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Azimuthal Angle Correlations of Muons Produced via Heavy-Flavor Decays in 5.02 TeV Pb + Pb and *pp* Collisions with the ATLAS Detector

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Angular correlations between heavy quarks provide a unique probe of the quark-gluon plasma created in ultrarelativistic heavy-ion collisions. Results are presented of a measurement of the azimuthal angle correlations between muons originating from semileptonic decays of heavy quarks produced in 5.02 TeV Pb + Pb and pp collisions at the LHC. The muons are measured with transverse momenta and pseudorapidities satisfying $p_{\mathrm{T}}^{\mu} > 4$ GeV and $|\eta^{\mu}| < 2.4$, respectively. The distributions of azimuthal angle separation $\Delta\phi$ for muon pairs having pseudorapidity separation $|\Delta\eta| > 0.8$, are measured in different Pb + Pb centrality intervals and compared to the same distribution measured in pp collisions at the same center-of-mass energy. Results are presented separately for muon pairs with opposite-sign charges, same-sign charges, and all pairs. A clear peak is observed in all $\Delta\phi$ distributions at $\Delta\phi \sim \pi$, consistent with the parent heavy-quark pairs being produced via hard-scattering processes. The widths of that peak, characterized using Cauchy-Lorentz fits to the $\Delta\phi$ distributions, are found to not vary significantly as a function of Pb + Pb collision centrality and are similar for pp and Pb + Pb collisions. This observation will provide important constraints on theoretical descriptions of heavy-quark interactions with the quark-gluon plasma.

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Heavy-flavor (HF) quarks have long been considered important probes of the quark-gluon plasma (QGP) created in ultrarelativistic heavy-ion collisions [1–10]. They are produced primarily in hard-scattering processes that occur at early times in the nuclear collisions with the result that heavy quarks experience the full evolution of the QGP. The interactions of the heavy quarks with the QGP can induce energy loss or "quenching" that is experimentally observed in the suppression of the yield of HF hadrons [11–15] and their decay products [16–25], or heavy-quark jets, especially bottom-tagged jets [26,27]. Separately, the coupling of the heavy quarks to collective expansion of the plasma [28,29], can be observed via the azimuthal anisotropy of HF hadrons [30–33] or their decay products [17,18,34].

Measurements sensitive to the angular deflection of heavy quarks in the plasma may provide an important, alternative probe of quark interactions in the plasma. On very general physics grounds, the interactions between the quarks and the hot plasma would be expected to induce some deflection of the quarks. Indeed, at momenta comparable to or less than the quark mass, HF quarks are thought to undergo Brownian motion with their transport being characterized by a diffusion coefficient [35] (also see Ref. [8] and references therein). At momenta much higher than the quark mass, the quarks would, in a weak-coupling scenario [36,37], be expected to multiply scatter in the plasma and thereby be "collisionally" broadened. However, the scattering will also stimulate gluon emission [36–43] that may damp the collisional broadening. The relative importance of the multiple scattering and radiative damping on the propagation of the heavy quarks, especially bottom quarks, is not currently well-constrained by data.

The angular deflections of the quarks can be experimentally probed by measuring azimuthal angles between quarks and antiquarks created in the same hard-scattering process, where momentum conservation induces a strong angular correlation between the two particles. Indeed, theoretical calculations have shown that angular correlations of bottom quarks are very sensitive to the relative importance of collisional and radiative scattering processes [44] in the bottom quark-medium interaction. The direct detection of bottom hadron pairs is difficult due to their complex decays, but detection of pairs of leptons resulting from simultaneous semileptonic decays of B hadrons is experimentally feasible, though no such measurements have been made prior to this Letter.

At LHC collision energies, muons having transverse momenta greater than a few GeV predominantly result from, HF decays [45]. Both charm and bottom hadrons

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contribute to single-muon production, but the contribution of charm quarks to the production of muon pairs where both muons have $p_{\mathrm{T}} > 4$ GeV, was found to be kinematically suppressed relative to bottom quarks, by about an order of magnitude in a POWHEG+PYTHIA8 [46–50] study shown in the Supplemental Material, Ref. [51]. The charges of the muons provide a further handle to suppress the contributions from charm. Namely, pairs of charm hadrons produced in hard-scattering processes will generate, nearly exclusively, opposite-sign muon pairs. However, in decays of B hadrons, muons may be produced either from the bottom hadrons themselves or from the decay of the secondary charm hadrons, in which case, the sign of the resulting muon can be reversed. As a result, $b\bar{b}$ pairs can produce two muons of the same sign. Separately, the mixing of neutral B mesons provides an efficient mechanism for generating same-sign muon pairs. Because of the short oscillation time (compared to the decay time) of neutral B mesons [52], about half of the muon pairs produced when one or both parents is a neutral B meson are of the same sign. Thus, same-sign muon pairs provide a clean probe of $b\bar{b}$ production, and a comparison of measurements using opposite-sign and same-sign muons allows potential contributions from $c\bar{c}$ pairs to be estimated.

This Letter presents ATLAS measurements of angular correlations between muons in opposite- and same-sign pairs produced in both Pb + Pb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV using datasets with integrated luminosities of 1.94 nb^{-1} and 0.26 fb^{-1}, respectively. The muons, which primarily result from semileptonic decays of charm and bottom hadrons, are measured over the transverse momentum (p_{T}^{μ}) and pseudorapidity [53] (η^{μ}) ranges, $p_{\mathrm{T}}^{\mu} > 4$ GeV and $|\eta^{\mu}| < 2.4$. Additionally, the average p_{T} of the two muons in the pair, $\bar{p}_{\mathrm{T}}$, is required to be larger than 5 GeV. The $\bar{p}_{\mathrm{T}} > 5$ GeV requirement removes pairs with very small trigger and reconstruction efficiencies (described below) and improves the statistical precision of the measurements. To suppress contributions from quarkonia decays and from the production of heavy-quark pairs within jets, the two muons are required to have a pseudorapidity separation, $|\Delta\eta^{\mu}| = |\eta^{\mu_1} - \eta^{\mu_2}| > 0.8$ where μ_1 and μ_2 refer to the two muons in the pair with arbitrary ordering. Distributions of azimuthal angle separation, $\Delta\phi = \phi^{\mu_1} - \phi^{\mu_2}$, are measured in different Pb + Pb collision centrality [54] intervals and in pp collisions. Backgrounds from Drell-Yan (DY) processes are estimated using Monte Carlo (MC) simulations, and are subtracted from the $\Delta\phi$ distributions. Results are obtained for same-sign, opposite-sign, and all pairs, all of which show clear enhancement on the "away side" (i.e., at $\Delta\phi = \pi$), consistent with contributions from hard-scattering processes. The widths of the away-side peaks are characterized by fitting the $\Delta\phi$ distributions with Cauchy-Lorentz functions which describe the data well. The centrality dependence of the width is the focus of the measurements in this Letter.

The ATLAS experiment [55] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The ID covers the pseudorapidity range $|\eta| < 2.5$. The calorimeter system consists of a liquid-argon (LAr) electromagnetic calorimeter covering $|\eta| < 3.2$, a steel-scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, a LAr hadronic calorimeter covering $1.5 < |\eta| < 3.2$, and a LAr forward calorimeter (FCal) covering $3.1 < |\eta| < 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. It includes a system of precision tracking chambers and fast detectors for triggering. A two-level trigger system [56], the first [level-1 (L1)] implemented in hardware and the second [high-level trigger (HLT)], implemented in software, is used to select events for this measurement. An extensive software suite [57] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The Pb + Pb events are classified into centrality percentiles based on the total transverse energy measured in the FCal [58,59]. In this classification, the 0%–10% centrality interval corresponds to the 10% of inelastic Pb + Pb collisions with the smallest impact parameter [54]. Events selected by two dimuon triggers are used in this analysis. The first trigger required a single muon with $p_{\mathrm{T}} > 4$ GeV at $L1$ and two muons having $p_{\mathrm{T}} > 4$ GeV at the HLT. The second trigger required two muons with $p_{\mathrm{T}} > 4$ GeV at both $L1$ and the HLT. Both triggers were used in the Pb + Pb data, and are further described in Ref. [60]. In the pp data taking, the first trigger was not implemented and all data used here were recorded by the second trigger.

Events used in the analysis are required to be recorded during stable running conditions of the LHC, to have no detector hardware or readout error, and to have a reconstructed collision vertex. Charged-particle tracks and collision vertices are reconstructed from hits in the ID using standard methods [61]. Muons are reconstructed by combining ID tracks with tracks reconstructed in the muon spectrometer. The muons are required to satisfy the *tight* muon selection requirements [62], which reduce the fraction of pairs containing a muon resulting from pion or kaon decay to less than 5% across the measured centrality range (estimated via the procedure detailed in Ref. [19]). For events containing more than two muons that satisfy the selection and kinematic requirements (about 2% of all events), all possible pairs are considered.

As noted above, to suppress contributions from quarkonium decays, muon pairs used in the measurement are required to have $|\Delta\eta^{\mu}| > 0.8$. This selection essentially eliminates dimuons produced by light vector mesons and J/ψ decays, but still admits a contribution from Υ decays. To remove those as well as pairs from Z-decays, opposite-sign pairs having masses in the ranges [9.2, 10.4] GeV and [70, 110] GeV are excluded from the measurement. In the Pb + Pb data, dimuons produced in $\gamma\gamma \to \mu^+\mu^-$ scattering processes [60,63,64], are almost fully removed by requiring the opposite-sign muon pairs to have $|\Delta\phi - \pi|/\pi > 0.01$ or $|p_{\mathrm{T}}^{\mu_1} - p_{\mathrm{T}}^{\mu_2}|/(p_{\mathrm{T}}^{\mu_1} + p_{\mathrm{T}}^{\mu_2}) > 0.08$.

To account for the loss of muon pairs due to reconstruction and trigger inefficiencies, each pair is assigned a weight which is the inverse of the product of the reconstruction and trigger efficiencies for the pair [60]. The efficiencies are calculated as a function of the p_{T} and η of the two muons in the pair [60]. The average weight for the pairs is ~2.3 (~2.4) in the pp (Pb + Pb) data set. A separate acceptance correction is applied to opposite-sign pairs to account for the losses resulting from the dimuon mass requirements to reject Υ and Z-bosons, and the requirements applied to suppress $\gamma\gamma \to \mu^+\mu^-$ events. These are obtained by applying the mass and $\gamma\gamma$ requirements to the same-sign pairs and evaluating the $\Delta\phi$-dependent fraction of pairs that survive. That fraction is taken to be the acceptance for opposite-sign pairs, $A^{\mathrm{opp}}(\Delta\phi)$, and is used to correct the measured distribution for the opposite-sign pairs. To check the sensitivity of the acceptance to possible differences in the single-muon and pair kinematics between same-sign and opposite-sign pairs, separate estimates of the pair acceptance are obtained using *mixed events*. In the mixed-event estimate, opposite-sign muon pairs are made using muons reconstructed in separate events, and $A^{\mathrm{opp}}(\Delta\phi)$ is estimated by evaluating what fraction of pairs satisfies the mass and $\gamma\gamma$ requirements. The events used to construct the mixed-event distributions only require a single muon in each event, as the pair is constructed by combining two events. Therefore, in order to have more statistics in the mixed-event distributions, the events used to make the mixed-event distributions are selected using a trigger that only required a single muon with $p_{\mathrm{T}} > 4$ GeV at both $L1$ and the HLT. Differences between the two estimates of $A^{\mathrm{opp}}(\Delta\phi)$ affect the final observables by less than 0.5%, and are included as systematic uncertainties. Contributions to the $\Delta\phi$ distributions from DY processes are evaluated using a POWHEG +PYTHIA8 [46–49] MC setup, further described in Ref. [60]. The estimated DY contribution is then subtracted from the measured distributions.

The measurements of muon angular correlations are presented in the form of two-muon correlation functions: $C(\Delta\phi) \equiv (1/N_{\mathrm{tot}})(\Delta N/\Delta\phi)$, where ΔN represents the number of efficiency-corrected muon pairs in a given $\Delta\phi$ interval and N_{tot} represents the $\Delta\phi$-integrated total number of muon pairs. The correlation functions are constructed using 32 equal $\Delta\phi$ intervals spanning the range $[-\pi/2, 3\pi/2]$. Figure 1 shows results obtained for the Pb + Pb 0%–10% centrality interval (top), as an example, and for the pp data set (bottom). The correlation

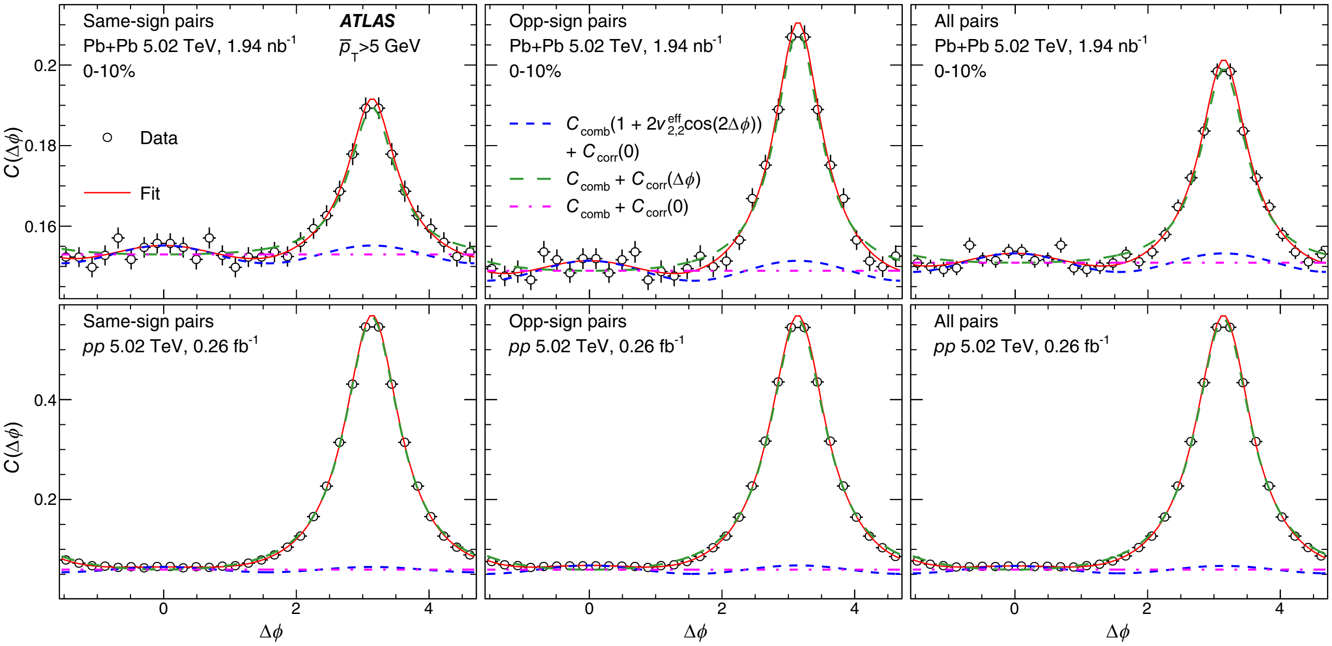

FIG. 1. Measured two-muon correlation functions $C(\Delta\phi)$. Top row: results for Pb + Pb data in the 0%–10% centrality interval; bottom row: pp results; left column: same-sign pairs; middle column: opposite-sign pairs; right column: all pairs. Also shown are the results of fits of the correlation functions to Eq. (1), along with different components of the fits.

functions are symmetrized about $\Delta\phi = 0$, with proper accounting of the statistical uncertainties. All the correlation functions show a clear enhancement near $\Delta\phi = \pi$ superimposed on a pedestal. That pedestal is significantly enhanced in Pb + Pb collisions due to the geometric enhancement of hard-scattering processes that can yield multiple uncorrelated $c\bar{c}$ or $b\bar{b}$ pairs in the same collision. Moreover, in Pb + Pb collisions, this combinatoric contribution is modified by the collective expansion of the QGP [19,65] with the result that the combinatoric background exhibits an elliptic ($\cos 2\Delta\phi$) modulation that is evident in Fig. 1.

To characterize the shape of the peak near $\Delta\phi = \pi$, the data are fit with the functional form

$$C^{\mathrm{fit}}(\Delta\phi) = C_{\mathrm{comb}}[1 + 2v_{2,2}^{\mathrm{eff}} \cos(2\Delta\phi)] + C_{\mathrm{corr}}(\Delta\phi), \quad (1)$$

with

$$C_{\mathrm{corr}}(\Delta\phi) = \frac{C_{\mathrm{corr}}^{\mathrm{max}}\Gamma^2}{(\Delta\phi - \pi)^2 + \Gamma^2}. \quad (2)$$

Here, C_{comb} represents the combinatoric contribution to $C(\Delta\phi)$, $v_{2,2}^{\mathrm{eff}}$ represents the Fourier coefficient for the elliptic modulation [66] of the combinatoric contribution, and C_{corr} represents the correlated contribution, which is centered at $\Delta\phi = \pi$, and is parametrized using a Cauchy-Lorentz distribution specified in Eq. (2). $C_{\mathrm{corr}}^{\mathrm{max}}$ represents the maximum value of C_{corr} and Γ the half width at half maximum of the Cauchy-Lorentz distribution. Here, C_{comb}, $v_{2,2}^{\mathrm{eff}}$, $C_{\mathrm{corr}}^{\mathrm{max}}$, and Γ, are fit parameters. $C_{\mathrm{corr}}(\Delta\phi)$ is folded at $\Delta\phi = -\pi/2$ and $3\pi/2$ to make it periodic in $\Delta\phi$. Because of the long tails of the Cauchy-Lorentz distribution and the folding, there is a "pedestal" to C_{corr}, separate from the C_{comb} term in Eq. (1), that nonetheless represents correlated production of muon pairs. The integrals of C_{corr} for the opposite-sign pairs are found to be approximately twice that for the same-sign pairs, similar to expectations from PYTHIA8.

Results of fits of Eq. (1) to the measured correlation functions are shown in Fig. 1. Also shown on Fig. 1 are the individual components of the fit: the combinatorial pedestal (pink), the flow modulation (blue), and the signal component (green). The peaks at $\Delta\phi \sim \pi$ are well reproduced by the assumed form for C_{corr}. In contrast, Gaussian, generalized-Gaussian, or von Mises forms [67,68] for C_{corr} fail to describe the shape of the away-side correlation. The modulation of the combinatoric contribution in the data is well-described by the assumed $\cos(2\Delta\phi)$ dependence. In the Pb + Pb data, the $v_{2,2}^{\mathrm{eff}}$ values are $\mathcal{O}(0.01)$ and are equal, within uncertainties, for same-sign and opposite-sign pairs. This result is consistent with the hypothesis that the modulation predominantly arises from an elliptic flow of muons produced in uncorrelated HF decays. While previous measurements [69] have demonstrated elliptic modulation of HF yields in pp collisions, the $v_{2,2}^{\mathrm{eff}}$ value in pp collisions measured here changes slightly if the $|\Delta\eta^{\mu}|$ requirement is increased from 0.8 indicating a residual near-side correlation that also contributes to the $v_{2,2}^{\mathrm{eff}}$. The change in the Γ values when the pp data are fit constraining $v_{2,2}^{\mathrm{eff}}$ to zero, are included in the systematic uncertainties.

The standard deviation of C_{corr} obtained from the fits, around $\Delta\phi = \pi$ is evaluated as $\sigma \equiv \sqrt{\int (\Delta\phi - \pi)^2 [C_{\mathrm{corr}}(\Delta\phi) - C_{\mathrm{corr}}(0)] \mathrm{d}\Delta\phi}$, where the integral is performed over the interval $[0, 2\pi]$. When evaluating σ, the pedestal of $C_{\mathrm{corr}}(\Delta\phi)$ i.e., $C_{\mathrm{corr}}(0)$, is subtracted out. Statistical uncertainties on the extracted Γ and σ values are evaluated using resamplings of the measured correlation functions assuming Gaussian-distributed statistical uncertainties for each point. Each of the resampled correlations functions is fit to Eq. (1) and the standard deviation of the resulting Γ and σ distributions are taken as the statistical uncertainties.

Systematic uncertainties on the Γ or σ may arise from the muon selection, the trigger and reconstruction efficiency corrections, corrections for the mass selection on opposite-sign pairs, parametrization of the combinatorial background in Eq. (1), and from the method used to extract the widths of the away-side peak. Effects from the p_{T}, η, and ϕ resolution of the reconstructed tracks are negligible in this measurement, and not included in the systematic uncertainties. The effect of the muon selection is studied by using the *medium* working point [62] that is less pure and, thus, has a larger contamination from non-HF hadron (mostly pion and kaon) decays. The effects of the trigger and reconstruction efficiency uncertainties on the measurement are determined by varying the efficiencies systematically up or down within their uncertainties and repeating the analysis. For the corrections related to the dimuon photoproduction and mass restrictions placed on the opposite-sign pairs, the systematic uncertainty is obtained by using an alternate estimate of $A^{\mathrm{opp}}(\Delta\phi)$ from mixed events, as described before. The sensitivity of the results to the parametrization of the modulation of the combinatoric background is done as follows: for the Pb + Pb measurements, this is done by including a $v_{3,3}^{\mathrm{eff}} \cos(3\Delta\phi)$ term in the square brackets in Eq. (1), with $v_{3,3}^{\mathrm{eff}}$ being an additional fit parameter; for the pp measurements, for reasons stated before, the data were instead fit constraining $v_{2,2}^{\mathrm{eff}}$ to zero. This is the leading systematic uncertainty for both σ and Γ. This uncertainty is ~1% (2.5%) for σ and ~2% (5.5%) for Γ in the Pb + Pb (pp) measurements. The correction for the DY background pairs is evaluated using a POWHEG+PYTHIA8 MC sample that uses the nNNPDF2.0 [70] nuclear PDFs. Systematic uncertainties are evaluated using the nCTEQ15 [71] and NNPDF3.0 [72] PDFs. To evaluate the sensitivity of the σ results to the assumed form for C_{corr}, an alternative method for extracting the width is applied. Namely, the measured correlation function over the range $[-\pi/2, \pi/2]$ is shifted by π and subtracted from that measured in the range $[\pi/2, 3\pi/2]$. Then, the standard deviation σ' is obtained directly from the subtracted correlation function, with $\Delta\phi$ restricted to $[\pi/2, 3\pi/2]$. This method produces a biased estimate of σ, as it assumes that the away-side correlation is restricted to $[\pi/2, 3\pi/2]$, while the observed away-side peak extends beyond this range. However, the results can be compared to a calculation of σ' from C_{corr} using the same shifted-subtraction method. The relative difference between the values of σ'—obtained directly from the measured correlation, and obtained from C_{corr} with this modified procedure—is taken to be the relative systematic uncertainty on σ.

Figure 2 shows the measured values of σ and Γ in Pb + Pb collisions as a function of centrality compared to the same quantity in pp collisions. The two quantities exhibit similar behavior. The widths are similar between same-sign and opposite-sign pairs; this behavior is expected if $b\bar{b}$ pairs dominate in the samples, as suggested by Ref. [51]. No significant variation of the σ and Γ is observed as a function of centrality over the 10%–80% centrality range. Over this centrality range, the Pb + Pb values are consistent with those measured in pp collisions. A significant decrease in σ and Γ is observed in the 0%–10% centrality interval. The interpretation of these results depends on the shape of the p_{T} spectra of the parent b quarks [44], which is modified by the energy loss of the quarks in the plasma. However, the shapes of the $\bar{p}_{\mathrm{T}}$ spectra in this measurement are found to be similar across the different centrality intervals, up to an overall normalization. The $\langle \bar{p}_{\mathrm{T}} \rangle$, where the $\langle \dots \rangle$ indicates averaging over all correlated pairs within a centrality interval, does not change significantly with centrality and is consistent with that measured in pp collisions, except for the 0%–10% centrality interval, where the $\langle \bar{p}_{\mathrm{T}} \rangle$ is ∼3% higher [73]. This change in the $\bar{p}_{\mathrm{T}}$ spectra may be partially responsible for the decrease in σ observed in the 0%–10% centrality interval. However, the expectation from Ref. [44] of a broadening in Γ that systematically increases from peripheral to central collisions, does not appear to be supported by the data. A POWHEG+PYTHIA8 study done as part of this analysis, shows that over the muon-p_{T} and η ranges used here, the angular correlation between the b hadron (c hadron) and the decay-muon has an rms width of 0.158 (0.058). These decay widths are significantly smaller than the angular correlation between the muons themselves (Fig. 2), and thus the impact of the decay on the measurements is small. The lower panels of Fig. 2 show the squared difference between the Pb + Pb and pp widths: $\sigma^2_{\mathrm{int}} = \sigma^2_{\mathrm{Pb+Pb}} - \sigma^2_{pp}$. This quantity represents the square of the additional angular broadening in Pb + Pb collisions, from interactions with the QGP [74]. Except for in the 0%–10% centrality interval, the Pb + Pb σ values are

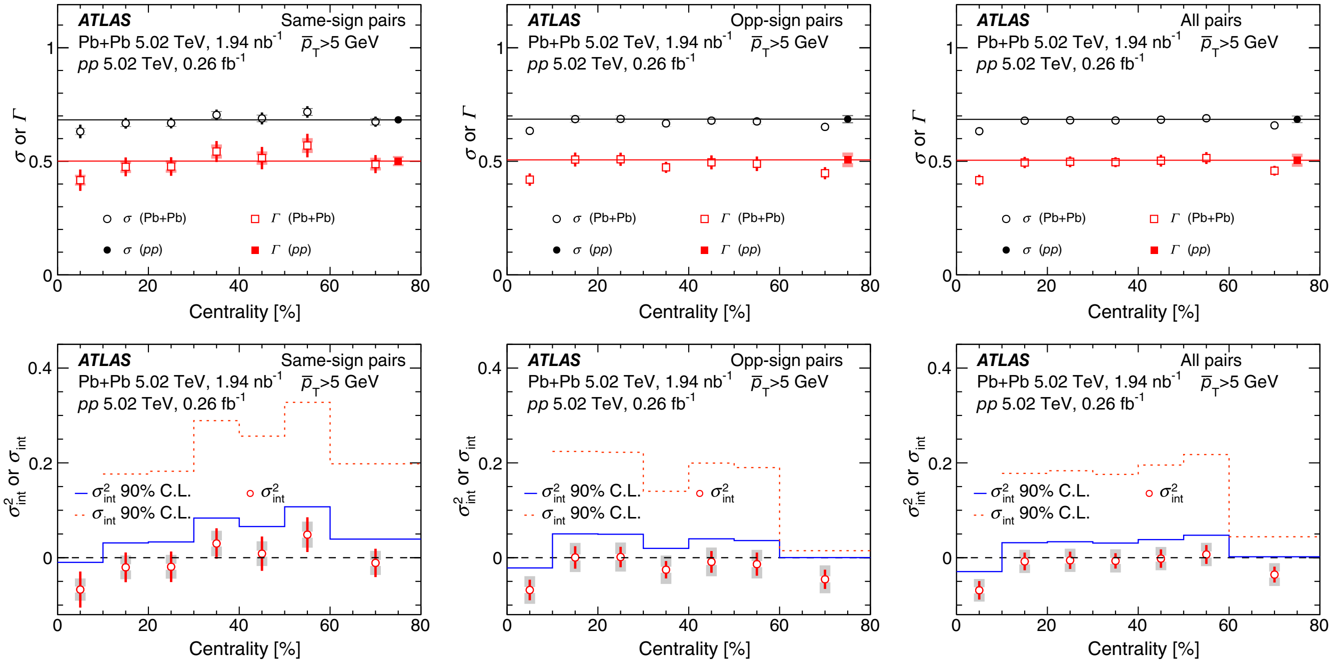

FIG. 2. Top panels: The measured widths σ of the away-side peak in the two-particle correlation functions in Pb + Pb collisions versus centrality. Also shown are the values of the Γ parameter in Eq. (1). The σ and Γ measured in pp collisions are also shown. The vertical lines (bands) on the data points represent the statistical (systematic) uncertainties. The horizontal lines indicate the nominal pp values. Bottom panels: The difference between the squared-widths of the Pb + Pb and pp measurements. Also shown are the upper limit on σ^2_{int} and σ_{int} at the 90% C.L. As the 90% C.L. on σ^2_{int} is negative for the 0%–10% centrality interval, the corresponding 90% C.L. on σ_{int} cannot be evaluated, and is not shown. The left, middle, and right panels correspond to same-sign pairs, opposite-sign pairs, and all pairs.

typically within about one standard deviation of the pp values. Figure 2 also shows the upper limit of σ^2_{int} (and σ_{int}) at the 90% confidence level (C.L.), evaluated using the combined statistical + systematic uncertainties.

In summary, this Letter presented results of a novel measurement of the angular correlations between heavy quarks produced in pp and Pb + Pb collisions at the LHC using semileptonic decays of the HF hadrons to muons. Muons with $p^{\mu}_{\mathrm{T}} > 4$ GeV and $|\eta^{\mu}| < 2.4$ were used in the analysis. Two-muon correlation functions were constructed from same-sign and opposite-sign pairs, with $\bar{p}_{\mathrm{T}} > 5$ GeV, and studied as a function of azimuthal angle difference $\Delta\phi$ for $|\Delta\eta| > 0.8$. A strong enhancement is observed in the correlation functions at $\Delta\phi \sim \pi$, consistent with the production of the muon pairs from semileptonic decays of heavy-quark pairs—primarily $b\bar{b}$ pairs—created in hard-scattering processes. The widths of the peaks at $\Delta\phi \sim \pi$, characterized by the half width at half maximum (Γ) and the standard deviation σ show no significant difference between pp collisions and Pb + Pb collisions and no significant variation with centrality except in the 0%–10% most central collisions, where a significant decrease in the Pb + Pb widths is observed. The results are consistent between same-sign pairs, which have negligible charm contribution, and opposite-sign pairs for which bottom pairs contribute ~90% of the yield in pp collisions. Limits, at the 90% confidence level, are placed on the standard deviation of additional angular deflection introduced by the QGP. For the all-pairs sample, the data limit the standard deviation of the additional *pair* broadening (σ_{int}) to $\lesssim$0.2, except in the 0%–10% interval for which the measured narrowing of the distribution is significant at the ~2σ level. These results provide a model-independent constraint on the stochastic deflection of bottom quarks in the QGP.

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