Elliptic and triangular flow in p+Pb and peripheral Pb+Pb collisions from parton scatterings

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Abstract

Using a multiphase transport model (AMPT) we calculate the elliptic, $v_2$, and triangular, $v_3$, Fourier coefficients of the two-particle azimuthal correlation function in proton-nucleus (p+Pb) and peripheral nucleus-nucleus (Pb+Pb) collisions. Our results for $v_3$ are in a good agreement with the CMS data collected at the Large Hadron Collider. The $v_2$ coefficient is very well described in p+Pb collisions and is underestimated for higher transverse momenta in Pb+Pb interactions. The characteristic mass ordering of $v_2$ in p+Pb is reproduced whereas for $v_3$ this effect is not observed. We further predict the pseudorapidity dependence of the two-particle azimuthal correlation function. Predictions for the higher order Fourier coefficients, $v_4$ and $v_5$, in p+Pb are also presented.

1. Introduction

Recently we argued [1] that the incoherent scattering of partons, as present in a multiphase transport model (AMPT) [2], with a modest elastic parton-parton cross-section $\sigma = 1.5 - 3$ mb, allows to understand qualitatively and quantitatively the long-range two-particle azimuthal correlation functions in proton-lead (p+Pb) and high-multiplicity proton-proton (p+p) collisions. Such correlations were recently observed by the CMS [3–5], ALICE [6, 7] and ATLAS [8, 9] collaborations at the Large Hadron Collider (LHC), and by the PHENIX collaboration in deuteron-gold collisions at the Relativistic Heavy Ion Collider (RHIC) [10].

Interestingly all features of the two-particle azimuthal correlation function observed in p+Pb collisions are very similar to those observed in A+A interactions, where such correlations are commonly attributed to the hydrodynamic expansion of the produced fireball. This naturally suggests that collective physics is present in p+A collisions [11–17, 1]. Particularly strong evidence in favour of hydrodynamics\textsuperscript{1} in p+A (and peripheral A+A) collisions is an approximate equality of multi-particle elliptic flow cumulants, $v_2(4) \approx v_2(6) \approx v_2(8)$, as predicted in Ref. [18], see also [19, 20], and confirmed recently by the CMS [21].

\textsuperscript{1}Or any other approach where the initial coordinate space anisotropy is transformed into the final momentum anisotropy.

Another strong evidence is the characteristic mass ordering of the elliptic flow, $v_2$, observed by the ALICE collaboration in Ref. [7], and successfully reproduced by hydrodynamic calculations [22, 23].

The experimental data for the two-particle azimuthal correlation function can be also fitted within the Color Glass Condensate framework [24], where the interesting part of the two-particle correlation function comes from the emission of two gluons in the so-called gluon diagram [25]. For a detailed discussion of this approach we refer the reader to Refs. [25–27].

It is important to clarify whether the signal in p+A collisions comes form the initial or final (or both) state effects. To this end several interesting observations were recently published [28–35] which could help to distinguish between competing models of p+A interactions. A simple conformal scaling argument, presented in Ref. [31], indicates a presence of a collective response to the geometry in p+Pb and Pb+Pb collisions.

In this paper we focus on the detailed discussion of the elliptic and triangular coefficients of the two-particle azimuthal correlation function in p+Pb and peripheral Pb+Pb collisions. Qualitatively we reproduce all trends observed in the data. In particular, we find that $v_2$ in p+Pb is in a good agreement with the CMS data for a broad range of $N_{\text{track}}$ and $p_t$. In peripheral Pb+Pb collisions $v_2$ is underestimated for higher $p_t$ and the integrated $v_2$ is...
20% below the data\(^2\) however, the \(N_{\text{track}}\) functional dependence is well reproduced. As far as the \(v_3\) coefficient \([36]\) is concerned we obtain a good description of the data in both \(p+\text{Pb}\) and \(\text{Pb}+\text{Pb}\) collisions. We observe that the integrated \(v_3\) is very similar in both systems for a broad range of \(N_{\text{track}}\). We further confirm the mass ordering of \(v_2\) which is a characteristic feature of collective dynamics. Finally we predict the dependence of the two-particle correlation function on the pseudorapidity sum, \(\eta_1 + \eta_2\), at a given pseudorapidity separation, \(\eta_1 - \eta_2\), between two particles. We observe that the near-side signal increases with the rapidity sum (that is when going towards a \(\text{Pb}\) fragmentation region), which is thought as a helpful probe to distinguish between various models of \(p+\text{Pb}\) collisions. We also predict the higher order Fourier coefficients, \(v_4\) and \(v_5\), in \(p+\text{Pb}\) collisions and find them roughly a factor of 2 smaller than the \(v_3\) coefficient.

In the next Section we shortly discuss the AMPT model and present our results for \(v_2\) and \(v_3\) in \(p+\text{Pb}\) and peripheral \(\text{Pb}+\text{Pb}\) collisions. In Section 3 we focus on the rapidity dependence of the two-particle azimuthal correlation function and present our predictions for \(v_4\) and \(v_5\) in \(p+\text{Pb}\) collisions. In the last Section we offer our conclusions.

\(^2\)Clearly we should not expect the AMPT model to work better than 20%.
2. Results

Similarly to our previous work we use the AMPT model with the string melting mechanism. In this model all initial minijets and soft strings are converted into quarks and antiquarks\(^3\) which undergo elastic scatterings with a partonic cross-section which is controlled by the strong coupling constant and the Debye screening mass. Subsequently a simple coalescence model is employed to form hadrons which further undergo hadronic scatterings. The detailed description of the AMPT model can be found in Ref. [2]. The AMPT model provides a consistent framework to understand many phenomena in p+p, p+A and A+A collisions. In particular, different orders of harmonic coefficients have been well reproduced in Au+Au collisions at the top RHIC energy [37] and Pb+Pb collisions at the LHC energy [38], which indicates that in A+A interactions the initial spatial asymmetry is transformed into the final momentum anisotropy via the incoherent parton scatterings [39]. It is believed that all harmonic flow coefficients contribute to the formation of the long-range two-particle azimuthal correlation function in A+A collisions. In our previous study, the long-range two-particle azimuthal correlations have been observed in p+p and p+Pb collisions at the LHC energies with a modest parton-parton cross-section of \(\sigma = 1.5 - 3\) mb [1]. Therefore, it is important to check if the flow coefficients \(v_n\) extracted from the long-range two-particle azimuthal correlation function are comparable with the data. In this work we simulate p+Pb collisions at \(\sqrt{s} = 5.02\) TeV and peripheral Pb+Pb collisions (50 – 100%) at \(\sqrt{s} = 2.76\) TeV with the parton-parton cross-section of 3 mb, being consistent with our previous study.

In Fig. 1 we present the elliptic and triangular Fourier coefficients from the long-range two-particle azimuthal correlation functions, i.e. \(v_n[2,|\Delta\eta| > 2]\), as a function of the transverse momentum, \(p_t\), in p+Pb (upper panel) and Pb+Pb collisions (lower panel) at \(\sqrt{s} = 5.02\) TeV and 2.76 TeV, respectively. In our analysis we exactly follow the CMS procedure as described in Ref. [5]. The description of the p+Pb data is very good for both \(v_2\) and \(v_3\) in the whole available transverse momentum range and for various centrality classes defined by the number of produced charged particles, \(N_{\text{track}}\), measured in \(|\eta| < 2.4\) and \(p_t > 0.4\) GeV. This is a nontrivial result suggesting that the AMPT model captures the main features of p+A physics. In Pb+Pb collisions \(v_3\) is consistent with the data, within the error bars, and surprisingly \(v_2\) is underestimated for \(p_t > 1\) GeV\(^4\). It is interesting to notice that \(v_2(p_t)\) in Pb+Pb has a characteristic maximum around \(p_t = 2.5\) GeV which is not present in p+Pb data. On the contrary \(v_3(p_t)\) is very similar in both systems and is well described by the AMPT model.

In Fig. 2 we present the integrated \((0.3 < p_t < 3\) GeV\) \(v_2\) and \(v_3\) for both p+Pb and Pb+Pb collisions. Again, \(v_2\) and \(v_3\) are very well described in p+Pb collisions for all available \(N_{\text{track}}\). Unfortunately, at present we cannot go to the highest values of \(N_{\text{track}} > 300\) to check whether \(v_3\) starts decreasing as suggested by the data. In Pb+Pb collisions the integrated \(v_3\) is consistent with the data for all \(N_{\text{track}}\) and the \(v_2\) coefficient is underestimated by roughly 20%. It is worth noticing that within the AMPT approach the integrated \(v_3\) in p+Pb and Pb+Pb interactions is roughly the same.

\[\text{Figure 3: The elliptic and triangular flow coefficients in p+Pb (120 < N_{\text{track}} < 260) as a function of the transverse momentum for pions, kaons and protons as obtained in the AMPT model with the string melting mechanism. The elastic parton-parton cross-section equals 3 mb.}\]

It is interesting to calculate \(v_2(p_t)\) and \(v_3(p_t)\) separately for pions, kaons and protons. The recently observed mass ordering of \(v_2\) in p+Pb collisions serves as a crucial test of the initial vs the final state effects. In hydrodynamics we naturally obtain the mass ordering which is not expected in the initial state scenarios, where the correlation is present from the very beginning. Indeed, recent hydrodynamic calculations [22, 23] reproduced the mass ordering of \(v_2(p_t)\) in p+Pb collisions and are in a satisfactory

\(^3\)In contrast to the default model where only partons from minijets interact.

\(^4\)We checked that increasing the cross-section in Pb+Pb to 10 mb only slightly improves the situation.
agreement with the ALICE data [7]. We checked that the mass ordering of \(v_2\) is present in the AMPT model, as presented in Fig. 3. Interestingly we do not observe the mass ordering for \(v_3\), being consistent with calculations of Ref. [22].

The results presented in this Section suggest that the incoherent scattering of partons (or other effective constituents) plays an important role in the early stage of p+Pb and peripheral Pb+Pb collisions. It is a rather non-trivial fact that all features present in the data can be qualitatively and quantitatively reproduced within a simple AMPT model.

3. Predictions

In this Section we present our predictions for the pseudorapidity dependence of the two-particle azimuthal correlation function in p+Pb collisions. In our calculations we take two narrow pseudorapidity bins with a given pseudorapidity separation \(\Delta \eta = \eta_2 - \eta_1\). Next we shift both bins simultaneously across the pseudorapidity axis to study the azimuthal correlation function for various values of the pseudorapidity sum, \(\Sigma \eta = \eta_1 + \eta_2\), at a given \(\Delta \eta\). Schematically this situation is presented in Fig. 4. We calculate the two-particle azimuthal correlation function, \(C(\Delta \phi)\), defined as

\[
C(\Delta \phi) \equiv \frac{Y_{\text{Same}}(\Delta \phi)}{Y_{\text{Mixed}}(\Delta \phi)} \times \int \frac{Y_{\text{Mixed}}(\Delta \phi) d\Delta \phi}{Y_{\text{Same}}(\Delta \phi) d\Delta \phi} \tag{1}
\]

where \(Y_{\text{Same}}(\Delta \phi = \phi_2 - \phi_1)\) and \(Y_{\text{Mixed}}(\Delta \phi)\) are, respectively, the numbers of particle pairs (i.e. one particle is in bin 1 and the other particle is in bin 2) at a given \(\Delta \phi\) and within a given \(p_t\) range. This definition of \(C(\Delta \phi)\) removes a trivial dependence on the number of produced particles in both bins [40, 41].

Our results are presented in Fig. 5. In this exercise we calculate for p+Pb events with \(N_{\text{track}} > 110\) (measured in \(|\eta| < 2.4\) and \(p_t > 0.4\) GeV) and for pairs of charged particles with \(1 < p_t < 2\) GeV. To illustrate the effect we choose five different \(\Sigma \eta\) configurations for a given \(\Delta \phi \sim 4\): (i) bins 1 and 2 are respectively given by \([-6.2, -5.8]\) and \([-2.2, -1.8]\) for \(\Sigma \eta \sim -8\), (ii) \([-4.2, -3.8]\) and \([-0.2, 0.2]\) for \(\Sigma \eta \sim -4\), (iii) \([-2.2, -1.8]\) and \([1.8, 2.2]\) for \(\Sigma \eta \sim 0\), (iv) \([-0.2, 0.2]\) and \([3.8, 4.2]\) for \(\Sigma \eta \sim 4\), (v) \([1.8, 2.2]\) and \([5.8, 6.2]\) for \(\Sigma \eta \sim 8\). In our calculations a Pb nucleus is characterized by a positive \(\eta\), which means that the increasing value of \(\Sigma \eta\) corresponds to shifting towards a Pb fragmentation region.

As seen in Fig. 5 the two-particle azimuthal correlation function at \(\Delta \phi = 0\) increases with increasing \(\Sigma \eta\), except for \(\Sigma \eta \sim 8\). It indicates that parton scatterings bring about
a larger collectivity if one moves from a p-going side to a Pb-going side in p+Pb collisions. This result is expected since on a Pb-going side we have significantly more produced partons and final particles. To illustrate the effect in a more transparent way we extract the second and the third Fourier coefficients of $C(\Delta \phi)$

\[
C(\Delta \phi) = 1 + \sum_n 2v_n^2 \cos(n\Delta \phi)
\]

and plot them as a function of $\Sigma \eta$. This result is presented in Fig. 6. Both $v_2$ and $v_3$ increase gradually when going from a proton side to a Pb-nucleus side. As expected, far in a nucleus fragmentation region both $v_2$ and $v_3$ start decreasing towards zero.

Finally, in Fig. 7 we present our predictions for the higher order Fourier coefficients, $v_4$ and $v_5$, in p+Pb collisions. In the AMPT model with the string melting mechanism, both $v_4$ and $v_5$ are roughly a factor of 2 smaller than the $v_3$ coefficient. In our plot we only show the results for one centrality class $120 < N_{\text{track}} < 150$ however, similarly to $v_2$ and $v_3$ presented in Fig. 1, the results for $v_4$ and $v_5$ weakly change with different $N_{\text{track}}$ classes.

4. Conclusions

In conclusion, using the AMPT model with the string melting mechanism, we investigated the elliptic and triangular Fourier coefficients of the long-range two-particle azimuthal correlation function in p+Pb and peripheral Pb+Pb collisions. In this model all initial minijets and soft strings are converted into partons which subsequently undergo elastic scatterings. This mechanism allows to understand various "flow" data measured in p+Pb and Pb+Pb collisions. In particular we obtain a good description of $v_2(p_t)$ and $v_3(p_t)$ in p+Pb for a broad range of the transverse momentum and for various centrality classes. The dependence of the integrated $v_2$ and $v_3$ on the number of produced charged particles, $N_{\text{track}}$, is also nicely reproduced. In peripheral Pb+Pb collisions $v_3(p_t)$ and the integrated $v_3$ coefficients are in a satisfactory agreement with the CMS data, however, $v_2$ is underestimated for higher transverse momentum resulting in 20% disagreement for the integrated $v_2$. We also verified the mass ordering of $v_2$ for pions, kaons and protons. We further predicted the pseudorapidity dependence of the two-particle azimuthal correlation function. We observed that $v_2$ and $v_3$ are gradually growing when going from a proton side to a Pb-nucleus side. Finally we calculated the higher order Fourier coefficients, $v_4$ and $v_5$, in p+Pb collisions and found them to be about a factor of 2 smaller than the $v_3$ coefficient.

We hope that the results presented in this paper will allow to disentangle between competing models of p+A collisions.

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