Characterizing the medium created in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV by means of the evolution of two-particle transverse momentum correlations

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Abstract. Two-particle correlations are powerful tools for studying the medium produced in heavy-ion collisions. In particular, two-particle transverse momentum correlations enable measurements of the collision dynamics sensitive to momentum currents. Their evolution with collision centrality, which is related to the system lifetime, provides information about the shear viscosity, $\eta/s$, and the system relaxation time, $\tau_\pi$. We report on measurements of two-particle transverse momentum correlations as a function of centrality in Pb–Pb collisions using the ALICE detector at the LHC. The centrality dependence of the near-side peak of the correlation function, particularly in the longitudinal dimension, provides information about the shear viscosity and the system relaxation time of the produced medium. The data are compared to predictions from selected Monte Carlo models. The charge independent momentum correlator exhibits a longitudinal broadening from peripheral to central collisions that is qualitatively consistent with expectations from a model with viscous effects. We will discuss an interpretation of the observed broadening in the context of this model.

1. Introduction
Properties of the medium formed in heavy-ion collisions can be extracted measuring the Fourier harmonic coefficients of the particles produced azimuthal distribution. Comparisons of these coefficients to hydrodynamical model predictions indicate that the medium has a specific shear viscosity, $\eta/s$, that nearly vanishes \[1\], approaching the behavior of a perfect liquid and unveiling the quark–gluon plasma (QGP) as a strongly coupled medium. The specific shear viscosity is the transport coefficient that most directly controls the expansion of the system. It quantifies the resistance the medium presents to its anisotropic deformation. It is responsible for the transfer of momentum between fluid cells as well as the damping of momentum fluctuations. Its effects are expected to grow with the lifetime of the system. Methods to determine $\eta/s$ rely on quantitative descriptions of heavy-ion collisions using a chain of models which incorporate initial conditions onset, pre-thermalization evolution, hydrodynamical expansion, particlization, and hadronic transport. The precision of model predictions used to be limited by uncertainties in the initial state conditions and by the selection of the concrete model to use. Recent models incorporate the parametrization of the initial conditions which in some way circumvents the high uncertainty initially associated with such model phase. Unfortunately a new source of uncertainties has been
also incorporated in the transition from the hydrodynamic phase to particles \[2\]. On the other hand, it was pointed out \[3\] that the strength of momentum current correlations may be sensitive to \(\eta/s\). It was shown, in particular, that the longitudinal broadening with increasing system lifetime of a transverse momentum (\(p_T\)) correlator, hereafter named \(G_2\), is directly sensitive to \(\eta/s\) while it does not have any explicit dependence on the initial conditions of the system.

The \(G_2\) correlator, defined in \[3\] \[4\], is experimentally calculated as

\[
G_2(\eta_1, \varphi_1, \eta_2, \varphi_2) = \frac{\left\langle n_{1,1}(\eta_1, \varphi_1) n_{1,2}(\eta_2, \varphi_2) \right\rangle}{\left\langle n_{1,1}(\eta_1, \varphi_1) \right\rangle \left\langle n_{1,2}(\eta_2, \varphi_2) \right\rangle} - \left\langle p_T(\eta_1, \varphi_1) p_T(\eta_2, \varphi_2) \right\rangle
\]

where \(\eta_\alpha, \varphi_\alpha, \alpha = 1, 2\), refer to single-track pseudorapidity and azimuthal angle, respectively; \(n_{1,1}\) and \(n_{1,2}\) are event-wise track counts at \((\eta_1, \varphi_1)\) and \((\eta_2, \varphi_2)\), respectively; \(p_T\) and \(p_T\) the transverse momentum components of particles in a given pair; and \(\langle p_T(\eta, \varphi) \rangle\) is the average transverse momentum of particles observed at \((\eta, \varphi)\). Angle brackets, \(\langle \cdots \rangle\), refer to event ensemble averages. For inferring the system lifetime the centrality of the collision is used as a proxy, such that the medium created in central collisions lives longer than the medium created in peripheral collisions.

2. Experimental measurements

The presented results (see \[3\] for more details) correspond to measurements based on 1.1 \(\times 10^7\) minimum bias Pb–Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV collected during LHC Run 1 by the ALICE experiment \[6\] \[7\]. The collision vertex, determined with tracks reconstructed in the Inner Tracking System (ITS) and the Time Projection Chamber (TPC), was required to be within 7 cm, along the beam axis, of the nominal interaction point. The results are reported in nine centrality classes corresponding to 0–5\% (most central), 5–10\%, 10–20\%, \ldots, 70–80\% (most peripheral) of the total interaction cross section, and whose ranges were estimated based on the hit multiplicity in the V0 detectors. The analysis was restricted to unidentified charged particle tracks which were measured with the TPC detector and required to be within the kinematic acceptance and for non uniform efficiency.

Differential charge independent (CI) and charge dependent (CD) two-particle transverse momentum correlators, \(G_{2}^{CI}\) and \(G_{2}^{CD}\), respectively, are measured as a function of pair pseudorapidity and azimuthal angle differences, \(\Delta \eta\) and \(\Delta \varphi\), for selected ranges of Pb–Pb collision centrality. Measurements of \(G_{2}(\eta_1, \varphi_1, \eta_2, \varphi_2)\) are averaged across the fiducial acceptance to obtain \(G_{2}(\Delta \eta, \Delta \varphi)\), where \(\Delta \eta = \eta_1 - \eta_2\) and \(\Delta \varphi = \varphi_1 - \varphi_2\) \[3\]. \(G_{2}^{CI}\) and \(G_{2}^{CD}\) correlators are extracted as the averaged sum and the averaged difference of the opposite charge and same charge correlators, respectively.

Figure 1 presents the \(G_{2}^{CI}(\Delta \eta, \Delta \varphi)\) correlator measured in 0–5\% and 30–40\% Pb–Pb collisions. The \(G_{2}^{CI}\) 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, \(|\Delta \varphi| < \pi/2\), atop the azimuthal modulation, the \(G_{2}^{CI}\) correlators feature a near-side peak whose amplitude monotonically decreases from peripheral to central collisions while its longitudinal width systematically broadens. Two structures develop from semi-central towards central collisions. On the near side, \(|\Delta \varphi| < \pi/2\), two longitudinally extended lobes give place to a depletion around \((\Delta \eta, \Delta \varphi) = (0, 0)\). On the away side, \(|\Delta \varphi - \pi| < \pi/2\), a long range depletion develops showing the dilution, in the short longitudinal reach, of the strength of the long range correlations driven by initial fluctuations and collective behavior.

Near-side longitudinal projections and azimuthal projections of the \(G_{2}^{CI}\) correlators are shown in Fig. 2 for the previous centrality collision intervals. The near-side longitudinal projections of
Figure 1. Two-particle transverse momentum correlations $G^C_{2}$ for the most central (left) and semi-central (right) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Under-corrected correlator values at $(\Delta\eta, \Delta\phi) = (0, 0)$ are not shown [5].

The $G^C_{2}$ correlator shows the monotonic growth of the amplitude of the near-side peak from central to peripheral collisions. The collective behavior, developed along the azimuthal dimension is present just as a uniform baseline on top of which the near-side peak develops. On top of this baseline the near-side peak broadens from peripheral to central collisions. From semi-central to central collisions the near-side peak shows a plateau consistent with the two lobes structure shown in Fig. 1. The azimuthal projections show the evolution with centrality of the long range collective behavior. The dilution on the away side of the long range correlation shown in Fig. 1 is also visible in the progress of the azimuthal projections from semi-central to peripheral collisions.

The focus now is on the evolution with centrality of the width of the two-particle transverse momentum correlation on the near-side peak. To extract such widths, along the azimuthal and longitudinal dimensions, the two-dimensional correlations are parametrized with a two-component model defined as

$$F(\Delta\eta, \Delta\phi) = B + \sum_{n=2}^{4} a_n \cos(n\Delta\phi) + A \frac{\gamma_{\Delta\eta}}{2\omega_{\Delta\eta}} \frac{\gamma_{\Delta\eta}}{\Gamma(1/\gamma_{\Delta\eta})} e^{-\left|\Delta\eta\right|^{2\gamma_{\Delta\eta}}/\Gamma(3/\gamma_{\Delta\eta})} \frac{\gamma_{\Delta\phi}}{2\omega_{\Delta\phi}} \frac{\gamma_{\Delta\phi}}{\Gamma(1/\gamma_{\Delta\phi})} e^{-\left|\Delta\phi\right|^{2\gamma_{\Delta\phi}}/\Gamma(3/\gamma_{\Delta\phi})},$$

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 $A$, $\omega_{\Delta\eta}$, $\omega_{\Delta\phi}$, $\gamma_{\Delta\eta}$ and $\gamma_{\Delta\phi}$, is intended to model the signal of interest. The longitudinal and azimuthal widths of the correlators, denoted $\sigma_{\Delta\eta}$ and $\sigma_{\Delta\phi}$, respectively, are extracted as the standard deviation of the generalized Gaussian

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

$$\sigma_{\Delta\phi} = \sqrt{\frac{\omega_{\Delta\phi}^2 \Gamma(3/\gamma_{\Delta\phi})}{\Gamma(1/\gamma_{\Delta\phi})}}$$

along each dimension. The longitudinal broadening of $G^C_{2}$ from peripheral to central collisions is interpreted as the increase in the reach of the viscous effects and used to infer the magnitude of the shear viscosity per unit of entropy density of the matter produced in Pb–Pb collisions. The longitudinal and azimuthal widths evolution of $G^C_{2}$ are used to assess the role of competing effects, including radial flow, diffusion, and the broadening of jets by interactions with the medium. A first measurement of the broadening of the two-particle transverse
3. Results and discussion

The evolution with collision centrality of the longitudinal and azimuthal widths of $G_{2}^{CL}$ and $G_{2}^{CD}$ correlators is shown in the top panels of Fig. 3. Longitudinally, $G_{2}^{CL}$ broadens by about 25% from peripheral to semi-central collisions, where its width saturates, while $G_{2}^{CD}$ narrows by about 10% from peripheral to central collisions. Azimuthally, both $G_{2}^{CL}$ and $G_{2}^{CD}$ consistently narrow by about 20%, although $G_{2}^{CD}$ stays wider. By comparison with the balance functions behavior \cite{12}, it is reasonable to infer that radial flow and larger $\langle p_T \rangle$, in more central collisions, together with delayed hadronization produce the observed narrowing of $G_{2}^{CD}$. That might also be the reason for the azimuthal $G_{2}^{CL}$ narrowing, drawing a scenario where broadening due to viscous effects competes with narrowing due to radial flow and delayed hadronization. The longitudinal broadening observed by STAR, which also saturates, reaches 70% \cite{9} pointing to a strong dependence on the beam energy.

The dependence with collision centrality of the measured longitudinal width of the two-
Figure 3. Top panels: collision centrality evolution of the longitudinal (left) and azimuthal (right) widths of the two-particle transverse momentum correlators $G^{CI}_2$ and $G^{CD}_2$ measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Central and bottom panels: widths evolution relative to the value in the most peripheral collisions of the two-particle transverse momentum correlators $G^{CI}_2$ (central) and $G^{CD}_2$ (bottom) along the longitudinal (left) and azimuthal (right) dimensions. Data are compared to HIJING [10] and AMPT [11] model expectations. In data vertical bars and shaded bands represent statistical and systematic uncertainties, respectively. For models, shaded bands represent statistical uncertainties [5].

Particle transverse momentum correlations $G^{CI}_2$ and $G^{CD}_2$ are compared to expectations from HIJING [10] and from three flavors of the AMPT [11] event generator in the central and bottom panels of Fig. 3 for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Although grossly failing to reproduce the longitudinal narrowing of $G^{CD}_2$ AMPT with string melting but without hadronic rescattering qualitatively describes the longitudinal broadening of $G^{CI}_2$ pointing to a potential early origin of such a broadening.

Interpreting the longitudinal broadening of $G^{CI}_2$ as originating exclusively from viscous effects, the authors of [3] extract the expression

$$\sigma^2_c - \sigma^2_0 = \frac{4}{T_c} \eta \left( \frac{1}{\tau_0} - \frac{1}{\tau_{c,f}} \right)$$

which relates $\eta/s$ with the difference of the squared longitudinal correlator widths for most central collisions and at formation time, $\sigma_c$ and $\sigma_0$, respectively, with the critical temperature, $T_c$, and with the difference of the inverses of the formation time and the freezeout time for most central collisions, $\tau_0$ and $\tau_{c,f}$, respectively. Equation 4, extracted from first order in
gradients expansion for the propagation of transverse momentum fluctuations, was used to infer the expected longitudinal widths of the correlator for the most central collisions for different values of $\eta/s$ as shown in Fig. 4. The $G^{CI}_{2}$ correlator width measured in the most central

![Graph showing expected longitudinal widths for the most central collisions of the two-particle transverse momentum correlation $G^{CI}_{2}$ for different values of $\eta/s$ by using the expression suggested in [3]. Data point error bars represent total uncertainties obtained by adding in quadrature statistical and systematic uncertainties. In the formula $\sigma_c$ is the longitudinal width for the most central collisions inferred by using this expression and represented for each of the $\eta/s$ values by the color discontinuous bands (continuous for $\eta/s = 1/4\pi$) at the highest number of participants, $\sigma_0$ is the longitudinal width for the most peripheral collisions (only two participants) which is obtained by extrapolating the fit, $T_c$ is the critical temperature, $\tau_0$ is the formation time and $\tau_{c,f}$ the freeze-out time. Error caps in the same color as the discontinuous bands, represent uncertainties of the inferred longitudinal widths for the most central collisions [5].

Figure 4. Expected longitudinal widths for the most central collisions of the two-particle transverse momentum correlation $G^{CI}_{2}$ for different values of $\eta/s$ by using the expression suggested in [3]. Data point error bars represent total uncertainties obtained by adding in quadrature statistical and systematic uncertainties. In the formula $\sigma_c$ is the longitudinal width for the most central collisions inferred by using this expression and represented for each of the $\eta/s$ values by the color discontinuous bands (continuous for $\eta/s = 1/4\pi$) at the highest number of participants, $\sigma_0$ is the longitudinal width for the most peripheral collisions (only two participants) which is obtained by extrapolating the fit, $T_c$ is the critical temperature, $\tau_0$ is the formation time and $\tau_{c,f}$ the freeze-out time. Error caps in the same color as the discontinuous bands, represent uncertainties of the inferred longitudinal widths for the most central collisions [5].

collisions favors rather small values of $\eta/s$, close to the KSS [13] limit of $1/4\pi$.

4. Conclusion

The near-side peak of the $G^{CD}_{2}$ correlator is observed to significantly narrow with collision centrality along the longitudinal and azimuthal directions. By contrast, the $G^{CI}_{2}$ correlator is found to narrow with collision centrality only in the azimuthal direction while broadens toward central collisions in the longitudinal direction. Using the model proposed in [3], which assigns the whole broadening to viscous effects, measured data favor a value of $\eta/s$ of order $1/4\pi$. String melting AMPT without the hadronic rescattering phase qualitatively reproduces the longitudinal broadening of $G^{CI}_{2}$, but misses the narrowing of $G^{CD}_{2}$ along that dimension.
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