Longitudinal and azimuthal evolution of two-particle transverse momentum correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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ALICE Collaboration

1. Introduction

Measurements of particle production and their correlations performed at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) provide compelling evidence that the matter produced in heavy-ion collisions is characterized by extremely high temperatures and energy densities consistent with a deconfined, but strongly interacting Quark–Gluon Plasma (QGP) [1–4]. Collective flow, which manifests itself by the anisotropy of particle production in the plane transverse to the beam direction, is characterized by the harmonic coefficients of a Fourier expansion of the azimuthal distribution of particles relative to the reaction plane. Comparisons of these harmonic coefficients with hydrodynamical model predictions indicate that the matter produced in those collisions has a shear viscosity per unit of entropy density, $\eta/s$, that nearly vanishes [2,5]. The shear viscosity quantifies the resistance that any medium presents to its anisotropic deformation. It contributes to the transfer of momentum from one fluid cell to its neighbors as well as the damping of momentum fluctuations. The reach of $\eta/s$ effects is expected to grow with the lifetime of the system. Recent measurements of flow coefficients and hydrodynamical predictions largely focus on the precise determination of $\eta/s$ [6–9]. However, quantitative descriptions of heavy-ion collisions with hydrodynamical models generally rely on specific parametrizations of the initial conditions of colliding systems, i.e., their initial energy and entropy density distribution in the transverse plane, the magnitude of initial fluctuations, the thermalization time, and several model parameters. It is found that the precision of model predictions is hindered, in particular, by uncertainties in the initial state conditions. Indeed, values of shear viscosity that best match the observed flow coefficients are dependent on the initial conditions, and unless the magnitude of the initial state fluctuations can be precisely assessed, the achievable precision on $\eta/s$ might remain limited [10,11]. Systematic studies of correlations between different order harmonic coefficients [12], shown to be sensitive to the initial conditions and the temperature dependence of $\eta/s$, can help to provide further constraints to those conditions and to the transport properties of the system. Novel approaches based on Bayesian parameter estimation [13,14] bring progress on a simultaneous characterization of the initial conditions and the QGP. Furthermore, it was pointed out [15] that the strength of momentum current correlations may be sensitive to $\eta/s$. It was shown, in particular, that the longitudinal broadening of a transverse momentum ($p_T$) correlator, formally defined below and hereafter named $G_2$, with increasing system lifetime is directly sensitive to $\eta/s$ while it does not have any explicit dependence on the initial state fluctuations in the transverse plane of the system.

A first measurement of the broadening of the two-particle transverse momentum correlator $G_2$ was reported by the STAR
collaboration [16]. Improved techniques to correct for instrumental effects have since then been reported [17–19]. In this letter, these techniques are used to measure differential charge independent (CI) and charge dependent (CD) two-particle transverse momentum correlators, \( G_{2}^{\mathrm{CI}} \) and \( G_{2}^{\mathrm{CD}} \) respectively, as a function of pair rapidity difference, \( \Delta \eta \), and azimuthal angle difference, \( \Delta \varphi \), for selected ranges of Pb–Pb collision centrality. The shapes of these correlators are studied with a two-component model and the longitudinal and azimuthal widths of their near-side peaks are studied as a function of the Pb–Pb collision centrality. The longitudinal broadening of \( G_{2}^{\mathrm{CI}} \) from peripheral to central collisions is used to assess the magnitude of \( \eta /s \) of the matter produced in Pb–Pb collisions while the longitudinal and azimuthal widths of \( G_{2}^{\mathrm{CD}} \) are used to assess the role of competing effects, including radial flow, diffusion, and the broadening of jets by interactions with the medium. In that context, measurements of \( G_{2} \) are also compared with previously reported measurements of the two-particle number correlator \( R_{2} \) and two-particle transverse momentum correlator \( P_{2} \) [18].

2. The \( G_{2} \) correlator

The dimensionless variant of the \( G_{2} \) correlator [15,20] reported in this letter is defined according to

\[
G_{2}(\eta_{1}, \varphi_{1}, \eta_{2}, \varphi_{2}) = \frac{1}{(p_{T,1})(p_{T,2})} \left[ \int \frac{d p_{T,1} d p_{T,2}}{p_{T,1} p_{T,2}} \frac{d p_{T,1} d p_{T,2}}{p_{T,1} p_{T,2}} \right] \left[ \frac{d \rho_{1}(p_{T,1}) d \rho_{2}(p_{T,1})}{d \rho_{1}(p_{T,1}) d \rho_{2}(p_{T,1})} \right] - \langle p_{T,1} \rangle \langle p_{T,2} \rangle (\eta_{1}, \varphi_{1}, \eta_{2}, \varphi_{2})
\]

where \( \Omega \) is the phase space region in which the measurement is performed; \( p_{T,1} \) and \( p_{T,2} \) are the three-momentum vectors of particles of a given pair; \( p_{T,1} \) and \( p_{T,2} \) their transverse momentum components, respectively; \( \rho_{1}(p_{T,1}) = d^{3}N / dp_{T,1} d\eta_{1} d\varphi_{1} \) and \( \rho_{2}(p_{T,1}, p_{T,2}) = d^{3}N / dp_{T,1} d\eta_{1} d\varphi_{1} d\rho_{2} d\eta_{2} d\varphi_{2} \) represent single and pair particle densities, expressed as functions of \( \eta_{1}, \varphi_{1}, p_{T,1} = 1, 2 \), and \( (\eta_{1}, \varphi_{1}) \); \( \langle p_{T,1} \rangle \langle p_{T,2} \rangle \) is the average transverse momentum of particles observed at \( (\eta_{1}, \varphi_{1}) \), with \( \eta_{1}, \varphi_{1}, i = 1, 2 \), referring to single-track pseudorapidity and azimuthal angle, respectively; and \( \langle p_{T,1} \rangle = \int d \rho_{1}(\eta_{1}, \varphi_{1}) d\eta_{1} d\varphi_{1} / \int d \rho_{1}(\eta_{1}, \varphi_{1}) d\eta_{1} d\varphi_{1} \). The present measurement of the \( G_{2} \) correlators is based on charged particle tracks measured with the TPC detector in the transverse momentum range \( 0.2 \leq p_{T} \leq 2.0 \) GeV/c and the pseudorapidity range \( |\eta| < 0.8 \). In order to ensure good track quality and to minimize secondary track contamination, the analysis is restricted to charged particle tracks involving a minimum of 50 reconstructed TPC space points out of a maximum of 159, and distances of closest approach (DCA) to the reconstructed primary vertex of less than 3.2 cm and 2.4 cm in the longitudinal and radial directions, respectively. An alternative criterion, used in the analysis of the systematic uncertainties, that relies on tracks reconstructed with the combination of the TPC and the ITS detectors, henceforth called “global tracks”, involves a minimum of 70 reconstructed TPC space points, hits either on any of two inner layers of the ITS, or in the third inner layer of the ITS, and a tighter DCA selection criterion in both, longitudinal and radial directions, the latter one \( p_{T} \)-dependent. Electrons (positrons), whose one of the largest sources are photon conversions into \( e^{+}e^{-} \) pairs, are suppressed discarding \( e^{+} \) and \( e^{-} \) by removing tracks with a specific energy loss \( dE / dx \) in the TPC closer than 3\( \sigma_{dE / dx} \) to the expected median for electrons and at least 5\( \sigma_{dE / dx} \) away from the \( \pi, K \) and \( p \) expectation values.

The single and pair efficiencies of the selected charged particles are estimated from a Monte Carlo (MC) simulation using the HIJING event generator [24] with particle transport through the detector performed with GEANT3 [25] tuned to reproduce the detector conditions during the 2010 run. Corrections for single track losses due to non-uniform acceptance (NUA) are carried out using a weighting technique [17] separately for data and for reconstructed MC data. Weights are extracted separately for positive and negative tracks, for each collision centrality range, as a function of \( \eta, \psi, p_{T} \) and the longitudinal position of the primary vertex of each event, \( z_{0\text{vx}} \). The \( p_{T} \)-dependent single track efficiency correction is extracted as the inverse of the ratio of the number of NUA corrected reconstructed HIJING tracks to generated tracks. Data are performed to obtain \( G_{2}(\Delta \eta, \Delta \varphi) \), where \( \Delta \eta = \eta_{1} - \eta_{2} \) and \( \Delta \varphi = \varphi_{1} - \varphi_{2} \), with a procedure similar to that used for \( R_{2} \) and \( P_{2} \) correlators [18].

3. Measurement techniques

The results presented in this letter are based on 1.1 \( \times 10^{7} \) selected minimum bias (MB) Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV collected during the 2010 LHC heavy-ion run by the ALICE experiment. Detailed descriptions of the ALICE detectors and their respective performances are given in Refs. [21,22]. The MB trigger was configured in order to have high efficiency for hadronic events, requiring at least two out of the following three conditions: i) two hits in the second inner layer of the Inner Tracking System (ITS), ii) a signal in the V0A detector, iii) a signal in the V0C detector. The amplitudes measured in the V0 detectors are additionally used to estimate the collision centrality reported in nine classes corresponding to 0–5% (most central), 5–10%, 10–20%, ... 70–80% (most peripheral) of the total interaction cross section [23]. The vertex position of each collision is determined with tracks reconstructed in the ITS and the Time Projection Chamber (TPC) and is required to be in the range \( |z_{0\text{vx}}| \leq 7 \) cm of the nominal interaction point (IP). Pile-up events, identified as events having multiple reconstructed vertices in the ITS, are rejected. Additionally, the extra activity observed in slow response detectors (e.g., TPC) relative to that measured in fast detectors (e.g., V0) for out of bunch pile-up events is used to discard these events. The remaining event pile-up contamination is estimated to be negligible. Longitudinally, the ITS covers \( |\eta| < 0.9 \), the TPC \( |\eta| < 0.9 \), V0A 2.8 < \( \eta \) < 5.1 and V0C \(-3.7 < \eta < -1.7 \). These four detectors feature full azimuthal coverage.
subsequently corrected with NUA and single track efficiency corrections. Pair losses due to track merging or crossing are corrected in part based on the technique described in [18] and in part based on the ratio of the average number of reconstructed HIJING pairs relative to the generated number of pairs. Corrections for pT dependent pair losses are not included in the reported results given they have a large (>20%) systematic uncertainty. Correlator values at |Δη| < 0.05, |Δφ| < 0.04 rad., left under-corrected by this last fact, are not reported in this work. However, this does not impact the shape and width of the G2 correlator, which are of interest for the determination of the viscous broadening. No filters are used to suppress like-sign (LS) particle correlations resulting from Hanbury Brown and Twiss (HBT) effects. For pions, which dominate the particle production, HBT produces a peak centered at Δη, Δφ = 0 in G2. The width of this peak decreases in inverse proportion to the size of the collision system. Given the number of HBT pairs is relatively small compared to the total number of pairs accounted for in G2, the implied reduction of the longitudinal broadening is relatively modest and thus not considered in this analysis.

4. Statistical and systematic uncertainties

Statistical uncertainties on the strength of G2 are extracted using the sub-sample method with ten sub-samples. Systematic uncertainties are determined by repeating the analysis under different event and track selection conditions. Deviations from the nominal results are considered significant and assessed as systematic uncertainties based on a statistical test [26]. The impact of potential TPC effects sensitive to the magnetic field polarity is assessed by splitting the whole data sample into positive and negative magnetic field configurations, whereas uncertainties associated with the collision centrality estimation are studied by comparing nominal results, based on the V0 detector, with those obtained with an alternative centrality measure based on hit multiplicity on the two inner layers of the ITS. Effects of the kinematic acceptance in which the measurement is performed are investigated by repeating the analysis with events in the range |z_{#text{beam}}| < 3 cm of the nominal IP. The presence of biases caused by secondary particles is checked using the “global tracks” selection criteria. Biases associated with pair losses are studied based on pair efficiency corrections obtained with HIJING/GEANT3 simulations. The largest systematic uncertainty amounts to a global shift in G2(Δη, Δφ) correlator strength which is independent of Δη and Δφ and is reported as δB. This shift affects the magnitude of the projections onto Δη and Δφ but not the shapes of the near-side peak, |Δφ| < π/2, of G2 along these coordinates. Systematic uncertainties in the shape of the near-side peak of G^{0}_{2} and G^{0}_{2} are mainly due to the presence of secondary particles. Overall, systematic uncertainties on the shapes of the projections of G^{0}_{2} and G^{0}_{2} along the longitudinal (azimuthal) dimension amount to 4%(5%) and 5%(10%), respectively, with decreasing values towards peripheral events.

5. Results

Fig. 1 presents the correlators G^{0}_{2}(Δη, Δφ) measured in 0–5%, 30–40%, 70–80% Pb–Pb collisions, and their respective projections along the Δη and Δφ axes. The G^{0}_{2} correlators feature sizable
$\Delta \varphi$ modulations, dominated in mid-central collisions by a strong elliptic flow ($\cos(2\Delta \varphi)$) component. On the near-side, atop the azimuthal modulation, the $G^C_{2\perp}$ correlators feature a near-side peak whose amplitude monotonically decreases from peripheral to central collisions while its longitudinal width systemically broadens. Qualitatively similar trends were observed for the $R_2$ and $P_2$ correlators reported by ALICE [18] and the $G^C_{2\perp}$ correlator (there named $C$) reported by STAR [16]. In most central collisions, the amplitude of the $\Delta \varphi$ modulations associated with collective flow decreases but the longitudinal broadening remains. Additionally, a depletion centered at $(\Delta \eta, \Delta \varphi) = (0, 0)$ consistent with previous ALICE results [27,28] can be seen.

In order to study the centrality evolution of the near-side peak of the $G^C_{2\perp}$ and $C^C_{2\perp}$ correlators independently of the underlying collective azimuthal behavior, they are separately parametrized with a two-component model defined as

$$F(\Delta \eta, \Delta \varphi) = B + \sum_{n=2}^{6} a_n \times \cos(n \Delta \varphi) + A \times \frac{\gamma_{\Delta \eta}}{2 \omega_{\Delta \eta} \Gamma \left( \frac{1}{\gamma_{\Delta \eta}} \right)} e^{-\frac{\Delta \eta}{\omega_{\Delta \eta}}} \left| \frac{\Delta \eta}{\gamma_{\Delta \eta}} \right|^{\frac{\gamma_{\Delta \eta}}{2 \omega_{\Delta \eta}}} \frac{\gamma_{\Delta \varphi}}{2 \omega_{\Delta \varphi} \Gamma \left( \frac{1}{\gamma_{\Delta \varphi}} \right)} e^{-\frac{\Delta \varphi}{\omega_{\Delta \varphi}}} \left| \frac{\Delta \varphi}{\gamma_{\Delta \varphi}} \right|^{\frac{\gamma_{\Delta \varphi}}{2 \omega_{\Delta \varphi}}}, \tag{4}$$

where $B$ and $a_n$ are intended to describe the long-range mean correlation strength and azimuthal anisotropy, while the bidimensional generalized Gaussian, defined by the parameters $A$, $\omega_{\Delta \eta}$, $\omega_{\Delta \varphi}$, $\gamma_{\Delta \eta}$ and $\gamma_{\Delta \varphi}$, is intended to model the signal of interest. The $(\Delta \eta, \Delta \varphi) = (0, 0)$ depletion present in the $G^C_{2\perp}$ correlator is not properly modeled by Eq. (4) and the depletion area, $|\Delta \eta| > 0.31$ and $|\Delta \varphi| < 0.26$ rad., is excluded from the fit. Bidimensional fits are carried out considering only statistical uncertainties. In the case of the $G^C_{2\perp}$ correlator the $\chi^2/n$dof values for semi-central to peripheral collisions are found in the range $1–2$; for central collisions they increase to 4. The area which contributes the most to the increase of the $\chi^2/n$dof is the region between the generalized Gaussian and the Fourier expansion. Excluding this area the $\chi^2/n$dof values obtained in central collisions are within the range $1–2.3$. Fits of $G^C_{2\perp}$ give $\chi^2/n$dof of the order of unity for peripheral to semi-central collisions and in the range $2–3.5$ for central collisions. Larger $\chi^2/n$dof values observed in central collisions because the near side peak starts to depart from the generalized Gaussian description. The actual focus is on the evolution of the widths. The longitudinal and azimuthal widths of the correlators, denoted $\sigma_{\Delta \eta}$ and $\sigma_{\Delta \varphi}$, respectively, are then extracted as the standard deviation of the generalized Gaussian

$$\sigma_{\Delta \eta(\Delta \varphi)} = \sqrt{\frac{\omega_{\Delta \eta(\Delta \varphi)}^2 \Gamma(3/\gamma_{\Delta \eta(\Delta \varphi)})}{\Gamma(1/\gamma_{\Delta \eta(\Delta \varphi)})}}, \tag{5}$$

and plotted as a function of collision centrality in the top panels of Fig. 2 for both $G^C_{2\perp}$ and $C^C_{2\perp}$ correlators. The global shift of the correlator strength, quoted as a systematic uncertainty in the projections of the correlators, does not affect the shape of the near-side peak of $G_2$. Accordingly, the widths are not affected either. Correlations between the contributors to the longitudinal width and the harmonic parameters for the $G^C_{2\perp}$ correlator are found as follows: $a_2$ and $a_4$ are anti-correlated with $\omega_{\Delta \eta}$ with values in the ranges $-0.8$ to $-0.4$ and $-0.5$–$0$, respectively, while $a_3$ is correlated with values $0.5$–$0$. On the other hand, $a_2$ and $a_4$ are correlated with

![Fig. 2. Top panels: collision centrality evolution of the longitudinal (left) and azimuthal (right) widths of the $G^C_{2\perp}$ and $C^C_{2\perp}$ correlators measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Central and bottom panels: width evolution relative to the value in the most peripheral collisions of the two-particle transverse momentum correlations $G^C_{1\perp}$ (central) and $G^C_{2\perp}$ (bottom) along the longitudinal (left) and azimuthal (right) dimensions. Data are compared with HIJING and AMPT model expectations. In data, vertical bars and shaded bands represent statistical and systematic uncertainties, respectively. For models, shaded bands represent statistical uncertainties.](image-url)
tent with those of $R_2$ and $P_2$ correlators measured in the same
kinematic range by the ALICE collaboration [18]. Note that the $G_2$
 correlator is sensitive to transverse momentum and number den-
sity fluctuations since both affect the momentum current density.
In contrast, $R_2$ is sensitive to number density fluctuations and $P_2$, sensitive to transverse momentum fluctuations, is designed to
minimize the contribution of those number density fluctuations [29].
In fact [29]

\[(P_2 + 1)(R_2 + 1) = (G_2 + 1)\]

so, the increase in transverse momentum currents could be due to
either the increase in multiplicity or the increase of transverse mo-
nentum. The $G_2^{CD}$ and $P_2^{CD}$ correlators feature approximately equal
widths while $R_2^{CD}$ is approximately 30% wider throughout its cen-
trality evolution. The centrality dependence of $G_2^{CD}$ is qualita-
tively consistent with that of balance function (BF) observations
[30,31]. Phenomenological analyses of the BFs suggest that their nar-
rowing with centrality is largely due to the presence of strong flow
and delayed hadronization in Pb–Pb collisions [30]. It is thus
reasonable to infer that radial flow and larger \(\langle p_T \rangle\), in more cen-
tral collisions, also produce the observed narrowing of $G_2^{CD}$. This
conjecture is supported by calculations of the collision centrality
dependence of $G_2^{CD}$ azimuthal widths with the HIJING and AMPT
models shown in the bottom right panel of Fig. 2. Radial flow
might also explain the observed azimuthal narrowing of the $G_2$
correlator with centrality, which is reasonably well reproduced by
calculations with AMPT string melting, not by HIJING or AMPT calcula-
tions with only hadronic rescattering as shown in central right
panel of Fig. 2.

The broadening of the longitudinal width of the $G_2^{CI}$ correla-
tor is of particular interest given predictions that it should grow
in proportion to $\eta/s$ of the matter produced in the collisions [15].
As expected for a system with finite viscosity, it is found that $G_2^{CI}$
broadens significantly with increasing collision centrality, while by
contrast, $G_2^{CD}$ exhibits a slight but distinct narrowing. This $G_2^{CD}$
longitudinal narrowing is expected from a boost of particle pairs
by radial flow but is not properly accounted for by AMPT cal-
culations shown in the bottom left panel of Fig. 2. Radial flow
should also produce a narrowing of the $G_2^{CI}$ correlator in the lon-
gitudinal direction. However competing effects, possibly associated
with the finite shear viscosity of the system, are instead producing
a significant broadening although reaching what seems a satu-
tion level at semi-central collisions. Note that HIJING and AMPT,
with the hadronic rescattering enabled, grossly fail to reproduce
the observed broadening and instead predict a slight narrowing
(Fig. 2 central left panel). AMPT with string melting and without
the hadronic rescattering phase qualitatively reproduces the lon-
gitudinal broadening of $G_2^{CI}$, even its saturation, but grossly miss
the narrowing of $G_2^{CD}$ along that dimension and thus cannot be
considered reliable in this context.

Particles produced by jet fragmentation are also known to ex-
hibit correlations and jet-medium interactions can broaden such
correlations. Two-particle correlation measurements, of particles
associated with high-$p_T$ jets, indeed show substantial broaden-
ing of low $p_T$ particle correlations relative to correlation functions
measured in pp collisions [27,28,32]. This broadening, however,
is observed in both the longitudinal and azimuthal directions in stark
contrast with the behavior of the inclusive $G_2^{CI}$ correlator mea-
sured in this work which exhibits a significant narrowing in the azi-
muthal direction. Additionally, the number of particles from jets
is relatively small compared to the number from the bulk. There-
fore, although jet fragmentation may contribute to the broadening
observed in the longitudinal direction, it is unlikely to amount to
a significant contribution given the observed narrowing in the $\Delta \phi$
direction and the relatively low impact of correlations from jet par-
ciles.

Fig. 4 compares results from this analysis with those reported
by the STAR collaboration [16]. For proper comparison, Fig. 4
presents root mean square (RMS) widths of $\Delta \eta$ projections of $G_2^{CI}$
calculated above a long range baseline as in the STAR analysis [16].
Although STAR reported results are based on the dimensional
version of $G_2^{CI}$, the same expression as in Eq. (1) but without the
normalization \(\langle p_{T1} \rangle \langle p_{T2} \rangle\), the correlator widths reported in this letter
are identical for both, the dimensional and dimensionless versions
of the $G_2$ correlator. The longitudinal broadening measured in this
analysis, using the 1D RMS method, amounts to 36% while that
observed by STAR reaches 74% showing also a saturation at semi-
central collisions. It was verified that the smaller broadening seen
in this analysis is not a result of the slightly narrower longitudinal
acceptance of the ALICE experiment by testing the analysis method
with Monte Carlo models reproducing the approximate shape and
strength of the measured correlation functions. The longitudinal

\[\text{Fig. 3. Left panel: collision centrality evolution of the longitudinal width of number correlator } R_2^{CD} \text{ and transverse momentum correlators } P_2^{CD} \text{ and } G_2^{CD}. \text{ Right panel: collision centrality evolution of the longitudinal width of } R_2^{CI}, P_2^{CI}, \text{ and } G_2^{CI}. \text{ Data for } R_2 \text{ and } P_2 \text{ are from } [18]. \text{ Vertical bars and shaded bands represent statistical and systematic uncertainties, respectively.}\]

\[\text{Fig. 4. Two-particle transverse momentum correlation } G_2^{CI} \text{ longitudinal width evolution with the number of participants in Au–Au collisions at } \sqrt{s_{NN}} = 200 \text{ GeV } [16] \text{ and in Pb–Pb collisions at } \sqrt{s_{NN}} = 2.76 \text{ TeV, measured in this work, using the bi-dimensional fit described in the text (2D) and the method used by the STAR experiment } [16] \text{ (1D). For completeness, STAR RMS low limit } [16] \text{ is also shown.}\]
broadening of $G_2^{\text{CI}}$ and its observed saturation thus appears to be potentially dependent on the beam energy.

Interpreting the longitudinal broadening of $G_2^{\text{CI}}$ as originating exclusively from viscous effects, an estimate of the shear viscosity per unit of entropy density, $\eta/s$, of the matter produced in heavy-ion collisions can be extracted [16] using the expression

$$\sigma_0^2 - \sigma_f^2 = \frac{4}{T_c} \frac{\eta}{s} \left( \frac{1}{\tau_0} - \frac{1}{\tau_{f,0}} \right)$$

(7)

derived in [15]. In Eq. (7), $\sigma_0$ is the longitudinal width for the most central collisions (ideally 0% centrality), $\sigma_f$ is the longitudinal width for the most peripheral collisions (ideally 100% centrality), $T_c$ is the critical temperature, $\tau_0$ is the formation time and $\tau_{f,0}$ the freeze-out time. The correlation width for the most peripheral Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV is estimated based on a power law extrapolation of the measured values, shown in Fig. 5, down to $N_{\text{part}} = 2$. Canonical values are used for the critical temperature, $T_c = 160$ MeV [33], the formation time $\tau_0 = 1$ fm/c [33], and the freeze-out time, $\tau_{f,0} = 10.5$ fm/c [34]. With these inputs in Eq. (7), $G_2^{\text{CI}}$ longitudinal widths for the most central collisions are calculated for several values of $\eta/s = 0.06, 1/4\pi, 0.14$ and 0.22 and also shown in Fig. 5 as color discontinuous (continuous for $\eta/s = 1/4\pi$) bands at the highest number of participants. Considering 2%, 30%, and 3% uncertainties for $T_c$ (155 < $T_c$ < 165 TeV), $\tau_0$, and $\tau_{f,0}$ ($10 < \tau_{f,0} < 11$ fm) respectively, the uncertainties of the four obtained $G_2^{\text{CI}}$ longitudinal widths for the most central collisions reach 9%, 10%, 12%, and 14%, respectively, also shown in Fig. 5 as error caps in the same color as the discontinuous bands. The $G_2^{\text{CI}}$ correlator width measured in central collisions thus favors rather small values of $\eta/s$, close to the KSS limit of $1/4\pi$ [35]. The authors of Ref. [15] obtain the correlator width values, for Au-Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV, without an actual measurement of $G_2^{\text{CI}}$ from the only available two-particle transverse momentum correlator which in its turn was inferred from event-wise mean transverse momentum fluctuations [36] and on its energy dependence [37]. They constrain $\eta/s$ to a relatively wide interval 0.08–0.30. The precision of the STAR measurement is limited by the relative uncertainty of the $G_2^{\text{CI}}$ correlator widths for Au-Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV: $\eta/s = 0.06–0.21$ was reported in [16].

7. Conclusions

Measurements of charge dependent (CD) and charge independent (CI) transverse momentum correlators $G_2$ in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV were presented aiming at the determination of the shear viscosity per unit of entropy density, $\eta/s$, of the matter formed in such collisions. The near-side peak of the $G_2^{\text{CI}}$ correlator is observed to significantly narrow with collision centrality both in the longitudinal and azimuthal directions. This behavior is found to be similar to that of the charge balance function as a result, most likely, of an increase of the average radial flow velocity from peripheral to central collisions. By contrast, the $G_2^{\text{CD}}$ correlator is found to narrow only in the azimuthal direction with collision centrality and features a sizable broadening in the longitudinal direction. The observed broadening along the longitudinal direction is expected based on friction forces associated with the finite shear viscosity of the system. Taking the model proposed in [15], an estimate of the value of $\eta/s$ of order 1/4$\pi$, in qualitative agreement with values obtained from other methods [14,38], is obtained.

String melting AMPT without the hadronic rescattering phase has been found to qualitatively reproduce the longitudinal broadening of $G_2^{\text{CI}}$ but grossly misses the narrowing of $G_2^{\text{CD}}$ along that dimension. The observed saturation in the longitudinal broadening and the sizable difference in broadening relative to that observed by STAR may result from the interplay of viscous forces and kinematic narrowing associated to radial flow. In the latter case, the difference compared to the STAR results due to a possible dependence on the beam energy could be better established with expanded experimental measurements for energies in the beam energy scan (BES) at RHIC or at 5.02 TeV at the LHC.

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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