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

The CMS Collaboration*

Abstract

The production cross sections of B^0_s 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 $B^0_s \to J/\psi(\mu^+\mu^-)\,\phi(1020)\,(K^+K^-)$ 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^0_s 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^0_s 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^0_s are found to be less suppressed than either inclusive charged hadrons or D^0 mesons, with the B^0_s R_{AA} value consistent with unity. The R_{AA} values found for the B^+ and B^0_s 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.

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1 Introduction

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

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

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

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN^{B^+,B^0_s}_{PbPb}}{dp_T} \Big/ \frac{d\sigma^{B^+,B^0_s}_{pp}}{dp_T}, \tag{1}$$

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 $1 < p_T < 10\,\text{GeV}/c$ 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 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 pp collision events are collected with a first-level trigger requiring the presence of two muon candidates, with no explicit momentum threshold. A subsequent high-level trigger required one of the muon candidates to be reconstructed using information from both the muon detectors and the inner tracker, while only information from the muon detectors is required for the other muon candidate. The dimuon candidates are further required to have an invariant mass within $1 < m_{\mu\mu} < 5\,\text{GeV}/c^2$.

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

The signal is extracted following the same procedure as for the PbPb results [52], as will be described. The same kinematic constraints are applied for the pp and PbPb samples to select muon candidates. The muons are required to match the trigger-level muon candidates and to pass the *soft muon* selection criteria [63]. Two muons of opposite charge, with an invariant mass within $\pm150\,\mathrm{MeV}/c^2$ 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 $p_{\mathrm{T}} > 500\,\mathrm{MeV}/c$. The resulting invariant mass, assuming the world-average charged-kaon mass [64] for each of the two tracks is required to lie within $\pm15\,\mathrm{MeV}/c^2$ 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 $p_{\mathrm{T}} < 10\,\mathrm{GeV}/c$ and $|y| < 2.4$ for $p_{\mathrm{T}} > 10\,\mathrm{GeV}/c$, 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 pp collisions are generated with PYTHIA8 v230 [65], with underlying event tunes CP5 [66] (signal) and CUETP8M1 [67] (background), respectively. The resulting particles are propagated through a model of the CMS detector using the GEANT4 package [68]. The decay of the B mesons is modeled with EVTGEN 1.6.0 [69], and the final-state photon radiation is simulated with PHOTOS 2.0 [70]. Pileup interactions (the number of concurrent interactions in the same bunch crossing) are also simulated according to a mean pileup of 3.5 in the data set.

The final B candidate selection is determined via multivariate discriminators based on a boosted decision tree (BDT) [71]. The same discriminating variables are employed as in the PbPb data analysis. These include the 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, $0.25 < |m_{\mathrm{B}^+} - m^{\mathrm{PDG}}_{\mathrm{B}^+}| < 0.30\,\mathrm{GeV}/c^2$ and $0.20 < |m_{\mathrm{B}^0_\mathrm{s}} - m^{\mathrm{PDG}}_{\mathrm{B}^0_\mathrm{s}}| < 0.30\,\mathrm{GeV}/c^2$, where $m^{\mathrm{PDG}}_{\mathrm{B}^+} = 5279.32\,(\pm0.14)\,\mathrm{MeV}/c^2$

and $m_{\mathrm{B_s^0}}^{\mathrm{PDG}} = 5366.89\,(\pm 0.19)\,\mathrm{MeV}/c^2$ 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 $|m_{\mathrm{B}} - m_{\mathrm{B}}^{\mathrm{PDG}}| < 0.08\,\mathrm{GeV}/c^2$.

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, $\mathrm{B} \to \mathrm{J}/\psi\mathrm{X}$. The Cabibbo-suppressed decay $\mathrm{B}^+ \to \mathrm{J}/\psi\,\pi^+$, 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 $\mathrm{B_s^0}$ meson, such misreconstructed and partially reconstructed background contributions are found to be negligible. Examples of the signal extraction from B^+ and $\mathrm{B_s^0}$ invariant-mass distributions, corresponding to the lowest and highest p_{T} ranges, are shown in Fig. 1.

The differential cross section for B meson production in pp collisions is calculated in each p_{T} interval according to

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

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, $\langle 1/(\alpha(p_{\mathrm{T}},y)\epsilon(p_{\mathrm{T}},y))\rangle$, is obtained employing two-dimensional (2D), fine-grained maps of acceptance $\alpha(p_{\mathrm{T}},y)$ and efficiency $\epsilon(p_{\mathrm{T}},y)$. 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 2D map-based correction factor and its impact is studied and included as a systematic uncertainty. The efficiency maps derived

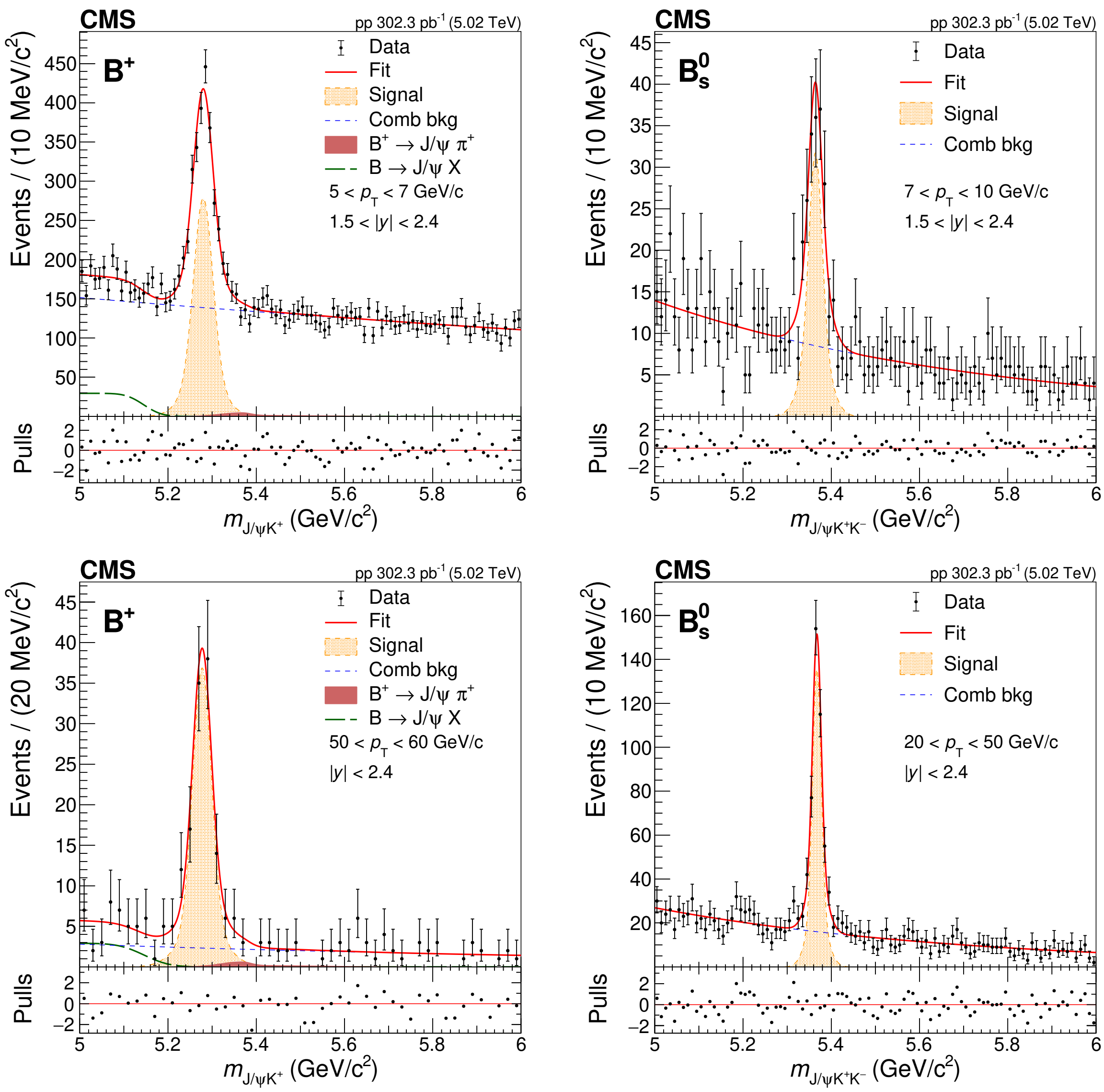

Figure 1: Invariant mass distributions of B^+ (left) and B_s^0 (right) candidates, for the lowest (upper) and highest (lower) p_T ranges in pp collisions at $\sqrt{s} = 5.02$ TeV. The bottom section in each panel shows the pulls, calculated as the difference between the data points and the fit results,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

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

4 Systematic uncertainties

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

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

The efficiency and acceptance determinations are affected by potential disagreements between data and simulation for the B meson selection efficiency, the track reconstruction efficiency, and the efficiency of the muon trigger, reconstruction, and identification. The systematic uncertainties associated with these effects are estimated as done for the PbPb analysis results [52]. To account for the potential discrepancy between data and simulation, the signal MC simulation is validated by inspecting the distributions of the discriminating variables listed in Section 3.1. For each p_T range, the signal distributions are extracted from the data employing the $_s\mathcal{P}lot$ 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_s^0 mesons. The MC simulation is weighted by the FONLL-to-PYTHIA ratios of p_T distributions, and the difference in the $\langle 1/(\alpha\,\epsilon)\rangle$ factors are assigned as systematic uncertainties to estimate the potential impact of the assumed B meson p_T shape in MC. The uncertainty arising from the p_T shape is negligible. The uncertainty in the efficiency of the muon trigger, reconstruction, and identification is evaluated using the tag-and-probe method [72]. The systematic uncertainty in the the muon efficiency has an insignificant effect on both the B^+ and B_s^0 meson results. The derived data-to-MC scale factors are employed to determine the nominal $(\alpha\,\epsilon)$ 2D maps, while the difference in the $\langle 1/(\alpha\,\epsilon)\rangle$ factors between the scaled and original values are taken as the systematic uncertainty. The difference in the track reconstruction efficiency in data and simulation is estimated by comparing 3-prong and 5-prong D^* decays, $D^* \to D^0(K\pi)\,\pi$ and $D^* \to D^0(K\pi\pi\pi)\,\pi$ [75]. This difference results in a 2.4% uncertainty in the efficiency determination for each hadronic track, independent of p_T. We consider this uncertainty to be uncorrelated between tracks. In addition, the selections on track quality are tightened and loosened. These selections include the relative p_T uncertainty, the normalized 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_s^0 cross sections. The systematic uncertainties resulting from the fitting model variation, the discrepancy between the MC simulation and the experimental results for the discriminating variables, the background contamination of the efficiency, the muon efficiency, the track selection, and the integrated luminosity for pp and PbPb are taken as independent and added in quadrature as the systematic uncertainty in the nuclear modification factors. On the other hand, for the R_{AA} calculations, the branching fractions are common to the pp and PbPb systems and, consequently, do not impact the results. The track reconstruction efficiencies used for the two systems also have common elements, resulting in partial cancellation of the corresponding uncertainties when calculating the R_{AA} values. The global uncertainties in R_{AA} consist of the uncertainties in T_{AA}, the number of minimum bias events, and the integrated luminosity in pp collisions.

Table 1: Summary of systematic uncertainties (in %) for the B^+ (upper table) and B^0_s (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.

	B^+ p_T (GeV/c)							
Source	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							

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

5 Results

The p_T-differential production cross sections of B^+ and B^0_s mesons are presented in Fig. 2. The results are compared to the cross sections obtained from FONLL calculations [33], which are obtained by scaling the FONLL total b quark production [31–33] by the world-average production fractions of B^+ (B^0_s) of 40.2 (10.5)% [64]. The calculated FONLL reference spectra are consistent with the pp spectra 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), are shown in Fig. 3 as a functions of p_T. For the B^+ meson a strong suppression is observed in PbPb collisions (with R_{AA} values significantly below unity). In the range $7 < p_T < 50\,\text{GeV}/c$, R_{AA}

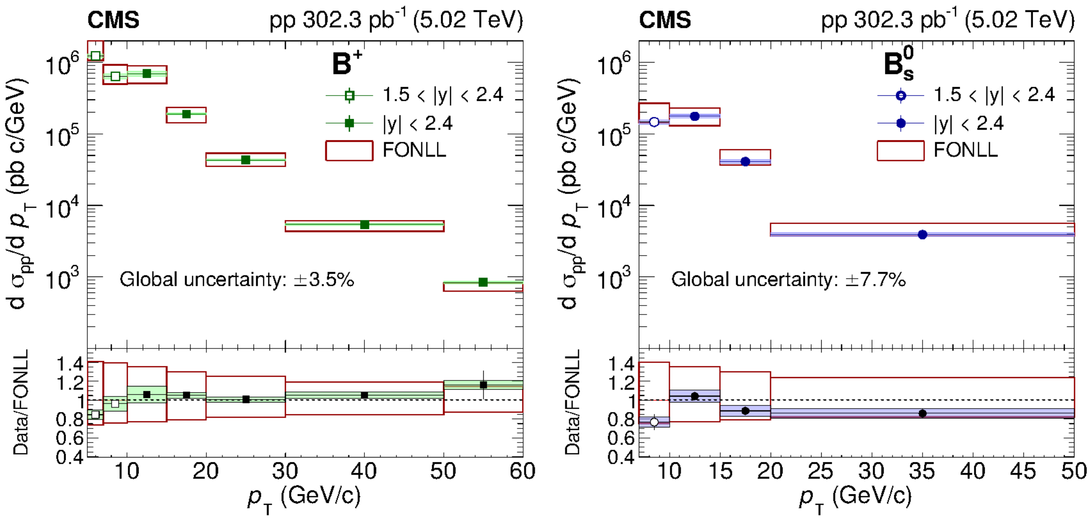

Figure 2: The p_T-differential cross sections of B^+ (left) and B^0_s (right) mesons in pp collisions at $\sqrt{s} = 5.02$ TeV. The vertical bars (shaded boxes) correspond to statistical (systematic) uncertainties. The horizontal bars reflect the bin widths. The global systematic uncertainty includes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

varies from 0.3 to 0.6. For the B^0_s meson, the central value is found to be larger than 1 (i.e., a production enhancement) in the range $7 < p_T < 10$ GeV/c, although the large uncertainty suggests that it is also consistent with the R_{AA} values at higher p_T. In the range $10 < p_T < 50$ 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 [77, 78] and CUJET3.0 [79–81]); (b) a transport model based on a Langevin equation featuring collisional energy loss and heavy quark diffusion in the medium (TAMU [24, 76]), with the spatial diffusion coefficient D_s characterizing the long-wavelength limit of heavy-flavor transport [6], and (c) a model based on the anti-de-Sitter/conformal field theory correspondence, that includes thermal fluctuations in the energy loss for heavy quarks in a strongly coupled plasma (AdS/CFT HH) [82, 83]. The AdS/CFT HH calculation is provided for two settings of the diffusion coefficient D of the heavy-quark propagation through the medium, either dependent on or independent of the quark momentum. Apart from the interactions between heavy quarks and the medium, the set of the (nuclear) parton distribution functions used for the initial heavy-quark p_T distributions are also different between these models. Furthermore, the difference includes the modeling of the PbPb medium (hydrodynamically [24, 79] or via a Glauber model [77, 78]) and the energy loss sources (partonic only [24, 79] or also hadronic [24]).

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

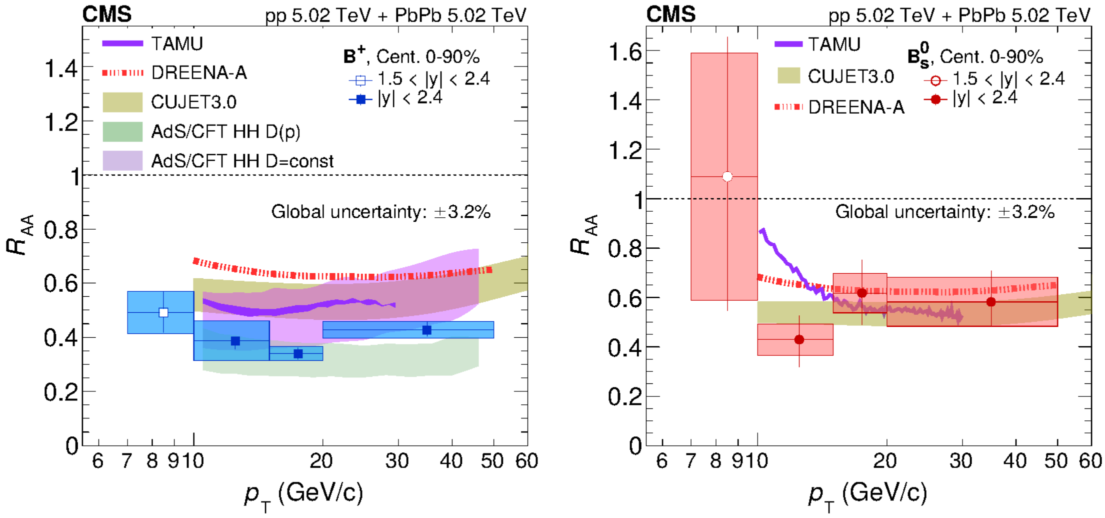

Figure 3: The p_T dependence of the nuclear modification factor of B^+ (left) and B^0_s (right) mesons using PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The horizontal bars reflect the bin widths and not uncertainties.The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

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

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

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

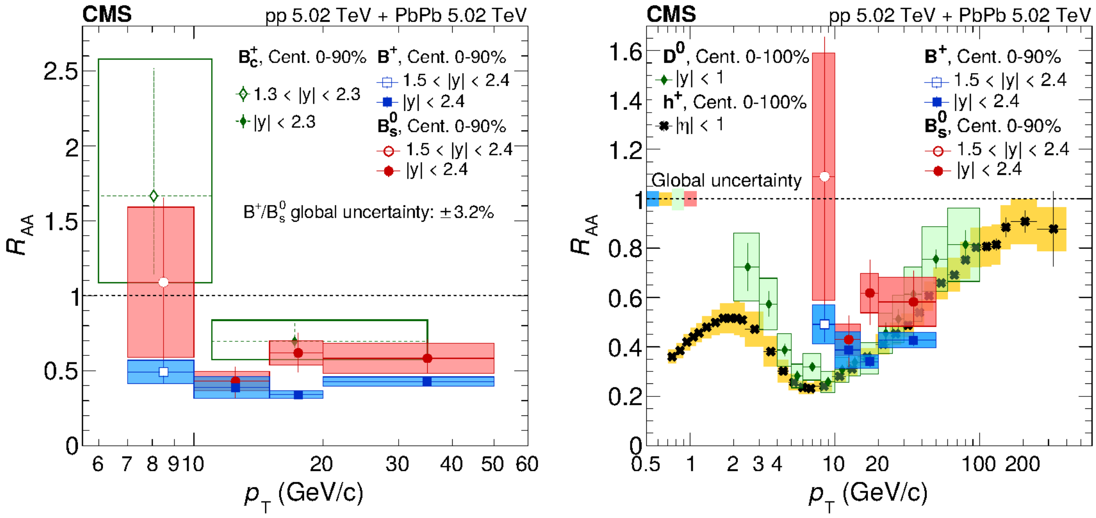

Figure 4: Comparison of the nuclear modification factor as a function of p_T of B^+ and B_s^0 mesons with B_c mesons [27] (left) as well as with D^0 mesons [86] and inclusive charged hadrons [60] (right) in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The vertical bars (boxes) correspond to statistical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

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

6 Summary

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

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

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

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References

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

[2] É. V. Shuryak, "Theory of hadronic plasma", *Sov. Phys. JETP* **47** (1978) 212.

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

[4] W. Busza, K. Rajagopal, and W. van der Schee, "Heavy ion collisions: the big picture, and the big questions", *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 339, doi:10.1146/annurev-nucl-101917-020852, arXiv:1802.04801.

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

[6] X. Dong, Y.-J. Lee, and R. Rapp, "Open heavy-flavor production in heavy-ion collisions", *Ann. Rev. Nucl. Part. Sci.* **69** (2019) 417, doi:10.1146/annurev-nucl-101918-023806, arXiv:1903.07709.

[7] L. Apolinário, Y.-J. Lee, and M. Winn, "Heavy quarks and jets as probes of the QGP", *Prog. Part. Nucl. Phys.* **127** (2022) 103990, doi:10.1016/j.ppnp.2022.103990, arXiv:2203.16352.

[8] J. D. Bjorken, "Energy loss of energetic partons in quark-gluon plasma: possible extinction of high p_{T} jets in hadron-hadron collisions", Fermilab pub, 1982.

[9] R. Baier, D. Schiff, and B. G. Zakharov, "Energy loss in perturbative QCD", *Ann. Rev. Nucl. Part. Sci.* **50** (2000) 37, doi:10.1146/annurev.nucl.50.1.37, arXiv:hep-ph/0002198.

[10] CMS Collaboration, "Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 2.76\,\mathrm{TeV}$", *Phys. Rev. C* **84** (2011) 024906, doi:10.1103/PhysRevC.84.024906, arXiv:1102.1957.

[11] ATLAS Collaboration, "Observation of a centrality-dependent dijet asymmetry in lead-lead collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 2.76\,\mathrm{TeV}$ with the ATLAS detector at the LHC", *Phys. Rev. Lett.* **105** (2010) 252303, doi:10.1103/PhysRevLett.105.252303, arXiv:1011.6182.

[12] A. Beraudo et al., "Extraction of heavy-flavor transport coefficients in QCD matter", *Nucl. Phys. A* **979** (2018) 21, doi:10.1016/j.nuclphysa.2018.09.002, arXiv:1803.03824.

[13] ALICE Collaboration, "K^0_S and Λ production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV", *Phys. Rev. Lett.* **111** (2013) 222301, doi:10.1103/PhysRevLett.111.222301, arXiv:1307.5530.

[14] STAR Collaboration, "Strangeness enhancement in Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. Lett.* **108** (2012) 072301, doi:10.1103/PhysRevLett.108.072301, arXiv:1107.2955.

[15] STAR Collaboration, "Energy and system size dependence of ϕ meson production in Cu+Cu and Au+Au collisions", *Phys. Lett. B* **673** (2009) 183, doi:10.1016/j.physletb.2009.02.037, arXiv:0810.4979.

[16] BRAHMS Collaboration, "Kaon and pion production in central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV", *Phys. Lett. B* **687** (2010) 36, doi:10.1016/j.physletb.2010.02.078, arXiv:0911.2586.

[17] STAR Collaboration, "Collision energy dependence of moments of net-kaon multiplicity distributions at RHIC", *Phys. Lett. B* **785** (2018) 551, doi:10.1016/j.physletb.2018.07.066, arXiv:1709.00773.

[18] PHENIX Collaboration, "ϕ meson production in the forward/backward rapidity region in Cu$+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. C* **93** (2016) 024904, doi:10.1103/PhysRevC.93.024904, arXiv:1509.06337.

[19] ALICE Collaboration, "Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions", *Nature Phys.* **13** (2017) 535, doi:10.1038/nphys4111, arXiv:1606.07424.

[20] J. Rafelski and B. Müller, "Strangeness production in the quark-gluon plasma", *Phys. Rev. Lett.* **48** (1982) 1066, doi:10.1103/PhysRevLett.48.1066, arXiv:nucl-th/0312100v2.

[21] D. Molnar and S. A. Voloshin, "Elliptic flow at large transverse momenta from quark coalescence", *Phys. Rev. Lett.* **91** (2003) 092301, doi:10.1103/PhysRevLett.91.092301, arXiv:nucl-th/0302014.

[22] V. Greco, C. M. Ko, and P. Levai, "Parton coalescence at RHIC", *Phys. Rev. C* **68** (2003) 034904, doi:10.1103/PhysRevC.68.034904, arXiv:nucl-th/0305024.

[23] V. Greco, C. M. Ko, and R. Rapp, "Quark coalescence for charmed mesons in ultrarelativistic heavy ion collisions", *Phys. Lett. B* **595** (2004) 202, doi:10.1016/j.physletb.2004.06.064, arXiv:nucl-th/0312100.

[24] M. He, R. J. Fries, and R. Rapp, "Heavy flavor at the large hadron collider in a strong coupling approach", *Phys. Lett. B* **735** (2014) 445, doi:10.1016/j.physletb.2014.05.050, arXiv:1401.3817.

[25] ALICE Collaboration, "Measurement of D^0, D^+, D^{*+} and D^+_s production in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *JHEP* **10** (2018) 174, doi:10.1007/JHEP10(2018)174, arXiv:1804.09083.

[26] CMS Collaboration, "Measurement of B^0_s meson production in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Lett. B* **796** (2019) 168, doi:10.1016/j.physletb.2019.07.014, arXiv:1810.03022.

[27] CMS Collaboration, "Observation of the B_c meson in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV and measurement of its nuclear modification factor", *Phys. Rev. Lett.* **128** (2022) 252301, doi:10.1103/PhysRevLett.128.252301, arXiv:2201.02659.

[28] CMS Collaboration, "Evidence for X(3872) in PbPb collisions and studies of its prompt production at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Rev. Lett.* **128** (2022) 032001, doi:10.1103/PhysRevLett.128.032001, arXiv:2102.13048.

[29] CMS Collaboration, "Overview of high-density QCD studies with the CMS experiment at the LHC", 5, 2024. arXiv:2405.10785.

[30] CMS Collaboration, "Luminosity measurement in proton-proton collisions at 5.02 TeV in 2017 at CMS", CMS Physics Analysis Summary CMS-PAS-LUM-19-001, 2021.

[31] M. Cacciari, M. Greco, and P. Nason, "The p_T spectrum in heavy-flavour hadroproduction", *JHEP* **05** (1998) 007, doi:10.1088/1126-6708/1998/05/007, arXiv:hep-ph/9803400.

[32] M. Cacciari and P. Nason, "Charm cross sections for the Tevatron Run II", *JHEP* **09** (2003) 006, doi:10.1088/1126-6708/2003/09/006, arXiv:hep-ph/0306212.

[33] M. Cacciari et al., "Theoretical predictions for charm and bottom production at the LHC", *JHEP* **10** (2012) 137, doi:10.1007/JHEP10(2012)137, arXiv:1205.6344.

[34] CMS Collaboration, "Measurement of the $B^{\pm}$ meson nuclear modification factor in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Rev. Lett.* **119** (2017) 152301, doi:10.1103/PhysRevLett.119.152301, arXiv:1705.04727.

[35] CMS Collaboration, "Measurement of the B^{+} production cross section in pp collisions at $\sqrt{s} = 7$ TeV", *Phys. Rev. Lett.* **106** (2011) 112001, doi:10.1103/PhysRevLett.106.112001, arXiv:1101.0131.

[36] CMS Collaboration, "Measurement of the B^0_s production cross section in pp collisions at $\sqrt{s} = 7$ TeV", *Phys. Rev. Lett.* **106** (2011) 252001, doi:10.1103/PhysRevLett.106.252001, arXiv:1104.2892.

[37] CMS Collaboration, "Measurement of the B^0_s production cross section with $B^0_s \to J/\psi\phi$ decays in pp collisions at $\sqrt{s} = 7$ TeV", *Phys. Rev. D* **84** (2011) 052008, doi:10.1103/PhysRevD.84.052008, arXiv:1106.4048.

[38] ATLAS Collaboration, "Measurement of the differential cross-section of B^{+} meson production in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS", *JHEP* **10** (2013) 042, doi:10.1007/JHEP10(2013)042, arXiv:1307.0126.

[39] LHCb Collaboration, "Measurement of the $B^{\pm}$ production cross-section in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **04** (2012) 093, doi:10.1007/JHEP04(2012)093, arXiv:1202.4812.

[40] LHCb Collaboration, "Measurement of B meson production cross-sections in proton-proton collisions at $\sqrt{s} = 7$ TeV", *JHEP* **08** (2013) 117, doi:10.1007/JHEP08(2013)117, arXiv:1306.3663.

[41] LHCb Collaboration, "Measurement of b-hadron production fractions in 7 TeV pp collisions", *Phys. Rev. D* **85** (2012) 032008, doi:10.1103/PhysRevD.85.032008, arXiv:1111.2357.

[42] LHCb Collaboration, “Measurements of $\mathrm{B_c^+}$ production and mass with the $\mathrm{B_c^+} \to \mathrm{J}/\psi\pi^+$ decay”, *Phys. Rev. Lett.* **109** (2012) 232001, doi:10.1103/PhysRevLett.109.232001, arXiv:1209.5634.

[43] CMS Collaboration, “Measurement of the ratio of the production cross sections times branching fractions of $\mathrm{B_c^\pm} \to \mathrm{J}/\psi\pi^\pm$ and $\mathrm{B^\pm} \to \mathrm{J}/\psi\mathrm{K^\pm}$ and $\mathcal{B}(\mathrm{B_c^\pm} \to \mathrm{J}/\psi\pi^\pm\pi^\pm\pi^\mp)/\mathcal{B}(\mathrm{B_c^\pm} \to \mathrm{J}/\psi\pi^\pm)$ in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$”, *JHEP* **01** (2015) 063, doi:10.1007/JHEP01(2015)063, arXiv:1410.5729.

[44] LHCb Collaboration, “Study of the production of Λ_b^0 and $\overline{\mathrm{B}}^0$ hadrons in pp collisions and first measurement of the $\Lambda_\mathrm{b}^0 \to \mathrm{J}/\psi\mathrm{pK^-}$ branching fraction”, *Chin. Phys. C* **40** (2016) 011001, doi:10.1088/1674-1137/40/1/011001, arXiv:1509.00292.

[45] LHCb Collaboration, “Measurement of $\mathrm{B_c^+}$ production in proton-proton collisions at $\sqrt{s} = 8\,\mathrm{TeV}$”, *Phys. Rev. Lett.* **114** (2015) 132001, doi:10.1103/PhysRevLett.114.132001, arXiv:1411.2943.

[46] ATLAS Collaboration, “Measurement of the relative $\mathrm{B_c^\pm}/\mathrm{B^\pm}$ production cross section with the ATLAS detector at $\sqrt{s} = 8\,\mathrm{TeV}$”, *Phys. Rev. D* **104** (2021) 012010, doi:10.1103/PhysRevD.104.012010, arXiv:1912.02672.

[47] CMS Collaboration, “Measurement of the total and differential inclusive $\mathrm{B^+}$ hadron cross sections in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$”, *Phys. Lett. B* **771** (2017) 435, doi:10.1016/j.physletb.2017.05.074, arXiv:1609.00873.

[48] LHCb Collaboration, “Measurement of the $\mathrm{B^\pm}$ production cross-section in pp collisions at $\sqrt{s} = 7$ and $13\,\mathrm{TeV}$”, *JHEP* **12** (2017) 026, doi:10.1007/JHEP12(2017)026, arXiv:1710.04921.

[49] LHCb Collaboration, “Measurement of the $\mathrm{B_c^-}$ meson production fraction and asymmetry in 7 and 13 TeV pp collisions”, *Phys. Rev. D* **100** (2019) 112006, doi:10.1103/PhysRevD.100.112006, arXiv:1910.13404.

[50] CMS Collaboration, “Study of B meson production in pPb collisions at $\sqrt{s_{_\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ using exclusive hadronic decays”, *Phys. Rev. Lett.* **116** (2016) 032301, doi:10.1103/PhysRevLett.116.032301, arXiv:1508.06678.

[51] LHCb Collaboration, “Measurement of $\mathrm{B^+}$, $\mathrm{B_s^0}$ and Λ_b^0 production in pPb collisions at $\sqrt{s_{_\mathrm{NN}}} = 8.16\,\mathrm{TeV}$”, *Phys. Rev. D* **99** (2019) 052011, doi:10.1103/PhysRevD.99.052011, arXiv:1902.05599.

[52] CMS Collaboration, “Observation of B_s^0 mesons and measurement of the $\mathrm{B}_s^0/\mathrm{B}^+$ yield ratio in PbPb collisions at $\sqrt{s_{_\mathrm{NN}}} = 5.02\,\mathrm{TeV}$”, *Phys. Lett. B* **829** (2022) 137062, doi:10.1016/j.physletb.2022.137062, arXiv:2109.01908.

[53] “HEPData record for this analysis”, 2024. doi:10.17182/hepdata.152831.

[54] Tracker Group of the CMS Collaboration, “The CMS phase-1 pixel detector upgrade”, *JINST* **16** (2021) P02027, doi:10.1088/1748-0221/16/02/P02027, arXiv:2012.14304.

[55] CMS Collaboration, “Track impact parameter resolution for the full pseudorapidity coverage in the 2017 dataset with the CMS phase-1 pixel detector”, CMS Detector Performance Note CMS-DP-2020-049, 2020.

[56] CMS Collaboration, "Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[57] CMS Collaboration, "Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[58] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[59] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[60] CMS Collaboration, "Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{_{\text{NN}}}} = 5.02\,\text{TeV}$", *JHEP* **04** (2017) 039, doi:10.1007/JHEP04(2017)039, arXiv:1611.01664.

[61] CMS Collaboration, "Study of jet quenching with isolated-photon+jet correlations in PbPb and pp collisions at $\sqrt{s_{_{\text{NN}}}} = 5.02$ TeV", *Phys. Lett. B* **785** (2018) 14, doi:10.1016/j.physletb.2018.07.061, arXiv:1711.09738.

[62] CMS Collaboration, "Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV", *JHEP* **02** (2010) 041, doi:10.1007/JHEP02(2010)041, arXiv:1002.0621.

[63] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7\,\text{TeV}$", *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[64] Particle Data Group, "Review of Particle Physics", *Prog. Theo. Expt. Phys.* **2022** (2022) doi:10.1093/ptep/ptac097.

[65] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[66] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

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

[68] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[69] D. J. Lange, "The EvtGen particle decay simulation package", *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.

[70] E. Barberio, B. van Eijk, and Z. Was, "PHOTOS: A universal Monte Carlo for QED radiative corrections in decays", *Comput. Phys. Commun.* **66** (1991) 115, doi:10.1016/0010-4655(91)90012-A.

[71] A. Hocker et al., “TMVA–Toolkit for Multivariate Data Analysis with ROOT: Users guide”, Technical Report CERN-OPEN-2007-007, 2007. arXiv:physics/0703039.

[72] CMS Collaboration, “Upsilon production cross-section in pp collisions at $\sqrt{s} = 7\,\text{TeV}$”, *Phys. Rev. D* **83** (2011) 112004, doi:10.1103/PhysRevD.83.112004, arXiv:1012.5545.

[73] M. J. Oreglia, “A Study of the Reactions $\psi' \to \gamma\gamma\psi$”. PhD thesis, Stanford University, 1980. Appendix D.

[74] M. Pivk and F. R. Le Diberder, “${}_s\mathcal{P}lot$: a statistical tool to unfold data distributions”, *Nucl. Instrum. Meth. A* **555** (2005) 356, doi:10.1016/j.nima.2005.08.106, arXiv:physics/0402083.

[75] CMS Collaboration, “Tracking POG results for pion efficiency with the D* meson using data from 2016 and 2017”, CMS Detector Performance Note CMS-DP-2018-050, 2018.

[76] M. He, R. J. Fries, and R. Rapp, “Heavy-quark diffusion and hadronization in quark-gluon plasma”, *Phys. Rev. C* **86** (2012) 014903, doi:10.1103/PhysRevC.86.014903, arXiv:1106.6006.

[77] D. Zigic et al., “Importance of higher harmonics and v_4 puzzle in quark-gluon plasma tomography”, *Phys. Rev. C* **106** (2022) 044909, doi:10.1103/PhysRevC.106.044909, arXiv:2208.09886.

[78] D. Zigic et al., “DREENA–A framework as a QGP tomography tool”, *Front. Phys.* **10** (2022) 957019, doi:10.3389/fphy.2022.957019, arXiv:2110.01544.

[79] J. Xu, J. Liao, and M. Gyulassy, “Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0”, *JHEP* **02** (2016) 169, doi:10.1007/JHEP02(2016)169, arXiv:1508.00552.

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

[81] J. Xu, A. Buzzatti, and M. Gyulassy, “Azimuthal jet flavor tomography with CUJET2.0 of nuclear collisions at RHIC and LHC”, *JHEP* **08** (2014) 063, doi:10.1007/JHEP08(2014)063, arXiv:1402.2956.

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

[83] R. Hambrock and W. A. Horowitz, “AdS/CFT predictions for azimuthal and momentum correlations of $\mathrm{b\bar{b}}$ pairs in heavy ion collisions”, 2017. arXiv:1703.05845.

[84] M. Rohrmoser, P. B. Gossiaux, T. Gousset, and J. Aichelin, “Constraining in-medium heavy-quark energy-loss mechanisms via angular correlations between heavy and light mesons”, *J. Phys. Conf. Ser.* **779** (2017) 012032, doi:10.1088/1742-6596/779/1/012032, arXiv:1611.01854.

[85] S. Cao, G.-Y. Qin, and S. A. Bass, “Heavy flavor dynamics in QGP and hadron gas”, *Nucl. Phys. A* **931** (2014) 569, doi:10.1016/j.nuclphysa.2014.09.011, arXiv:1408.0503v1.

[86] CMS Collaboration, “Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Lett. B* **782** (2018) 474, doi:10.1016/j.physletb.2018.05.074, arXiv:1708.04962.

[87] Y. L. Dokshitzer, V. A. Khoze, and S. I. Troian, “On specific QCD properties of heavy quark fragmentation ('dead cone')”, *J. Phys. G* **17** (1991) 1602, doi:10.1088/0954-3899/17/10/023.

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