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Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the ATLAS detector

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ABSTRACT

Azimuthal anisotropies of muons from charm and bottom hadron decays are measured in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The data were collected with the ATLAS detector at the Large Hadron Collider in 2015 and 2018 with integrated luminosities of 0.5 nb^{-1} and 1.4 nb^{-1}, respectively. The kinematic selection for heavy-flavor muons requires transverse momentum $4 < p_{\mathrm{T}} < 30$ GeV and pseudorapidity $|\eta| < 2.0$. The dominant sources of muons in this p_{T} range are semi-leptonic decays of charm and bottom hadrons. These heavy-flavor muons are separated from light-hadron decay muons and punch-through hadrons using the momentum imbalance between the measurements in the tracking detector and in the muon spectrometers. Azimuthal anisotropies, quantified by flow coefficients, are measured via the event-plane method for inclusive heavy-flavor muons as a function of the muon p_{T} and in intervals of Pb+Pb collision centrality. Heavy-flavor muons are separated into contributions from charm and bottom hadron decays using the muon transverse impact parameter with respect to the event primary vertex. Non-zero elliptic (v_2) and triangular (v_3) flow coefficients are extracted for charm and bottom muons, with the charm muon coefficients larger than those for bottom muons for all Pb+Pb collision centralities. The results indicate substantial modification to the charm and bottom quark angular distributions through interactions in the quark-gluon plasma produced in these Pb+Pb collisions, with smaller modifications for the bottom quarks as expected theoretically due to their larger mass.

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1. Introduction

The paradigm for the time evolution of heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) involves the formation and hydrodynamic expansion of a region of hot and dense quark–gluon plasma (QGP) with a small ratio of the shear viscosity to entropy density. In this paradigm, the QGP is considered to be a nearly perfect fluid [1,2]. Initial geometric inhomogeneities of the QGP are translated into momentum anisotropies of the final-state hadrons via large pressure gradients. Extensive measurements of light-hadron azimuthal anisotropies have been performed, in which the single-particle azimuthal distributions are expressed in terms of a Fourier expansion:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n)), \tag{1}$$

where the event-plane angle, Ψ_n, specifies the orientation of the initial density profile in the transverse plane [3], and Fourier coefficients, v_n, quantify the magnitude of the modulation with respect to the event-plane angle. The second- and third-order v_n coefficients are referred to as elliptic (v_2) and triangular (v_3) flow coefficients, respectively, with the term 'flow' invoking the hydrodynamic paradigm.

Heavy-flavour (charm and bottom) quarks have masses much larger than the temperature of the QGP ($m_{c,b} > T$), with maximum temperatures at early times ranging between 300 and 500 MeV [4]. Thus, thermal production of heavy quarks during the QGP phase is highly suppressed. Instead, heavy quarks are typically produced at the earliest times via high-momentum-transfer collisions between incoming partons. Once created, the heavy quarks persist throughout the dynamical time evolution of the QGP and thus act as sensitive probes of the hot and dense medium.

Owing to their larger masses, radiative energy loss of heavy quarks in the QGP is suppressed relative to that of light quarks [5]. However, it was still postulated that charm quarks interact strongly enough to flow with the QGP [6]. Experimental data at RHIC and then at the LHC reveals that heavy-quark hadrons, as well as their decay leptons, have transverse momentum (p_{T}) distributions

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that are strongly modified by the QGP relative to observations in proton–proton (pp) collisions [7–12]. Charm hadrons [13,14] and heavy-quark hadron decay leptons [7,15] are also observed to have significant azimuthal anisotropies, suggesting that they participate in the overall collective flow of the medium. For recent reviews of heavy-flavour measurements in heavy-ion collisions, see Refs. [16–18].

For $p_{\mathrm{T}} \lesssim 4$–6 GeV, it was proposed that heavy quarks can be described via a Langevin approach with drag and diffusion terms [19]. Modified p_{T} distributions and azimuthal anisotropies of D mesons have been used to constrain heavy-quark transport coefficients [20,21]. Other models of heavy-flavor kinematics in the QGP, including a Boltzmann approach, have also been explored [22–26]. At higher momenta $p_{\mathrm{T}} \gtrsim 5-10$ GeV, heavy-quark energy loss is thought to dominate, with collisional and induced radiative processes both contributing [27]. At intermediate p_{T} hadronization effects can be important as azimuthal anisotropies for the deconfined heavy-quark is transferred to the heavy-flavor hadron [28]. There are numerous theoretical predictions for the azimuthal anisotropies of bottom quarks, e.g. in Refs. [29–31]; however, only limited experimental data are currently available. Precision experimental data for p_{T} distributions and azimuthal anisotropies is crucial as this over-constrains the calculations that depend on the heavy-quark to QGP coupling as well as the QGP space-time evolution.

The flow coefficients v_2, v_3, and v_4 of inclusive heavy-flavour muon production, which includes both muons from charm hadron decays ("charm muons") and muons from bottom hadron decays ("bottom muons"), have been measured by the ATLAS experiment [7] and ALICE experiment [32] in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The measurement indicates significant elliptic flow for heavy-flavour muons with $4 < p_{\mathrm{T}} < 10$ GeV. Recently, the heavy-flavour muon v_2 has also been measured in high-multiplicity $\sqrt{s} = 13$ TeV pp collisions [33]. Unlike the earlier Pb+Pb measurement, the pp measurement examined charm muons and bottom muons separately, finding a non-zero v_2 for charm muons while the v_2 for bottom muons is consistent with zero within uncertainties.

In the measurement presented in this paper, the procedure of the previous $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb+Pb analysis using the event-plane method is followed [7], and is extended to extract separate flow coefficients for charm and bottom muons. These measurements extends the previously published ones to the higher $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV Pb+Pb beam energy, using a larger event sample provided by the 2015 and 2018 combined data sets. The larger data sample enables measurements over a larger momentum range $4 < p_{\mathrm{T}} < 30$ GeV for inclusive heavy-flavour muons. It also allows the separation of the inclusive heavy-flavour muons into charm and bottom contributions. Results for charm and bottom muon elliptic v_2 and triangular v_3 flow coefficients are presented as a function of muon p_{T} for various ranges of overlap between the colliding nuclei, referred to as "centrality".

2. ATLAS detector

The ATLAS detector [34–36] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector (ID) covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking (TRT) detectors. 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) optimised for electromagnetic and hadronic measurements respectively. The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers, covering $|\eta| < 2.4$ and $|\eta| < 2.7$ respectively, and measures 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. The minimum-bias trigger scintillators (MBTS) 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 calorimeters (ZDC) measure neutral particles at pseudorapidities $|\eta| \geq 8.3$ and consist of layers of alternating quartz rods and tungsten plates. A two-level trigger system [37] is used to select events. The first-level trigger (L1) is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to below 100 kHz. This is followed by a software-based high-level trigger (HLT) stage that reduces the accepted event rate to 1–4 kHz depending on the data-taking conditions during Pb+Pb collisions.

3. Event selection

Data used in this analysis were recorded with the ATLAS detector in 2015 and 2018 from Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with integrated luminosities of 0.5 nb^{-1} and 1.4 nb^{-1}, respectively. Events were selected online using a set of muon triggers that require a muon at the HLT stage with p_{T} larger than 3, 4, 6, or 8 GeV [37]. The muon trigger selecting $p_{\mathrm{T}} > 8$ GeV sampled the full luminosity in both 2015 and 2018, while triggers with lower p_{T} thresholds were prescaled to reduce the overall data rate. Thus the higher-threshold triggers are utilised at a given muon p_{T} to sample a larger fraction of the full luminosity. The resulting sampled luminosities are 0.3 nb^{-1}, 0.6 nb^{-1}, and 1.9 nb^{-1} for muons with $4 < p_{\mathrm{T}} < 6$ GeV, $6 < p_{\mathrm{T}} < 8$ GeV and $p_{\mathrm{T}} > 8$ GeV, respectively. The selected events are further required to satisfy offline minimum-bias Pb+Pb collision criteria to reject pile-up based on a combination of the total transverse energy measured in the FCal, denoted by $\Sigma E_{\mathrm{T}}^{FCal}$, and the ZDC energy.

The centrality of each Pb+Pb event is characterised by its $\Sigma E_{\mathrm{T}}^{FCal}$. For the results shown here, the minimum-bias $\Sigma E_{\mathrm{T}}^{FCal}$ distribution is divided into percentiles ordered from the most central (large $\Sigma E_{\mathrm{T}}^{FCal}$, small impact parameter) to the most peripheral (small $\Sigma E_{\mathrm{T}}^{FCal}$, large impact parameter): 0–10%, 10–20%, 20–30%, 30–40%, and 40–60%, where 0–100% corresponds to the total Pb+Pb inelastic cross section. A Monte Carlo Glauber [38] calculation is used to characterise each centrality interval [39]. The above centrality intervals have an average number of participating nucleons $\langle N_{\mathrm{part}} \rangle = 358.8 \pm 2.3$, 264.1 ± 2.9, 189.2 ± 2.8, 131.4 ± 2.6, and 70.5 ± 2.2 respectively.

Muons with $4 < p_{\mathrm{T}} < 30$ GeV and $|\eta| < 2.0$ reconstructed in both the ID and the MS are selected and required to pass 'medium' selection requirements, detailed in Ref. [40], without any requirement on the number of TRT hits, due to the high occupancy in heavy-ion running. Candidate muons are required to be matched

[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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

with a muon reconstructed by the event trigger. Each muon is assigned a weight given by the inverse of the reconstruction and trigger efficiency for the specific muon kinematics.

The muon reconstruction and trigger efficiencies are determined using the $J/\psi \to \mu^+\mu^-$ tag-and-probe method as detailed in Ref. [40]. The muon reconstruction efficiency is factorised as the product of ID and MS reconstruction efficiencies. The ID reconstruction efficiency is obtained from Pb+Pb data directly, while the MS reconstruction efficiency is obtained both from Pb+Pb data and by overlaying Pb+Pb minimum-bias events on simulated J/ψ produced by Pythia 8 [41] with the CTEQ6L1 [42] parton distribution functions, using the same tag-and-probe method. The events in overlay simulations are then given weights such that the $\Sigma E_{\mathrm{T}}^{FCal}$ distribution matches the muon-triggered Pb+Pb data distribution. The MS reconstruction efficiency obtained from simulation is used as the central value for MS reconstruction, with additional data-to-MC scale factors applied to account for residual differences between data and overlay simulation. The same $J/\psi \to \mu^+\mu^-$ tag-and-probe method is used to determine the muon trigger efficiency. The central value of the single-muon trigger efficiency correction is obtained from simulations without overlaying Pb+Pb minimum-bias events. Additional correction factors of order 1–10% are obtained from data and applied to the selection to correct for trigger detector performance differences between data and simulation, as well as the centrality dependence of the muon trigger efficiency in Pb+Pb data.

4. Analysis procedure

The analysis follows the event-plane method for measuring flow coefficients as used in previous ATLAS measurements [7,39] and is briefly summarised here. Each Pb+Pb event has a geometric orientation of the impact parameter vector, and the event can also have a tilt relative to that due to fluctuations in the geometry of the resulting QGP. In any particular Pb+Pb collision, one can estimate the orientation, represented by the FCal-determined n^{th}-order event-plane angle Ψ_n. The azimuthal distribution of transverse energy deposited in the forward and backward rapidity FCal is used to determine the event plane. A comparison of event planes, as measured separately in the forward-rapidity FCal and the backward-rapidity FCal, enables a determination of the event-plane resolution $\mathrm{Res}\{n\Psi_n\}$ as detailed in Ref. [39]. In each Pb+Pb centrality interval and in each muon p_{T} selection, the muons are divided into a finite number of intervals in $\phi - \Psi_n$, where ϕ is the azimuthal angle of the muon. As different harmonic orders are orthogonal to each other, the Fourier decomposition of the angular distribution (introduced in Eq. (1)) at a given order n can be expressed as

$$\frac{1}{N_X^\mu}\frac{\mathrm{d}N_X^\mu}{\mathrm{d}(n(\phi-\Psi_n))} = 1 + 2v_n^{\mathrm{raw}}\cos\left(n(\phi-\Psi_n)\right),$$

where the v_n^{raw} are the raw flow coefficients and the N_X^μ are the extracted yields for the muons of interest. Three types of signal are considered in this measurement (X = charm, bottom, and inclusive heavy-flavour). The final v_n coefficients are obtained by correcting for the event-plane resolution: $v_n = v_n^{\mathrm{raw}}/\mathrm{Res}\{n\Psi_n\}$. The leading sources of background contribution in the selected muon samples are muons from decay-in-flight and punch-through of π and K (π/K background) and muons from non-heavy-flavour components such as direct quarkonia, low-mass resonances, τ-leptons and W/Z decays (labelled "light/onia background"). Other sources of background from hadronic showers and fake muons are found to be very small and are only considered in systematic uncertainties.

Similarly to previous ATLAS publications [7,33,43], different sources of muons are separated using two variables. The first is the 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. Real muons have a ρ distribution peaked around zero while the π/K background has a broader ρ distribution that is shifted toward higher values. The different shapes of the ρ distribution for the π/K background and other muons enable the isolation of the π/K background muons. The analysis is repeated using the transverse momentum imbalance, as opposed to the total momentum imbalance ρ, and no difference is observed. The second variable is the transverse impact parameter, d_0, relative to the event's primary vertex [44]. Charm and bottom muons have different d_0 distributions due to the different decay lengths of charm and bottom hadrons.

A two-step fit in ρ and d_0 is performed in data, using ρ and d_0 line-shape templates for different sources of muons obtained from simulations. First, the yields of inclusive heavy-flavour and π/K background muons are extracted from a fit to the ρ distribution. The relative yields of light/onia background muons and inclusive heavy-flavour muons are fixed to the fractions obtained from Pythia 8 simulations, which are approximately 4% on average. Then, with the extracted π/K background yields fixed, a fit to the d_0 distribution is performed to determine the relative fraction of charm and bottom muons within the yield of inclusive heavy-flavour muons.

The muon ID momentum resolution in Pythia 8 simulations overlaid with minimum-bias Pb+Pb events is found to be worse than the resolution in Pb+Pb data. Thus, the ρ templates are obtained from simulation without Pb+Pb event overlay. The single-muon ID and MS momentum responses in the Pythia 8 simulation are shifted and smeared in order to match those in Pb+Pb data. The single-muon momentum shift and smearing parameters are determined by comparing the invariant mass resolution of simulated $J/\psi \to \mu^+\mu^-$ events in Pythia 8 with that from Pb+Pb data at different centralities. The charm and bottom muon ρ templates are determined from multijet hard-scattering pp collision events at $\sqrt{s} = 13$ TeV filtered on the presence of a generator-level muon in Pythia 8 with parameter values as in the A14 tune [45] and using the NNPDF23LO parton distribution functions [46]. The π/K background ρ templates are obtained from non-diffractive QCD simulations of pp collisions at $\sqrt{s} = 13$ TeV in Pythia 8, also with the A14 tune and NNPDF23LO parton distribution functions. The ρ templates for the light/onia background contribution are obtained from simulations of direct J/ψ in pp collisions at $\sqrt{s} = 5.02$ TeV. No differences in the template shapes were observed between simulations at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 5.02$ TeV. The signal muon ρ distribution shape shows no obvious dependence on muon p_{T}, but is found to be broader in the endcap muon detector and in most central events due to poorer muon momentum resolution in the ID.

As the d_0 resolution is sensitive to the primary vertex position resolution, the d_0 templates are all obtained from Pythia 8 simulations at $\sqrt{s} = 5.02$ TeV overlaid with minimum-bias Pb+Pb events to best approximate the primary vertex resolution. The distributions of d_0 are shifted and smeared to remove residual differences between overlay simulations and Pb+Pb data. The d_0 shift and smearing parameters are found by comparing the distributions of high-quality prompt-tracks between Pb+Pb data and overlay simulations. The charm and bottom muon d_0 templates are obtained from multijet hard-scattering simulations filtered on the presence of a generator-level muon, whereas the π/K background d_0 templates are from non-diffractive QCD simulations, and the templates for light/onia background are obtained from direct J/ψ simulations. The signal muon d_0 distribution shape shows no dependence

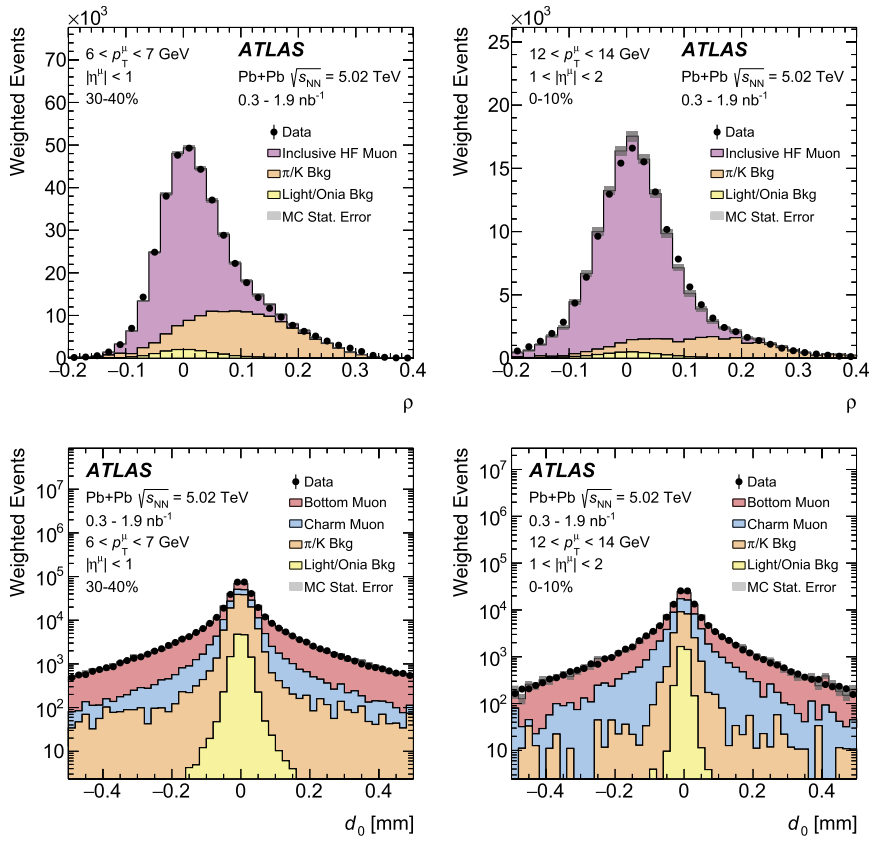

Fig. 1. Example fits to ρ (top) and d_0 (bottom) for muons with $6 < p_T < 7$ GeV and $|\eta| < 1$ in 30–40% centrality Pb+Pb collisions (left) and $12 < p_T < 14$ GeV and $1 < |\eta| < 2$ in 0–10% centrality Pb+Pb collisions (right) both integrated over $n|\phi - \Psi_n|$. Muon trigger and reconstruction efficiency corrections are applied to the data.

on muon p_T or event centrality but a moderate dependence on parent charm and bottom hadron p_T due to the strong correlation between decay length and particle velocity. Additional reweighting is applied to the charm and bottom muon signal samples to match the input charm and bottom hadron p_T spectra to those measured in Pb+Pb collisions by ALICE [11] and CMS [8,47].

The fits are performed independently in differential intervals of muon p_T, centrality, $n|\phi - \Psi_n|$ and two intervals of muon η. The two muon η intervals ($|\eta| < 1$ and $1 < |\eta| < 2$) are fitted independently to minimise residual data/MC difference in the barrel and endcap muon detectors separately, and then combined to obtain charm, bottom, and inclusive heavy-flavour muon yields in the given p_T, centrality, and $n|\phi - \Psi_n|$ intervals as reported in the results. Fluctuations in the simulation templates are incorporated in the fitting procedure. Examples of selected fits in ρ and d_0 based on simulation templates are shown in Fig. 1 for two different muon p_T selections ($6 < p_T < 7$ GeV and $12 < p_T < 14$ GeV) integrated over $n|\phi - \Psi_n|$.

The top row of Fig. 2 shows the inclusive heavy-flavour muon yield as a function of $2|\phi - \Psi_2|$ (left) and $3|\phi - \Psi_3|$ (right), and the bottom row shows the charm and bottom muon yields as a function of $2|\phi - \Psi_2|$ (left) and $3|\phi - \Psi_3|$ (right). The lines indicate the second (left) and third (right) extracted Fourier harmonics from which the v_2^{raw} and v_3^{raw} coefficients are extracted.

5. Systematic uncertainties

Systematic uncertainties are presented for different categories covering each step of the analysis procedure: 1) muon efficiency; 2) ρ fit; 3) d_0 fit; 4) light/onia background; 5) other background; 6) ρ–d_0 correlation; 7) event-plane resolution; and 8) jet bias. Table 1 summarises the contributions from different sources of systematic uncertainty to the final flow-coefficient results. Systematic uncertainties from all sources are summed in quadrature to determine the total uncertainty.

The systematic uncertainties from the MS reconstruction efficiency and muon trigger efficiency corrections are dominated by the uncertainty in determining the data-to-MC scale factor. The scale factor uncertainties are evaluated following the procedure from previous ATLAS measurements [40] including variations in the tag-and-probe efficiency extraction method, object-matching resolution, and purity of the sample. The systematic uncertainty in the muon trigger efficiency also includes the determination of the centrality-dependent correction factors. The uncertainty on the flow coefficients resulting from uncertainties in the muon ID reconstruction efficiency is evaluated by comparing the results with and without the ID efficiency correction, as the ID efficiency is approximately 99% for all centralities. The muon efficiency systematic uncertainties are correlated between the resulting charm and bottom muon results.

The systematic uncertainty of the ρ fit is due to the uncertainty in the shifts and smearing parameters for single-muon momentum response in simulation, which is evaluated by comparing the nominal results with those 1) without any shifts or smearing, 2) only applying shifts and smearing to the signal muons, and 3) incorporating additional smearing of the background ρ distributions in simulation to match data distributions in the background-enriched region ($\rho > 0.2$). The changes resulting from these variations are combined in quadrature. The combined uncertainty from the ρ fit is 1%–10% for the charm and bottom muon results, depending on the muon p_T and η, but without dependence on centrality. The relative systematic variations are found to be the largest at low p_T and large η. The ρ fit systematic uncertainties are correlated between the resulting charm and bottom muon results.

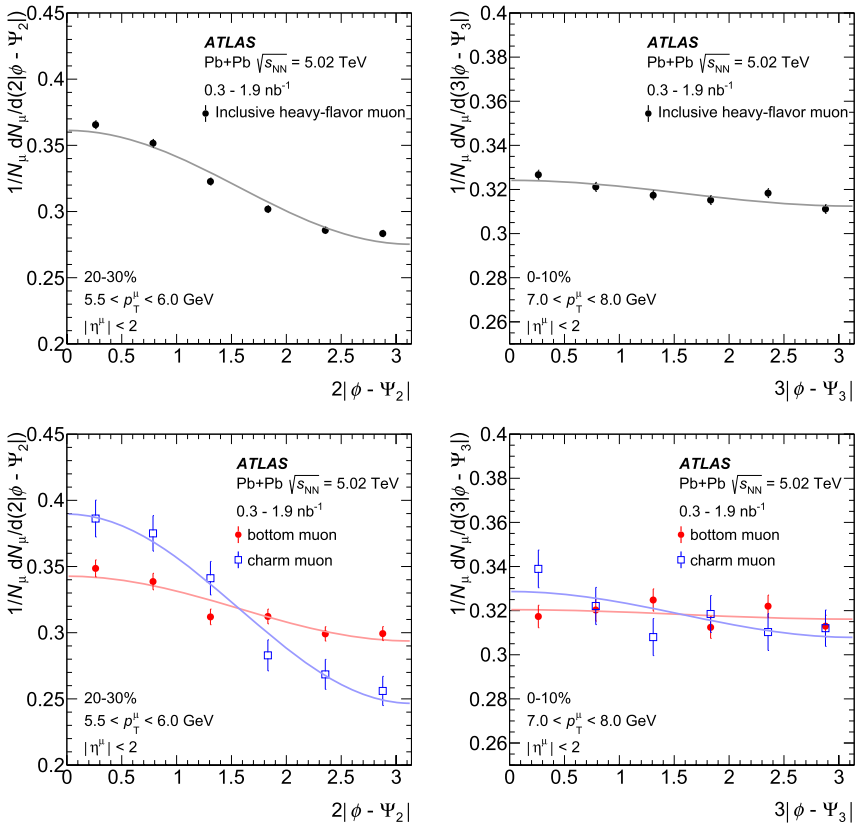

Fig. 2. Examples of Fourier decomposition of inclusive heavy-flavour muon yields (top) and bottom/charm muon yields (bottom) in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of $2|\phi - \Psi_2|$ (left) and $3|\phi - \Psi_3|$ (right) for two selected intervals in muon p_T and centrality. The inclusive heavy-flavour muon yields are obtained from ρ template fits, while the bottom and charm muon yields are further separated using d_0 fits. In all cases the error bars on data indicate the statistical uncertainties obtained from the ρ or d_0 fit. The lines indicate the extracted second (left) and third (right) Fourier harmonics.

Table 1
Summary of the typical sizes of the absolute systematic uncertainties of all categories for the flow coefficient results. The d_0 related systematic uncertainties are not relevant for the heavy-flavour inclusive flow measurements as the d_0 fit is not utilised for these results. Systematic uncertainties from the event-plane resolution and jet bias are negligible and not included in the final uncertainties, and therefore are not shown in the table. The "<" symbol indicates the provided values are the maximum systematic variation for a given category.

Category	Inclusive heavy-flavour muon v_2 (v_3)	Charm muon v_2 (v_3)	Bottom muon v_2 (v_3)
Muon efficiency	< 0.0002 (0.0006)	< 0.006 (0.001)	< 0.001 (0.001)
ρ fit	< 0.004 (0.006)	< 0.009 (0.01)	< 0.005 (0.003)
d_0 fit	N/A	< 0.02 (0.03)	< 0.01 (0.01)
Light/onia bkg	< 0.004 (0.002)	< 0.02 (0.01)	< 0.008 (0.004)
Other bkg	< 0.000001 (0.000001)	< 0.002 (0.004)	< 0.001 (0.0004)
ρ–d_0 correlation	N/A	< 0.01 (0.004)	< 0.007 (0.005)

The uncertainty in the d_0 template shift and smearing parameters is tested by comparing results when determining the parameters using 2018 data (as in the nominal results) with results when using the 2015 Pb+Pb data to determine the parameters, which covers the slightly different detector alignment between the two data sets. Sensitivity to the charm and bottom hadron p_T spectra reweighting in simulation is covered by a variation in which the p_T spectra are reweighted to agree with those from Pythia 8 simulations without any modification due to QGP. The variations in the results due to d_0 template shift and smearing and p_T spectra reweighting are considered to be uncorrelated and are combined in quadrature, and the combined systematic uncertainty is 1%–20% for the charm and bottom muon results, depending on muon p_T and centrality. The relative systematic variations are found to be the largest at high p_T and in more peripheral events. The d_0 fit systematic uncertainties are anti-correlated between the resulting charm and bottom muon results.

The magnitude of the light/onia contribution is held at a fixed fraction relative to the inclusive heavy-flavour muon contribution, based on the Pythia 8 MC sample. The analysis is repeated to study this choice, first ignoring the light/onia contribution and then fixing it to twice the fraction predicted by Pythia 8. As is shown in Ref. [48], Pythia overestimates prompt quarkonium production at the LHC, and thus these variations of the light/onia contribution are large enough to not underestimate the uncertainty. Each nominal result is assigned a systematic uncertainty equal to the larger of the changes from the two variations. For the nominal results, light/onia muons are assumed to have the same v_2 and v_3 as the inclusive heavy-flavour muons. The analysis is repeated with variations assuming light/onia muons have zero flow coefficients or double the inclusive heavy-flavour muon flow coefficients. The larger of the resulting changes is assigned as the systematic uncertainty. The light/onia systematic uncertainties are anti-correlated between the resulting charm and bottom muon results.

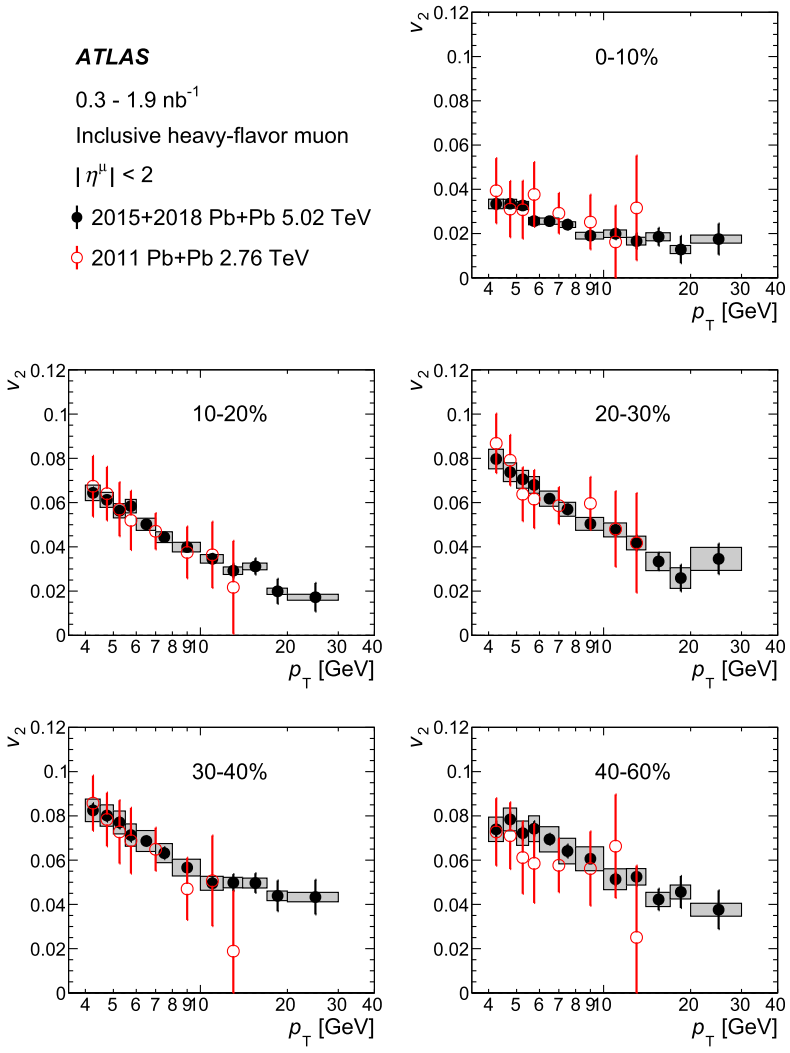

Fig. 3. Inclusive heavy-flavour muon v_2 as a function of p_{T} in the combined 2015 and 2018 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV Pb+Pb data compared with the results in the $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb+Pb data [7]. Statistical uncertainties are shown as vertical lines and systematic uncertainties as boxes for the $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV results. For better visibility the statistical and systematic uncertainties of the $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV data are combined in quadrature and shown as vertical lines. Each panel represents a different centrality interval.

The contributions of hadronic showers are ignored in the nominal analysis. They were included in the analysis based on ρ and d_0 templates from the Pythia 8 simulation with a fixed relative fraction of a few percent also obtained from Pythia 8 simulation. The deviation from the nominal result is found to be negligible for the inclusive heavy-flavour muon flow coefficients, and approximately 8% at low p_{T} (< 8 GeV) and less than 1% at high p_{T} (> 12 GeV) for charm and bottom muon flow coefficients.

All muons are assumed to have independent ρ and d_0 distributions in the nominal results, which is only true for signal muons. To test the sensitivity to this assumption, d_0 fits in data are repeated with a requirement of $\rho < 0.1$ on the sample, thus significantly reducing the background contribution. The difference between results with and without the restriction on ρ is assigned as a systematic uncertainty to cover the systematic effect of ignoring any correlation between ρ and d_0 for background muons.

The systematic uncertainty associated with the event-plane angle resolution is evaluated by measuring the event-plane resolution in two subregions of the FCal ($3.2 < |\eta| < 4.0$ and $4.0 < |\eta| < 4.8$), following a previous ATLAS flow analysis [39]. The systematic uncertainties are evaluated independently for Ψ_2 and Ψ_3. The maximum difference between these two variations and the nominal results is considered as a systematic uncertainty. The uncertainty associated with the event-plane angle resolution is found to be negligible compared to other systematic uncertainties, and thus is not included in the results.

The charm and bottom muons are often produced with a recoil jet. The orientation of Ψ_n could be biased to align with the signal muon if the recoil jet reaches the FCal [7]. The magnitude of this bias in muon v_2 and v_3 is studied with Pythia generator-level muon flow in samples overlaid with Pb+Pb data. The bias is found to be 0.3%–0.4% for v_2 and v_3, and it is larger in peripheral events than in more-central events. This small bias is negligible and is not included as a systematic uncertainty.

6. Results

Fig. 3 shows the inclusive heavy-flavour muon elliptic flow coefficient v_2 as a function of p_{T} in the $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV Pb+Pb data. Each panel corresponds to a different Pb+Pb centrality interval. The v_2 results decrease steadily with p_{T} over the entire p_{T} range and in all centrality intervals. The overall magnitude of v_2 is smaller in the most central 0–10% selection, as expected since the corresponding smaller impact parameter Pb+Pb collisions have smaller initial geometric ellipticity.

Fig. 4 shows the inclusive heavy-flavour muon triangular flow coefficient v_3 as a function of p_{T} in the $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV Pb+Pb data. Each panel corresponds to a different Pb+Pb centrality in-

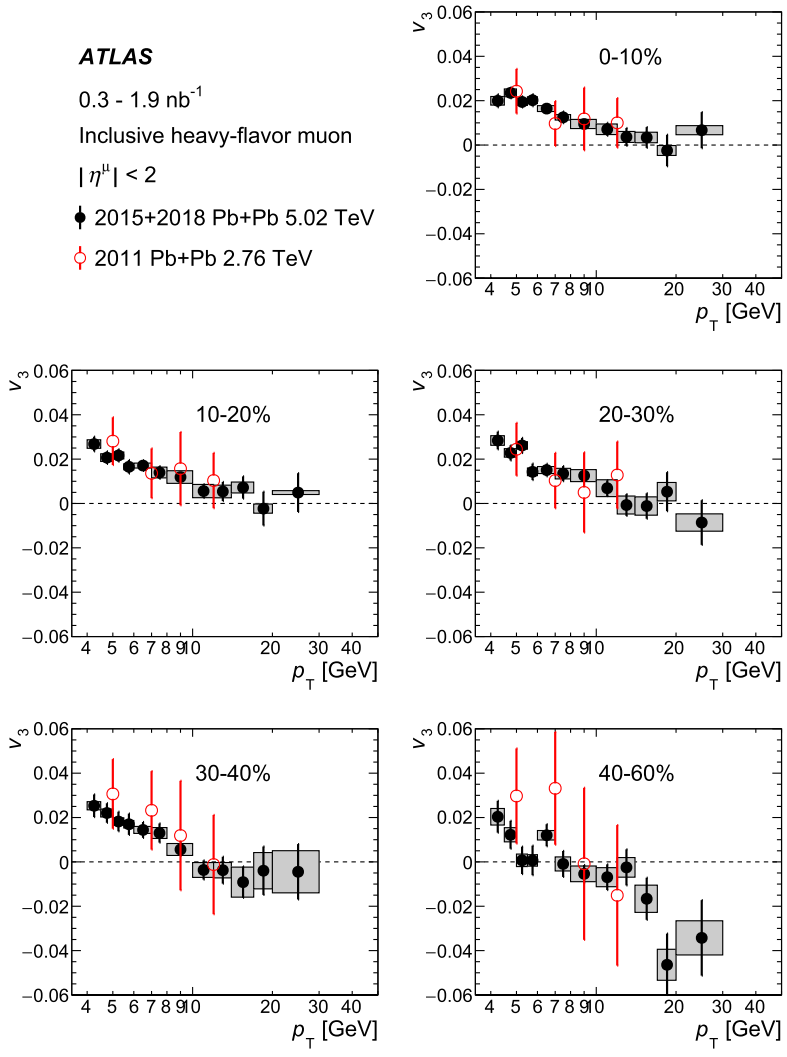

Fig. 4. Inclusive heavy-flavour muon v_3 as a function of p_{T} in the combined 2015 and 2018 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV Pb+Pb data compared with the results in the $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb+Pb data [7]. Statistical uncertainties are shown as vertical lines and systematic uncertainties as boxes for the $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV results. For better visibility the statistical and systematic uncertainties of the $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV data are combined in quadrature and shown as vertical lines. Each panel represents a different centrality interval.

terval. The v_3 results decrease steadily with p_{T} over the entire p_{T} range in all centrality intervals within statistical and systematic uncertainties. The overall magnitude of v_3 is quite similar in all centrality intervals, as expected since triangular deformations of the initial geometry are primarily the result of fluctuations and are generally unrelated to any intrinsic geometry from the colliding nuclei [49].

Each panel of Figs. 3 and 4 also presents previous ATLAS results from $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb+Pb data [7]. Compared to the earlier result, the present $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV results significantly improve the statistical precision of the measurements and extend the p_{T} range. The $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb+Pb data inclusive heavy-flavour muon v_2 and v_3 coefficients are consistent with each other within uncertainties. Indeed, according to hydrodynamical models, no significant differences are expected between Pb+Pb collisions at the two different energies [50]. Thus the observed consistency between $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV data is in agreement with expectations. The inclusive charged-particle flow coefficients are also observed to be nearly identical at the two collision energies [39].

Fig. 5 shows the separated charm and bottom muon v_2 as a function of p_{T}, with each panel presenting a different Pb+Pb centrality interval. The charm and bottom flow coefficients are extracted only up to $p_{\mathrm{T}} = 20$ GeV, since above that transverse momentum range the inclusive heavy-flavour v_2 values are small and the charm-to-bottom separation procedure becomes sensitive to fluctuations in data and yields unstable results. The results indicate a non-zero v_2 for both the charm and bottom muons, with substantially larger elliptic flow coefficients for charm muons. The statistical and systematic uncertainties have a significant contribution that is anti-correlated between the charm and bottom v_2, i.e. an upward fluctuation in the charm v_2 in a particular p_{T} bin will be correlated with a downward fluctuation in the bottom v_2 in the same bin and vice versa. For $p_{\mathrm{T}} < 14$ GeV, both charm and bottom muon v_2 increase from central to mid-central events, reaching maximum between 20% and 40% centrality. Over the range of $p_{\mathrm{T}} > 14$ GeV, the charm and bottom muon v_2 show no obvious centrality dependence with larger uncertainties.

Qualitatively, the charm and bottom v_2 ordering matches theoretical expectations where the heavier bottom quarks have a smaller modification to their initial momentum trajectories due to their larger masses. Light quarks and heavy quarks can lose energy in traversing the QGP via induced gluon radiation [51]; however, heavy quarks with momentum less than or approximately equal to the quark mass ($p \lesssim m$) radiate less than light quarks due to a suppression of radiation at small angles relative to the quark direction, referred to as the 'dead-cone' effect [5]. Thus, at high $p_{\mathrm{T}} >> m$, all quark flavors should lose comparable energy in the

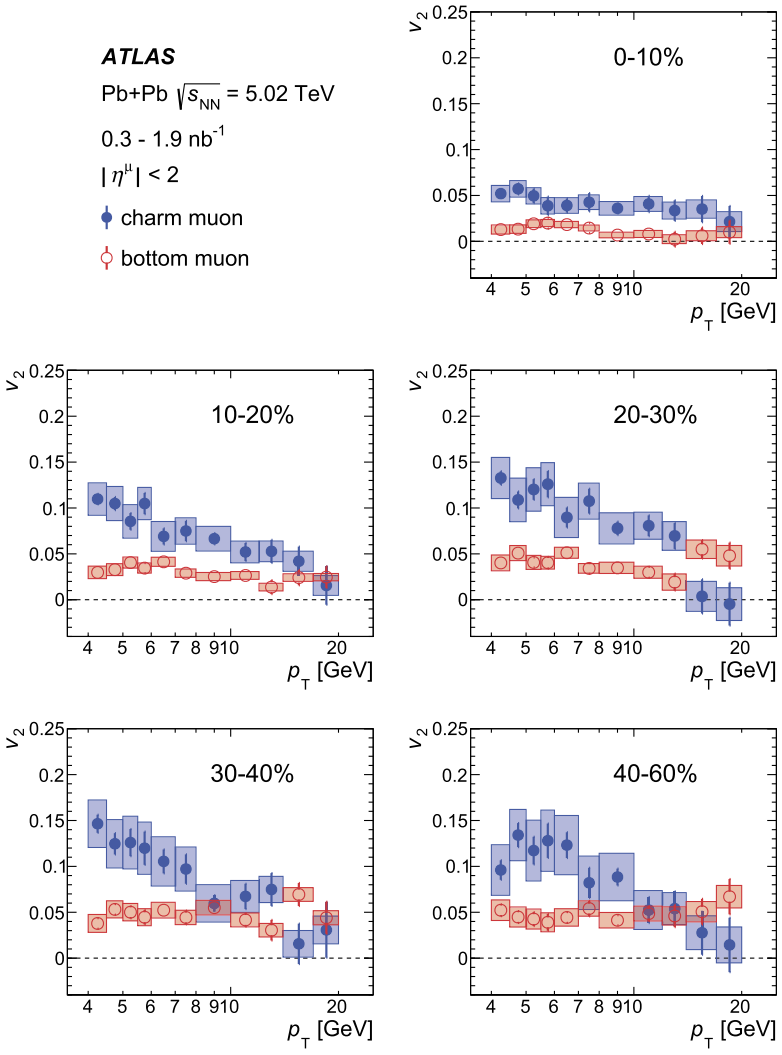

Fig. 5. Charm and bottom muon v_2 as a function of p_T in the combined 2015 and 2018 $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb data. Statistical uncertainties are shown as vertical lines and systematic uncertainties as boxes for charm and bottom muons. The charm and bottom uncertainties are partially anti-correlated. Each panel presents a different centrality interval.

QGP, while at lower p_T there should be a hierarchy with light quarks losing the most energy, then charm quarks, and finally bottom quarks losing the least energy. Thus the heavier bottom quarks with $p_T \lesssim 20 - 30$ GeV are expected to lose less energy in the QGP and thus have a smaller azimuthal anisotropy.

Fig. 6 shows the separated charm and bottom muon v_3 as a function of p_T, with each panel presenting a different Pb+Pb centrality interval. The charm muons show significant non-zero v_3 values, which are independent of centrality. The bottom muons have v_3 values that are significantly below that of charm muons at all p_T and in all centrality intervals.

Fig. 7 shows the results for v_2 versus p_T, from Fig. 5, compared with theoretical calculations: DREENA-B from Ref. [30], and DAB-MOD from Refs. [29,52] for charm and bottom decay muons in the Pb+Pb 0–10% (left) and 40–60% (right) centrality intervals. 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 [53]. The DREENA-B theoretical uncertainties reflect the range of magnetic to electric screening masses as constrained by non-perturbative calculations [53]. The predicted D meson v_2 is higher than the B meson v_2, with the two converging at $p_T \approx 25$ GeV as expected when the p_T is much larger than the charm and bottom quark masses. Using PYTHIA 8 for decay kinematics, the charm muon and bottom muon v_2 results are calculated and shown. The predominant effect in going from the parent meson $v_2(p_T)$ to the daughter muon $v_2(p_T)$ is a shift downward in p_T. The predictions are in reasonable agreement with the experimental data, although they overestimate the v_2 at high p_T of bottom muons in central events. The DAB-MOD framework includes calculations with only Langevin drag and diffusion contributions. The curves shown here are obtained with TRENTO geometric initial conditions [54], heavy-quark Langevin dynamics with the Moore and Teaney parameterisation [19], 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 decoupling temperature of heavy quarks from the medium is $T = 160$ MeV and both coalescence and fragmentation are implemented for hadronisation. The DAB-MOD predictions with only Langevin dynamics are roughly a factor of three (two) lower for charm (bottom) muons compared with DREENA-B. Additional energy loss contributions to DAB-MOD, not included here, tend to increase the high p_T anisotropies. At lower p_T, the DREENA-B v_2 results rise significantly. A key component of these calculations is the modelling of the QGP transverse

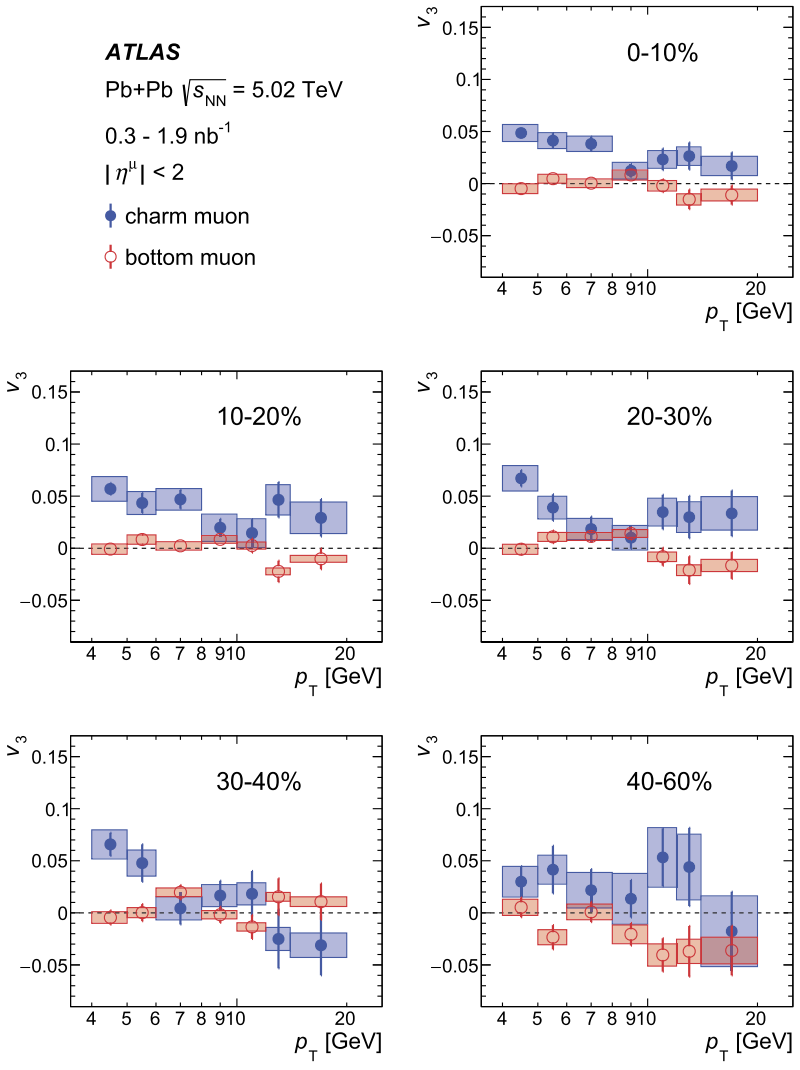

Fig. 6. Charm and bottom muon v_3 as a function of p_T in the combined 2015 and 2018 $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb data. Statistical uncertainties are shown as vertical lines and systematic uncertainties as boxes for charm and bottom muons. The charm and bottom uncertainties are partially anti-correlated. Each panel presents a different centrality interval.

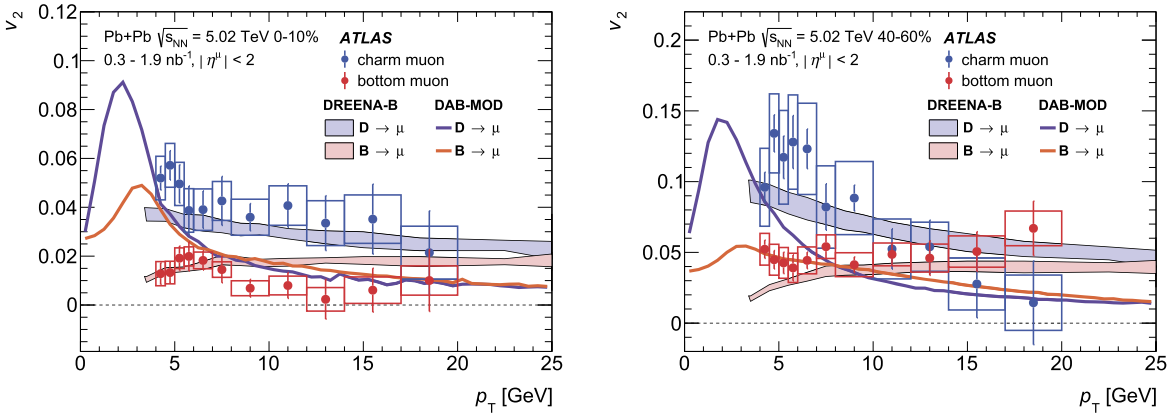

Fig. 7. Charm and bottom muon v_2 as a function of p_T in the $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb data for the 0–10% (left) and 40–60% (right) centrality interval, compared with theoretical predictions based on DREENA-B [30] and DAB-MOD [29,52] in the same centrality intervals for charm and bottom muon v_2. For the data, statistical uncertainties are shown as vertical lines and systematic uncertainties as boxes. The charm and bottom uncertainties are partially anti-correlated.

expansion, and thus it will be instructive in the future to compare the calculations with a common QGP model to test whether the differences arise from the QGP modelling or the energy-loss implementation.

7. Conclusion

In summary, a measurement of elliptic and triangular flow coefficients for heavy-flavour decay muons in Pb+Pb collisions at

$\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is presented, including a separation between charm and bottom contributions. The measurement uses a combined 2015 and 2018 data set corresponding to a total integrated luminosity of up to 1.9 nb^{-1} recorded by the ATLAS experiment at the LHC. The inclusive heavy-flavour muon v_2 and v_3 values measured in $4 < p_{\mathrm{T}} < 30$ GeV are observed to decrease with p_{T} for all centrality intervals. The v_2 and v_3 values are consistent within uncertainties with previous Pb+Pb measurements at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. Further separating the inclusive heavy-flavour muons into charm and bottom muons reveals a significantly larger v_2 and v_3 for charm muons than for bottom muons. The results indicate that while both the charm and bottom quarks have their trajectories and momenta modified when traversing the QGP, the effect is stronger for the charm quarks. At fixed p_{T}, the charm and bottom muon v_2 values decrease from 40-60% to 0-10% centrality intervals as observed in charged hadron elliptic-flow measurements [55]. Theoretical calculations have a similar qualitative trend with smaller flow coefficients for muons from decays of the heavier bottom quarks. The results can significantly discriminate between models of heavy-quark energy loss and constrain heavy-quark transport coefficients in the QGP.

Declaration of competing interest

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

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