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

The CMS collaboration

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

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

Keywords: B Physics, Heavy Ion Experiments, Quark Gluon Plasma

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Contents

1 Introduction

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

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

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

$$R_\mathrm{AA}(p_\mathrm{T}) = \frac{1}{T_\mathrm{AA}} \frac{\mathrm{d}N^{\mathrm{B}^+,\mathrm{B}^0_\mathrm{s}}_\mathrm{PbPb}}{\mathrm{d}p_\mathrm{T}} \Bigg/ \frac{\mathrm{d}\sigma^{\mathrm{B}^+,\mathrm{B}^0_\mathrm{s}}_\mathrm{pp}}{\mathrm{d}p_\mathrm{T}}, \tag{1.1}$$

where T_AA is the average number of NN binary collisions per PbPb interaction divided by the NN total inelastic cross section, which can be interpreted as the NN-equivalent integrated luminosity per heavy ion collision [52]. The reported R_AA results are for collisions with 0–90% centrality, corresponding to the 90% of collisions having the largest overlap of the two nuclei [10, 52]. Throughout this paper, unless otherwise specified, the y and p_T variables refer to the B mesons. All references to B mesons in the text also include the corresponding charge-conjugate state, although the quoted cross sections correspond to individual states i.e., the average of the two yields), as was done for the previous PbPb analysis [52]. Tabulated results are provided in the HEPData record for this analysis [53].

2 The CMS apparatus

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 3.0$. During the LHC running period when the data used in this paper were recorded, the silicon tracker consisted of 1856 silicon pixel and 15 148 silicon strip detector modules. Details on the pixel detector can be found in ref. [54]. For nonisolated particles of $1 < p_\mathrm{T} < 10\,\mathrm{GeV}/c$ and $|\eta| < 3.0$, the track resolutions are typically 1.5% in p_T and 20–75 μm in the transverse impact parameter [55]. Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The single-muon trigger efficiency exceeds 90% over the full η range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured

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in the silicon tracker results in a relative p_T resolution, for muons with $p_T < 100\,\text{GeV}/c$, of 1% in the barrel and 3% in the endcaps. The p_T resolution in the barrel is better than 7% for muons with $p_T < 1\,\text{TeV}/c$ [56]. The hadron forward (HF) calorimeters, situated 11.2 m from the interaction region on both sides, with the coverage in the range $3.0 < |\eta| < 5.2$, utilize steel for absorption and quartz fibers as sensitive material. Information from the HF is used for determining the centrality.

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

3 Analysis method

3.1 Candidate reconstruction and selection

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

For the offline analysis, events must pass a set of selection criteria designed to reject non-collision events and to select only inelastic hadronic collisions [60, 61]. Events are required to have at least one reconstructed primary interaction vertex, formed by two or more tracks, with a distance from the center of the nominal interaction region of less than 25 cm along the beam axis. The shapes of the clusters in the pixel detector must be compatible with those expected from particles produced in a ppcollision [62]. To select inelastic hadronic collisions, the ppevents are also required to have at least one tower in both of the HF detectors with an energy deposit of more than 4 GeV.

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

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

The final B candidate selection is determined via multivariate discriminators based on a boosted decision tree (BDT) [71]. The same discriminating variables are employed as in the PbPb data analysis. These include the χ^2 probability of the decay vertex (the probability for the muon tracks from the J/ψ meson decay and the other charged-hadron track(s) to originate from a common vertex), the distance from the primary to the B decay vertices (normalized by its uncertainty), the pointing angle (the angle between the line segment connecting the primary and decay vertices and the momentum vector of the B meson), the p_T of the daughter charged-hadron track(s), and the transverse and longitudinal track distances of closest approach to the primary vertex, normalized by their uncertainties. For the B^0_s meson, an additional selection variable is used: the absolute difference between the reconstructed $\phi(1020)$ meson invariant mass and its nominal value. The BDT training is performed by employing the MC-simulated B signal samples, and background samples taken from data sidebands constructed using candidates with the invariant mass away from the B meson nominal mass, $0.25 < |m_{B^+} - m^{PDG}_{B^+}| < 0.30\,\mathrm{GeV}/c^2$ and $0.20 < |m_{B^0_s} - m^{PDG}_{B^0_s}| < 0.30\,\mathrm{GeV}/c^2$, where $m^{PDG}_{B^+} = 5279.32\,(\pm 0.14)\,\mathrm{MeV}/c^2$ and $m^{PDG}_{B^0_s} = 5366.89\,(\pm 0.19)\,\mathrm{MeV}/c^2$ are the world-average masses given by the Particle Data Group (PDG) [64]. The signal samples are scaled to the expected number of B candidates calculated by the measured integrated luminosity and cross sections predicted by FONLL perturbative QCD calculations [33]. The BDT selection is individually optimized for each meson and p_T range to maximize the figure of merit $S/\sqrt{S+B}$. Here, S and B are the number of signal and background candidates, respectively, in the signal region after applying the selection criteria. The signal region is defined as $|m_B - m^{PDG}_B| < 0.08\,\mathrm{GeV}/c^2$.

3.2 Differential cross sections

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

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

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

$$\frac{d\sigma_{pp}}{dp_T} = \frac{1}{2}\frac{N_{obs}(p_T)}{\mathcal{B}\,\mathcal{L}}\frac{1}{\Delta p_T}\left\langle\frac{1}{\alpha(p_T,y)\,\epsilon(p_T,y)}\right\rangle, \tag{3.1}$$

where N_{obs} is the raw signal yield extracted in each p_T interval of width Δp_T, $\mathcal{B}$ is the branching fraction of the corresponding decay chain obtained from ref. [64], and $\mathcal{L}$ is the integrated luminosity. The factor $\frac{1}{2}$ is to quote the production cross sections for particles, whereas the raw yields include both particles and antiparticles. The acceptance and efficiency factor, $\langle 1/(\alpha(p_T,y)\epsilon(p_T,y))\rangle$, is obtained employing two-dimensional (2D), fine-grained maps of acceptance $\alpha(p_T,y)$ and efficiency $\epsilon(p_T,y)$. The acceptance corresponds to the fraction of generated signal events passing the muon and kaon selection thresholds. The efficiency is determined as the fraction of accepted signal events that pass the complete analysis selection criteria, including losses resulting from inefficiencies in the event trigger. These maps are determined from MC-simulated samples of B meson signal events generated within the fiducial region in the analysis. The maps are used to determine the $1/(\alpha\epsilon)$ value for each B candidate in data, based on the kinematics (p_T, y) of the candidates. The corresponding average $\langle 1/(\alpha\epsilon)\rangle$ was obtained for the candidates within a $\pm 80\,\mathrm{MeV}/c^2$ window centered on the B meson's world-average mass. Combinatorial background can influence the p_T and y dependent correction factor by distorting the average $1/(\alpha\epsilon)$ value from that which would be obtained if this background could be excluded. The impact of combinatorial background is studied and included as a systematic uncertainty. The efficiency maps derived from the simulation are corrected by data-to-simulation scale factors for the muon reconstruction and trigger efficiencies, obtained by applying the "tag-and-probe" method [72] using the J/ψ resonance.

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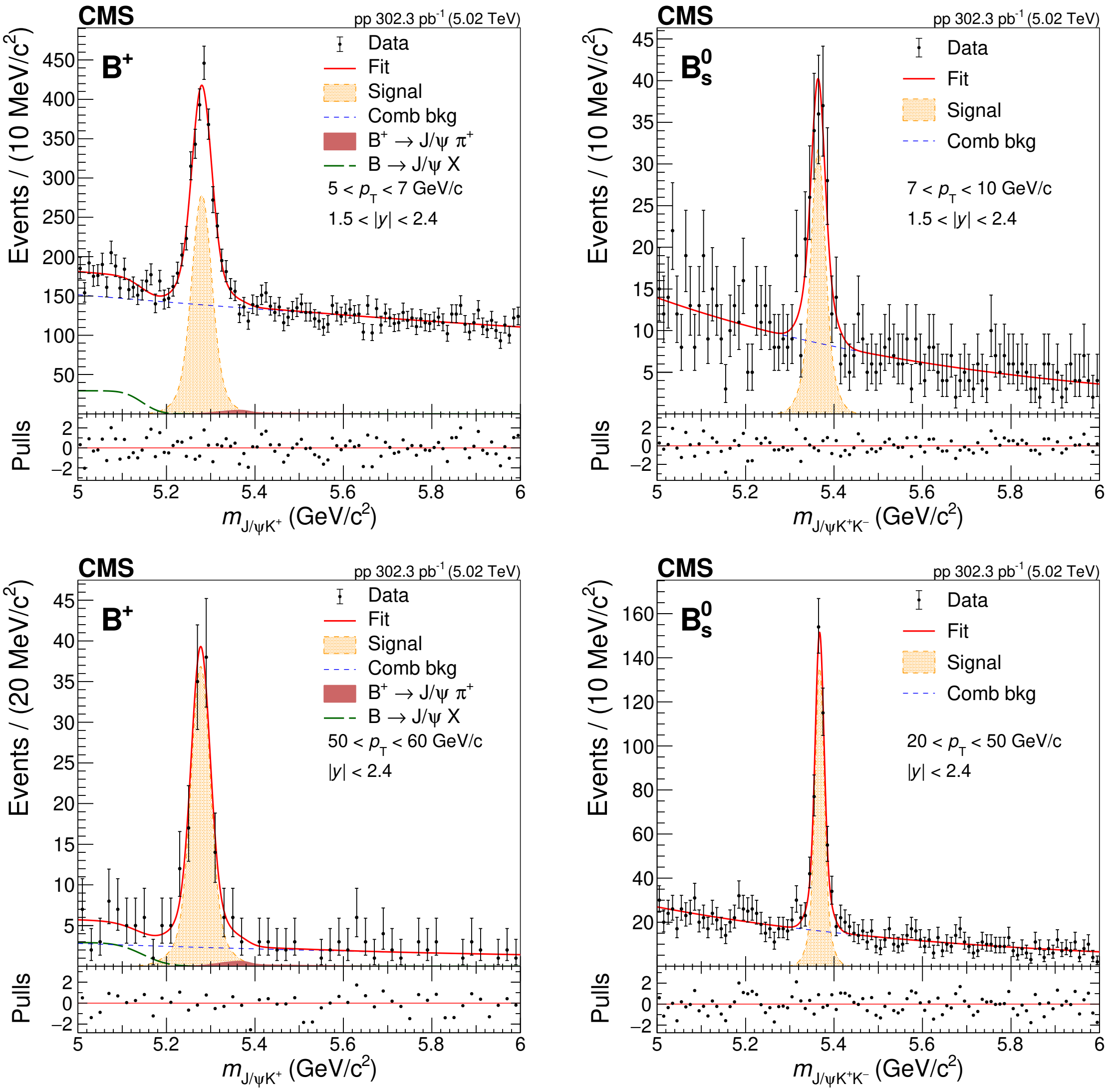

Figure 1. Invariant mass distributions of B^+ (left) and B^0_s (right) candidates, for the lowest (upper) and highest (lower) p_T ranges in ppcollisions at $\sqrt{s} = 5.02$ TeV. The bottom section in each panel shows the pulls, calculated as the difference between the data points and the fit results,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

4 Systematic uncertainties

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

The uncertainty in the raw yield extraction is evaluated by considering the following fitting model variations: (i) using a sum of three Gaussian functions with a common mean, (ii) using a sum of a Gaussian function and a Crystal Ball function [73], (iii) fixing the double-Gaussian mean to its MC simulation value for the signal modeling instead of letting it be a free parameter, (iv) using low-order polynomials for describing the combinatorial

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background, and (v) changing the fitting range from 5–6 GeV/c^2 to 5.19–6 GeV/c^2 to minimize the $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{X}$ component in the background modeling. For each p_T interval, we take the maximum of the percent difference between the varied and the nominal yield among (i)–(iii) as the signal uncertainty and (iv)–(v) as the background uncertainty. The signal and background uncertainties are added in quadrature as the systematic uncertainty in raw yield extraction.

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

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

The total systematic uncertainties in the cross sections are computed as the sum in quadrature of the different contributions mentioned above, which are summarized in table 1 for the B^+ and B^0_s cross sections. The systematic uncertainties resulting from the fitting model

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

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

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

variation, the discrepancy between the MC simulation and the experimental results for the discriminating variables, the background contamination of the efficiency, the muon efficiency, the track selection, and the integrated luminosity for ppand PbPb are taken as independent and added in quadrature as the systematic uncertainty in the nuclear modification factors. On the other hand, for the R_{AA} calculations, the branching fractions are common to the ppand PbPb systems and, consequently, do not impact the results. The track reconstruction efficiencies used for the two systems also have common elements, resulting in partial cancellation of the corresponding uncertainties when calculating the R_{AA} values. The global uncertainties in R_{AA} consist of the uncertainties in T_{AA}, the number of minimum bias events, and the integrated luminosity in ppcollisions.

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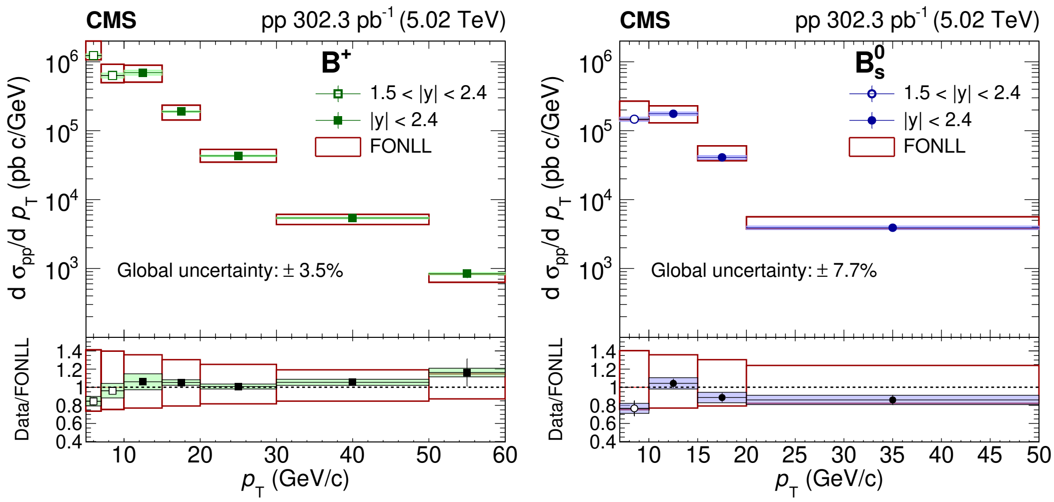

Figure 2. The p_T-differential cross sections of B^+ (left) and B^0_s (right) mesons in ppcollisions at $\sqrt{s} = 5.02\,\mathrm{TeV}$. The vertical bars (shaded boxes) correspond to statistical (systematic) uncertainties. The horizontal bars reflect the bin widths. The global systematic uncertainty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

5 Results

The p_T-differential production cross sections of B^+ and B^0_s mesons are presented in figure 2. The results are compared to the cross sections obtained from FONLL calculations [33], which are obtained by scaling the FONLL total b quark production [31–33] by the production fractions at high energy of 40.1% for B^+ mesons [76] and 10.3% for B^0_s mesons [77]. The calculated FONLL reference spectra are consistent with the ppspectra measured for both the B^+ and B^0_s mesons within the quoted uncertainties. With smaller experimental uncertainties, these measurements are useful for constraining the b-quark fragmentation functions.

The nuclear modification factors of B^+ and B^0_s, determined according to eq. (1.1), are shown in figure 3 as a functions of p_T. For the B^+ meson a strong suppression is observed in PbPb collisions (with R_AA values significantly below unity). In the range $7 < p_\mathrm{T} < 50\,\mathrm{GeV}/c$, R_AA varies from 0.3 to 0.6. For the B^0_s meson, the central value is found to be larger than 1 (i.e., a production enhancement) in the range $7 < p_\mathrm{T} < 10\,\mathrm{GeV}/c$, although the large uncertainty suggests that it is also consistent with the R_AA values at higher p_T. In the range $10 < p_\mathrm{T} < 50\,\mathrm{GeV}/c$ the R_AA values are also smaller than unity, but larger than those found for the B^+ meson. This observation, together with the trend of B^0_s production enhancement observed over higher p_T ranges, suggests that recombination may play an important role in the production of B^0_s mesons, especially at low p_T, although reduced uncertainties for the PbPb results are needed to establish this effect.

The p_T dependence of the B^+ R_AA values are compared to the predictions of three types of models: (a) two perturbative QCD-based models that include both collisional and radiative energy loss (DREENA-A [79, 80] and CUJET3.0 [81–83]); (b) a transport model based on a

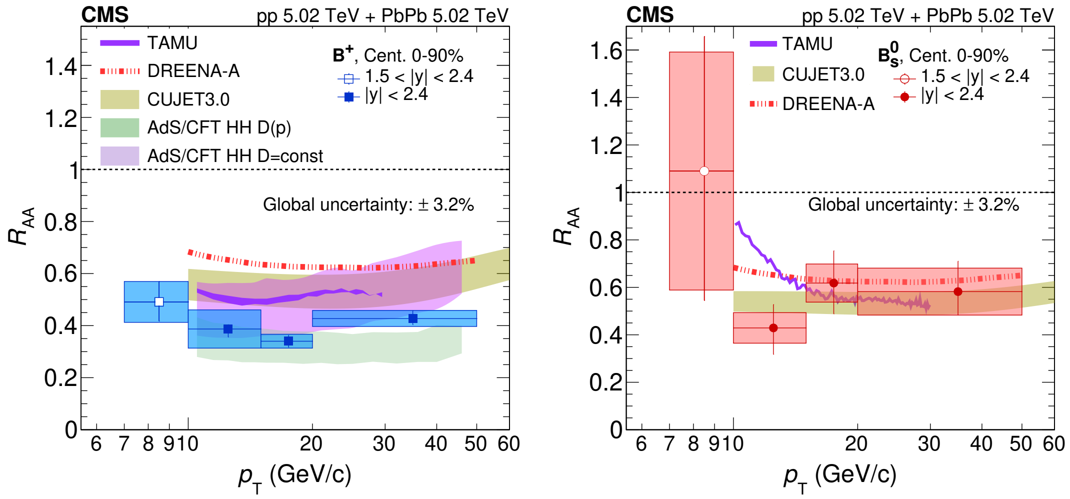

Figure 3. The p_{T} dependence of the nuclear modification factor of B^+ (left) and $\mathrm{B}^0_{\mathrm{s}}$ (right) mesons using PbPb and ppcollisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The horizontal bars reflect the bin widths and not uncertainties.The global systematic uncertainty includes the uncertainties in the integrated luminosity, T_{AA}, and the number of minimum bias events [52]. For the B^+ meson, four theoretical calculations are also shown for comparison: TAMU [24, 78], DREENA-A [79, 80], CUJET3.0 [81–83], and AdS/CFT HH [84, 85] with the diffusion coefficient either dependent or independent of the quark momentum. For the $\mathrm{B}^0_{\mathrm{s}}$ meson, three theoretical calculations are shown for comparison: TAMU [24, 78], DREENA-A [79, 80], and CUJET3.0 [81–83]. The line width of the theoretical calculation from refs. [24, 78] indicates the uncertainty in the total b quark coalescence probability (no shadowing is applied). The rapidity range is $|y| < 2.4$ for all the theoretical predictions and, therefore, these predictions can only be compared to the measurements in the range of $p_{\mathrm{T}} > 10\,\mathrm{GeV}/c$.

Langevin equation featuring collisional energy loss and heavy quark diffusion in the medium (TAMU [24, 78]), with the spatial diffusion coefficient D_s characterizing the long-wavelength limit of heavy-flavor transport [6], and (c) a model based on the anti-de-Sitter/conformal field theory correspondence, that includes thermal fluctuations in the energy loss for heavy quarks in a strongly coupled plasma (AdS/CFT HH) [84, 85]. The AdS/CFT HH calculation is provided for two settings of the diffusion coefficient D of the heavy-quark propagation through the medium, either dependent on or independent of the quark momentum. Apart from the interactions between heavy quarks and the medium, the set of the (nuclear) parton distribution functions used for the initial heavy-quark p_{T} distributions are also different between these models. Furthermore, the difference includes the modeling of the PbPb medium (hydrodynamically [24, 81] or via a Glauber model [79, 80]) and the energy loss sources (partonic only [24, 81] or also hadronic [24]).

The TAMU model, which does not include radiative energy loss, overpredicts the observed B^+ R_{AA} values over the available $p_{\mathrm{T}} > 10\,\mathrm{GeV}/c$ range, where the radiative energy loss is expected to play a more significant role. The perturbative QCD-based models CUJET3.0 and DREENA-A both predict slightly weaker suppression than TAMU, despite the inclusion of radiative energy loss, with DREENA-A predicting the least suppression in the $10 < p_{\mathrm{T}} < 15\,\mathrm{GeV}/c$ range. The AdS/CFT HH calculation with the diffusion coefficient dependent

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on the quark momentum has the broadest agreement with the data, although it slightly underestimates the R_{AA} value in the highest p_T range. The R_{AA} values are compatible with the lower-end values predicted by AdS/CFT HH calculation with the diffusion coefficient independent of the quark momentum. The experimental R_{AA} value for the highest p_T range falls between the two AdS/CFT HH model predictions.

Given that the experimental uncertainties are smaller than the uncertainties of the theoretical calculations from CUJET3.0 and AdS/CFT HH, the current results could be used to optimize parameter settings in such models (e.g., the parton-medium coupling parameters in the AdS/CFT HH model) and constrain the relevance of collisional and radiative processes in the b quark energy loss [86, 87]. The B_s^0 R_{AA} result is compared to DREENA-A, TAMU, and CUJET3.0. The difference between TAMU and CUJET3.0 below $p_T = 15\,\mathrm{GeV}/c$ reflects the contribution from recombination processes, which are included in the TAMU model, but are not present in the CUJET3.0 model. Given the current statistical and systematic uncertainties, these three theoretical predictions are roughly compatible with the measurement.

The B^+ and B_s^0 R_{AA} are compared in figure 4 to the CMS measurements of the R_{AA} of B_c mesons [27], D^0 mesons [88], and charged particles [60] performed at the same energy and in either the same (0–90%) or a similar (0–100%) centrality range. For the heavy B_c mesons, the rapidity is similarly limited to the forward region at low p_T, and for the lighter charged particles and D^0 mesons the measurement is performed at mid-rapidity. The R_{AA} value for B_c mesons in the $7 < p_T < 50\,\mathrm{GeV}/c$ range is higher than that for B^+ mesons, with B_s^0 values falling in between. For B^+ mesons, the R_{AA} values are consistent with those of charged particles and D^0 mesons for $p_T > 10\,\mathrm{GeV}/c$. At lower p_T, a reduced level of suppression is observed, which is in line with expectations based on the quark mass dependence of parton energy loss [7, 89].

6 Summary

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

The nuclear modification factors (R_{AA}) are obtained from these differential cross sections and the corresponding measurements in lead-lead collisions. The R_{AA} of B_s^0 and B^+ mesons are significantly lower than unity for $p_T > 10\,\mathrm{GeV}/c$, while at lower p_T the B_s^0 meson results hint at having larger R_{AA} values than found for B^+ mesons. The R_{AA} data for B^+ and B_s^0 mesons are compared to theoretical calculations, providing constraints for the mechanisms of bottom quark energy loss and hadronization in the quark-gluon plasma. The results are also compared to experimental R_{AA} values for charm and light-flavor hadrons. The B^+ meson R_{AA} values are compatible with those found for generic charged hadrons and D^0 mesons in the p_T range from 10 to 30 GeV/c, while the R_{AA} values from 7 to 10 GeV/c are consistent with expectations based on the quark mass dependence of parton energy loss.

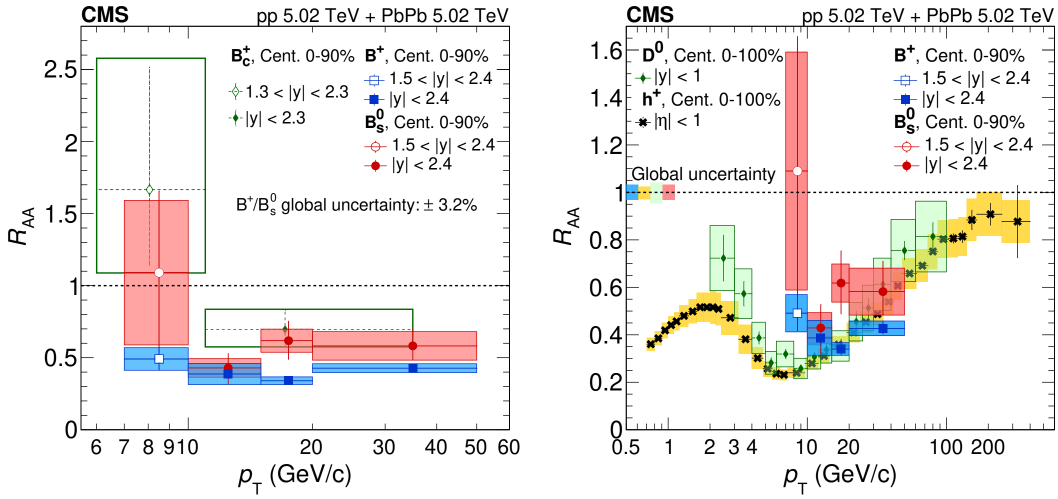

Figure 4. Comparison of the nuclear modification factor as a function of p_T of B^+ and B_s^0 mesons with B_c mesons [27] (left) as well as with D^0 mesons [88] and inclusive charged hadrons [60] (right) in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The horizontal bars reflect the bin widths. The global systematic uncertainties, written in text on the left plot and depicted in shaded boxes around $R_{AA} = 1$ on the right plot, comprise the uncertainties in T_{AA}, the number of minimum-bias events, and the luminosity in ppcollisions. The dashed lines and the open boxes in the B_c data (left plot) represent bin-to-bin-uncorrelated and total uncertainties, respectively.

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], T. Janssen, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[4], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Alves Gallo Pereira, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, A. Moraes, P. Rebello Teles, M. Soeiro, A. Vilela Pereira[5]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins[8], C. Mora Herrera, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

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Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

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

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

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu, K. Yi[9,10]

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

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

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

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

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

Nanjing Normal University, Nanjing, China
G. Bauer[15], B. Li, J. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[16]

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

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

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

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, S. Mishra, A. Starodumov[17], T. Susa

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

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[18,19], B. El-mahdy, S. Elgammal[19]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
H. Kirschenmann, K. Osterberg, M. Voutilainen

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

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, P. Busson, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[21], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

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

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[22], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[17], I. Lomidze, Z. Tsamalaidze[17]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung,

M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[23], S. Wiedenbeck, S. Zaleski

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

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

Deutsches Elektronen-Synchrotron, Hamburg, Germany

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

University of Hamburg, Hamburg, Germany

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

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[29], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, B. Maier, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

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

G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[29], A. Stakia

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National and Kapodistrian University of Athens, Athens, Greece
P. Kontaxakis, G. Melachroinos, Z. Painesis, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
C. Hajdu, D. Horvath[30,31], K. Márton, A.J. Rádl[32], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[33], M.M.A. Gadallah[34], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
F. Nemes[33], T. Novak

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[35], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[36], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[37], D. Kumar[37], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

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Tata Institute of Fundamental Research-A, Mumbai, India
S. Dugad, G.B. Mohanty, B. Parida, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[38], C. Kar, D. Maity[39], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[39], K. Naskar[39], A. Nayak[39], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[39], D. Vats[39]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[40], A. Alpana, S. Dube, B. Gomber[40], P. Hazarika, B. Kansal, A. Laha, B. Sahu[40], S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[41], A. Jafari[42], M. Zeinali[43]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[44], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie[45], M. Mohammadi Najafabadi, S. Tizchang[46]

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,47], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], P. Capiluppi[a,b], A. Castro[†,a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,48], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,49], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,49], C. Tuve[a,b]

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

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Meola[50], D. Piccolo

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

P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

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

A. Benaglia[a], G. Boldrini[a,b], F. Brivio[a], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], B.S. Pinolini[a], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy

S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,51], P. Paolucci[a,29], B. Rossi[a]

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

R. Ardino[a], P. Azzi[a], N. Bacchetta[a,52], M. Benettoni[a], A. Bergnoli[a], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A. Bragagnolo[a,b], A.C.M. Bulla[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], E. Lusiani[a], M. Margoni[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b]

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

C. Aimè[a], A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

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

S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,53], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

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

C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], M. Cipriani[a,b],

V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

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

C. Baldenegro Barrera[a,b], P. Barria[a], C. Basile[a,b], M. Campana[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a]

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

N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], R. White[a,b]

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

S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b]

Kyungpook National University, Daegu, Korea

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

Department of Mathematics and Physics - GWNU, Gangneung, Korea

M.S. Kim

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

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

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh, S. Yang

Sejong University, Seoul, Korea

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

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

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

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Gharbia

Kuwait University - College of Science - Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[54], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[55], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

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University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, H. Legoinha, N. Leonardo, G.B. Marozzo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic

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

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

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Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, P. Leguina, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Bhowmik, S. Blanco Fernández, J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[56], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[57], K. Liyanage, N. Perera

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

Paul Scherrer Institut, Villigen, Switzerland
T. Bevilacqua[60], L. Caminada[60], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[60], L. Noehte[60], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[59], M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[59], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani,

L. Marchese, C. Martin Perez, A. Mascellani[59], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, R. Seidita, J. Steggemann[59], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

C. Adloff[62], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[37], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

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

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

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

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

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

Middle East Technical University, Physics Department, Ankara, Turkey

G. Sokmen, M. Yalvac[67]

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[68], O. Kaya[69], S. Tekten[70]

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak[63,71], G.G. Dincer[63], Y. Komurcu, S. Sen[72]

Istanbul University, Istanbul, Turkey

O. Aydilek[73], B. Hacisahinoglu, I. Hos[74], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey

S. Cerci[66], B. Isildak[75], D. Sunar Cerci, T. Yetkin

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

A. Boyaryntsev, B. Grynyov

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National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[76], K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[77], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

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

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

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

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[80], E. Usai, R. Yi

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

Brown University, Providence, Rhode Island, USA
G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, J.M. Hogan[81], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, M. Narain[†], N. Pervan, T. Russell, S. Sagir[82], F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan

University of California, Davis, Davis, California, USA
S. Abbott, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, Y. Yao, S. Yoo, F. Zhang

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

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, M. Gordon, G. Hanson, W. Si

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

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

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

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

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

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

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

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

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

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[85], M. Hohlmann, M. Rahmani, E. Yanes

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

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[86], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[87], O. Neogi, H. Ogul[88], Y. Onel, A. Penzo, C. Snyder, E. Tiras[89]

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Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, M. Pitt, S. Popescu[90], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

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

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

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

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

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

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

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

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University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[17], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
A. Basnet, B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

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

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik

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

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar, A. Pathak

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

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[91], E. Popova[91], R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

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

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Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, O. Bouhali[92], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[93], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

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

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu

Wayne State University, Detroit, Michigan, USA
S. Bhattacharya, P.E. Karchin

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

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin[†], I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[94], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[95], A. Zarubin, I. Zhizhin, G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[94], P. Levchenko[96], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev[†], Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[97,98], V. Popov, A. Zhokin, R. Chistov[94], M. Danilov[94], S. Polikarpov[94], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, L. Khein, O. Kodolova[98], V. Korotkikh, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan, V. Blinov[94], T. Dimova[94], A. Kozyrev[94], O. Radchenko[94], Y. Skovpen[94], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin[99]

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

[†] *Deceased*

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

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[51] *Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*
[52] *Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[53] *Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy*
[54] *Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
[55] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
[56] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
[57] *Also at Saegis Campus, Nugegoda, Sri Lanka*
[58] *Also at National and Kapodistrian University of Athens, Athens, Greece*
[59] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
[60] *Also at Universität Zürich, Zurich, Switzerland*
[61] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
[62] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[63] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
[64] *Also at Konya Technical University, Konya, Turkey*
[65] *Also at Izmir Bakircay University, Izmir, Turkey*
[66] *Also at Adiyaman University, Adiyaman, Turkey*
[67] *Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey*
[68] *Also at Marmara University, Istanbul, Turkey*
[69] *Also at Milli Savunma University, Istanbul, Turkey*
[70] *Also at Kafkas University, Kars, Turkey*
[71] *Now at Istanbul Okan University, Istanbul, Turkey*
[72] *Also at Hacettepe University, Ankara, Turkey*
[73] *Also at Erzincan Binali Yildirim University, Erzincan, Turkey*
[74] *Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
[75] *Also at Yildiz Technical University, Istanbul, Turkey*
[76] *Also at Vrije Universiteit Brussel, Brussel, Belgium*
[77] *Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
[78] *Also at IPPP Durham University, Durham, United Kingdom*
[79] *Also at Monash University, Faculty of Science, Clayton, Australia*
[80] *Also at Università di Torino, Torino, Italy*
[81] *Also at Bethel University, St. Paul, Minnesota, USA*
[82] *Also at Karamanoğlu Mehmetbey University, Karaman, Turkey*
[83] *Also at California Institute of Technology, Pasadena, California, USA*
[84] *Also at United States Naval Academy, Annapolis, Maryland, USA*
[85] *Also at Ain Shams University, Cairo, Egypt*
[86] *Also at Bingol University, Bingol, Turkey*
[87] *Also at Georgian Technical University, Tbilisi, Georgia*
[88] *Also at Sinop University, Sinop, Turkey*
[89] *Also at Erciyes University, Kayseri, Turkey*
[90] *Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania*
[91] *Now at another institute or international laboratory covered by a cooperation agreement with CERN*
[92] *Also at Texas A&M University at Qatar, Doha, Qatar*
[93] *Also at Kyungpook National University, Daegu, Korea*
[94] *Also at another institute or international laboratory covered by a cooperation agreement with CERN*
[95] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*
[96] *Also at Northeastern University, Boston, Massachusetts, USA*
[97] *Also at Imperial College, London, United Kingdom*
[98] *Now at Yerevan Physics Institute, Yerevan, Armenia*
[99] *Also at Universiteit Antwerpen, Antwerpen, Belgium*

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