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# Transverse spherocity dependence of global observables in heavy-ion collisions at the LHC using AMPT model

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Transverse spherocity is a tool that separates events based on geometrical shapes, i.e., jetty and isotropic events. Transverse spherocity based studies are widely understood in small systems like proton-proton (pp) collisions, but it is yet to be explored in heavy-ion collisions. In this work, we attempt to study different global observables in heavy-ion collisions, such as squared speed of sound, Bjorken energy density and kinetic freeze-out properties for different centrality classes as a function of transverse spherocity. This study has been carried out using a multi-phase transport model (AMPT) in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. Contrary to pp collisions, where jetty events are dominated, heavy-ion collisions are found to be dominated by isotropic events. Squared speed of sound and Bjorken energy density is found to be insensitive to transverse spherocity. In contrast, kinetic freeze-out properties such as transverse radial flow velocity and kinetic-freezeout temperature are found to be susceptive to transverse spherocity.

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## 1. Introduction

Transverse spherocity is an event-shape observable which is quite capable of distinguishing between pQCD-dominated jetty events from non-pQCD-dominated isotropic events. Transverse spherocity is extensively studied, and quite successful in pp collisions [1–9], which are appraised to have a higher contribution from the hard QCD processes than heavy-ion collisions. In this study, we aim to perform a feasibility test of transverse spherocity on some global observables in heavy-ion collisions, where quark-gluon plasma (QGP) is already established and are dominated with soft QCD processes. The transverse spherocity ($S_0$) is defined for a unit vector $\hat{n}(n_T, 0)$ as:

$$S_0 = \frac{\pi^2}{4}\min\left(\frac{\sum_i |\vec{p_{T_i}} \times \hat{n}|}{\sum_i |\vec{p_{T_i}}|}\right)^2 \tag{1}$$

Here $\hat{n}$ is chosen to minimise the bracketed term in Eq. 1. $p_{T_i}$ is the transverse momentum of $i$th hadron, where the summation over $i$ runs for all the hadrons in the pseudo-rapidity region, $|\eta| < 0.8$. Multiplication of $\pi^2/4$ ensures $S_0$ lies between 0 and 1. The calculation of $S_0$ is done for particles' $p_\mathrm{T} > 0.15$ GeV/c, and with events having at least five charged particles. We have used a multi-phase transport (AMPT) (version 2.26t7, released: 28/10/2016) model [10] to simulate the dataset for Pb–Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV, with string melting enabled. We have used AMPT settings as mentioned in Ref. [11].

## 2. Results and Discussions

The heavy-ion collisions at relativistic speeds aim to reproduce the scenario of thermally equilibrated deconfined partons that occurred shortly after the Big Bang, known as quark-gluon plasma (QGP). QGP is dominated with soft QCD processes and is accredited to have a very high energy density ( $> 1$ GeV/fm$^3$), whose estimation in ultra-relativistic heavy ion collisions can be articulated by Bjorken energy density ($\epsilon_\mathrm{Bj}$). This makes it interesting to see, for a given centrality class, how the choice of soft or hard QCD-dominated processes affects the initial (Bjorken) energy density, defined as [12]:

$$\epsilon_{Bj} = \frac{1}{\tau S_T}\frac{dE_T}{dy}. \tag{2}$$

where $\tau$ is the formation time, usually taken to be one fm/c, $S_\mathrm{T}$ is the transverse overlap area approximated as $S_\mathrm{T} = \pi R^2$. $R$ is the radius of the overlap region and is given by $R = R_0 A^{1/3}$, where $A$ can be replaced by $N_\mathrm{part}/2$. $E_\mathrm{T}$ is the transverse energy, and $y$ is the rapidity. One can approximate the transverse energy at midrapidity as follows [13–15]:

$$\frac{dE_\mathrm{T}}{dy} \approx \frac{3}{2} \times \left(\langle m_\mathrm{T}\rangle \frac{dN}{dy}\right)_{\pi^\pm} + 2 \times \left(\langle m_\mathrm{T}\rangle \frac{dN}{dy}\right)_{K^\pm, p, \bar{p}}. \tag{3}$$

where, $\langle m_\mathrm{T}\rangle$ is the mean transverse mass, and $dN/dy$ is the multiplicity density evaluated at $p_\mathrm{T} > 0.15$ GeV/c and $|y| < 0.5$.

In experiments [16], pseudorapidity distribution is approximated by a double Gaussian function of the form:

$$\frac{dN}{d\eta} = A_1 e^{\frac{-\eta^2}{2\sigma_1^2}} - A_2 e^{\frac{-\eta^2}{2\sigma_2^2}}. \tag{4}$$



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Where, $A_1$, $A_2$, $\sigma_1$, and $\sigma_2$ are normalisation constants and widths of Gaussian distribution respectively. In the framework of Landau hydrodynamics [17], the widths of the rapidity distribution are related to the speed of sound ($c_s$) by the following relation:

$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^2}\ln\left(\frac{\sqrt{s_{\rm NN}}}{2m_p}\right). \tag{5}$$

Where $m_p$ is the mass of the proton. We fit Eq. 4 to the pseudorapidity distribution to obtain the Gaussian widths which is used in Eq. 5 to calculate the squared speed of sound. The details of the fitting procedure can be found in Ref. [18].

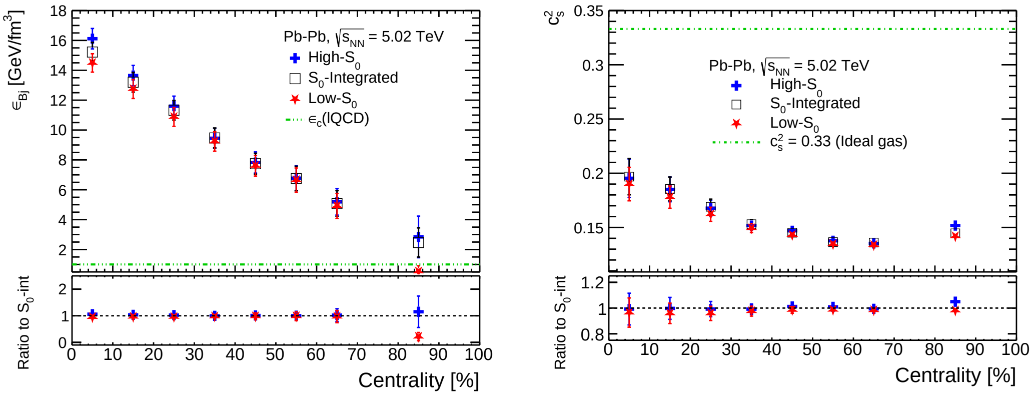


**Figure 1:** (Color online) Bjorken energy density ($\epsilon_{\rm Bj}$) (left), and squared speed of sound ($c_s^2$) (right) as a function of centrality for different spherocity classes in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV using AMPT [18]

Figure 1 represents the $S_0$ dependence on the Bjorken energy density ($\epsilon_{\rm Bj}$) (left) and squared speed of sound ($c_s^2$) (right) plotted against different centralities in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. One can notice a significant dependence of $\epsilon_{\rm Bj}$ and $c_s^2$ on centrality, decreasing towards peripheral collisions. However, for a given centrality, we do not observe any spherocity dependence on both $\epsilon_{\rm Bj}$ and $c_s^2$. As shown in Ref. [18], both $\langle m_T\rangle$, and $dN/dy$ have remarkable spherocity dependence, however $dN/dy$ is positively correlated to spherocity while $\langle m_T\rangle$ is anti-correlated. Since $\epsilon_{\rm Bj}$ has contributions from both $dN/dy$ and $\langle m_T\rangle$, the spherocity dependence seem to have canceled out in $\epsilon_{\rm Bj}$. Bjorken energy density, throughout the centrality, is observed to be larger than the lQCD prediction for a possible medium formation, and $c_s^2$ is within the ideal gas limit.

The deconfined medium of thermally equilibrated partons cools down with the expansion of the system until kinetic freeze-out is achieved. This kinetic freeze-out is characterised by fixed transverse momentum spectra of the final state particles, and this transverse momentum spectra at kinetic freeze-out are well explained by the Boltzmann Gibbs Blastwave function [19], defined as:

$$\left.\frac{d^2N}{dp_T dy}\right|_{y=0} = C\, p_T\, m_T \int_0^{R_0} r\, dr\, K_1\Big(\frac{m_T\, \cosh\rho}{T_{\rm kin}}\Big)\, I_0\Big(\frac{p_T\, \sinh\rho}{T_{\rm kin}}\Big). \tag{6}$$

Here, $C$ is normalisation constant, $K_1$ and $I_0$ are modified Bessel's functions, and $T_{\rm kin}$ is the kinetic freeze-out temperature. Here $\rho = \tanh^{-1}\beta_{\rm T}$ and $\beta_{\rm T} = \beta_{\rm s}\xi^{\rm n}$. $\beta_{\rm T}$ is called radial flow, $\xi = (r/R_0)$, $\beta_{\rm s}$ is the maximum surface velocity, $r$ is the radial distance and $R_0$ is the maximum radius of the source at freeze-out. The mean transverse velocity is given by, $\langle\beta_{\rm T}\rangle = 2\beta_s/(2+n)$. We have

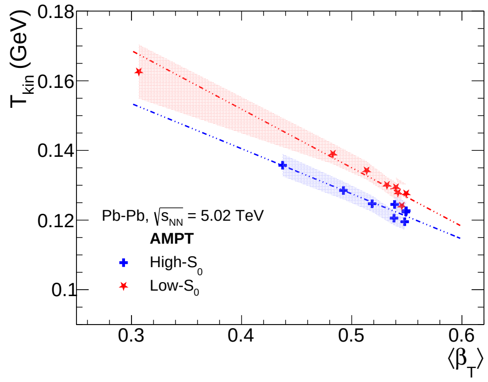


**Figure 2:** (Color Online) Kinetic freeze-out temperature ($T_{kin}$) as a function of mean transverse radial flow velocity ($\langle\beta_T\rangle$) for high-$S_0$ and low-$S_0$ classes in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV using AMPT [18]

performed simultaneous fitting of equation 6 to identified particles' $p_T$ spectra for high-$S_0$ and low-$S_0$ classes in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, to extract $T_{\rm kin}$ and $\langle\beta_{\rm T}\rangle$ as shown in figure 2. $T_{\rm kin}$ is observed to be anti-correlated to $\langle\beta_{\rm T}\rangle$. Central collisions have higher $\langle\beta_{\rm T}\rangle$, and lower $T_{\rm kin}$ value. One observes significant spherocity dependence on both $\langle\beta_{\rm T}\rangle$ and $T_{\rm kin}$. Low-$S_0$ events have higher $T_{\rm kin}$ and lower $\langle\beta_{\rm T}\rangle$ value high-$S_0$ events for a given centrality. This observed low kinetic freeze-out for high-$S_0$ events is because they have a higher contribution from soft particles, thus requiring higher time to reach the freeze-out, which results in lower kinetic freeze-out temperature.

## 3. Summary

This work demonstrates the sensitivity of transverse spherocity on the global observables in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV using AMPT. We found out that $\epsilon_{\rm Bj}$ and $c_s^2$ do not have any noticeable $S_0$ dependence due to some counterbalancing effects from the medium. However, $T_{\rm kin}$ is anti-correlated with $S_0$ while $\langle\beta_{\rm T}\rangle$ is positively correlated. Because high-$S_0$ events have a higher contribution from soft particles, they have higher flow velocity and require more time to reach freeze-out and lower $T_{\rm kin}$. From this study, it is to be concluded that the sensitivity of $S_0$ depends on the observables under study. This sensitivity may differ depending upon the influence of counterbalancing effects from the medium in heavy-ion collisions.

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