Measurement of Azimuthal Anisotropy of Muons from Charm and Bottom Hadrons in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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The elliptic flow of muons from the decay of charm and bottom hadrons is measured in pp collisions at $\sqrt{s} = 13$ TeV using a data sample with an integrated luminosity of 150 pb^{-1} recorded by the ATLAS detector at the LHC. The muons from heavy-flavor decay are separated from light-hadron decay muons using momentum imbalance between the tracking and muon spectrometers. The heavy-flavor decay muons are further separated into those from charm decay and those from bottom decay using the distance-of-closest-approach to the collision vertex. The measurement is performed for muons in the transverse momentum range 4–7 GeV and pseudorapidity range $|\eta| < 2.4$. A significant nonzero elliptic anisotropy coefficient v_2 is observed for muons from charm decays, while the v_2 value for muons from bottom decays is consistent with zero within uncertainties.

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In high-energy collisions between large nuclei at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), a quark-gluon plasma is formed, which rapidly expands as described by nearly inviscid hydrodynamics [1,2]. Heavy quarks, which have a large mass and dead-cone radiation region [3], are expected to interact with the medium through a different interplay of radiative and collisional processes with respect to ordinary light quarks [4]. However, it was hypothesized that even these massive heavy quarks may scatter within the medium and be redirected in a way that results in collective flow patterns [5]. Measurements of decay electrons from charm and bottom hadrons by the PHENIX experiment in Au + Au collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV revealed that heavy quarks undergo significant scattering in the medium and thus lose energy and align with the geometry of the expanding medium [6]. More recent measurements using decay leptons and full reconstruction of charm and bottom hadrons indicate substantial modifications to the momentum distributions of heavy quarks in heavy-ion collisions relative to that in proton-proton (pp) collisions at both RHIC and the LHC (see Ref. [7] for a recent review).

Smaller collision systems, including p + Pb and even pp, have particle emission patterns with large azimuthal anisotropies, also described by nearly inviscid hydrodynamics [1,8,9]. A common hydrodynamic description of pp, p + Pb, and Pb + Pb azimuthal anisotropies as resulting from initial geometry anisotropies is compelling [10]. New measurements of similar anisotropies for reconstructed D mesons and heavy-flavor decay electrons in p + Pb collisions [11,12] highlight that charm quarks are scattered in the medium in smaller collision systems as well. These measurements of anisotropies with almost no modification to the transverse momentum (p_T) distribution [13] are somewhat surprising, because such scattering in the A + A case leads simultaneously to azimuthal anisotropies and a softening of the transverse momentum distributions [14]. It is of interest to measure heavy-flavor anisotropies in pp collisions in order to obtain information about the interaction of heavy quarks with the medium in the smallest hadronic collision system at the LHC. In this Letter, measurements of azimuthal anisotropies for muons from heavy-flavor decays in pp collisions at 13 TeV are presented. Additionally, the heavy-flavor muons are separated to provide information about the anisotropies of muons from charm and bottom decay separately.

The ATLAS experiment [15] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle. [Coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center 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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.] It consists of an inner tracking

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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 detectors. The muon spectrometer (MS) surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. The trigger system consists of a hardware-based first-level trigger and a software-based high-level trigger (HLT) [16], which reconstructs the event in a manner similar to that performed off-line.

Data for this analysis were recorded during a special running period in 2017 in which the mean number of pp interactions per beam crossing was two. Events were recorded using triggers that require a muon at the HLT stage with p_T larger than 4 GeV in coincidence with various triggers designed to select high-multiplicity events [17]. The latter included requirements on the transverse energy in the calorimeter, and the number of space points recorded in the silicon microstrip detector, and the number of charged-particle tracks reconstructed by the HLT. The trigger with the highest threshold for the number of tracks sampled 150 pb^{-1}, while triggers with lower thresholds were prescaled and sampled less integrated luminosities. For each charged-track multiplicity range reported here, analyzed events are taken exclusively from the trigger that sampled the largest integrated luminosity.

Charged-particle tracks and collision vertices are reconstructed in the ID using algorithms described in Ref. [18]. Tracks with $p_T > 0.4$ GeV and $|\eta| < 2.5$ satisfying the set of quality requirements [17] are used in this analysis. Muons with $4 < p_T < 7$ GeV and $|\eta| < 2.4$ reconstructed in both the ID and the MS are selected and required to pass “medium” selection requirements described in Ref. [19]. Events are required to have at least one but not more than four reconstructed vertices to reduce the contribution from in-time pileup events containing multiple pp collisions per event. The number of reconstructed tracks with $p_T > 0.4$ GeV associated with the vertex containing the muon is denoted by $N_{\mathrm{ch}}^{\mathrm{rec}}$.

Simulated events were generated using PYTHIA8 [20] with the NNPDF23LO parton distribution function set [21] and A14 [22] set of tuned parameters. Multijet hard-scattering events filtered on the presence of a generator-level muon were passed through a GEANT4 simulation [23,24] of the detector and reconstructed under the same conditions as the data including pileup background events. A muon trigger emulator is included in the simulation to evaluate the trigger efficiency.

This analysis follows two-particle correlation methods used in previous ATLAS measurements [17,25] and summarized here. Two-particle correlations are measured as a function of $\Delta\phi \equiv \phi^{\mu} - \phi^{h}$ and $\Delta\eta \equiv \eta^{\mu} - \eta^{h}$, where particles μ and h are muons and charged hadrons, respectively. For each muon, correlation functions $S(\Delta\eta, \Delta\phi)$ and $B(\Delta\eta, \Delta\phi)$ are formed [26]. The correlation function $S(\Delta\eta, \Delta\phi)$ uses charged hadrons from the same event. The function $B(\Delta\eta, \Delta\phi)$ is constructed by selecting charged hadrons from different events of similar $N_{\mathrm{ch}}^{\mathrm{rec}}$ ($|\Delta N_{\mathrm{ch}}^{\mathrm{rec}}| < 10$) and vertex position z_{vtx} ($|\Delta z_{\mathrm{vtx}}| < 10$ mm). Detector acceptance effects largely cancel out in the ratio S/B within the precision of these measurements. Each muon-hadron pair is weighted by the inverse product of the trigger and reconstruction efficiencies for the muon and the reconstruction efficiency for the charged hadron.

One-dimensional correlation functions $C(\Delta\phi)$ are obtained by integrating $S(\Delta\eta, \Delta\phi)$ and $B(\Delta\eta, \Delta\phi)$ over the pseudorapidity interval $1.5 < |\Delta\eta| < 5$:

$$C(\Delta\phi) = \frac{\int_{1.5}^{5} d|\Delta\eta| S(|\Delta\eta|, \Delta\phi)}{\int_{1.5}^{5} d|\Delta\eta| B(|\Delta\eta|, \Delta\phi)} \equiv \frac{S(\Delta\phi)}{B(\Delta\phi)},$$

and $S(\Delta\phi)$ and $B(\Delta\phi)$ are normalized such that the average value of $C(\Delta\phi)$ is unity. Requiring a gap in $\Delta\eta$ that excludes $|\Delta\eta| < 1.5$ reduces the contribution to the correlations from jet fragmentation. Previous hadron-hadron correlation results used a larger gap, integrating over $2 < |\Delta\eta| < 5$ instead [17,25]; however, studies of shape variation versus different $|\Delta\eta|$ selections with the PYTHIA8 sample described above indicate that the jet-fragmentation correlation for heavy-flavor quarks is insignificant for muon-hadron pairs with $|\Delta\eta| > 1.5$.

In order to separate the flow contribution from back-to-back dijets and resonance decays, together referred to as nonflow, a template fitting method developed for previous ATLAS analyses [17,25] is used. This method assumes that the shape of non-flow correlations is independent of the particle multiplicity in the events, an assumption which results in a good description of the correlation functions in these measurements and is tested in simulation [27]. Hence the correlation function in low particle-multiplicity (LM) events dominated by nonflow is used to estimate the nonflow contribution in high multiplicity (HM) events. The resulting template fit function:

$$C^{\mathrm{templ}}(\Delta\phi) = F C^{\mathrm{LM}}(\Delta\phi) + C^{\mathrm{ridge}}(\Delta\phi),$$

where

$$C^{\mathrm{ridge}}(\Delta\phi) = G\left[1 + \sum_{n=2}^{4} 2 v_{n,n} \cos(n\Delta\phi)\right],$$

has free parameters F and nth-order flow (anisotropy) coefficients $v_{n,n}$; the coefficient G is fixed by requiring that the integrals of $C^{\mathrm{templ}}(\Delta\phi)$ and $C(\Delta\phi)$ are equal. The template fits include harmonics 2–4 because the contribution from higher-order coefficients is negligible. Based on the assumption of flow factorization [28], the flow coefficients v_n of muons are obtained as $v_n^{\mu}(p_T^{\mu}) = v_{n,n}(p_T^{\mu}, p_T^h)/v_n^h(p_T^h)$, where $v_n^h(p_T^h)$ are the flow coefficients of charged hadrons previously measured by ATLAS using the same template fit method in different analyses [17,25].

The selected muon sample includes background muons from particles produced from light-hadron decay and from punch-through hadrons. Previous studies [29,30] showed that the signal (heavy-flavor) and background muons can be separated statistically using the fractional momentum imbalance, $\Delta p/p_{\mathrm{ID}} = (p_{\mathrm{ID}} - p_{\mathrm{MS}})/p_{\mathrm{ID}}$, where p_{ID} is the muon momentum measured in the ID, and p_{MS} is that measured in the MS corrected via simulation for the energy loss inside the calorimeter. The signal fraction f^{sig} is obtained by fitting the measured $\Delta p/p_{\mathrm{ID}}$ distribution with signal and background template distributions obtained from simulation. The signal muon sample includes remaining contributions from non-heavy-flavor components such as quarkonia, low-mass resonances, and τ leptons; these amount to ∼2.5%, based on PYTHIA8 simulation.

Figure 1 shows muon-hadron correlation functions and template fits for muons with $4 < p_T < 6$ GeV and charged hadrons with $0.5 < p_T < 5$ GeV from events with $110 \leq N_{\mathrm{ch}}^{\mathrm{rec}} < 120$; the $N_{\mathrm{ch}}^{\mathrm{rec}} < 40$ region is used for LM events. The two panels represent different $\Delta p/p_{\mathrm{ID}}$ regions, characterized by different f^{sig} values, as indicated in the plots. The amplitude of the $v_{2,2}$ modulation changes with the signal fraction. The values of $v_{2,2}$ are determined from muon-hadron correlation functions generated using muons in three different regions of $\Delta p/p_{\mathrm{ID}}$, and $v_{2,2}$ as a function of f^{sig} is extracted from a linear fit to the points. Then $v_{2,2}$ from heavy-flavor muon-hadron correlations $v_{2,2}^{\mathrm{sig}}(p_T^{\mu}, p_T^h)$ is calculated by extrapolating to $f^{\mathrm{sig}} = 1$, based on

$$v_{2,2}(p_T^{\mu}, p_T^h) = f^{\mathrm{sig}} v_{2,2}^{\mathrm{sig}}(p_T^{\mu}, p_T^h) + (1 - f^{\mathrm{sig}}) v_{2,2}^{\mathrm{bkg}}(p_T^{\mu}, p_T^h),$$

where $v_{2,2}^{\mathrm{bkg}}(p_T^{\mu}, p_T^h)$ is $v_{2,2}$ from background muon-hadron correlations.

Muons from heavy-flavor decays can be further separated into those from charm and those from bottom decays, based on the different decay lengths of charm and bottom hadrons. Template distributions of the impact parameter of the muon relative to the associated collision vertex in the transverse direction (d_0) for charm, bottom, non-heavy-flavor signal, and background muons obtained from the full detector simulation are used to fit the data distributions differentially in p_T and η. The d_0 resolution of charged hadrons with $4 < p_T < 7$ GeV is 20–40 μm, depending on p_T and η, and independent of $N_{\mathrm{ch}}^{\mathrm{rec}}$. Figure 2 shows the fit to the d_0 distribution for muons with $-0.2 < \Delta p/p_{\mathrm{ID}} < 0.4$ and $4.5 < p_T < 5$ GeV in events with $80 \leq N_{\mathrm{ch}}^{\mathrm{rec}} < 90$. The background fraction is fixed in accord with the fit results in $\Delta p/p_{\mathrm{ID}}$. The contribution from non-heavy-flavor signal muons is also fixed, using the fraction obtained from PYTHIA8 simulation. The $|d_0| < 0.02$ mm region is dominated by non-heavy-flavor signal and background muons and is excluded in the fit procedure. The fraction of muons from bottom decays relative to all heavy-flavor muons, $f^{b\to\mu} = (b \to \mu)/(c \to \mu + b \to \mu)$, is found to be ∼0.4 at $p_T = 4$ GeV and increases to ∼0.6 at $p_T = 7$ GeV. These values are compatible with those determined via a fixed-order plus next-to-leading-logarithm (FONLL) calculation [31] and the PYTHIA8 simulation.

In order to measure $v_{2,2}$ from charm muon-hadron correlations and bottom muon-hadron correlations separately, muons are divided into two d_0 regions, $|d_0| < 0.12$ mm and $|d_0| > 0.12$ mm. In the $|d_0| < 0.12$ mm region where $f^{c\to\mu} > f^{b\to\mu}$, there is a significant hadronic background contribution and thus $v_{2,2}^{\mathrm{sig}}(p_T^{\mu}, p_T^h)$ is

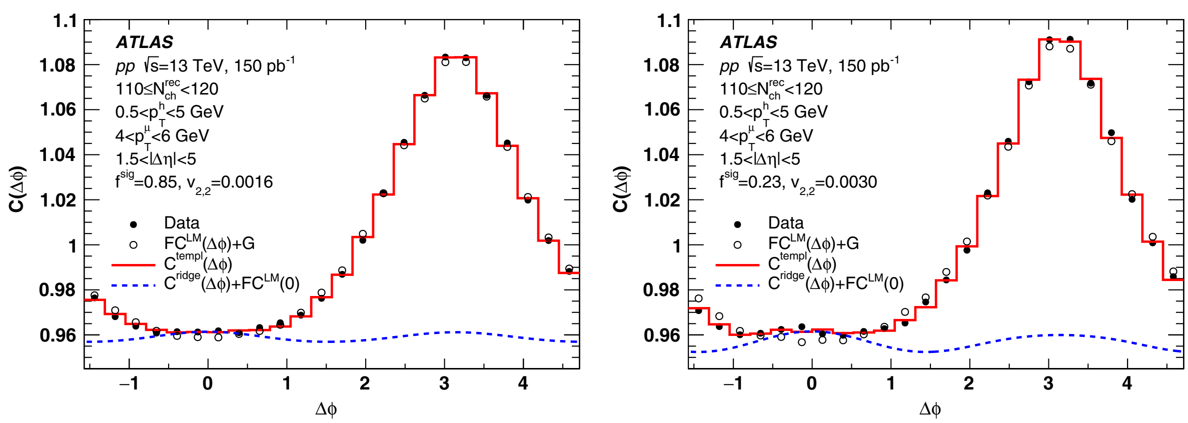

FIG. 1. Template fit to the muon-hadron correlation function, $C(\Delta\phi)$, with pseudorapidity interval $1.5 < |\Delta\eta| < 5$ and track multiplicity $110 \leq N_{\mathrm{ch}}^{\mathrm{rec}} < 120$. Muons with transverse momentum $4 < p_T < 6$ GeV and charged particles with $0.5 < p_T < 5$ GeV are used. Each panel shows the muon-hadron correlation function for muons of a different signal fraction (f^{sig}). The solid red lines show the final function $C^{\mathrm{templ}}(\Delta\phi)$, while the open points and dashed blue lines show the scaled $C^{\mathrm{LM}}(\Delta\phi)$ and $v_{n,n}$ components, each above a vertical pedestal for visibility.

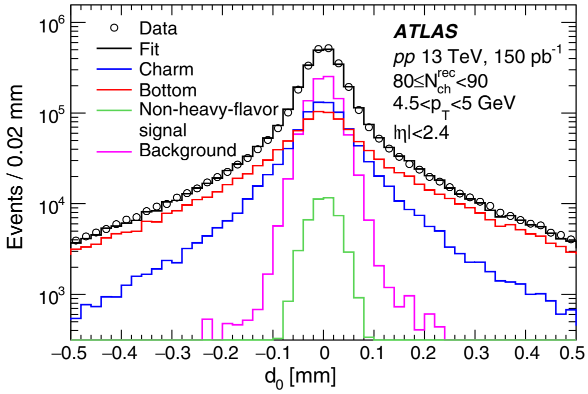

FIG. 2. Fit (gray histogram) to the transverse impact parameter, d_0, distribution of muons with transverse momentum $4.5 < p_T < 5$ GeV and pseudorapidity $|\eta| < 2.4$, with template d_0 distributions of different components obtained from PYTHIA8 simulations.

obtained in three different $\Delta p/p_{\mathrm{ID}}$ bins and extrapolated to $f^{\mathrm{sig}} = 1$. In contrast, in the region $|d_0| > 0.12$ mm where $f^{c\to\mu} < f^{b\to\mu}$, there is negligible background and thus $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ is obtained directly. Given two $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ values with different $f^{b\to\mu}$ values, $v_{2,2}^{c}(p_T^\mu, p_T^h)$ and $v_{2,2}^{b}(p_T^\mu, p_T^h)$ can be determined separately.

The sources of systematic uncertainty in $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ originate from the LM event selection, the $\Delta\eta$-gap selection, event pileup, trigger and reconstruction efficiency, and signal fraction extraction. The impact on the $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ measurement is evaluated by repeating the analysis with variations intended to test the sensitivity to these effects. In many cases, the evaluated variation in $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ is driven by statistical fluctuations. Sensitivity to the choice of the LM range may arise due to a change in the dijet shape from the LM to HM events. The uncertainty is studied using two alternative $N_{\mathrm{ch}}^{\mathrm{rec}}$ ranges, 0–30 and 20–40, for $C^{\mathrm{LM}}(\Delta\phi)$. The resulting variation in $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ is 15–35% depending on $N_{\mathrm{ch}}^{\mathrm{rec}}$, and is the largest systematic uncertainty. The sensitivity to the width of the $\Delta\eta$ gap is tested by using $2 < |\Delta\eta| < 5$ to obtain a wider excluded range ($|\Delta\eta| < 2$), and the resulting change in $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ is smaller than the statistical uncertainty. The results may be sensitive to a residual in-time pileup contribution when two closely spaced pp events are reconstructed with a single merged vertex. This effect is studied using a tighter event selection to reject events containing more than two reconstructed vertices per event. The $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ obtained is consistent with the $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ from the nominal event selection within the statistical uncertainties. The uncertainty associated with the signal fraction extraction is evaluated by modifying the momentum-imbalance templates from simulation, and considering the systematic uncertainties in the muon momentum resolution and scale. For signal muons, the impact of using a data-driven template with muons from $J/\psi \to \mu\mu$ candidates is also considered. No systematic uncertainty on the $v_{2,2}^{\mathrm{sig}}(p_T^\mu, p_T^h)$ is assigned from this study.

The uncertainty in $v_{2,2}^{c}(p_T^\mu, p_T^h)$ and $v_{2,2}^{b}(p_T^\mu, p_T^h)$ additionally includes the uncertainty in $f^{b\to\mu}$. The extracted $f^{b\to\mu}$ values are sensitive to the shape of the p_T spectra of initial charm and bottom hadrons, the background muon fraction, the non-heavy-flavor muon contribution, fit range, and d_0 -template shapes. The shape of the initial hadron p_T distribution is varied from PYTHIA8 to that from a fixed-order plus next-to-leading-logarithm. The non-heavy-flavor muon contribution, which is estimated to be 2.5% of the signal muon yield using simulation, is varied in the range 0%–5% and included in the d_0 fit procedure to evaluate the impact on $f^{b\to\mu}$. The sensitivity to the fit range is evaluated by repeating the d_0 fit with different exclusion regions, either 0 or 0.04 mm, and the uncertainty from the d_0-template shape is evaluated with d_0-template shape

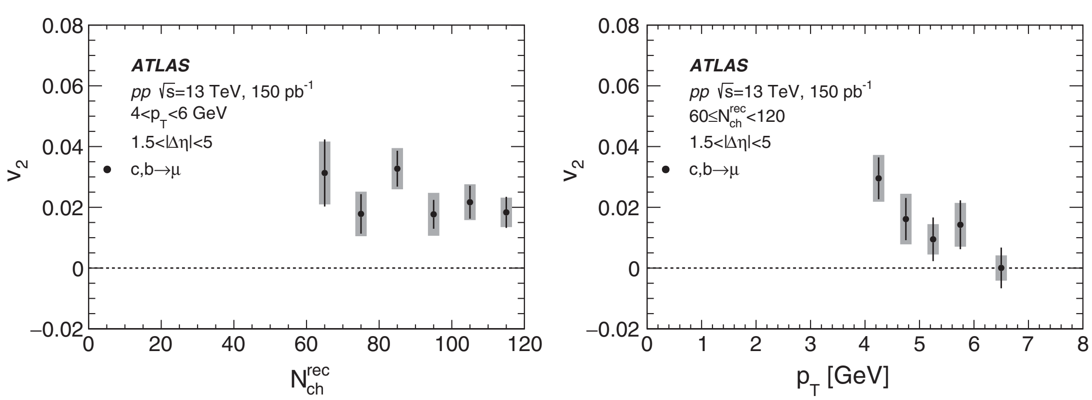

FIG. 3. Elliptic anisotropy coefficient v_2 of inclusive heavy-flavor muons as a function of track multiplicity $N_{\mathrm{ch}}^{\mathrm{rec}}$ for muons with transverse momentum $4 < p_T < 6$ GeV (left) and as a function of p_T for the $60 \le N_{\mathrm{ch}}^{\mathrm{rec}} < 120$ multiplicity range (right). The vertical bars and shaded bands represent statistical and systematic uncertainties, respectively.

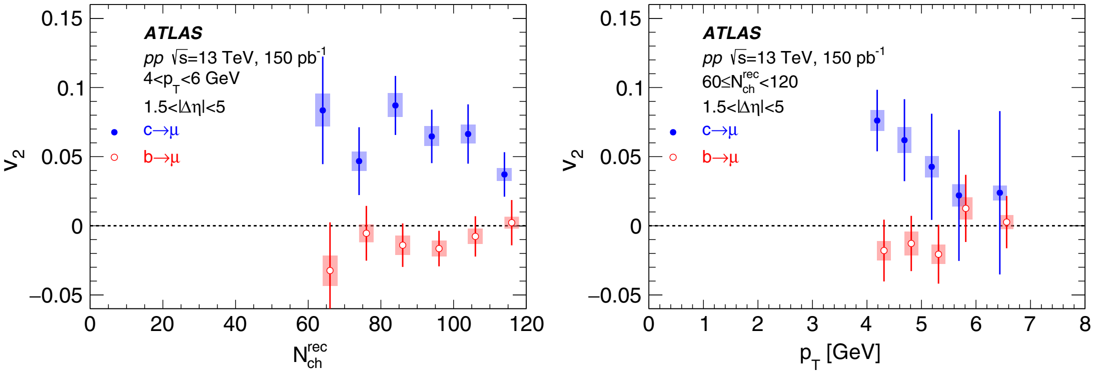

FIG. 4. Elliptic anisotropy coefficient v_2 of muons from charm and bottom decays as a function of track multiplicity $N_{\rm ch}^{\rm rec}$ for muons with transverse momentum $4 < p_T < 6$ GeV (left) and as a function of p_T for the $60 \leq N_{\rm ch}^{\rm rec} < 120$ multiplicity range (right). Data points are shifted by ± 1 in $N_{\rm ch}^{\rm rec}$ and ± 0.125 GeV in p_T for better visibility. The vertical bars and shaded bands represent statistical and systematic uncertainties, respectively.

variation extracted from the d_0 shape comparison between the data and simulation. These variations are included in the final systematic uncertainties. The resulting systematic uncertainty in $f^{b\to\mu}$ is 8%–10%, and this uncertainty is propagated into the uncertainties in $v_{2,2}^c(p_T^\mu, p_T^h)$ and $v_{2,2}^b(p_T^\mu, p_T^h)$ by combining it in quadrature with those in $v_{2,2}^{\rm sig}(p_T^\mu, p_T^h)$. Finally, it was checked in the generation-level and reconstruction-level PYTHIA8 events that $v_{2,2}(p_T^\mu, p_T^h)$ for inclusive heavy-flavor muons as well as for muons from c and b decays is consistent with zero as expected.

Figure 3 shows the v_2 of inclusive heavy-flavor muons, determined as $v_2^\mu(p_T^\mu) = v_{2,2}(p_T^\mu, p_T^h)/v_2^h(p_T^h)$, where $v_2^h(p_T^h)$ is taken from Ref. [17]. The systematic uncertainty in the charged-hadron v_2 is included in the total uncertainty, but is negligible compared with the other uncertainties introduced in this measurement. The v_2 value is presented as a function of $N_{\rm ch}^{\rm rec}$ for $4 < p_T < 6$ GeV (left) and as a function of p_T for $60 \leq N_{\rm ch}^{\rm rec} < 120$ (right). Within the uncertainties there is no clear $N_{\rm ch}^{\rm rec}$ dependence, but the value decreases as the heavy-flavor muon p_T increases from 4 to 7 GeV.

Figure 4 shows the v_2 values for muons from charm and bottom decays separately, as a function of $N_{\rm ch}^{\rm rec}$ for $4 < p_{\rm T} < 6$ GeV (left) and as a function of p_T for $60 \leq N_{\rm ch}^{\rm rec} < 120$ (right). The v_2 of muons from bottom decays is consistent with zero in the entire $N_{\rm ch}^{\rm rec}$ range of the measurement and has no discernible p_T dependence. In contrast, the v_2 of muons from charm decays is nonzero at lower p_T but consistent with zero at higher p_T within the sizable uncertainties. It also shows no significant $N_{\rm ch}^{\rm rec}$ dependence within the uncertainties.

In summary, a measurement of elliptic flow coefficients for heavy-flavor decay muons in pp collisions at 13 TeV is presented, including a separation between charm and bottom contributions. The measurement uses a dataset corresponding to an integrated luminosity of 150 pb^{-1} recorded by the ATLAS experiment at the LHC. The inclusive heavy-flavor muon v_2 values are not dependent on $N_{\rm ch}^{\rm rec}$ in the range 60–120 and show a clear decrease with p_T from 4 to 7 GeV. The bottom-decay muons have v_2 values consistent with zero within statistical and systematic uncertainties, while the charm-decay muons have significant non-zero v_2 values. These results indicate that bottom quarks, unlike light and charm quarks, do not participate in the collective behavior in high-multiplicity pp collisions. There are theoretical calculations within a linearized Boltzmann-Langevin transport framework for Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV predicting larger v_2 for D meson than v_2 for B meson at $p_T < 10$ GeV and similar v_2 at $p_T > 10$ GeV [32]. However, no such calculations have been published for smaller systems including high-multiplicity pp events. The results will provide fundamental new input to the theoretical models which attempt to describe heavy-quark transport and energy loss in these smallest collision systems.

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