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The torque effect and fluctuations of entropy deposition in rapidity in ultra-relativistic nuclear collisions

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A B S T R A C T

The decorrelation of the orientation of the event-plane angles in the initial state of relativistic Pb–Pb and p–Pb collisions, the "torque effect", is studied in a model of entropy deposition in the longitudinal direction involving fluctuations of the longitudinal source profile on large scales. The radiation from a single wounded nucleon is asymmetric in space–time rapidity. It is assumed that the extent in rapidity of the region of deposited entropy is random. Fluctuations in the deposition of entropy from each source increase the event-plane decorrelation: for Pb–Pb collisions the change is moderate, while for p–Pb collisions the mechanism is absolutely essential to generate any sizable decorrelation. We also show that the experimental data for rank-four flow may be explained via folding of the elliptic flow. The results suggest the existence of long range fluctuations in the space–time distribution of entropy in the initial stages of relativistic nuclear collisions.

1. Introduction

During the collective expansion of the fireball formed in relativistic heavy-ion collisions azimuthal deformations of the density are transformed into azimuthal asymmetry of particle emission spectra [1,2]. In the presence of collective flow, the particle spectra contain the harmonic components

$$\frac{dN}{p_\perp dp_\perp d\eta\, d\phi} \propto \ldots + v_2(p_\perp,\eta)\cos[2(\phi-\psi_2)] + v_3(p_\perp,\eta)\cos[3(\phi-\psi_3)] + \ldots . \quad (1)$$

In each collision, the event-plane of the second or third order harmonic flow is oriented predominantly along the direction of elliptic or triangular deformations of the fireball. It has been suggested that the angles ψ_n of the event-plane orientation might vary as a function of pseudorapidity [3] or transverse momentum [4]. The effect leads to the factorization breaking for the two-particle cumulant flow coefficients,

$$V_{n\Delta}(t_1,t_2) < \sqrt{V_{n\Delta}(t_1,t_1)V_{n\Delta}(t_2,t_2)}\,, \quad (2)$$

where t_i is the transverse momentum or pseudorapidity,

$$V_{n\Delta}(t_1,t_2) = \langle\langle \cos[n(\phi_1-\phi_2)]\rangle\rangle, \quad (3)$$

and the average is taken over events and over all particle pairs with particles i in a bin around t_i.

The factorization breaking in transverse momentum has been studied quantitatively in dynamical models [4–6] in p–Pb and Pb–Pb collisions. The hydrodynamic response from fluctuating initial conditions can describe the experimentally observed event-plane fluctuations and the factorization breaking in $p_\perp$ [7,8].

The decorrelation of the event-plane angles at different pseudorapidities is seen in a number of calculations, both in hydrodynamic, cascade, or hybrid models [3,9–14]. Nevertheless, a simultaneous description of the Pb–Pb and p–Pb data [8] poses a real challenge. In this paper we propose a decorrelation mechanism which is capable to grasp the basic experimental features of both reactions. A schematic view of the model is depicted in Fig. 1, showing an early stage of the collision just after the two nuclei have passed through each other. The key ingredient is that the entropy deposition from the wounded nucleons [15] is made in string-like objects whose end-point is randomly distributed; some are longer and some shorter, with the length generated uniformly in the available rapidity interval. The idea is closely related to the model of Ref. [16].

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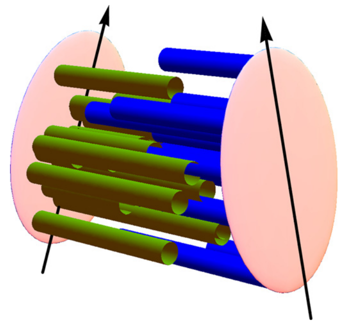

Fig. 1. Schematic view of the entropy distribution in an early stage of an ultrarelativistic nuclear collision. The matter deposited from each wounded nucleon occupies an interval in space–time rapidity with a randomly distributed end. As a result, the event-plane angles in the forward and backward bins are decorrelated.

2. The correlation measure

It is very difficult to disentangle the genuine event-plane decorrelation due to the collective expansion of a "torqued" fireball from non-flow fluctuations of short range in pseudorapidity [3]. This difficulty is cleverly solved by using a factorization ratio using three bins with a large separation in pseudorapidity, as proposed by the CMS Collaboration [8]:

$$r_n(\eta^a,\eta^b)=\frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}\ , \tag{4}$$

with the forward reference bin $4,4<\eta_b<5$ well separated from the two central bins where $|\eta_a|<2.5$. The departure of the factorization ratio r_n from unity is a measure of the event-plane angle decorrelation as a function of the pseudorapidity separation $\Delta\eta=2\eta_a$.

In Ref. [14], the factorization ratio for elliptic and triangular flow in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV was calculated in event-by-event viscous hydrodynamic simulations with Glauber initial conditions. Assuming an asymmetric entropy deposition in space–time rapidity from left- and right-going wounded nucleons, one finds that the orientation of the fireball deformation depends on space–time rapidity, as the contribution to the fireball entropy from target and projectile wounded nucleons changes with η [3]. Calculations show that the event-plane decorrelation in pseudorapidity can be described qualitatively, but the factorization ratio is noticeably underestimated. Moreover, the calculation cannot reproduce the observed factorization breaking in p–Pb collisions. In the following, we discuss a mechanism introducing additional fluctuations in the entropy deposition, with long range correlations, that improves the description of the measured factorization ratio r_n.

In the presence of collective expansion, the orientations of the event-planes and the elliptic or triangular deformation are transformed into the orientation and the magnitude of the corresponding harmonic flow components [17]. By the same mechanism, the torque of the event plane as a function of space–time rapidity is transformed into the rapidity dependence of the event-plane orientation extracted from particle spectra. This relation is expected to hold for decorrelation effects on large scales, while fluctuation in rapidity on small scales can be modified and washed out by the hydrodynamic evolution, resonance decays, mini-jets, etc. In the following, we investigate a model of fluctuations in the entropy deposition in space–time rapidity in the initial state. Hydrodynamic simulations show that the initial torque of the fireball in space–time rapidity is transformed into a very similar torque in the pseudorapidity dependence of the harmonic flow event-planes [3,14]. Unfortunately, precise hydrodynamic calculations including non-flow effects are very demanding. In this paper, event-plane decorrelation in pseudorapidity for the second and third harmonic flow are approximated by the event-plane decorrelation in spacetime rapidity in the initial state.

Statistical hadronization, where a finite number of hadrons in a given bin is produced from a fireball with principal axes ψ_n, leads to large decorrelation effects [3] whose origin is trivial and needs to be canceled out. The CMS ratios (4) accomplish this goal. Indeed, suppose we compute cumulants for the produced hadrons between the largely separated bins around η_a and η_b. Then

$$\begin{aligned}V_{n\Delta}(\eta^a,\eta^b)&=\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle=\langle\langle e^{in(\psi_n(\eta_a)+\phi_1'-\psi_n(\eta_b)-\phi_2')}\rangle\rangle\\&\simeq\langle e^{in[\psi_n(\eta_a)-\psi_n(\eta_b)]}\rangle\langle\langle e^{in\phi_1'-in\phi_2'}\rangle\rangle,\end{aligned} \tag{5}$$

where the azimuths of the produced hadrons, ϕ_1 and ϕ_2, are evaluated in some reference frame, $\psi_n(\eta_a)$ and $\psi_n(\eta_b)$ are the event-plane angles of the fireball, and ϕ_1' and ϕ_2' are evaluated relative to $\psi_n(\eta_a)$ and $\psi_n(\eta_b)$, respectively. The factorization in Eq. (5) applies if the torque angle magnitude is uncorrelated with the flow magnitude. The factors $\langle\langle e^{in\phi_1'-in\phi_2'}\rangle\rangle$ cancel out in appropriate ratios. For the symmetric A–A collisions the production around η_a is the same as around $-\eta_a$, hence taking the ratio (4) accomplishes the goal. For asymmetric collisions, as p–A, the appropriate measure proposed by CMS is $\sqrt{r_n(\eta_a,\eta_b)r_n(-\eta_a,-\eta_b)}$.

According to the above discussion, the factorization ratio can be written as

$$r_n(\eta_a,\eta_b)=\frac{\langle\cos[n(\psi_n(-\eta_a)-\psi_n(\eta_b))]\rangle}{\langle\cos[n(\psi_n(\eta_a)-\psi_n(\eta_b))]\rangle}\ , \tag{6}$$

where the average is taken over events. Expanding $\psi_n(\pm\eta_a)\simeq\psi_n(0)\pm\frac{d\psi_n(\eta)}{d\eta}\eta_a$ yields

$$r_n(\eta_a,\eta_b)\simeq \frac{\langle\cos[n(\psi_n(0)-\psi_n(\eta_b))]-n\sin[n(\psi_n(0)-\psi_n(\eta_b))]\frac{d\psi_n(0)}{d\eta}\eta_a\rangle}{\langle\cos[n(\psi_n(0)-\psi_n(\eta_b))]+n\sin[n(\psi_n(0)-\psi_n(\eta_b))]\frac{d\psi_n(0)}{d\eta}\eta_a\rangle}. \tag{7}$$

For small values of the decorrelation angle, further expansion leads to

$$r_n(\eta_a,\eta_b)\simeq 1-2n^2\langle(\psi_n(0)-\psi_n(\eta_b)))\frac{d\psi_n(0)}{d\eta}\rangle\eta_a\ . \tag{8}$$

The deviation of the factorization ratio from 1 is found to be approximately linear in η_a, as observed by the CMS Collaboration [8]. The deviation of the factorization ratio from 1 in the initial state is given by the correlation of the twist angle and its derivative

$$\begin{aligned}1-r_n&\simeq 2n^2\langle(\psi_n(0)-\psi_n(\eta_b)))\frac{d\psi_n(0)}{d\eta}\rangle\eta_a\\&\propto\langle(\psi_n(0)-\psi_n(\eta_b))^2\rangle\eta_a\ .\end{aligned} \tag{9}$$

The last proportionality holds approximately because of the strong correlation between $\psi_n(0)-\psi_n(\eta_b)$ and $\frac{d\psi_n(0)}{d\eta}$. The slope f_n of the linear dependence of

$$r_n(\eta_a,\eta_b)=1-2f_n\eta_a \tag{10}$$

can be related to the variance of the event-plane angle difference between the central and the forward bin. Due to event-by-event fluctuations, $\langle(\psi_n(0)-\psi_n(\eta_b)))^2\rangle$ is found to be nonzero in several model calculations of the initial state [3,9,10].

The F_n^η parameter used by the CMS Collaboration,

$$r_n(\eta_a,\eta_b)=e^{-2F_n^\eta\eta_a}, \tag{11}$$

is approximately equal to the slope f_n of the linear dependence (10) for small factorization breaking. Parametrically $F_n^\eta\propto n^2$, which