Characterizing the initial conditions of heavy-ion collisions at the LHC with mean transverse momentum and anisotropic flow correlations

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Abstract. The study of the initial conditions of relativistic heavy-ion collisions and the subsequent development of hot and dense nuclear matter at the LHC is fundamental for the understanding of the strong nuclear force. The traditional approach of comparing observables with hydrodynamical models based on different initial conditions typically fails to isolate the effects of the initial conditions due to the sensitivity of the observables to the collective behaviour of the expanding system. Correlations of the mean transverse momentum $p_T$ and the anisotropic flow Fourier coefficients $v_n$ have been shown to serve as a unique probe of the initial conditions of the heavy-ion collisions with little to no bias from final state effects. In this talk, correlations between $p_T$ and $v_2$ or $v_3$ are presented as a function of centrality in Pb–Pb and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 5.44$ TeV, respectively, measured with ALICE. Additionally, measurements of the higher-order correlation between $p_T$, $v_2$, and $v_3$ is measured for the first time. All of these measurements are compared with hydrodynamical models using IP-Glasma or TRENTo initial conditions. The former is based on Color Glass Condensate effective theory with gluon saturation and the latter is a parameterized model with nucleons as the relevant degrees of freedom. The data is best described by models using IP-Glasma initial conditions, whereas the TRENTo based models fail to describe the data regardless of the parametrization.

1. Introduction
The system created in heavy-ion collisions is well described by hydrodynamics on a timescale between 1 fm/$c$ and 10 fm/$c$, where quark-gluon plasma (QGP) is predicted to be the dominant phase of matter [1, 2]. Prior to this, the initial conditions and pre-equilibrium dynamics of the collisions determine the onset of the subsequent hydrodynamic evolution. The most state-of-the-art theoretical calculations based on Bayesian analysis [3, 4, 5, 6] or on IP-Glasma initial conditions have been successful in describing heavy-ion collisions, but have large uncertainty in the extracted transport properties of the QGP. The hydrodynamical models v-USPhydro [7], Bayesian analysis Trajectum [5] and Bayesian analysis JETSCAPE [6] are based on TRENTo [8] initial conditions. TRENTo is an effective model to produce initial entropy profiles without assuming specific physical mechanisms for entropy production, pre-equilibrium dynamics or thermalization. The IP-Glasma+MUSIC+UrQMD hydrodynamical model is based on the Color Class Condensate (CGC) [9] framework for multi-particle production and with fluctuating colour charges. In order to distinguish between competing initial conditions, an observable which is only sensitive to the initial state is required. The initial conditions cannot be directly measured in
Figure 1. Comparison of initial state estimators and final state calculations of $\rho(v_2^2, p_T)$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from the IP-Glasma+MUSIC+UrQMD [18], v-USPhydro [20], Trajectum [5] and JETSCAPE [6] models. The initial-state estimations (ISE) are represented by lines, while the full hydrodynamic model calculations are shown with hatched bands.

experiments as the experiments only measure the final state particles. The difficulty is then in constructing an observable, which is not sensitive to the hydrodynamic evolution and the final hadronic rescattering, and instead is only sensitive to the initial state. The anisotropic flow $v_n$ is a measure of the initial geometry or shape of the overlap of the colliding nuclei. However, the flow coefficients are highly sensitive to the transport properties of the QGP. Measurements of the flow coefficients, $v_n$, and their event-by-event fluctuations have been successful in constraining the specific shear viscosity, $\eta/s$ and specific bulk viscosity, $\zeta/s$ of the QGP [10, 11, 12, 13]. Event-by-event fluctuations of the size of the initial system (at fixed entropy) affect the transverse momentum, $p_T$, spectra of the final state particles. The mean transverse momentum, $\mean{p_T}$, of all particles in a single event can then be used as a measure of the initial size of the system. The interplay between the initial shape and size of the system can be measured with a modified Pearson correlation coefficient [14]

$$\rho(v_2^2, [p_T]) = \frac{\cov(v_2^2, [p_T])}{\sqrt{\var(v_2^2)} \sqrt{\mean{p_T^2}}},$$

where $\cov(v_2^2, [p_T])$ is the covariance between $v_2^2$ and $[p_T]$ and is calculated as a three-particle correlation with the three-subevent method as in eq. (4) of [14]. The dynamic fluctuations of $p_T$ is given by $c_k$ [15, 16, 14, 17] and the variance of $v_n$ is given by $\var(v_n^2) = v_n\{2\}^4 - v_n\{4\}^4$. The $\rho(v_2^2, [p_T])$ is insensitive to the hydrodynamic and hadronic phase and can be quantitatively reproduced with only initial state estimators [18, 19, 20]. The insensitivity to the final state can be seen in figure 1 where the centrality dependence of $\rho(v_2^2, [p_T])$ is shown using initial state estimators and full hydrodynamical calculations. The initial state estimators agree with the full calculations regardless of the model. This agreement suggests that the $\rho(v_2^2, [p_T])$ observable is sensitive only to the initial state of the heavy-ion collisions. Additionally, the $\rho(v_2^2, [p_T])$ is found to also be sensitive to the nuclear deformation in central collisions [21]. The high precision of high-energy heavy-ion experiments thus enables a new tool to study the nuclear structure of deformed nuclei.
Figure 2. Centrality dependence of $\rho(v^2, p_T)$ (left) and $\rho(v^2, p_T)$ (right) in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The initial-state estimations (ISE) are represented by lines, while IP-Glasma+MUSIC+UrQMD [18], v-USPhydro [20], Trajectum [5], and JETSCAPE [6] hydrodynamic model calculations are shown with hatched bands.

In this talk, the ALICE measurements of the centrality dependence of $\rho(v^2, [p_T])$ and $\rho(v^3, [p_T])$ in Pb–Pb and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 5.44 TeV, respectively, are presented [22]. The centrality of the collisions is determined using the measured amplitudes in the forward V0 detectors scintillator arrays, V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$) [23, 24]. Events that pass central, semi-central and minimum bias trigger criteria and have a primary interaction vertex within ±10 cm are selected for analysis. In total, 245 million Pb–Pb events and 1.2 million Xe–Xe events are used for analysis. Particle tracks are required to have $0.2 < p_T < 3.0$ GeV/$c$ and $|\eta| < 0.8$. In order to suppress non-flow correlations, which are short-range correlations not due to collective behaviour, the central barrel is divided into three subevents A, B and C. The subevents A ($-0.8 < \eta < -0.4$) and C ($0.4 < \eta < 0.8$) are used for the $v_n$ measurements and subevent B ($-0.4 < \eta < 0.4$) is used for the $[p_T]$ measurements. Particles used in the measurements of $v_n$, $[p_T]$ and their correlations are corrected for non-uniform detector acceptance, and inefficiencies in the track-reconstruction using the Generic Framework with 3-subevent method [25, 26].

Figure 2 shows the centrality dependence of $\rho(v^2, p_T)$ and $\rho(v^2, p_T)$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The $\rho(v^2, p_T)$ shows a positive correlation between $v_2$ and $[p_T]$ with a weak centrality dependence. The hydrodynamic and initial state calculations from v-USPhydro [7], Trajectum [5], JETSCAPE [6], and IP-Glasma+MUSIC+UrQMD [8] are compared to the ALICE measurements. The JETSCAPE calculations of $\rho(v^2, [p_T])$ deviate strongly from the data and show a negative correlation above 40% centrality. The v-USPhydro and Trajectum calculations are somewhat better but also predict a much stronger centrality dependence than seen in the data and show a negative correlation above 50% centrality. The IP-Glasma+MUSIC+UrQMD calculation accurately describes the centrality trend of the data but overestimates the magnitude of the correlation. The $\rho(v^2, [p_T])$ measurements show no centrality dependence with only a slight increase in the magnitude of the correlation at 50-60% centrality. The correlation is positive in the presented centrality range, which indicates that $v_3$ and $[p_T]$ are positively correlated in this centrality region. Similarly to $\rho(v^2, [p_T])$, the JETSCAPE calculation of $\rho(v^2, [p_T])$ performs the worst compared to the data and shows a negative correlation above 10% centrality. The Trajectum calculation is slightly better than the JETSCAPE calculation, but still predicts the wrong sign for $\rho(v^2, [p_T])$ above 20% centrality. The v-USPhydro and IP-Glasma+MUSIC+UrQMD...
describe the data reasonably well while only slightly underestimating the data in more peripheral collisions. It was suggested in [27] that the $\rho(v_{2}^{2}, p_{T})$ is highly sensitive to the nucleon width, $\omega$, used in the initial state calculations and the positive correlation of $\rho(v_{2}^{2}, p_{T})$ suggest a nucleon width of around 0.4-0.5 fm. This is consistent with the observed trend of the models, where JETSCAPE performs the worst in describing the data while having the largest nucleon width (1.1 fm) of the models compared. The IP-Glasma+MUSIC+UrQMD models succeed in describing the data, possibly due to its small nucleon width, $\omega = 0.5$ fm. Recently, it has been shown that including the total hadronic cross section, which is highly sensitive to the nucleon width, as an input in the Bayesian analysis [28] will constrain the nucleon width at much lower values and enables the model to reproduce the measured $\rho(v_{2}^{2}, p_{T})$. This confirms the importance of the $\rho(v_{2}^{2}, p_{T})$ observable as a tool to constrain the initial state of heavy-ion collisions.

Figure 3 shows the centrality dependence of $\rho(v_{2}^{2}, p_{T})$ and $\rho(v_{3}^{2}, p_{T})$ in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The initial-state estimations (ISE) are represented by lines, while IP-Glasma+MUSIC+UrQMD [18] and v-USPhydro [20] hydrodynamic model calculations are shown with hatched bands. Both initial and final state calculations are shown with different values of the deformation parameter $\beta_{2}$.

In conclusion, the measurements of the correlation between anisotropic flow and mean transverse momentum, $\rho(v_{n}^{2}, p_{T})$ (n = 2,3), are important in constraining the initial conditions of heavy-ion collisions. Positive correlations are observed in both Pb–Pb and Xe–Xe collisions. In particular, the observables are sensitive to the nucleon width, and the observed positive correlations in Pb–Pb suggest a nucleon width around 0.4-0.5 fm. Additionally, the $\rho(v_{2}^{2}, p_{T})$ can be used to study the nuclear deformation at high energies, although a larger data sample of deformed nuclei is needed.
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