S. Butalla, T. Elkafrawy<sup>87</sup>, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu

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

M. Alhusseini, K. Dilsiz<sup>88</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili<sup>89</sup>, A. Moeller, J. Nachtman, H. Ogul<sup>90</sup>, Y. Onel, F. Ozok<sup>91</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi<sup>92</sup>

*The University of Iowa, Iowa City, USA*

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

*Johns Hopkins University, Baltimore, USA*

C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

*The University of Kansas, Lawrence, USA*

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, A. Mohammadi

*Kansas State University, Manhattan, USA*

F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

*University of Maryland, College Park, USA*

D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, G.J. Kim, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, Z. Wang, B. Wyslouch

*Massachusetts Institute of Technology, Cambridge, USA*

R.M. Chatterjee, A. Evans, S. Guts<sup>†</sup>, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, I. Kravchenko, J.E. Siado, G.R. Snow<sup>†</sup>, B. Stieger, W. Tabb, F. Yan

*University of Nebraska-Lincoln, Lincoln, USA*

G. Agarwal, H. Bandyopadhyay, C. Harrington, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, B. Roozbahani

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

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

*Northeastern University, Boston, USA*

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

*Northwestern University, Evanston, USA*

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko<sup>46</sup>, R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

*University of Notre Dame, Notre Dame, USA*

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

*The Ohio State University, Columbus, USA*

P. Das, G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

*Princeton University, Princeton, USA*

S. Malik, S. Norberg

*University of Puerto Rico, Mayaguez, USA*

V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, M. Stojanovic<sup>16</sup>, N. Trevisani, F. Wang, R. Xiao, W. Xie

*Purdue University, West Lafayette, USA*

T. Cheng, J. Dolen, N. Parashar

*Purdue University Northwest, Hammond, USA*

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts<sup>†</sup>, J. Rorie, W. Shi, A.G. Stahl Leiton

*Rice University, Houston, USA*

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

*University of Rochester, Rochester, USA*

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban<sup>24</sup>, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

H. Acharya, A.G. Delannoy, S. Spanier

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>93</sup>, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>94</sup>, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov, J. Sturdy

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

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

*Texas Tech University, Lubbock, USA*

E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

*Vanderbilt University, Nashville, USA*

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

P.E. Karchin, N. Poudyal, P. Thapa

Wayne State University, Detroit, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

University of Wisconsin - Madison, Madison, WI, USA

† Deceased.

<sup>1</sup> Also at TU Wien, Wien, Austria.

<sup>2</sup> Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

<sup>3</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>4</sup> Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

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

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

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

<sup>8</sup> Also at Universidade Federal de Pelotas, Pelotas, Brazil.

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

<sup>10</sup> Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia.

<sup>11</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>12</sup> Now at British University in Egypt, Cairo, Egypt.

<sup>13</sup> Now at Cairo University, Cairo, Egypt.

<sup>14</sup> Also at Zewail City of Science and Technology, Zewail, Egypt.

<sup>15</sup> Now at Fayoum University, El-Fayoum, Egypt.

<sup>16</sup> Also at Purdue University, West Lafayette, USA.

<sup>17</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>18</sup> Also at Tbilisi State University, Tbilisi, Georgia.

<sup>19</sup> Also at Erzincan Binali Yildirim University, Erzincan, Turkey.

<sup>20</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>21</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>22</sup> Also at University of Hamburg, Hamburg, Germany.

<sup>23</sup> Also at Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran.

<sup>24</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>25</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>26</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

<sup>27</sup> Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.

<sup>28</sup> Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

<sup>29</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>30</sup> Also at IIT Bhubaneswar, Bhubaneswar, India.

<sup>31</sup> Also at Institute of Physics, Bhubaneswar, India.

<sup>32</sup> Also at G.H.G. Khalsa College, Punjab, India.

<sup>33</sup> Also at Shoolini University, Solan, India.

<sup>34</sup> Also at University of Hyderabad, Hyderabad, India.

<sup>35</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>36</sup> Also at Indian Institute of Technology (IIT), Mumbai, India.

<sup>37</sup> Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

<sup>38</sup> Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.

<sup>39</sup> Now at INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy.

<sup>40</sup> Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.

<sup>41</sup> Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

<sup>42</sup> Also at Università di Napoli 'Federico II', Napoli, Italy.

<sup>43</sup> Also at Riga Technical University, Riga, Latvia.

<sup>44</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

<sup>45</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

<sup>46</sup> Also at Institute for Nuclear Research, Moscow, Russia.

<sup>47</sup> Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

<sup>48</sup> Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.

<sup>49</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>50</sup> Also at University of Florida, Gainesville, USA.

<sup>51</sup> Also at Imperial College, London, United Kingdom.

<sup>52</sup> Also at Moscow Institute of Physics and Technology, Moscow, Russia, Moscow, Russia.



- <sup>53</sup> Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- <sup>54</sup> Also at INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy, Padova, Italy.
- <sup>55</sup> Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- <sup>56</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>57</sup> Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- <sup>58</sup> Also at INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy.
- <sup>59</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.
- <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 Gaziosmanpasa University, Tokat, Turkey.
- <sup>64</sup> Also at Şırnak University, Şırnak, Turkey.
- <sup>65</sup> Also at Department of Physics, Tsinghua University, Beijing, China.
- <sup>66</sup> Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
- <sup>67</sup> Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey.
- <sup>68</sup> Also at Istanbul Aydın University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey.
- <sup>69</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>70</sup> Also at Tarsus University, MERSIN, Turkey.
- <sup>71</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>72</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>73</sup> Also at Necmettin Erbakan University, Konya, Turkey.
- <sup>74</sup> Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- <sup>75</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>76</sup> Also at Milli Savunma University, Istanbul, Turkey.
- <sup>77</sup> Also at Kafkas University, Kars, Turkey.
- <sup>78</sup> Also at Istanbul Bilgi University, Istanbul, Turkey.
- <sup>79</sup> Also at Hacettepe University, Ankara, Turkey.
- <sup>80</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>81</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>82</sup> Also at IPPP Durham University, Durham, United Kingdom.
- <sup>83</sup> Also at Monash University, Faculty of Science, Clayton, Australia.
- <sup>84</sup> Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
- <sup>85</sup> Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- <sup>86</sup> Also at California Institute of Technology, Pasadena, USA.
- <sup>87</sup> Also at Ain Shams University, Cairo, Egypt.
- <sup>88</sup> Also at Bingol University, Bingol, Turkey.
- <sup>89</sup> Also at Georgian Technical University, Tbilisi, Georgia.
- <sup>90</sup> Also at Sinop University, Sinop, Turkey.
- <sup>91</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>92</sup> Also at Nanjing Normal University Department of Physics, Nanjing, China.
- <sup>93</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>94</sup> Also at Kyungpook National University, Daegu, Korea, Daegu, Korea.