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Measurement of the nuclear modification factor for muons from charm and bottom hadrons in Pb+Pb collisions at 5.02 TeV with the ATLAS detector

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Heavy-flavour hadron production provides information about the transport properties and microscopic structure of the quark–gluon plasma created in ultra-relativistic heavy-ion collisions. A measurement of the muons from semileptonic decays of charm and bottom hadrons produced in Pb+Pb and pp collisions at a nucleon–nucleon centre-of-mass energy of 5.02 TeV with the ATLAS detector at the Large Hadron Collider is presented. The Pb+Pb data were collected in 2015 and 2018 with sampled integrated luminosities of 208 μb^{-1} and 38 μb^{-1}, respectively, and pp data with a sampled integrated luminosity of 1.17 pb^{-1} were collected in 2017. Muons from heavy-flavour semileptonic decays are separated from the light-flavour hadronic background using the momentum imbalance between the inner detector and muon spectrometer measurements, and muons originating from charm and bottom decays are further separated via the muon track's transverse impact parameter. Differential yields in Pb+Pb collisions and differential cross sections in pp collisions for such muons are measured as a function of muon transverse momentum from 4 GeV to 30 GeV in the absolute pseudorapidity interval $|\eta| < 2$. Nuclear modification factors for charm and bottom muons are presented as a function of muon transverse momentum in intervals of Pb+Pb collision centrality. The measured nuclear modification factors quantify a significant suppression of the yields of muons from decays of charm and bottom hadrons, with stronger effects for muons from charm hadron decays.

1 Introduction

Quark–gluon plasma (QGP) is a state of matter in which the quarks and gluons are deconfined from colour-neutral hadronic states. Ultra-relativistic collisions of large nuclei create nuclei-sized droplets of QGP at temperatures in excess of 300–500 MeV [1, 2]. These droplets exist for a mere 10^{-23} seconds and hence there is no way to fire an external probe at the droplet to investigate its properties. Instead, the probes must be generated in the collision itself and then interact with the droplet. Interactions with the QGP, both radiative and collisional, may provide key information regarding the properties and constituents of the QGP [3]. Specifically, the balance of radiative and collisional energy transfer depends on the mass of the constituents [4, 5]. Heavy quarks, charm and bottom, have masses much larger than the droplet temperature. Thus, they are produced in the initial collision via high-momentum-transfer interactions between incident quarks and gluons, where thermal production is highly suppressed. The strong-force interactions conserve the quantum numbers associated with the charm and bottom quarks. Thus, once created, these quarks can have substantial modifications to their momentum distributions when traversing the QGP, but they cannot be destroyed. In addition, radiative energy loss is suppressed for heavy quarks by the so-called 'dead-cone effect' [6], i.e. gluon radiation is suppressed at angles smaller than the quark's mass to energy ratio. A key to constraining the relative contribution of radiative energy loss is to measure the modification of the momentum distributions for charm and bottom quarks separately, since the dead-cone effect will be more pronounced for bottom quarks than for charm quarks at the same momentum.

There are numerous publications detailing the modifications of momentum distributions of heavy-flavour hadrons measured in heavy-ion collisions via direct reconstruction and via decay leptons in heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) [7] and the Large Hadron Collider (LHC) [8] – current measurements and theory calculations are reviewed in Refs. [9, 10]. In nucleus–nucleus (A+A) collisions, each event is described by its centrality, which reflects the overlap of the colliding nuclei. The geometry of each event is calculated using a Monte Carlo (MC) Glauber model – for details see Ref. [11]. The modification to particle yields in A+A collisions relative to pp collisions is quantified by a nuclear modification factor R_{AA} defined as:

$$R_{\mathrm{AA}} = \frac{N_{\mathrm{AA}}/N_{\mathrm{evt}}}{\langle T_{\mathrm{AA}}\rangle \times \sigma_{pp}}, \quad (1)$$

where N_{AA} is the number of observed particles of interest in Pb+Pb collisions, N_{evt} is the number of minimum-bias Pb+Pb events, $\langle T_{\mathrm{AA}}\rangle$ is the average value of the nuclear thickness function, and σ_{pp} is the particle production cross section in pp collisions at the same collision energy. If R_{AA} equals unity, the production in A+A collisions is the same as in pp collisions but scaled up by the larger parton–parton luminosity, while $R_{\mathrm{AA}} < 1$ indicates a suppression.

The nuclear modification factors for inclusive 'heavy-flavour muons' (mostly muons from D and B meson semileptonic decays) have been measured in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV by the ATLAS experiment [12] and the ALICE experiment [13]. The ALICE experiment measured the nuclear modification factor for inclusive heavy-flavour electrons at the same energy [14, 15] and also at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [16]. Nuclear modification factors for charm hadrons D^0, D_s, D^*, and Λ_c have been measured by the CMS [17] and ALICE [18, 19] experiments in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, and by the STAR [20–23] experiment in Au+Au collisions at a lower energy of $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. These measurements indicate significant suppression for heavy-flavour hadrons in Pb+Pb collisions. At transverse momentum (p_{T}) greater than 4 GeV, the prompt-D^0 R_{AA} is found to be consistent within the uncertainties with the R_{AA} of inclusive charged particles (dominated by π), while at lower p_{T} values D^0 mesons have a smaller suppression (larger R_{AA}) compared to charged particles.

The measurement presented here follows the previous ATLAS measurement of muons originating from heavy-flavour hadron decays in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [12]. This Letter, based on the higher number of events in the combined 2015 and 2018 Pb+Pb datasets and the 2017 pp dataset at 5.02 TeV, extends results to the transverse momentum range $4 < p_{\mathrm{T}} < 30$ GeV. This Letter also separates the inclusive heavy-flavour muons into contributions from charm hadron decays (charm muons) and bottom hadron decays (bottom muons), based on the muon track's transverse impact parameter, similar to the method used in previous ATLAS measurements [24, 25]. Results for charm and bottom muon cross sections in pp collisions are shown as a function of muon p_{T} and compared with perturbative QCD calculations. The nuclear modification factor is presented as a function of muon p_{T} in various Pb+Pb centrality intervals. Finally, the R_{AA} measurements, along with a previous measurement of the heavy-flavour muon momentum anisotropies [25], are compared with the expectations from theoretical calculations. The R_{AA} value quantifies the average energy loss while azimuthal anisotropy such as elliptic flow, v_2 [25], quantifies the azimuthal angle dependence of energy loss. Simultaneous constraints on R_{AA} and v_2 for the same final state are important in distinguishing the relative impacts of different heavy-quark energy loss mechanisms and in understanding the influence of the initial QGP droplet geometry on the resulting evolution of kinematics of heavy-flavour quarks in the medium.

2 ATLAS detector

The ATLAS detector [26–28] at the LHC covers nearly the entire solid angle around the collision point.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets with eight coils each. The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$.

The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, with the first hit typically in the insertable B-layer installed before Run 2 [27, 28]. It is followed by the silicon microstrip tracker which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules (FCal), covering the forward regions of $3.1 < |\eta| < 4.9$, optimized for electromagnetic and hadronic measurements respectively. The minimum-bias trigger scintillators detect charged particles over $2.07 < |\eta| < 3.86$ using two hodoscopes of 12 counters positioned at $z = \pm 3.6$ m. The zero-degree

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

calorimeters (ZDC) measure neutral particles at pseudorapidities $|\eta| \geq 8.3$ and consist of layers of alternating quartz rods and tungsten plates.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by superconducting air-core toroids. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. A set of precision chambers covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions. Events of interest are selected to be recorded by the first-level trigger (L1) system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger (HLT) [29]. The first-level trigger selects events from the 40 MHz bunch crossings at a rate below 100 kHz (75 kHz) for pp (Pb+Pb) collisions, and the high-level trigger reduces the average event output rate to about 1.2 kHz for recording. An extensive software suite [30] is used for real and simulated data reconstruction and analysis, for operation and in the trigger and data acquisition systems of the experiment.

3 Event selection

The pp data used in this analysis were recorded with the ATLAS detector in 2017, while the Pb+Pb data were recorded in 2015 and 2018. Both the pp and Pb+Pb events were selected online using a trigger that requires a muon at the L1 and HLT with a p_{T} larger than 4 GeV [29, 31]. After selecting run periods when the detector subsystems were operational and taking into account the fraction of the total luminosity sampled by the triggers, the datasets used in the analysis correspond to integrated luminosities of 1.17 pb^{-1} for pp data, 208 $\mu\mathrm{b}^{-1}$ for 2015 Pb+Pb data, and 38 $\mu\mathrm{b}^{-1}$ for 2018 Pb+Pb data. The 2017 pp data, with a small average number of interactions per bunch crossing in the range from 0.4 to 4, were collected to serve as the baseline for Pb+Pb collision measurements at the same centre-of-mass energy. The smaller sampled luminosity of 2018 Pb+Pb data is due to a smaller fraction of the sampled events being recorded by the specific muon triggers used in the analysis. The selected Pb+Pb events are further required to satisfy offline minimum-bias Pb+Pb collision criteria, identical to those used in Ref. [25]. This additional requirement identifies and rejects 0.2% of the selected events as pile-up events, based on a combination of the total transverse energy measured in the FCal, denoted by $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$, and the ZDC energy.

The centrality of each Pb+Pb event is characterized by its $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ value. For the results shown here, the minimum-bias $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ distribution is divided into percentiles ordered from the most central (large $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$, small impact parameter) to the most peripheral (small $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$, large impact parameter): 0–10%, 10–20%, 20–30%, 30–40%, and 40–60%. The interval 0–100% corresponds to the total Pb+Pb inelastic cross section [32]. An MC Glauber [11] model is used to calculate $\langle T_{\mathrm{AA}} \rangle$ for each centrality interval [33].

Muons with $4 < p_{\mathrm{T}} < 30$ GeV and $|\eta| < 2$ reconstructed in both the ID and the MS are selected and required to pass 'medium' selection requirements, detailed in Ref. [34]. Selected muons are required to be matched with an online muon candidate that fires the event trigger. Each muon is assigned a weight which is the inverse of the product of the reconstruction and trigger efficiencies, evaluated for muons as a function of their kinematic variables, and in the case of Pb+Pb data as a function of centrality as well.

The muon reconstruction and identification efficiency is factorized as the product of the individual reconstruction efficiencies in the ID and MS. The ID and MS efficiencies in pp collisions are determined in the large pp dataset collected in 2017 at $\sqrt{s} = 13$ TeV, using the tag-and-probe method on $J/\psi \to \mu^{+}\mu^{-}$

events as detailed in Ref. [34]. They are applied to the pp data at $\sqrt{s} = 5.02$ TeV used in this analysis, in fine intervals of muon p_{T} and η. The expected difference between the muon reconstruction efficiencies at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV is approximately 0.3% [34], and it is neglected in this analysis. The MS efficiencies obtained from pp and Pb+Pb data collected in the same year show no significant difference. Thus, the MS efficiencies for 2015 and 2018 Pb+Pb data are obtained from the large pp datasets at $\sqrt{s} = 13$ TeV in the corresponding years in fine intervals of muon p_{T} and η. The resulting MS efficiency plateaus at 97% at $p_{\mathrm{T}} > 7$ GeV. The ID efficiency in Pb+Pb events is obtained from Pb+Pb data using the same $J/\psi \to \mu^{+}\mu^{-}$ tag-and-probe method in intervals of muon p_{T} and η. The measured Pb+Pb ID efficiency is about 98% with the efficiency in 2018 being 3% lower than that in 2015 at $1 < |\eta| < 2$ independent of p_{T}, while no difference between 2015 and 2018 is observed at $|\eta| < 1$. No centrality dependence is observed for MS and ID efficiencies for muons in Pb+Pb collisions.

The initial estimations of the muon trigger efficiency are obtained from $J/\psi \to \mu^{+}\mu^{-}$ Pythia 8 [35] simulations in fine intervals of muon p_{T} and η using the tag-and-probe method [31]. All generated events were passed through a Geant4 simulation [36, 37] of the ATLAS detector under the same conditions as present during data-taking and were digitized and reconstructed in the same way as the data. The same simulated trigger efficiency is used in pp and Pb+Pb data. Relative efficiency differences between simulations and data and between pp and Pb+Pb collisions are covered by additional corrections described as follows. Mis-modelling of the trigger performance in simulation, quantified by the ratio of measured efficiencies in data and the simulations, is accounted for by applying a multiplicative correction not exceeding 10%. To account for the different online muon momentum scale in pp and Pb+Pb data, as well as the slightly different trigger performance in 2015 and 2018, an additional correction factor, determined by the Pb+Pb to pp data-driven efficiency ratio, is applied to Pb+Pb data as a function of muon p_{T} and η, the centrality, and the year of Pb+Pb data-taking.

4 Signal extraction

As detailed in previous ATLAS publications [12, 24, 25, 38], the background contributions in the selected muon samples (labelled 'bkg' in Figures 1 and 2) have three components. The first one is called the 'prompt-muon background' and includes contributions from decays of non-open–heavy-flavour particles such as direct quarkonia, low-mass resonances, τ-leptons, and massive electroweak W/Z bosons. The second component is the 'hadronic background' resulting from π and K decaying into muons in the volume of the ID or punching through the calorimeter. The last component is from random combinations of uncorrelated track segments from the ID and MS, called the 'fake-muon background'. The prompt-muon background is estimated in simulations, while the hadronic and fake-muon backgrounds are subtracted from the signal muons by fitting the muon momentum imbalance, $\rho = (p^{\mathrm{ID}} - p^{\mathrm{MS}})/p^{\mathrm{ID}}$, where p^{ID} is the muon momentum measured in the ID, and p^{MS} is that measured in the MS corrected for the energy loss inside the calorimeter. The ρ distribution shapes of hadronic and fake-muon backgrounds are extracted from simulations while their yields are determined from the fit procedure.

The prompt-muon background contribution in pp events is estimated from Pythia 8 simulations of prompt J/ψ, $\psi(2S)$, and $\Upsilon(nS)$ production based on a non-relativistic QCD colour-octet model [39], and from W and Z production simulated with the Powheg Box v2 generator [40] interfaced to the Pythia 8 parton shower model. The CT10 PDF set [41] was used in the matrix element, while the CTEQ6L1 PDF set [42] was used for the modelling of non-perturbative effects in the initial-state parton shower. The simulated prompt-muon background processes are all scaled by process-dependent single scaling factors to match previous ATLAS measurements in pp collisions at $\sqrt{s}$ = 5.02 TeV [43, 44]. Other contributions from low-mass resonances and τ-leptons in the measured muon p_{T} range are found to be less than 1% [24, 38] and are neglected in this analysis. In Pb+Pb collisions, the estimated prompt-muon background rates take into account nuclear modifications measured in Refs. [45–48].

Muons from hard scattering have a symmetric ρ distribution peaked at zero, while the hadronic background has a broader ρ distribution and the peak shifted toward higher values. This change in shape is due to differences between the actual energy loss of this background and the estimated energy loss based on muon simulations. Only energy loss of muons is properly corrected for and added to the MS momentum measurement. The different shapes of the ρ distributions for the hadronic background and the other muons allow the hadronic background to be isolated using a template-fitting procedure [24, 25]. The yields of inclusive heavy-flavour muons and hadronic background muons are extracted from the ρ template fit. The templates for the charm and bottom muon ρ distributions are determined from multijet hard-scattering Pythia 8 pp collision events at $\sqrt{s}$ = 5.02 TeV filtered for the presence of a generator-level muon produced with parameter values as in the A14 tune [49] and using the NNPDF23lo parton distribution functions [50]. The templates for the charm and bottom muon ρ distributions (and track transverse impact parameter, d_0, distributions, described below) in multijet hard-scattering QCD Pythia 8 samples are found to be identical to those from non-diffractive QCD Pythia 8 samples, while hard-scattering QCD Pythia 8 samples have much higher muon filter efficiency. The ρ templates for the prompt-muon background are obtained from the simulation procedure described in the previous paragraph. The hadronic background and fake-muon ρ templates are obtained from non-diffractive QCD simulations of pp collisions at $\sqrt{s}$ = 5.02 TeV in Pythia 8, with the A14 tune and NNPDF23lo parton distribution functions. The fake-muon contribution is fixed relative to the hadronic background, with the ratio obtained from simulations. The momenta of the reconstructed muons selected in Pythia 8 simulations are calibrated to match the muon momentum response in pp and Pb+Pb data. The calibration is performed via shift and smearing parameters [25] determined from the invariant mass response in $J/\psi \to \mu^{+}\mu^{-}$ events. The same calibration is applied to all muon candidates including those from background contributions. Alternative calibrations for background contributions are used for the systematic uncertainty evaluation. The signal muon ρ distribution shape shows no obvious dependence on muon p_{T}, but is found to be broader in the more forward pseudorapidity region and more central Pb+Pb collisions, both due to poorer muon momentum resolution in the ID. The hadronic background ρ distribution becomes broader at higher p_{T} and in more central collisions. Examples of the ρ template fit are shown in Figure 1 for muons with $6 < p_{\mathrm{T}} < 7$ GeV in pp collisions and 20–30% centrality Pb+Pb collisions.

Charm and bottom muons are further separated using the muon track's transverse impact parameter, d_0, which is calculated relative to the beam spot [51]. Due to the different lifetimes of charm and bottom hadrons, the corresponding muons have different d_0 distributions, and their fractional contributions can be extracted using a template-fitting procedure. Background contributions are subtracted from data distributions of d_0 as shown in the upper panels in Figure 2. For each of the three background sources, the d_0 shape is determined in simulations. In pp data analysis, the d_0 shape templates of various background sources are obtained from the Pythia 8 simulations used to build the ρ templates. In Pb+Pb data analysis, the same Pythia 8 events overlaid with minimum-bias Pb+Pb events collected in 2015 are used to build the background d_0 templates to approximate background distributions in Pb+Pb collisions. The d_0 distributions from high-quality prompt tracks in simulations and 2018 Pb+Pb data are smeared to match those in 2015 Pb+Pb data. The prompt-muon background d_0 distribution normalization is constrained by the yield estimates from MC simulations. The hadronic and fake-muon background d_0 distribution normalization factors are extracted from the ρ template fit. The signal muon d_0 distribution in Pb+Pb data is narrower than in pp data because of a smaller transverse beam size. The background d_0 distribution becomes

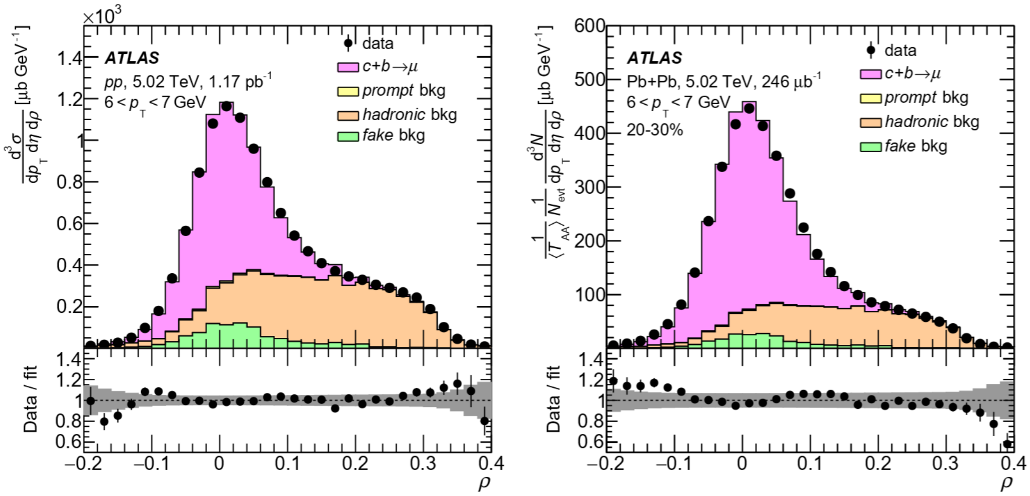

Figure 1: Fit results of the ρ distribution for muons with $6 < p_{\mathrm{T}} < 7$ GeV in pp collisions (left) and in Pb+Pb collisions with 20–30% centrality (right). The ratios of the data to fit results are shown in the lower panels. The prompt-muon background contributions are very small in the fitted muon kinematic region. The grey bands in the lower panels indicate the statistical and systematic uncertainties combined in quadrature.

moderately narrower with increasing p_{T} and shows no evident centrality dependence. After subtraction, the remaining d_0 distribution in data contains only contributions from heavy-flavour muons.

The d_0 fit is performed in the range of $|d_0| < 0.5$ mm as events with $|d_0| > 0.5$ mm are statistically limited in both data and simulations and have little sensitivity to the charm muon contribution. For pp data, the charm and bottom muon d_0 templates are obtained from the muon-filtered multijet Pythia 8 simulations at $\sqrt{s} = 5.02$ TeV, as done for ρ templates. Bottom muons contain the $b \to c \to \mu$ cascade contribution. The d_0 distributions of signal muons show no obvious dependence on the muon p_{T}, but they become broader with increasing parent B and D meson p_{T}. The simulated samples from Pythia 8 are reweighted to match the inclusive B and D meson p_{T} spectra from fixed-order next-to-leading-log (FONLL) resummation calculations [52, 53]. The charm and bottom baryon-to-meson ratios in the simulations are corrected to match the measured values in Refs. [54, 55]. The yield of D^+ relative to D^0 is corrected to match the measured value in Refs. [56, 57]. In the Pb+Pb analysis, the charm and bottom muon d_0 templates are obtained from the pp Pythia 8 simulations overlaid with minimum-bias Pb+Pb events from 2015, similar to what is done for the background d_0 templates. Besides the FONLL resummation and baryon-to-meson corrections as applied in pp collisions, an additional correction is applied to match the modified charm and bottom hadron p_{T} spectra measured in Pb+Pb collisions by ALICE [18] and CMS [17]. Examples of d_0 template fits for muons with $6 < p_{\mathrm{T}} < 7$ GeV are shown in Figure 2 for pp collisions and 20–30% centrality Pb+Pb collisions. The relative fractions of charm and bottom muons are extracted from the d_0 template fit.

5 Systematic uncertainties

Systematic uncertainties associated with the various steps of the analysis are assessed. The measured cross section in pp collisions, per-event yields in Pb+Pb collisions and R_{AA} are recalculated by systematically

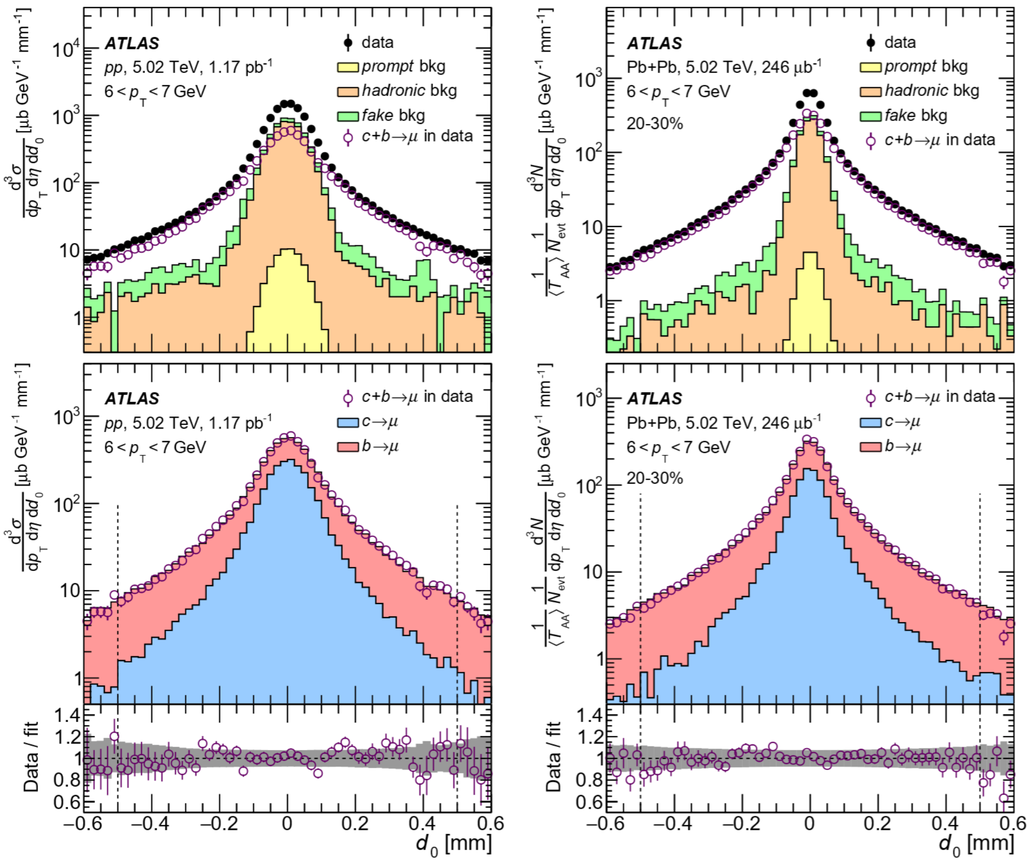

Figure 2: (Top) d_0 templates for different background contributions, and data d_0 distributions before (solid points) and after (open points) background subtraction for muons with $6 < p_{\mathrm{T}} < 7$ GeV in pp collisions (left) and in Pb+Pb collisions with 20–30% centrality (right). (Bottom) Fit results of the background-subtracted d_0 distribution for muons with $6 < p_{\mathrm{T}} < 7$ GeV in pp collisions (left) and in Pb+Pb collisions with 20–30% centrality (right). The vertical dashed lines indicate the d_0 range, $|d_0| < 0.5$ mm, used in the fit procedure. Data to fitted result ratios are shown in the bottom panels. The grey bands indicate the statistical and systematic uncertainties combined in quadrature.

varying the effect of each source of uncertainty and then compared with the nominal results. The resulting difference is assigned as a systematic uncertainty. Each group of systematic uncertainties described in the following subsections are considered as uncorrelated, and are therefore summed in quadrature. Some sources of systematic uncertainties that are correlated between pp and Pb+Pb collisions partially cancel out in R_{AA}.

5.1 Muon correction uncertainties

The systematic uncertainties from the muon reconstruction efficiency and muon trigger efficiency corrections for pp collisions are dominated by the uncertainty in determining these efficiencies in data with the tag-and-probe method. These are evaluated following the procedures in previous ATLAS measurements [31, 34], including variations in the tag-and-probe efficiency extraction method, online–offline matching requirement, and muon purity in the selected sample. The Pb+Pb efficiency is affected by the systematic uncertainty sources mentioned above, due to the use of the pp efficiency in the factorized treatment. An additional uncertainty in Pb+Pb is associated with the determination of the ID reconstruction efficiency in data using the tag-and-probe method. Uncertainties in the trigger efficiency correction are determined from the Pb+Pb to pp efficiency ratio and residual discrepancies between fully corrected Pb+Pb muon spectra measured in the 2015 and 2018 data-taking periods. Apart from specific Pb+Pb uncertainties, other uncertainties are correlated between collision systems and thus cancel out in R_{AA}.

5.2 Background removal uncertainties

The systematic uncertainty in the momentum imbalance templates includes the effect of the uncertainty in the muon momentum calibration parameters, the uncertainty due to the dedicated hadronic-background calibration, and the uncertainty due to ρ–d_0 correlation in the hadronic background. Charm muon yields are more sensitive to the background removal procedure as charm muons have narrower d_0 distributions around 0 where the background contamination is large. The systematic uncertainties in the calibration parameters, which originate from the uncertainty in the determination of $J/\psi \rightarrow \mu^+\mu^-$ invariant mass [58], contribute 3% relative uncertainty to the final charm muon yields and 1% to the bottom muon yields. Since the hadronic background could have a different momentum scale than that for real muons, the results are also examined using a data-driven hadronic-background momentum calibration in the background-dominated region $\rho > 0.2$. The difference is included as a systematic uncertainty which is about 10% (4%) for charm (bottom) muon yields at low p_{T} and decreases with increasing p_{T}. To account for the small ρ–d_0 correlation in hadronic background, the corresponding ρ templates in different d_0 selections are used and the resulting difference is assigned as an additional systematic uncertainty. The relative uncertainty due to the background ρ–d_0 correlation is about 3% for charm muon yields and less than 1% for bottom muon yields. The ρ-template-related systematic uncertainties are treated as correlated between pp and Pb+Pb data, and partially cancel out in R_{AA}.

In the analysis, the size of each prompt-muon background contribution is held at a fixed value obtained from Pythia 8 simulations scaled to match existing measurements. To assess the associated uncertainty, the pp and Pb+Pb analyses are repeated while varying the estimated sizes of the different prompt-muon contributions by the corresponding experimental uncertainties in their production rates [43, 44] and R_{AA} values [45–48]. The sensitivity to the fake-muon rate estimation is evaluated by varying the fake-muon candidate definition in simulations with different truth-level and reconstruction-level objects matching criteria. The resulting variation of the fake-muon rate is about 20–40%, and produces 5% variations, on average, in the measured charm and bottom yields. The fake-muon systematic uncertainty is assumed to be uncorrelated between the pp and Pb+Pb results.

5.3 Charm–bottom separation uncertainties

The systematic uncertainties in the impact parameter template, that are common for pp and Pb+Pb results, include several components. Uncertainties in the FONLL calculations are evaluated based on Ref. [52, 53]. Uncertainties coming from baryon-to-meson ratio mis-modelling correction use measurements published in Ref. [54, 55]. Uncertainties in D^+/D^0 mis-modelling correction are based on reported uncertainties in Ref. [59, 60]. They are propagated to the pp and Pb+Pb results, and are treated as correlated between the pp and Pb+Pb results. The muon p_{T} spectra predicted by FONLL calculations are weighted to match the measured charm and bottom muon spectra reported in this Letter. The resulting weighting factors are used to adjust signal d_0 templates to quantify the bias due to observed mis-modelling in the FONLL calculations.

The resulting difference of 1–5% in the muon yields is assigned as an additional uncertainty and is treated as correlated between the pp and Pb+Pb results. Uncertainties in the nuclear modification factor for parent hadrons in Pb+Pb are propagated using the experimental uncertainties in D and B meson R_{AA} values from Refs. [17, 18]. Minimum-bias Pb+Pb events collected in 2018, instead of 2015 events, are used to overlay with Pythia 8 simulations to test the sensitivity to slightly different overlay conditions. Resulting changes in the muon yields due to different overlay conditions are assigned as a systematic uncertainty in the Pb+Pb results. Uncertainties in the determination of d_0 shift and smearing parameters are found to have a negligible impact, less than 0.5%, on the extracted charm and bottom yields.

5.4 Global normalization uncertainties

In the 2017 pp data, the LUCID-2 detector [61] is used for the primary luminosity measurement. The uncertainty in the integrated luminosity is derived using the methods described in Ref. [62], and is 1.6%. For Pb+Pb collisions, the systematic uncertainty in $\langle T_{\mathrm{AA}} \rangle$ is estimated by varying the MC Glauber model parameters as detailed in Ref. [33].

5.5 Uncertainty summary

Table 1 summarizes relative uncertainties in the measurement of charm and bottom muon production in pp and Pb+Pb collisions, and in the nuclear modification factor R_{AA}. The leading sources of uncertainty in all muon p_{T} bins and Pb+Pb collision centralities are the background removal and charm–bottom separation uncertainties, and at low muon p_{T} in central Pb+Pb collisions the evaluation of the muon efficiency.

Table 1: Contributions to systematic uncertainties given in percent for the cross section in pp, yields in Pb+Pb, and nuclear modification factor of charm and bottom muons. Ranges indicate the minimum and maximum systematic uncertainties found in all muon p_{T} bins and centralities for a given source.

Source	σ_{pp} [%]		N_{AA} [%]		R_{AA} [%]	
	$c \to \mu$	$b \to \mu$	$c \to \mu$	$b \to \mu$	$c \to \mu$	$b \to \mu$
Muon efficiency	0.5–1.0	0.4–0.6	0.6–16	0.3–16	0.3–16	0.2–16
Background removal	4.3–12	0.8–3.8	2.5–30	1.0–5.1	1.9–27	0.5–4.7
Charm–bottom separation	4.5–9.8	3.2–8.0	9.2–37	6.2–16	5.1–23	4.1–13
Global normalization	1.6	1.6	0.9–4.6	0.9–4.6	1.8–4.9	1.8–4.9
Total systematic uncertainty	5.8–13	3.1–7.4	10–47	6.9–19	6.5–35	5.4–18

6 Results

Figure 3 shows the differential cross section for muons from charm and bottom hadron decays within $|\eta| < 2$ as a function of muon p_{T} in pp collisions at $\sqrt{s} = 5.02$ TeV. The measurements are compared with theoretical calculations for muons from D and B meson decays in the FONLL resummation framework [63]. Uncertainties affecting the FONLL calculations include uncertainties in the parton distribution functions, heavy-flavour quark masses, and the renormalization and factorization scales. For muons from charm quarks, the FONLL calculation reaches the experimental data with the upper edge of its uncertainty band at $p_{\mathrm{T}} < 10$ GeV, but underestimates the data at higher p_{T}. Similar differences between FONLL calculations and prompt-charm measurements were observed in previous measurements at LHC energies, for example, in ALICE measurements of prompt D mesons [64] and inclusive heavy-flavour leptons [16, 65], and in an LHCb measurement of prompt D mesons [66]. The measured cross section for muons from bottom quarks is a factor of 1.3–1.4 higher than the FONLL-calculated central value (including $b \to c \to \mu$) but still inside the FONLL calculation's uncertainty band at low p_{T}, while the calculated central value agrees with the data within experimental uncertainties for $p_{\mathrm{T}} > 10$ GeV, similar to observations in a previous ATLAS measurement of non-prompt charmonium [58] and an ALICE measurement of non-prompt D mesons [59].

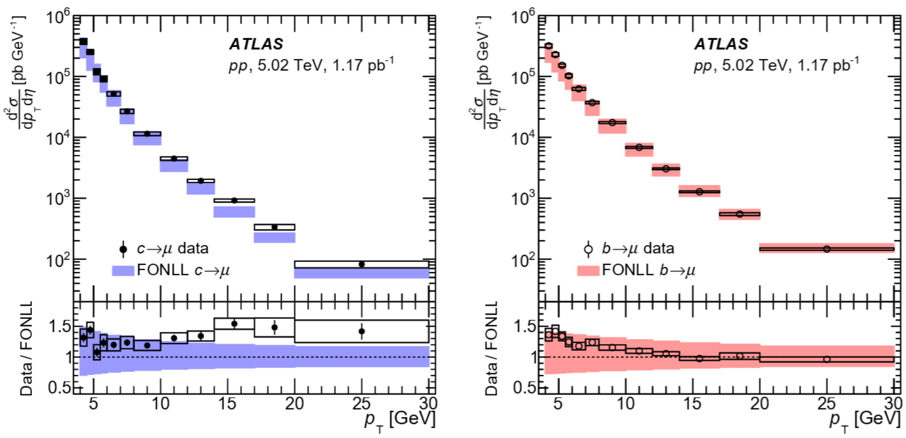

Figure 3: Differential cross section of charm (left) and bottom (right) muons as a function of muon p_{T}, plotted at the centres of the p_{T} intervals, in pp collisions at $\sqrt{s} = 5.02$ TeV in comparison with FONLL calculations. Data results and FONLL calculations for bottom muons both include the $b \to c \to \mu$ contribution. Statistical uncertainties in the data are shown as vertical lines and systematic uncertainties in the data and calculation are shown as boxes.

Figure 4 shows the differential per-event invariant yields for muons from charm and bottom hadron decays, in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV as a function of muon p_{T}. To quantify the modification of the momentum distribution between pp and Pb+Pb collisions the nuclear modification factor is calculated according to Eq. (1) in several centrality intervals. The resulting charm and bottom muon R_{AA} values are shown in Figure 5 as a function of muon p_{T}. There is substantial suppression of muons from both charm and bottom hadron decays for all analysed Pb+Pb centrality intervals. The suppression increases monotonically from the 40–60% interval to the most central 0–10% interval. The monotonic centrality dependence follows expectations as the heavy quarks spend a longer time in the hotter and larger QGP droplet formed in collisions that have larger nuclear overlap, i.e. the more central intervals. Charm muon R_{AA} shows weak p_{T} dependence in all centrality intervals, while bottom muon R_{AA} first decreases with increasing muon p_{T} up to 10 GeV and then remains mostly unchanged in all centralities.

Muons from charm decays have a stronger suppression than muons from bottom decays at low p_{T} in all centrality intervals. This difference in suppression is highlighted in Figure 6, which overlays the 0–10% and 40–60% centrality intervals already presented in Figure 5 for both charm and bottom muon R_{AA}. The

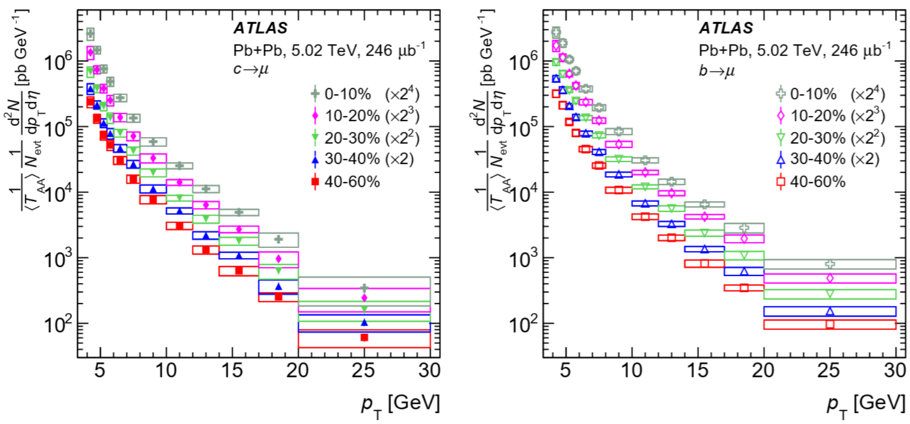

Figure 4: Differential per-event invariant yields of muons from charm hadron decays (left) and bottom hadron decays (right) as a function of p_{T}, plotted at the centres of the p_{T} intervals, for different centrality intervals in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. For each centrality interval from peripheral to central, an additional scaling factor of 2 is applied to the plotted points for visual clarity. Statistical uncertainties are shown as vertical lines and systematic uncertainties as boxes.

mass ordering of the measured R_{AA} follows expectations, as the charm quarks, being lighter than the bottom quarks, are expected to lose more energy in the QGP. Thus the charm quarks are pushed further to lower p_{T}, and emerge more strongly suppressed than bottom quarks when compared with the cross section in pp collisions.

Figure 6 also compares the experimental data with theoretical calculations referred to as DREENA-B [67] and DAB-MOD [68, 69]. The DREENA-B calculation includes radiative and collisional energy loss of the heavy quarks traversing the QGP, the latter modelled via a 1 + 1D Bjorken expansion [70] with path-length distributions calculated following the procedure described in Ref. [71]. The width of the band corresponding to the DREENA-B theoretical uncertainties reflects the range of the ratio of magnetic to electric screening masses as constrained by non-perturbative calculations [70]. As discussed in Ref. [67], the predicted R_{AA} is higher for B mesons than for D mesons, converging to the same value at $p_{\mathrm{T}} \approx 25$ GeV as is expected when the particle p_{T} becomes much larger than the mass of the heavier b-quark. The corresponding R_{AA} for muons shown for direct comparison with the experimental data is calculated using PYTHIA 8, which simulates meson decay kinematics. The DREENA-B prediction is in reasonable agreement with the experimental data. The DAB-MOD framework used here includes calculations with only Langevin drag and diffusion contributions for the heavy quarks in the QGP. The curves shown here are obtained with TRENTO geometric initial conditions [72], heavy-quark Langevin dynamics with the Moore and Teaney parameterization [73], and coupling values for charm (bottom) of $D/2\pi T = 2.23$ (2.79), where D is the spatial diffusion coefficient and T is the temperature. The temperature at which heavy quarks decouple from the medium is $T = 160$ MeV and both coalescence and fragmentation are implemented for hadronization. The DAB-MOD predictions with only Langevin dynamics shown in Figure 6 as coloured solid lines are in qualitative agreement with the experimental data, but have a stronger p_{T} dependence than the experimental data, particularly in the most central collisions. No uncertainties are included for DAB-MOD calculations shown here.

It is notable that both of these calculations also predict the azimuthal anisotropies of the heavy-flavour muons. ATLAS has previously published azimuthal anisotropies quantified by the elliptic flow coefficient,

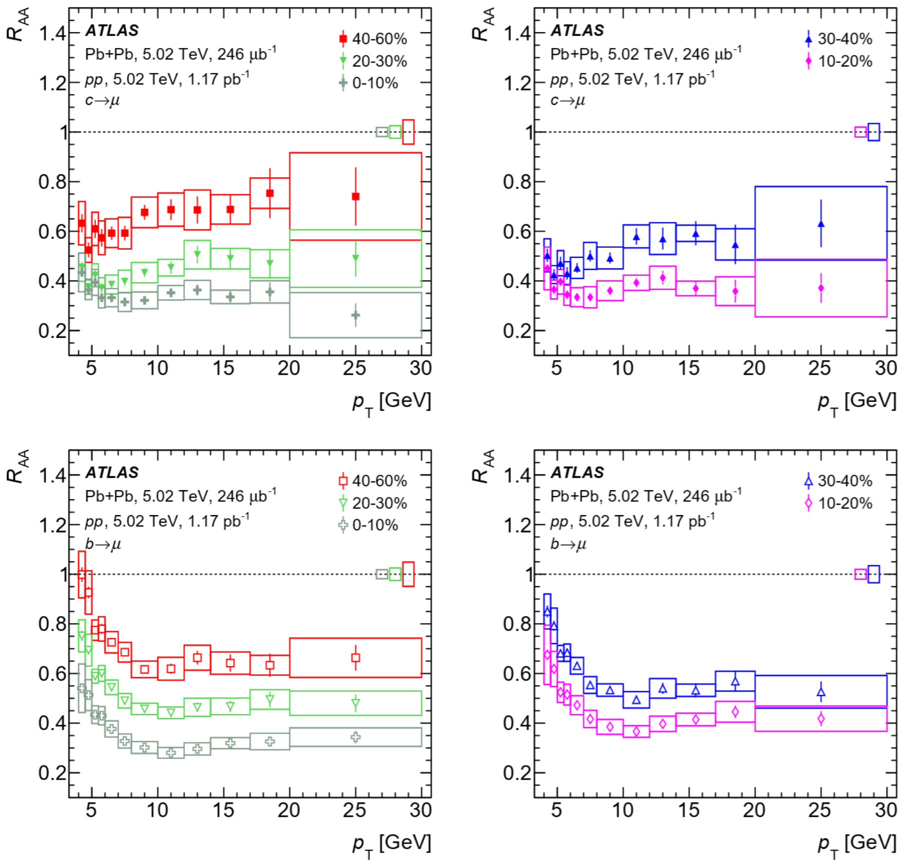

Figure 5: Nuclear modification factor, R_{AA}, for muons from charm hadron decays (top panels) and bottom hadron decays (bottom panels) as a function of p_{T} for five different centrality intervals. The centrality intervals are separated for clarity into the left (0–10%, 20–30%, 40–60%) and right (10–20%, 30–40%) panels. Statistical uncertainties are shown as vertical lines and uncorrelated systematic uncertainties as boxes around the points. Correlated fractional systematic uncertainties, including T_{AA} and pp luminosity uncertainties, are isolated as coloured boxes around unity for different centrality intervals.

v_2, for muons from charm and bottom hadron decays [25]. The lower panels of Figure 6 show those ATLAS measurements of v_2 as a function of p_{T} in comparison with both the DREENA-B and DAB-MOD calculations. The DREENA-B calculations agree qualitatively with both v_2 and R_{AA} for both charm and bottom muons, while the previously described implementation of DAB-MOD underestimates the charm muon v_2 even though it qualitatively matches the R_{AA}. In all theoretical implementations, a larger coupling of charm and bottom quarks to the QGP results in a reduced R_{AA} (i.e. more suppression) and an increased v_2 (i.e. larger anisotropy). Thus, increasing the coupling of charm to the QGP in DAB-MOD, for example, could bring the predicted v_2 into closer agreement with data but would simultaneously decrease R_{AA}, pushing the calculation further below the data. That said, another key component of these calculations is the modelling of the QGP space-time evolution, and thus it could be instructive in the future to compare the different theory calculations with a common QGP model to test whether the differences in R_{AA} and v_2 arise from the QGP modelling or the energy-loss implementation.

Figure 7 shows the measured ratio of charm muon R_{AA} to bottom muon R_{AA} as a function of p_{T} in

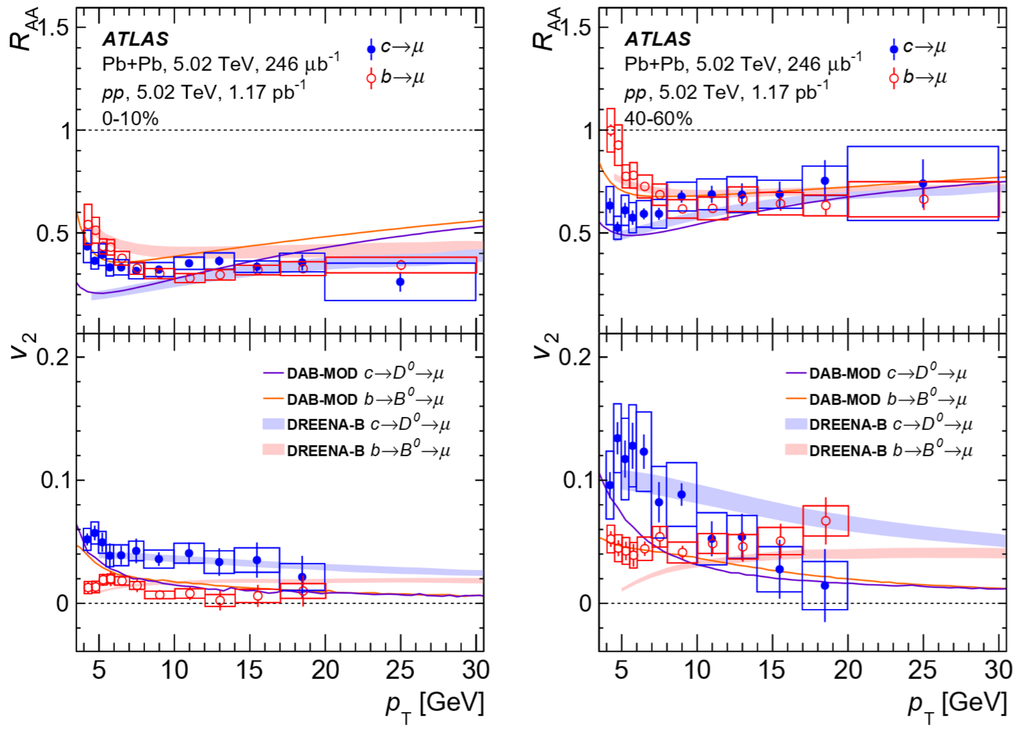

Figure 6: Nuclear modification factor, R_{AA}, (top) and elliptic flow, v_2, results taken from Ref. [25] (bottom) for muons from bottom hadron decays and charm hadron decays for 0–10% (left) and 40–60% (right) centrality intervals as a function of p_{T}. Statistical uncertainties are shown as vertical lines and systematic uncertainties as boxes. Also shown are theoretical calculations from the DREENA-B and DAB-MOD models. See text regarding the uncertainty band of DREENA-B model calculations.

comparison with DREENA-B and DAB-MOD calculations. The large uncertainty in the measured ratio is due to a strong negative correlation between the charm and bottom muon R_{AA} uncertainties. As indicated by the measured R_{AA} ratios, charm muons are significantly more suppressed than bottom muons in the $p_{\mathrm{T}} < 8$ GeV range. However, no strong conclusion about the relative strength of their suppression can be drawn at higher p_{T} due to the large uncertainties. Compared with the ratios measured in data, the calculations underestimate the R_{AA} ratios for 0–10% centrality, while they mostly capture the magnitude and p_{T} dependence of the ratio for 40–60% centrality. As shown in Figure 6, the discrepancy between data and the models in the 0–10% centrality interval is primarily due to the underestimation of charm muon R_{AA}.

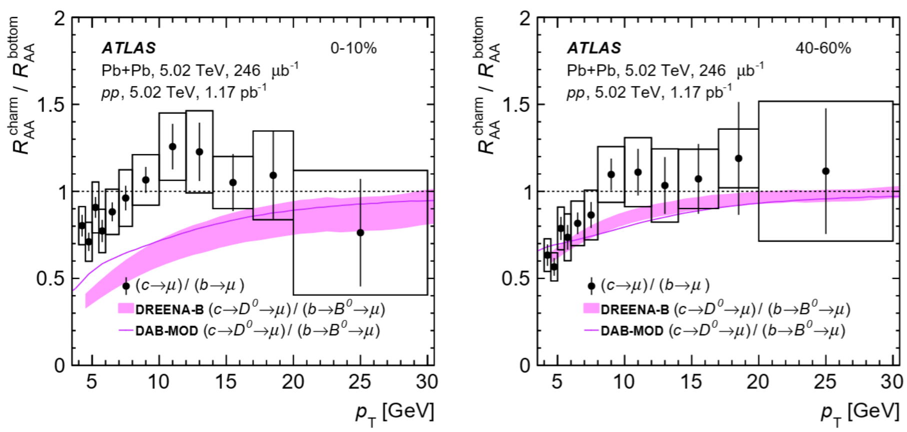

Figure 7: The ratio of charm muon R_{AA} to bottom muon R_{AA}, $R_{\mathrm{AA}}^{\mathrm{charm}}/R_{\mathrm{AA}}^{\mathrm{bottom}}$, for 0–10% (left) and 40–60% (right) Pb+Pb centrality intervals as a function of muon p_{T}. Statistical uncertainties are shown as vertical lines and systematic uncertainties as boxes. Also shown are theoretical calculations for the decay muons from DREENA-B and DAB-MOD in the same centrality intervals.

7 Conclusion

The ATLAS experiment at the LHC has measured the production rates and nuclear modification factors, R_{AA}, of muons from semileptonic decays of heavy-flavour hadrons in pp and Pb+Pb collisions at 5.02 TeV. The measurement uses 2017 pp data and combined 2015 and 2018 Pb+Pb data corresponding to integrated luminosities of 1.17 pb^{-1} and 246 μb^{-1} respectively. Compared to a previous ATLAS measurement of heavy-flavour muons, this Letter reports separate results for charm and bottom muons and covers a wider p_T range. The differential cross section measured in pp collisions for muons from decays of hadrons containing a bottom quark is reproduced with FONLL calculations. For muons from decays of hadrons containing a charm quark, the FONLL calculation is lower than the data at all measured p_T but agrees with it within the systematic uncertainties of the calculations below 10 GeV. The R_{AA} measurements indicate a significant suppression of the yield of muons from both charm and bottom hadron decays, with a suppression that increases monotonically from peripheral to central collisions. The suppression is stronger for charm quarks than for bottom quarks, as expected theoretically. The simultaneous constraints imposed by the measurements of R_{AA} presented here and the flow measurements previously published by ATLAS could provide important information for understanding heavy-quark transport and QGP properties.

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