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

G. Aad et al.*

(ATLAS Collaboration)

(Received 5 September 2019; revised manuscript received 29 November 2019; accepted 22 January 2020; published 26 February 2020)

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.

DOI: 10.1103/PhysRevLett.124.082301

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 $4\pi$ 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 ($r$, $\phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$ axis. The pseudorapidity is defined in terms of the polar angle $\theta$ 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
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 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.

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 $N_{\text{ch}}^{\text{rec}}$.

Simulated events were generated using PYTHIAS [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 $\mu$ 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 $N_{\text{ch}}^{\text{rec}}$ ($|\Delta N_{\text{ch}}^{\text{rec}}| < 10$) and vertex position $z_{\text{vtx}}$ ($|\Delta z_{\text{vtx}}| < 10$ 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 $1.5 < |\Delta \eta| < 5$:

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

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 PYTHIAS 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:

$$C_{\text{templ}}(\Delta \phi) = F C_{\text{LM}}(\Delta \phi) + C_{\text{ridge}}(\Delta \phi),$$

where

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

has free parameters $F$ and $n$th-order flow (anisotropy) coefficients $v_{n,n}$; the coefficient $G$ is fixed by requiring that the integrals of $C_{\text{templ}}(\Delta \phi)$ 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
\[
v_n(p_T^\mu) = v_{n,\mu}(p_T^\mu, p_T^h)/v_{n,\mu}(p_T^h),
\]
where \( v_n(p_T^h) \) 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, \( \Delta p/p_{\text{ID}} = (p_{\text{ID}} - p_{\text{MS}})/p_{\text{ID}} \), where \( p_{\text{ID}} \) is the muon momentum measured in the ID, and \( p_{\text{MS}} \) is that measured in the MS corrected via simulation for the energy loss inside the calorimeter. The signal fraction \( f_{\text{sig}} \) is obtained by fitting the measured \( \Delta p/p_{\text{ID}} \) 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 \( \tau \) leptons; these amount to \( \sim 2.5\% \), based on PYTHIA8 simulation.

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

\[
v_{2,2}(p_T^\mu, p_T^h) = f_{\text{sig}} v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h) + (1 - f_{\text{sig}}) v_{2,2}^{\text{bkg}}(p_T^\mu, p_T^h),
\]

where \( v_{2,2}^{\text{bkg}}(p_T^\mu, p_T^h) \) 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 \( \eta \). The \( d_0 \) resolution of charged hadrons with \( 4 < p_T < 7 \text{ GeV} \) is \( 20\% - 40\% \mu \text{m} \), depending on \( p_T \) and \( \eta \), and independent of \( N_{\text{ch}}^\text{rec} \). Figure 2 shows the fit to the \( d_0 \) distribution for muons with \( -0.2 < \Delta p/p_{\text{ID}} < 0.4 \) and \( 4.5 < p_T < 5 \text{ GeV} \) in events with \( 80 \leq N_{\text{ch}}^\text{rec} \leq 90 \). The background fraction is fixed in accord with the fit results in \( \Delta p/p_{\text{ID}} \). The contribution from non-heavy-flavor signal muons is also fixed, using the fraction obtained from PYTHIA8 simulation. The \( |d_0| < 0.02 \text{ mm} \) 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, \( f_{b->\mu}^\text{trig} = (b \rightarrow \mu)/((c \rightarrow \mu + b \rightarrow \mu) \), is found to be \( \sim 0.4 \) at \( p_T = 4 \text{ GeV} \) and increases to \( \sim 0.6 \) at \( p_T = 7 \text{ GeV} \). 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, \( |d_0| < 0.12 \text{ mm} \) and \( |d_0| > 0.12 \text{ mm} \). In the \( |d_0| < 0.12 \text{ mm} \) region where \( f_{c->\mu} > f_{b->\mu} \), there is a significant hadronic background contribution and thus \( v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h) \) 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 \( 110 \leq N_{\text{ch}}^\text{rec} < 120 \). Muons with transverse momentum \( 4 < p_T < 6 \text{ GeV} \) and charged particles with \( 0.5 < p_T < 5 \text{ GeV} \) are used. Each panel shows the muon-hadron correlation function for muons of a different signal fraction \( f_{\text{sig}} \). The solid red lines show the final function \( C_{\text{emp}}(\Delta \phi) \), while the open points and dashed blue lines show the scaled \( C_{\text{LM}}(\Delta \phi) \) and \( v_{n,n} \) components, each above a vertical pedestal for visibility.
the LM range may arise due to a change in the dijet shape driven by statistical fluctuations. Sensitivity to the choice of 

\[ v_{2} \]

obtained in three different \( \Delta p/p_{\text{ID}} \) bins and extrapolated to \( f^{\text{sig}} = 1 \). In contrast, in the region \( |d_0| > 0.12 \text{ mm} \) where \( f^{c-\mu} < f^{b-\mu} \), there is negligible background and thus \( v_{2,3}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) is obtained directly. Given two \( v_{2,3}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) values with different \( f^{b-\mu} \) values, \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) and \( v_{2,3}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) can be determined separately.

The sources of systematic uncertainty in \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) 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 \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) measurement is evaluated by repeating the analysis with variations intended to test the sensitivity to these effects. In many cases, the evaluated variation in \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) 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 \( N_{\text{ch}}^{\text{rec}} \) ranges, 0–30 and 20–40, for \( cL^{\text{M}}(\Delta \phi) \). The resulting variation in \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) is 15–35% depending on \( N_{\text{ch}}^{\text{rec}} \), 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 \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) 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 \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) obtained is consistent with the \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) 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 \( J/\psi \rightarrow \mu \mu \) candidates is also considered. No systematic uncertainty on the \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) is assigned from this study.

The uncertainty in \( v_{2,2}^{\text{sig}}(p_{T}^{\mu}, p_{T}^{b}) \) and \( v_{2,2}^{\text{sig}}(p_{T}^{b}, p_{T}^{b}) \) additionally includes the uncertainty in \( f^{b-\mu} \). The extracted \( f^{b-\mu} \) 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 \( f^{b-\mu} \). 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.
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 $f^{b-\mu}$ is 8%–10%, and this uncertainty is propagated into the uncertainties in $v_{2,2}^c(p_T^c, p_T^b)$ and $v_{2,2}^b(p_T^c, p_T^b)$ by combining it in quadrature with those in $v_{2,2}^{\text{sig}}(p_T^c, p_T^b)$. Finally, it was checked in the generation-level and reconstruction-level PYTHIA8 events that $v_{2,2}^c(p_T^c, p_T^b)$ 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 $v_2^c(p_T^c) = v_{2,2}^c(p_T^c, p_T^b)/v_{2,2}^{\text{sig}}(p_T^c, p_T^b)$, where $v_{2,2}^{\text{sig}}(p_T^c, p_T^b)$ 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 $N_{\text{ch}}^{\text{rec}}$ for $4 < p_T < 6$ GeV (left) and as a function of $p_T$ for $60 \leq N_{\text{ch}}^{\text{rec}} < 120$ (right). Within the uncertainties there is no clear $N_{\text{ch}}^{\text{rec}}$ 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 $N_{\text{ch}}^{\text{rec}}$ for $4 < p_T < 6$ GeV (left) and as a function of $p_T$ for $60 \leq N_{\text{ch}}^{\text{rec}} < 120$ (right). The $v_2$ of muons from bottom decays is consistent with zero in the entire $N_{\text{ch}}^{\text{rec}}$ 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 $N_{\text{ch}}^{\text{rec}}$ 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 $N_{\text{ch}}^{\text{rec}}$ 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.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IFRF, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC Ki, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg...
Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, USA. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’ Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, Spain; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [33].

[1] P. Romatschke and U. Romatschke, Relativistic fluid dynamics in and out of equilibrium—ten years of progress in theory and numerical simulations of nuclear collisions, arXiv:1712.05815.
[2] U. Heinz and R. Snellings, Collective flow and viscosity in relativistic heavy-ion collisions, Annu. Rev. Nucl. Part. Sci. 63, 123 (2013).
[3] Y. L. Dokshitzer and D. E. Kharzeev, Heavy-quark colorimetry of QCD matter, Phys. Lett. B 519, 199 (2001).
[4] R. Sharma, I. Vitov, and B.-W. Zhang, Light-cone wave function approach to open heavy flavor dynamics in QCD matter, Phys. Rev. C 80, 054902 (2009).
[5] S. Batsouli, S. Kelly, M. Gyulassy, and J. L. Nagle, Does the charm flow at RHIC?, Phys. Lett. B 587, 26 (2003).
[6] PHENIX Collaboration, Energy Loss and Flow of Heavy Quarks in Au + Au Collisions at $\sqrt{s_{NN}} = 200\text{ GeV}$, Phys. Rev. Lett. 98, 172301 (2007).
[7] X. Dong, Y.-J. Lee, and R. Rapp, Open heavy-flavor production in heavy-ion collisions, Annu. Rev. Nucl. Part. Sci. 69, 417 (2019).
[8] CMS Collaboration, Observation of long-range near-side angular correlations in proton-proton collisions at the LHC, J. High Energy Phys. 09 (2010) 091.
[9] J. L. Nagle and W. A. Zajc, Small system collectivity in relativistic hadronic and nuclear collisions, Annu. Rev. Nucl. Part. Sci. 68, 211 (2018).
[10] R. D. Weller and P. Romatschke, One fluid to rule them all: Viscous hydrodynamic description of event-by-event central $p + p$, $p + Pb$ and $Pb + Pb$ collisions at $\sqrt{s} = 5.02\text{ TeV}$, Phys. Lett. B 774, 351 (2017).
[11] CMS Collaboration, Elliptic Flow of Charm and Strange Hadrons in High-Multiplicity $p + \text{Pb}$ Collisions at $\sqrt{s_{NN}} = 8.16\text{ TeV}$, Phys. Rev. Lett. 121, 082301 (2018).
[12] ALICE Collaboration, Azimuthal Anisotropy of Heavy-Flavor Decay Electrons in $p$-$Pb$ Collisions at $\sqrt{s_{NN}} = 5.02\text{ TeV}$, Phys. Rev. Lett. 122, 072301 (2019).
[13] ALICE Collaboration, $D$-meson production in $p$-$Pb$ collisions at $\sqrt{s_{NN}} = 5.02\text{ TeV}$ and $pp$ collisions at $\sqrt{s} = 7\text{ TeV}$, Phys. Rev. C 94, 054908 (2016).
[14] G. D. Moore and D. Teaney, How much do heavy quarks thermalize in a heavy ion collision?, Phys. Rev. C 71, 084904 (2005).
[15] ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, J. Instrum. 3, S08003 (2008).
[16] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, Eur. Phys. J. C 77, 317 (2017).
[17] ATLAS Collaboration, Measurements of long-range azimuthal anisotropies and associated Fourier coefficients for $pp$ collisions at $\sqrt{s} = 5.02$ and 13 TeV and $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02\text{ TeV}$ with the ATLAS detector, Phys. Rev. C 96, 024908 (2017).
[18] ATLAS Collaboration, Track reconstruction performance of the ATLAS inner detector at $\sqrt{s} = 13\text{ TeV}$, Report No. ATL-PHYS-PUB-2015-018, 2015, https://cds.cern.ch/record/2037683.
[19] ATLAS Collaboration, Muon reconstruction performance of the ATLAS detector in proton-proton collision data at $\sqrt{s} = 13\text{ TeV}$, Eur. Phys. J. C 76, 292 (2016).
[20] T. Sjöstrand, S. Mrenna, and P. Z. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178, 852 (2008).
[21] R. D. Ball et al., Parton distributions with LHC data, Nucl. Phys. B867 (2013) 244.
[22] ATLAS Collaboration, ATLAS PYTHIA 8 tunes to 7 TeV data, Report No. ATL-PHYS-PUB-2014-021, 2014, https://cds.cern.ch/record/1966419.
[23] S. Agostinelli et al., GEANT4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).
[24] ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C 70, 823 (2010).
[25] ATLAS Collaboration, Observation of Long-Range Elliptic Azimuthal Anisotropies in $\sqrt{s} = 13$ and 2.76 TeV $pp$ Collisions with the ATLAS Detector, Phys. Rev. Lett. 116, 172301 (2016).
[26] PHENIX Collaboration, Dihadron azimuthal correlations in Au + Au collisions at $\sqrt{s_{NN}} = 200\text{ GeV}$, Phys. Rev. Lett. 100, 024908 (2019).
[27] ATLAS Collaboration, Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{NN}} = 2.76\text{ TeV}$ lead-lead collisions with the ATLAS detector, Phys. Rev. C 86, 014907 (2012).
[28] ATLAS Collaboration, Measurements of the electron and muon inclusive cross-sections in proton-proton collisions at $\sqrt{s} = 7\text{ TeV}$ with the ATLAS detector, Phys. Lett. B 707, 438 (2012).
[29] ATLAS Collaboration, Measurement of the suppression and azimuthal anisotropy of muons from heavy-flavor decays in
Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector, Phys. Rev. C 98, 044905 (2018).

[31] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, Theoretical predictions for charm and bottom production at the LHC, J. High Energy Phys. 10 (2012) 137.

[32] W. Ke, Y. Xu, and S. A. Bass, Linearized Boltzmann-Langevin model for heavy quark transport in hot and dense QCD matter, Phys. Rev. C 98, 064901 (2018).

[33] ATLAS Collaboration, ATLAS computing acknowledgments, Report No. ATL-GEN-PUB-2016-002, https://cds.cern.ch/record/2202407.
28c Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
28d National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
28e University Politehnica Bucharest, Bucharest, Romania
28f West University in Timisoara, Timisoara, Romania
29a Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
29b Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
30a Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
30b California State University, California, USA
30c Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
30d Department of Physics, University of Cape Town, Cape Town, South Africa
30e Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
30f University of South Africa, Department of Physics, Pretoria, South Africa
30g School of Physics, University of the Witwatersrand, Johannesburg, South Africa
30h Department of Physics, Carleton University, Ottawa ON, Canada
30i Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco
30j Faculté des Sciences, Université Ibn-Toufayl, Kénitra, Morocco
30k Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
30l Faculté des Sciences, Université Mohammed V, Rabat, Morocco
30m CERN, Geneva, Switzerland
30n Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
30o LPC, Université Clermont Auvergne, CNRS-IN2P3, Clermont-Ferrand, France
30p Nevis Laboratory, Columbia University, Irvington, New York, USA
30q Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
30r Dipartimento di Fisica, Università della Calabria, Rende, Italy
30s INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
30t Physics Department, Southern Methodist University, Dallas, Texas, USA
30u Physics Department, University of Texas at Dallas, Richardson, Texas, USA
30v National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece
30w Department of Physics, Stockholm University, Sweden
30x Oskar Klein Centre, Stockholm, Sweden
31a Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
31b Lehrstuhl für Experimentelle Physik VII, Technische Universität Dortmund, Dortmund, Germany
31c Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
31d Department of Physics, Duke University, Durham, North Carolina, USA
31e SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
31f INFN e Laboratori Nazionali di Frascati, Frascati, Italy
31g II. Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
31h Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
31i Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
31j Dipartimento di Fisica, Università di Genova, Genova, Italy
31k INFN Sezione di Genova, Italy
31l II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
31m SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
31n LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
31o Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
31p Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
31q Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
31r School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China
31s Tsung-Dao Lee Institute, Shanghai, China
31t Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
31u Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
31v Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
31w Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
31x Department of Physics, University of Hong Kong, Hong Kong, China
Also at Graduate School of Science, Osaka University, Osaka, Japan.
a Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
c Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
d Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
e Also at CERN, Geneva, Switzerland.
f Also at Department of Physics, Stanford University, Stanford, California, USA.
g Also at Manhattan College, New York, New York, USA.
h Also at Joint Institute for Nuclear Research, Dubna, Russia.
i Also at Hellenic Open University, Patras, Greece.
j Also at The City College of New York, New York, New York, USA.
k Also at Department of Physics, California State University, Sacramento, USA.
l Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
m Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
n Also at Louisiana Tech University, Ruston, Louisiana, USA.
o Also at School of Physics, Sun Yat-sen University, Guangzhou, China.p Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
q Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
r Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
s Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
t Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
u Also at National Research Nuclear University MEPhI, Moscow, Russia.
v Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
w Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
x Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
y Also at LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France.
z Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.