Violation of mass ordering for multi-strange hadrons at RHIC and LHC

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Abstract

We study effects of the hadronic rescattering on final observables especially for multi-strange hadrons such as \(\phi\), \(\Xi\) and \(\Omega\) in high-energy heavy-ion collisions within an integrated dynamical approach. In this approach, \((3+1)\)-dimensional ideal hydrodynamics is combined with a microscopic transport model, JAM. We simulate the collisions with or without hadronic rescatterings and compare observables between these two options so that we quantify the effects of the hadronic rescattering. We find that the mean transverse momentum and the elliptic flow parameter of multi-strange hadrons are less affected by hadronic rescattering and, as a result, the mass ordering of the \(p_T\)-differential elliptic flow parameter \(v_2(p_T)\) is violated: At the RHIC and the LHC energies the \(v_2(p_T)\) for \(\phi\)-mesons is larger than that for protons in the low-\(p_T\) regions.

Keywords: high-energy heavy-ion collisions, multi-strange hadrons, elliptic flow

1. Introduction

The main purpose in the physics of high-energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) is to extract properties of the quark gluon plasma (QGP), the deconfined nuclear matter consisting of strongly interacting quarks and gluons. In particular, transport properties of nearly perfect QGP fluids attract a great deal of attention.

The QGP created in the collisions expands, cools down and finally turns into a hadron gas. Hadrons resscatter with each other in this late stage of the collision, thus information about the QGP is usually contaminated by the hadronic rescatterings. This fact makes it difficult to observe the QGP directly. For this reason it is suggested that multi-strange hadrons can be utilised as direct probes of the QGP. Since the multi-strange hadrons have small cross sections with pions, the dominant constituents of a hadron gas, their distributions reflect the state of the system just after hadronization. Unlike conventional penetrating probes such as photons and dileptons which are emitted during the entire evolution of the system, the multi-strange hadrons provide information about this specific stage of the collisions.
Hydro + cascade calculations predicted several years ago that the elliptic flow coefficient $v_2(p_T)$ for protons and $\phi$-mesons violates the mass ordering of this coefficient. This phenomenon reflects the small scattering cross section of $\phi$-meson, and was recently observed by the STAR collaboration \[7\].

In this contribution, we study the violation of mass ordering more systematically and quantitatively by focusing on $p_T$ distributions and elliptic flow of hadrons, in particular for $\Xi$- and $\Omega$-baryons and $\phi$-mesons. An integrated dynamical model, a more sophisticated version of the hydro + cascade approach, is employed here to make the investigation more realistic.

2. Model

We simulate Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV on an event by event basis by employing an integrated dynamical approach \[9\]. This approach consists of three stages. In the initial stage, entropy-density distribution after the collision is calculated by using a Monte Carlo Glauber model. The subsequent QGP fluid expansion is described by fully (3 + 1) dimensional ideal hydrodynamics. After we switch the description from fluids to particles, we utilise a hadron cascade model, JAM \[10\], to describe the evolution of hadron gas. As for an equation of state (EOS), we employ hydrodynamics. Switching from hydrodynamics to JAM is done by using the Cooper-Frye formula on the isothermal low temperature. Note that this particular version of the model EOS is designed to include all the hadrons in few (or not at all) resonances. Thus multi-strange hadrons have smaller cross sections than non-strange hadrons due to a phenomenological strangeness suppression factor. Furthermore, the experimentally known scattering cross sections of multi-strange hadrons are small, since they form very few (or not at all) resonances. Thus multi-strange hadrons have smaller cross sections than non-strange hadrons. Note here that, in order to study the effects of hadronic rescattering on $\phi$-meson efficiently, we switch off the decay channel $\phi \rightarrow K^+K^-$. This does not affect the kinetic evolution of the system because the lifetime of $\phi$-mesons ($\sim 47$ fm/$c$) \[12\] is larger than typical lifetime of the system ($\sim 10$ fm/$c$). For further details, see Ref. \[9\].

3. Results

To investigate the effects of hadronic rescattering on final observables, we simulate the collisions with two options in JAM. One of them is the default setting, in which the rescatterings occur until all hadrons have decoupled, and resonances decay according to their lifetimes and decay channels. By using this option, we are able to reasonably reproduce final experimental observables such as the $p_T$-spectra and differential $v_2$ at both the RHIC \[13\] and the LHC energies. In the other option, the hadronic rescatterings are deactivated but resonances decay. These calculations serve the information just after the fluid-dynamical stage. Comparisons of observables calculated using these two options show how much the hadronic rescattering affects final observables.

The phenomenon of violation of mass ordering in $v_2(p_T)$ can be interpreted as a result of interplay between hadronic rescattering effects on mean transverse momentum, $\langle p_T \rangle$, and those on $p_T$-averaged $v_2$ because the slope of $v_2(p_T)$ is roughly approximated by the relation \[13\], $dv_2(p_T)/dp_T \approx v_2/\langle p_T \rangle$. Therefore we quantify the effects on $\langle p_T \rangle$ and $v_2$ for each hadron by taking ratio of the observables just after the fluid stage to the final observables. As shown in Fig. 8 (a) in Ref. \[13\], the ratio of $\langle p_T \rangle$ for pions, kaons and protons follow the tendency obtained from $m_T$ scaling ansatz, in which it is assumed that all the hadrons flow with common velocity. However multi-strange hadrons obviously deviate from this pattern. From this observation, multi-strange hadrons do not fully participate in the radial flow during the hadronic stage and therefore freeze out earlier than non-strange hadrons. As for $v_2$ shown in Fig. 8 (b) in Ref. \[14\],

$$v_2 \sim \frac{1}{\langle p_T \rangle}.$$
hadronic rescattering in minimum bias Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV. The lower panels of the plots show the ratio of \( v_2^p \) to \( v_2^\phi \).

Pion \( v_2 \) increases by about 20% during the hadronic stage, whereas the \( v_2 \) of all the other hadrons shows much smaller increase of 0-5%. By combining the results of these two observables, we see that both \( \langle p_T \rangle \) and \( v_2 \) for multi-strange hadrons are hardly affected by hadronic rescatterings, but either one of these two observables is affected for all the other particles. This fact is reflected in \( v_2(p_T) \) for each hadron. In Fig. 6 in Ref. [14], we showed \( v_2(p_T) \) with or without hadronic rescatterings to see how rescatterings affect it. \( \phi \)-meson \( v_2(p_T) \) is almost identical in both cases since the hadronic rescatterings do not change its slope. However, the situation is different in the case for non-strange hadrons. Pion \( v_2(p_T) \) goes up because \( p_T \)-averaged \( v_2 \) increases but \( \langle p_T \rangle \) remains almost unchanged in the hadronic stage. On the other hand, for protons, \( p_T \)-averaged \( v_2 \) does not change a lot, but \( \langle p_T \rangle \) increases. Consequently, proton \( v_2(p_T) \) shifts to higher \( p_T \) region and crosses \( \phi \)-meson \( v_2(p_T) \) at \( \sim 1.5 \) GeV violating the conventional mass ordering.

At the LHC energy, this phenomenon appears in the same way. Figure 6(b) shows \( v_2(p_T) \) for pions, protons and \( \phi \)-mesons in minimum bias Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV from the integrated dynamical approach. To see this behaviour clearly, we also plot the ratio \( v_2^p/v_2^\phi \) in lower panels of the figures. In the case without hadronic rescatterings shown in Fig. 6(a), the mass ordering behaviour, \( v_2^\pi(p_T) > v_2^p(p_T) > v_2^\phi(p_T) \) for \( m_\pi < m_p < m_\phi \), appears due to the collective flow in the fluid stage. However, in Fig. 6(b), this pattern is reversed below about 2 GeV between protons and \( \phi \)-mesons: \( v_2^\pi(p_T) < v_2^p(p_T) \) even though \( m_\pi < m_\phi \). These are qualitatively the same results to those at the RHIC energy but quantitatively the crossing point between these two shown in Fig. 6(b) shifts to higher \( p_T \) region compared to that at the RHIC energy as shown in Fig. 6(b) in Ref. [14].

In addition to these results, we also show the normalised freeze-out time distributions for identified hadrons. In Figs. 7(a) and (b), we show the results for mesons and for baryons in separate panels for clarity. Also switching time distributions from fluids to particles are shown with shaded areas. Prominent peaks around 10 fm/c for \( \phi \)-mesons and \( \Omega \)-baryons can be seen and look quite similar to the ones of the switching time distributions. The distribution for \( \Xi \)-baryons has also a peak in the early time but its height is lower than for \( \phi \)-mesons and \( \Omega \)-baryons. This is because the decay contribution from long-lived resonance \( \Xi(1530) \) to \( \Xi \) forms a long tail in the late time. Therefore primordial \( \Xi \)-baryons freeze out as early as \( \phi \)-mesons and \( \Omega \)-baryons. These results prove that the multi-strange hadrons freeze out soon after the fluid stage since they rarely rescatter in the hadronic stage.
Fig. 2. Normalised freeze-out time (τ) distributions for (a) mesons (π, K and φ) and (b) baryons (p, Λ, Ξ and Ω) near midrapidity |y| < 1.0 in minimum bias Pb+Pb collisions at √s_{NN} = 2.76 TeV. The shaded areas represent the distributions of charged hadrons at the time switching from fluids to particles.

4. Summary

We have studied the effects of the hadronic rescattering on observables especially for multi-strange hadrons. We have used an integrated dynamical approach, a model combining the ideal hydrodynamics with a hadronic cascade model, JAM. In order to investigate the hadronic rescattering effects within this approach, we have compared p_T-distributions and elliptic flow with hadronic rescatterings to the ones without rescatterings. By studying the effects on mean transverse momentum and integrated elliptic flow parameters, we have found that these observables for the multi-strange hadrons are less affected by the rescatterings. Furthermore theoretically and experimentally suggested phenomenon indicating the less rescatterings of φ-mesons, violation of mass ordering in v_2(p_T), has been interpreted as a results of the effects on mean p_T and v_2. These results at the RHIC energy had been discussed in Ref. [14]. Now we have shown that this behaviour also appears at the LHC energy. By considering these results, we claim that the multi-strange hadrons can be utilised as “penetrating” probes of the QGP in high-energy heavy-ion collisions.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Numbers 12J08554 (K.M.) and 25400269 (T.H.), and by BMBF under contract no. 06FY9092 (P.H.).

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