

Hadron production by quark combination in central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeVChang-en Shao,¹ Jun Song,² Feng-lan Shao,¹ and Qu-bing Xie²¹*Department of Physics, Qufu Normal University, Shandong 273165, People's Republic of China*²*Department of Physics, Shandong University, Shandong 250100, People's Republic of China*

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The quark combination mechanism of QGP hadronization is applied to nucleus-nucleus collisions at the top energy available at the CERN Super Proton Synchrotron (SPS). The yields, rapidity, and transverse momentum distributions of identified hadrons in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV are systematically studied. The calculated results agree with the experimental data from the NA49 Collaboration. The longitudinal and transverse collective flows and strangeness of the hot and dense quark matter produced in nucleus-nucleus collisions at the top SPS energy are investigated. It is found that the collective flow of strange quarks is stronger than that for light quarks; this result is similar to that obtained at energies currently available at the BNL Relativistic Heavy Ion Collider, and the strangeness is almost the same as those at $\sqrt{s_{NN}} = 62.4, 130,$ and 200 GeV.

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I. INTRODUCTION

Lattice QCD predicts that at extremely high temperature and density, the confined hadronic matter will undergo a phase transition to a new state of matter called the quark-gluon plasma (QGP) [1,2]. The relativistic heavy ion collisions can provide the condition to create this deconfined partonic matter [3]. In general, two approaches are used to study the properties of the deconfined hot and dense quark matter produced in AA collisions. One approach studies the high p_T hadrons from initial hard jets, in which one can invoke the perturbative QCD to a certain degree [4]. The other involves investigating the properties of thermal hadrons frozen out from the hot and dense quark matter. For the latter, the hadronization of the hot and dense quark matter (a typical nonperturbative process) is of great significance. Only through a reliable hadronization mechanism can we reversely obtain various information of QGP properties from the final state hadrons measured experimentally. The abundant experimental data [5,6] and phenomenological studies [7–12] at energies currently available at the BNL Relativistic Heavy Ion Collider (RHIC) suggest that the quark combination mechanism is one of the most hopeful candidates. The two most noticeable results are the successful explanation of the high baryon/meson ratios and the constituent quark number scaling of the hadronic elliptic flow in the intermediate transverse momentum range [8,9], which cannot be understood at all in the partonic fragmentation picture. Recently, the NA49 Collaboration measured the elliptic flow of identified hadrons at the top energy available at the CERN Super Proton Synchrotron (SPS) [13] and found that the quark number scaling of elliptic flow was shown to hold also. That result immediately gave us the idea that the quark combination mechanism may be applicable at the top SPS energy. On the other hand, the NA49 Collaboration also found three interesting phenomena around 30A GeV [14], i.e., the steepening of the energy dependence for pion multiplicity, a maximum in the energy dependence of the strangeness to pion ratio, and a characteristic plateau of the effective temperature for kaon production. These phenomena

are indicative of the onset of deconfinement at low SPS energies. One can estimate via the Bjorken method that the primordial spatial energy density in Pb + Pb collisions at the top SPS energy is about $3.0 \text{ GeV}/\text{fm}^3$ [15], exceeding the critical energy density (about $1 \text{ GeV}/\text{fm}^3$) predicted by lattice QCD. Therefore, the deconfined hot and dense quark matter has probably been created, and we can extend the quark combination mechanism to SPS energies.

As is well known, hadron yield is one of the most basic and important observables helpful in testing our understanding of the hadronization mechanism for the hot and dense quark matter created in the relativistic heavy ion collisions. In most recombination/coalescence models, the hadron wave function is necessary to obtain the hadron yield. As the wave functions for almost all hadrons are unknown at present, it is difficult for these models to study this issue quantitatively [7,8,16]. In addition, these models do not satisfy the unitarity that is important to the issue as well [17]. Different from those models, the quark combination model [18,19] uses the near-correlation in phase space and $SU_f(3)$ symmetry, instead of hadron wave function, to determine the hadron multiplicity. In addition, the model satisfies unitarity as well and has reproduced many experimental data at RHIC [20–23]. Therefore, we apply it in this paper to systematically study the yields, rapidity, and transverse momentum distributions of various hadrons in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. On one hand, one tests the applicability of the quark combination mechanism at this collision energy. We note that the first attempt of the mechanism at SPS energies, for hadron yields alone, was the ALCOR model [24,25]. Now, the rich experimental data of hadron multiplicities and momentum spectra provide an opportunity to make a further systematical and even decisive test of the mechanism at SPS energies. On the other hand, the parton momentum distributions at hadronization, which carry the information on the evolution of the hot and dense quark matter, are extracted from the final hadrons at top SPS energy and compared with those at RHIC energies. We concentrate the comparison on two properties

related to strange hadron production. One is the difference in collective flow between light and strange quarks, which occurs at RHIC energies [23,26]. The other is the strangeness enhancement, a significant property of QGP [27].

The paper is arranged as follows. In the next section, we briefly introduce the quark combination model. In Sec. III, we calculate the yields and rapidity distributions of identified hadrons in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. In Sec. IV, the results of transverse momentum distributions of various hadrons are shown. In Sec. V, we first make a detailed analysis of the longitudinal and transverse collective flow of the hot and dense quark matter at top SPS energy; then we extract and analyze the energy dependence of the strangeness in the hot and dense quark matter. Section VI presents a summary.

II. AN INTRODUCTION OF THE QUARK COMBINATION MODEL

The starting point of the model is a color singlet system that consists of constituent quarks and antiquarks. All kinds of hadronization models demand that they satisfy the rapidity or momentum correlation for quarks in the neighborhood of phase space. The essence of this correlation agrees with the fundamental requirement of QCD [28]. According to QCD, a $q\bar{q}$ may be in a color octet or a singlet. The color factors are $\langle (q\bar{q})_8 | \frac{-\lambda^a \lambda^a}{4} | (q\bar{q})_8 \rangle = \frac{1}{6}$ and $\langle (q\bar{q})_1 | \frac{-\lambda^a \lambda^a}{4} | (q\bar{q})_1 \rangle = -\frac{4}{3}$, which means there is a repulsive or an attractive interaction between them. Here, λ^a are the Gell-Mann matrices. If they are close to each other in phase space, they can interact with sufficient time to be in the color singlet and form a meson. Similarly, a qqq can be in a sextet or an antitriplet, and the color factors are $\langle (qqq)_6 | \frac{\lambda^a \lambda^a}{4} | (qqq)_6 \rangle = \frac{1}{3}$ and $\langle (qqq)_3 | \frac{\lambda^a \lambda^a}{4} | (qqq)_3 \rangle = -\frac{2}{3}$. If its nearest neighbor in phase space is a q , they form a baryon. If the neighbor is a \bar{q} , because the attraction strength of the singlet is two times that of the antitriplet, then $q\bar{q}$ will win the competition to form a meson and leave a q alone to combine with other quarks or antiquarks. Based on the above QCD and near-correlation in phase space requirements, we have proposed a quark combination rule (QCR) [18,28] that combines all these quarks and antiquarks into initial hadrons. When the transverse momentum of quarks are negligible, all q and \bar{q} can always line up stochastically in rapidity. The QCR reads as follows:

- (i) Start from the first parton (q or \bar{q}) in the line.
- (ii) If the baryon number of the second parton in the line is of a different type than the first, i.e., the first two partons are either $q\bar{q}$ or $\bar{q}q$, they combine into a meson and are removed from the line, then go back to point 1. If they are either qq or $\bar{q}\bar{q}$, then go to the next point.
- (iii) Look at the third parton, if it is of a different type than the first, the first and third partons form a meson and are removed from the line; then go back to point 1. Otherwise, the first three partons combine into a baryon or an antibaryon and are removed from the line; then go back to point 1.

The following example shows how the QCR works:

$$\begin{aligned} & q_1 \bar{q}_2 \bar{q}_3 \bar{q}_4 \bar{q}_5 q_6 \bar{q}_7 q_8 q_9 q_{10} \bar{q}_{11} q_{12} q_{13} q_{14} \bar{q}_{15} q_{16} q_{17} \bar{q}_{18} \bar{q}_{19} \bar{q}_{20} \\ & \rightarrow M(q_1 \bar{q}_2) \bar{B}(\bar{q}_3 \bar{q}_4 \bar{q}_5) M(q_6 \bar{q}_7) B(q_8 q_9 q_{10}) M(\bar{q}_{11} q_{12}) \\ & \quad \times M(q_{13} \bar{q}_{15}) B(q_{14} q_{16} q_{17}) \bar{B}(\bar{q}_{18} \bar{q}_{19} \bar{q}_{20}). \end{aligned}$$

If the quarks and antiquarks are stochastically arranged in rapidity, the probability distribution for N pairs of quarks and antiquarks to combine into M mesons, B baryons, and B antibaryons is

$$X_{MB}(N) = \frac{2N(N!)^2(M+2B-1)!}{(2N)!M!(B!)^2} 3^{M-1} \delta_{N,M+3B}. \quad (1)$$

Hadronization is the soft process of the strong interaction and is independent of flavor, so the net flavor number remains constant during the process. In the quark combination scheme, this means that the quark number for each certain flavor prior to hadronization equals that of all initially produced hadrons after it. Obviously the quark number conservation is automatically satisfied in the model. It is different from the nonlinear algebraic method in the ALCOR model [24], which introduces the normalization factor for each quark flavor with the constraint of the quark number conservation.

The average numbers of initially produced mesons $M(N)$ and baryons $B(N)$ are given by

$$\langle M(N) \rangle = \sum_M \sum_B M X_{MB}(N), \quad (2)$$

$$\langle B(N) \rangle = \sum_M \sum_B B X_{MB}(N). \quad (3)$$

Then the multiplicity of various initial hadrons is obtained according to their production weights

$$\langle M_j^{\text{initial}} \rangle = C_{M_j} \langle M(N) \rangle, \quad \langle B_j^{\text{initial}} \rangle = C_{B_j} \langle B(N) \rangle, \quad (4)$$

where C_{M_j} and C_{B_j} are normalized production weights for the meson M_j and baryon B_j , respectively. If only three quark flavors are considered, we can obtain the production weights using the $SU_f(3)$ symmetry with a strangeness suppression factor λ_s [18,19]; they are listed in Table I. The extension of the symmetry to excited states, exotic states, and more quark flavors is also straightforward [19,22,29].

TABLE I. Normalized production weight for baryons and mesons in the $SU_f(3)$ ground state. r_i is the number of strange quarks in the hadron. The ratio of the vector ($J^P = 1^-$) to pseudoscalar ($J^P = 0^-$) meson follows the spin counting, while that of the decuplet ($J^P = \frac{3}{2}^+$) to octet ($J^P = \frac{1}{2}^+$) baryon suffers a spin suppression effect; see Refs. [19,29] for details.

	$C_{M_i} = \frac{2J_i+1}{4(2+\lambda_s)^2} \lambda_s^{r_i}$, except
C_M	$C_\eta = \frac{2J_\eta+1}{4(2+\lambda_s)^2} \frac{1+2\lambda_s^2}{3}$ $C_{\eta'} = \frac{2J_{\eta'}+1}{4(2+\lambda_s)^2} \frac{2+\lambda_s^2}{3}$
	$C_{B_i} = \frac{4}{(2+\lambda_s)^3(2J_i+1)} \lambda_s^{r_i}$, except
C_B	$C_\Lambda = C_{\Sigma^0} = C_{\Sigma^*0} = C_{\Lambda(1520)} = \frac{3}{2(2+\lambda_s)^3} \lambda_s$

Considering the decay contributions from the resonances, we can obtain the yields of final state hadrons

$$\langle h_i^{\text{final}} \rangle = \langle h_i^{\text{initial}} \rangle + \sum_j B_r(j \rightarrow i) \langle h_j \rangle, \quad (5)$$

where $B_r(j \rightarrow i)$ is the weighted decay branching ratio for h_j to h_i [30].

In principle, the hadron production probability should be calculated from the matrix element $\langle q\bar{q}|M\rangle$ for meson or $\langle qqq|B\rangle$ for baryon. However, the wave functions for almost all hadrons which are governed by the nonperturbative QCD are unknown at present. It is difficult to study quantitatively the production of hadrons through their wave functions. In view of this, the hadron production probability in our model is determined by the $SU_f(3)$ symmetry with a strangeness suppression. This symmetry has been supported by many experiments, particularly by the coincidence of the observed λ_s obtained from various mesons and baryons [31]. Therefore, the model can quantitatively describe many global properties for the bulk system by virtue of the Monte Carlo method [19–23,29].

When applying the model to describe the hadronization of the hot and dense quark matter produced in heavy ion collisions, the net-baryon quantum number of the system perplexes the analysis formula of Eq. (1), but it can be easily evaluated in the Monte Carlo program. On the other hand, the transverse momentum of quarks is not negligible thanks to the strong collective flow of quark matter. In principle, we should define the QCR in three-dimensional phase space, but it is quite complicated to do that, because one does not have an order or one has to define an order in a sophisticated way so that all quarks can combine into hadrons in a particular sequence. In practice, the combination is still put into rapidity, and meanwhile the maximum transverse momentum difference Δ_p between (anti)quarks is constrained as they combine into hadrons. The transverse spectra of hadrons have a relationship with the quark spectra as follows (e.g., for meson):

$$\frac{dN_M}{d^2\mathbf{p}_T} \propto \int d^2\mathbf{p}_{1,T} d^2\mathbf{p}_{2,T} f_q(\mathbf{p}_{1,T}) f_{\bar{q}}(\mathbf{p}_{2,T}) \times \delta^2(\mathbf{p}_T - \mathbf{p}_{1,T} - \mathbf{p}_{2,T}) \Theta(\Delta_p - |\mathbf{p}_{1,T}^* - \mathbf{p}_{2,T}^*|), \quad (6)$$

where $f_{q/\bar{q}}(\mathbf{p}_T)$ is the transverse momentum distribution of the quark/antiquark, assumed to be rapidity independent in the present work. The asterisk denotes the quark momentum in the center-of-mass frame of the formed hadron. The limitation Δ_p is treated as a parameter in our study and fixed to be $\Delta_p = 0.3$ GeV for mesons and $\Delta_p = 0.6$ GeV for baryons both at RHIC and SPS energies. Note that the spectrum normalization is determined by the multiplicity in Eq. (4), i.e., the constraint of the parameter Δ_p on the hadron yield is neglected.

One issue that is often questioned is the energy and entropy conservation in the quark combination process. As the nonperturbative QCD is unsolved, there is no rigorous theory that can incorporate the partonic phase as well as the hadronic phase, thus it is difficult to justify or condemn this issue in essence at the moment. As we know, a lot of the experimental phenomena in the intermediate transverse momentum range at RHIC can be explained beautifully only in the quark combination scenario. That suggests that maybe this ‘‘puzzling’’

issue does not exist. As far as the quark combination itself is concerned, there is no difference for the combination occurred in the different (intermediate or low) transverse momentum range. Therefore, whether the properties of low p_T hadrons can be reproduced or not is also a significant test of the quark combination mechanism, as the vast majority of hadrons observed experimentally are just these with low transverse momentum.

III. HADRON YIELDS AND RAPIDITY DISTRIBUTIONS

In high energy nucleus-nucleus collisions, the energy deposited in the collision region excites large numbers of newborn quarks and antiquarks from the vacuum. Subsequently, the hot and dense quark matter mainly composed of these newborn quarks will expand hydrodynamically until hadronization. The net quarks from the colliding nuclei still carry a fraction of beam energy, thus their evolution is different from the newborn quarks. Some of the net quarks are stopped in the hot and dense quark matter and hadronize together with it. The rest of the net quarks penetrate the hot quark matter and run up to the forward rapidity region. The latter, together with a small amount of newborn quarks, form the leading fireball. Their hadronization should be earlier than that of the hot and dense quark matter with a prolonged expansion stage, and the hadronization outcomes consist of nucleons and a small amount of mesons.

The current version of the quark combination model simulates only the hadronization of the hot and dense quark matter and subsequent resonance decays. One indispensable input is the momentum distributions of thermal quarks and antiquarks at hadronization, which are the results of the hydrodynamic evolution in partonic phase. To focus our attention on testing the quark combination mechanism in this and next sections, we reversely extract the quark distributions by fitting the experimental data in the model. A detailed analysis of quark distributions at hadronization will be given in Sec. V. Figure 1 shows the rapidity distributions of newborn light and strange quarks at hadronization, obtained from the π^- and K^+ data [32], and the rapidity distribution of net quarks in the hot and dense quark matter, which is extracted from net-proton data [33].

First, we calculate the yields and rapidity densities at midrapidity of various hadrons in most central Pb + Pb

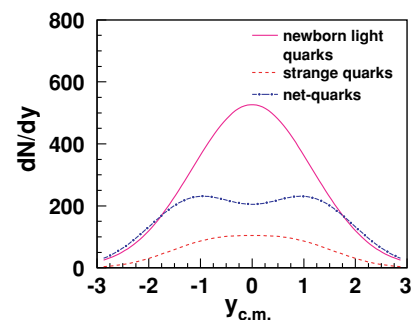


FIG. 1. (Color online) Rapidity spectra of newborn quarks and net-quarks at hadronization in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV.

TABLE II. Yields (left) and rapidity densities at midrapidity (right) of identified hadrons in central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The experimental data are from Refs. [32,34–38].

	Yield		$\frac{dN}{dy} _{y=0}$	
	Data	Model	Data	Model
π^+	$619 \pm 17 \pm 31$	566	$170.1 \pm 0.7 \pm 9$	168.2
π^-	$639 \pm 17 \pm 31$	630	$175.4 \pm 0.7 \pm 9$	183.5
K^+	$103 \pm 5 \pm 5$	92.5	$29.5 \pm 0.3 \pm 1.5$	27.3
K^-	$51.9 \pm 1.6 \pm 3$	45.3	$16.8 \pm 0.2 \pm 0.8$	15.7
K_s^0	75 ± 4	66.7	$26.0 \pm 1.7 \pm 2.6$	20.7
ϕ	$8.46 \pm 0.38 \pm 0.33$	15.2	$2.44 \pm 0.1 \pm 0.08$	5.26
p		120	$29.6 \pm 0.9 \pm 2.96$	25.9
\bar{p}		3.2	$1.66 \pm 0.17 \pm 0.17$	1.53
Λ	$44.9 \pm 0.6 \pm 8$	52.9	$9.5 \pm 0.1 \pm 1.0$	13.3
$\bar{\Lambda}$	$3.07 \pm 0.06 \pm 0.31$	2.88	$1.24 \pm 0.03 \pm 0.13$	1.35
Ξ^-	$4.04 \pm 0.16 \pm 0.57$	4.9	$1.44 \pm 0.1 \pm 0.15$	1.43
Ξ^+	$0.66 \pm 0.04 \pm 0.08$	0.58	$0.31 \pm 0.03 \pm 0.03$	0.26

collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The results are shown in Table II. From the energy dependence of the rapidity density for the net baryon [39], one can see that the nucleus-nucleus collisions at SPS energies exhibit a strong stopping power. Therefore, the leading particles contribute little to yields and rapidity distributions of various hadrons.

The calculated yields and rapidity densities of vector meson ϕ are shown to be about twice as high as the experimental data. The results of the other hadrons basically agree with the experimental data, but slight deviations exist also. The overpredictions of ϕ meson may be associated with the exotic particle $f_0(980)$, which has a possible tetraquark structure containing a strange quark and a strange antiquark [40]. As a bond state containing strange components, it has a slightly lower mass than ϕ meson but is not included in the $SU_f(3)$ ground states. In the present work, we consider only the production of 36-plets of meson and 56-plets of baryon in the $SU_f(3)$ ground states, and the excited states and exotic states are not taken into account. The $f_0(980)$ multiplicity is found to be nearly the same as ϕ meson in the e^+e^- annihilations [30]. The m_T distribution of $f_0(980)$ measured by the STAR Collaboration in Au + Au collisions at $\sqrt{s_{NN}} =$

200 GeV is also shown to be comparable to that of ϕ [41,42]. Therefore, the overprediction of the ϕ meson can be removed by incorporating the $f_0(980)$ production.

Subsequently, we will calculate the longitudinal rapidity distributions of various hadrons. Because of the deviations in hadron yields, it is difficult to directly compare the calculated hadron spectra with the experimental data. To focus our attention on the property of hadron momentum spectra, we will scale the calculated rapidity densities to the center value of the experimental data when we show the hadronic rapidity and p_T spectra in Figs. 2 and 4, respectively, thereby removing these deviations in hadron yields.

The pion is the lightest and most abundant hadron produced in AA collisions, and its momentum distribution can best reflect the global evolution property of the hot and dense quark matter. In various models of high energy heavy ion collisions, the reproduction of the pion meson is always taken as a paramount test of models. In the Landau hydrodynamic model [43], the pion rapidity distribution can be well described, and the sound velocity (which is an important physical quantity standing for the property of the hot and dense quark matter) can be extracted from the pion distribution. For

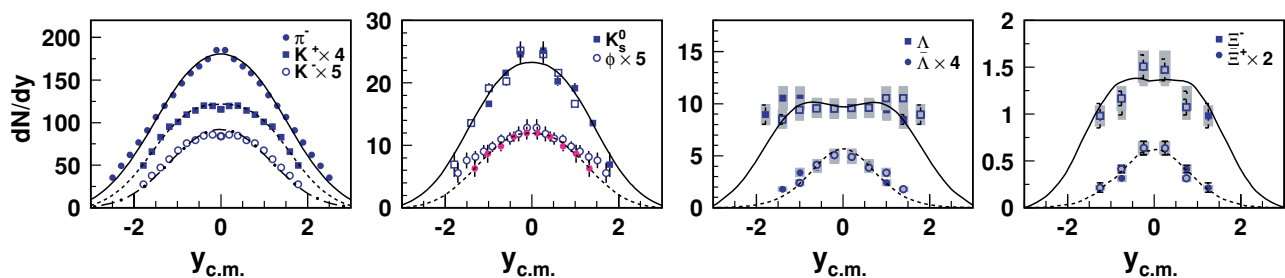


FIG. 2. (Color online) Scaled rapidity distributions of identified hadrons in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The contributions from leading particles are not included. The open circles of ϕ data in the second panel are the latest results measured by the NA49 Collaboration [35], and filled circles are the previous ones [47]. Other experimental data are from Refs. [32,37,38]. The open symbols of K_s^0 , Λ , and Ξ show data points reflected around midrapidity.

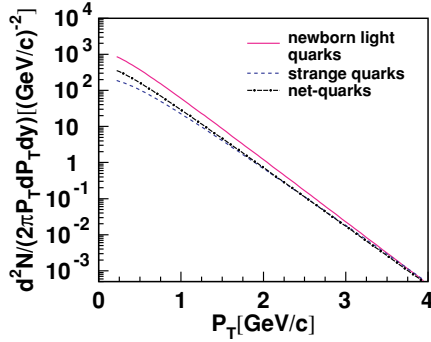


FIG. 3. (Color online) Transverse momentum distributions of constituent quarks in the midrapidity region at hadronization in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV.

other hadrons, such as kaons, protons, Λ , Ξ , and so on, the Landau model cannot describe their rapidity distributions with the same sound velocity or freeze-out temperature [44–46]. For a systematic description of the rapidity distributions of various hadrons, the detailed longitudinal dynamics, e.g., the evolution of net-baryon density which will result in the yield and spectrum asymmetry between hadron and antihadron, should be included. In addition, the hadronization mechanism is especially important in describing the differences in the yield and momentum distribution of various hadron species. Using the extracted quark distributions in Fig. 1, we calculated the rapidity distributions of pions, kaons, $\Lambda(\bar{\Lambda})$, $\Xi^-(\bar{\Xi}^+)$ and ϕ in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The results are shown in Fig. 2 and compared with the experimental data. The calculated rapidity spectrum of the ϕ meson is narrower than the latest data of NA49 Collaboration (open circles in the second panel), but is in good agreement with previous data (filled circles). The rapidity spectra of

other hadrons are well reproduced. One can see that the quark combination mechanism is applicable to describing the longitudinal distributions of various hadrons at top SPS energy.

IV. HADRONS TRANSVERSE MOMENTUM DISTRIBUTIONS

In this section, we calculate the transverse momentum distributions of various hadrons in the midrapidity range. In this paper, we only consider the hadronization of the hot and dense quark matter. The transverse momentum invariant distribution of constituent quarks at hadronization is taken to be an exponential form $\exp(-m_T/T)$, where T is the slope parameter, which is also called the effective production temperature. Figure 3 shows the midrapidity p_T spectra of constituent quarks at hadronization in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The spectra of newborn light and strange quarks are extracted from the data of π^+ and K^+ , respectively [48]. The net-quark distribution is fixed by the data of K^-/K^+ ratio as a function of p_T [48]. A detailed analysis of the quark p_T spectra will be shown in Sec. V.

Figure 4 shows the calculated p_T spectra of pions, kaons, protons, $\Lambda(\bar{\Lambda})$, $\Xi^-(\bar{\Xi}^+)$, and ϕ in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. For kaons, protons, Λ , and Ω , the spectral slopes of antihadrons measured experimentally are all steeper than those of hadrons [48–50]. However, the spectrum of Ξ^- is abnormally steeper than that of $\bar{\Xi}^+$ [37]. Our predictions are in good agreement with all the data except Ξ^- .

The exponential function $\exp(-m_T/T)$ is often used experimentally to fit the transverse momentum distributions of identified hadrons in the low p_T range and to extract the effective production temperature T of various hadrons.

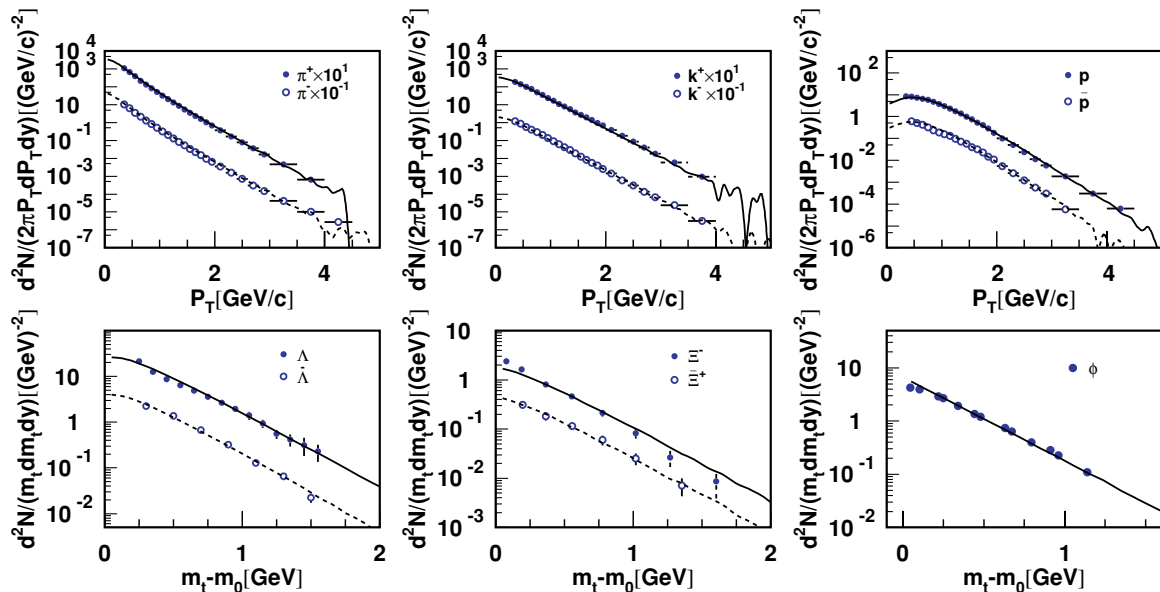


FIG. 4. (Color online) Scaled transverse momentum distributions of identified hadrons at midrapidity in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. Only the combination of thermal quarks is taken into account. Solid lines are the calculated results for hadrons; dashed lines, antihadrons. The experimental data are from Refs. [35,37,48].

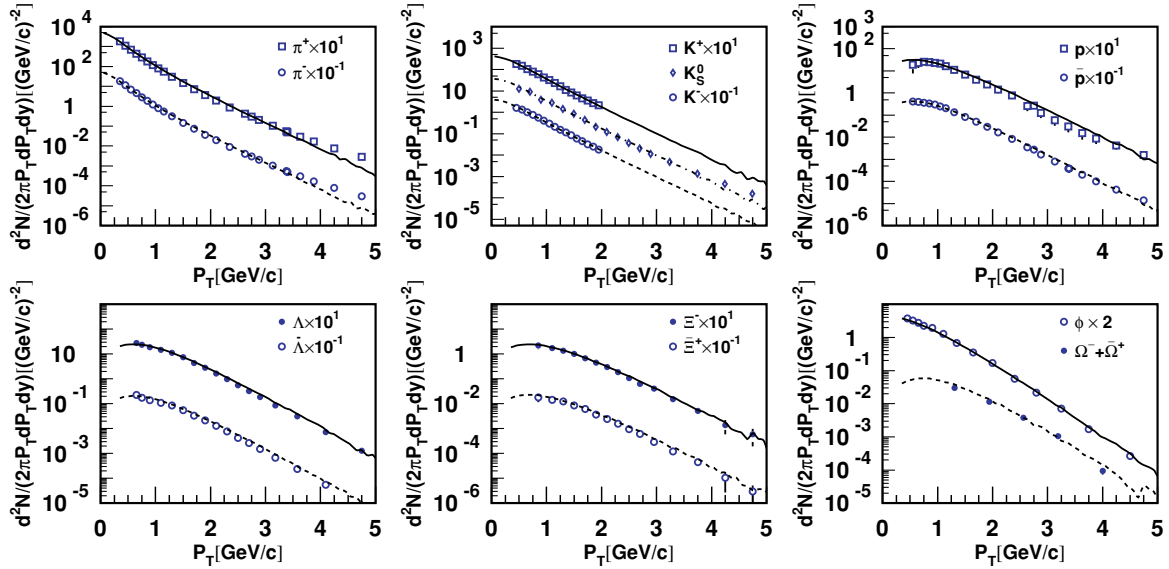


FIG. 5. (Color online) Transverse momentum distributions of identified hadrons at midrapidity in most central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Only the combination of thermal quarks is taken into account. Solid lines are the calculated results for hadrons; dashed lines, antihadrons. The experimental data are from Refs. [5,53,54].

It is found that at the top SPS energy, all final-state hadrons except the pion meson have much higher T than the critical temperature [51], which indicates a strong collective flow at this collision energy. It is regarded in Ref. [52] that this observed flow mainly develops in the late hadronic rescattering stage. But the results in Figs. 2 and Fig. 4 all show that both longitudinal and transverse spectra of various hadrons can be coherently explained by the same quark distributions, respectively. This suggests that the observed flow should mainly come from the expansive evolution stage of the hot and dense quark matter before hadronization, but not from the post-hadronization stage. In addition, the same constituent quark spectra contained in light, single-strange, and multistrange hadrons also imply that the hot quark matter hadronizes into these initial hadrons almost simultaneously, i.e., the hadronization is a rapid process.

In Fig. 5, we calculate the p_T spectra of pions, kaons, protons, Λ ($\bar{\Lambda}$), Ξ ($\bar{\Xi}$), ϕ , and Ω ($\bar{\Omega}$) in most central Au + Au collisions at top RHIC energy. The momentum distributions of constituent quarks at hadronization are taken

to be $\exp(-m_T/0.375)$ for strange quarks and $\exp(-m_T/0.34)$ for light quarks. The numbers and rapidity spectra of the light and strange quarks and antiquarks have been obtained in the study of the longitudinal hadron production [55]. Here, the result of ϕ meson is multiplied by a factor 0.5. One can see that the p_T spectra of various hadrons are well reproduced.

The baryon/meson ratio as a function of p_T is sensitive to the hadronization mechanism. As we know, the observed high baryon/meson ratios in the intermediate p_T range at RHIC energies [5] cannot be understood at all in the scheme of parton fragmentation, but they can be easily explained in the quark combination mechanism. Figure 6 shows the model predictions of \bar{p}/π^- , Λ/K_s^0 and Ω/ϕ at midrapidity in both central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV and central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In the intermediate p_T range where hadron production is dominated by the combination of thermal quarks, the baryon/meson ratios increase with increasing p_T . One can see that the experimental data in this region are well reproduced. The falling tendency of measured baryon/meson ratios after peak position is due

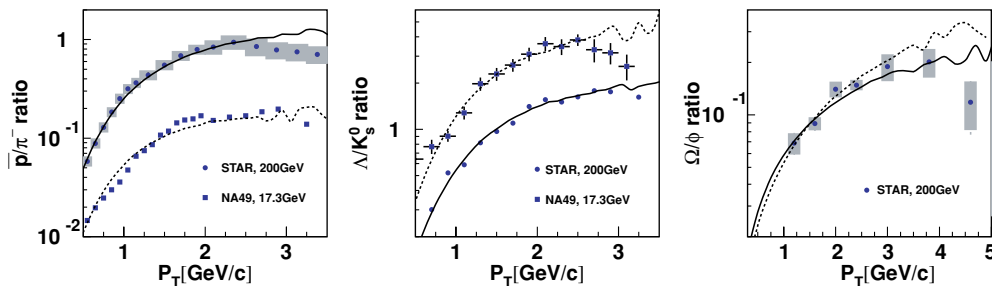


FIG. 6. (Color online) Ratios of \bar{p}/π^- , Λ/K_s^0 , and Ω/ϕ at midrapidity in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV and Au + Au collisions at 200 GeV. Only the combination of thermal quarks is taken into account. Solid lines are the calculated results in Au + Au collisions; dashed lines, Pb + Pb collisions. The experimental data are from Refs. [5,48,54,56,57].

to the abundant participation of jet quarks, which is beyond the concern of the present paper. Besides the hadronization mechanism, the baryon/meson ratio in the intermediate p_T region is also influenced by two other factors. One is the nuclear stopping power in collisions. Compared with the strong collision transparency at the top RHIC energy [39], the strong nuclear stopping at the top SPS energy causes the detention of abundant net quarks in the midrapidity region. These net quarks significantly suppress the production of antibaryons and enhance that of baryons. Therefore, the \bar{p}/π^- ratio at top SPS energy is much lower than that at top RHIC energy, while the Λ/K_s^0 ratio at top SPS energy is higher than that at top RHIC energy. The other influencing factor is the momentum distribution of constituent quarks at hadronization. This can be illustrated by the Ω/ϕ ratio, because the production of these two hadron species is less influenced by the net quarks. The calculated Ω/ϕ ratio shows a weak dependence on the collision energy in the intermediate p_T range. The good description of various baryon/meson ratios in such a wide energy range is an indication of the universality for the quark combination mechanism.

V. ANALYSIS OF PARTON DISTRIBUTIONS AT HADRONIZATION

The constituent quark distributions at hadronization provide information on the evolution of hot and dense quark matter in partonic phase. In this section, we focus our attention on the longitudinal and transverse collective flows and strangeness enhancement of the hot and dense quark matter produced at the top SPS energy.

A. Longitudinal and transverse collective flow

Because of thermal pressure, the hot and dense quark matter created in high energy heavy ion collisions expands during the evolution before hadronization. The longitudinal and transverse collective flow of final hadrons measured experimentally is the exhibition of this early thermal expansion in the partonic phase. Utilizing the relativistic hydrodynamic evolution of the hot and dense quark matter, one can obtain the collective flow in the quark level from the extracted quark momentum distributions and compare it with that at RHIC energies.

There are two well-known hydrodynamic models for the description of the space-time evolution of the hot and dense quark matter produced in heavy ion collisions. One is the Bjorken model [58], which supposes that the collision is transparent, and it is appropriate to extremely high energy collisions, such as those at the CERN Large Hadron Collider (LHC). The other is the Landau model [43] with an assumption of the full stopping for nucleus-nucleus collisions. The longitudinal evolution result is equivalent to the superposition of a set of thermal sources in the rapidity axis, with a (Bjorken) uniform or (Landau) Gaussian weight. In general, when applying the model to describe the hadron rapidity distributions, different parameter values are required to make a good fit of different hadron species [44]. In this paper, we apply the hydrodynamic

description to the evolution in the quark level, thus the collective flow of various hadrons can be coherently explained.

One can see from the energy dependence of the net-baryon rapidity distribution [39] that the collisions at the top SPS energy are neither full transparent nor full stopping. The suppositions of nuclear stopping power in the two models are inappropriate to the nucleus-nucleus collisions at the top SPS energy. For the description of the rapidity distribution for constituent quarks, one can limit the boost invariance into a finite rapidity range in the framework of the Bjorken model. This modification is often used to analyze the longitudinal collectivity in the hadronic level [44,59]. The rapidity distribution in an isotropic, thermalized fluid element moving with a rapidity η is

$$\frac{dN_{\text{th}}}{dy}(y - \eta) = A T_f^3 \exp\left(-\frac{m}{T_f} \cosh(y - \eta)\right) \times \left(\frac{m^2}{T_f^2} + \frac{m}{T_f} \frac{2}{\cosh(y - \eta)} + \frac{2}{\cosh^2(y - \eta)}\right). \quad (7)$$

The rapidity distribution of constituent quarks in the hot and dense quark matter is the longitudinal boost-invariant superposition of multiple isotropic, thermalized fluid elements

$$\frac{dN}{dy} = \int_{-\eta_{\text{max}}}^{\eta_{\text{max}}} \frac{dN_{\text{th}}}{dy}(y - \eta) d\eta, \quad (8)$$

where η_{max} is the maximal boost rapidity of fluid elements. The average longitudinal collective velocity is taken to be $\langle\beta_L\rangle = \tanh(\eta_{\text{max}}/2)$.

Here, T_f is the temperature of the locally thermalized hot and dense quark matter at hadronization, taken to be $T_f = 170$ MeV. Also, m is the constituent mass of quarks when they evolve to the transition point; it is taken to be 340 MeV for light quarks and 500 MeV for strange quarks.

We have mentioned above that the net quarks, still carrying a fraction of initial collision energy, have a more complex evolution than hydrodynamic expansion in the longitudinal axis [60]. Therefore, we extract the longitudinal collective flow from the rapidity distribution of newborn quarks. Since most of the data are measured in the rapidity range of about $[-1.5, 1.5]$, the rapidity spectra of constituent quarks extracted from experimental data are valid only in this region. Using the above equations to fit the rapidity distribution of newborn constituent quarks in Fig. 1, we obtain $\langle\beta_L\rangle = 0.58$ for light quarks and $\langle\beta_L\rangle = 0.65$ for strange quarks. It is interesting to find that the average longitudinal collective velocity of strange quarks is obviously greater than that of light quarks.

For the transverse expansion of the hot and dense quark matter, we adopt a blast-wave model proposed by Heinz [59] within the boost-invariant scenario. The quarks and antiquarks transversely boost with a flow velocity $\beta_r(r)$ as a function of transverse radial position r . $\beta_r(r)$ is parametrized by the surface velocity β_s , that is, $\beta_r(r) = \beta_s \xi^n$, where $\xi = r/R_{\text{max}}$, and R_{max} is the thermal source maximum radius ($0 < \xi < 1$). The transverse momentum distribution of constituent quarks in the hot and dense quark matter can be equivalently described by a superposition of a set of thermalized fluid elements, each

boosted with transverse rapidity $\rho = \tanh^{-1}\beta_r$

$$\frac{dN}{2\pi p_T dp_T} = A \int_0^1 \xi d\xi m_T \times I_0\left(\frac{p_T \sinh \rho}{T_f}\right) \times K_1\left(\frac{m_T \cosh \rho}{T_f}\right). \quad (9)$$

Here, I_0 and K_1 are the modified Bessel functions. $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass of the constituent quark. The average transverse velocity can be written as

$$\langle \beta_r \rangle = \frac{\int \beta_s \xi^n d\xi}{\int \xi d\xi} = \frac{2}{n+2} \beta_s. \quad (10)$$

With fixed parameter $n = 0.3$, the average transverse velocity $\langle \beta_r \rangle$ is able to characterize the transverse collective flow of the hot and dense quark matter. Using the above equations to fit the transverse momentum distributions of the newborn quarks in Fig. 3, we obtain $\langle \beta_r \rangle = 0.41$ for strange quarks and $\langle \beta_r \rangle = 0.36$ for light quarks. One can see that the $\langle \beta_r \rangle$ of strange quarks is obviously greater than that of light quarks.

Both longitudinal and transverse results at the top SPS energy show that the strange constituent quarks get a stronger collective flow than the light quarks in the hydrodynamic evolution of partonic matter. By analyzing the data of multistrange hadrons [26] and primary charged hadrons [23], the same property is found also at the top RHIC energy, which suggests that the hot and dense quark matter produced at the top SPS energy undergoes a similar hydrodynamic evolution to that found at RHIC energies. It is generally believed that a decoupled QGP has been created at RHIC energies [61]. This similarity of collective flow properties in the quark level may be regarded as a signal of QGP creation at the top SPS energy.

B. Enhanced strangeness

An interesting phenomenon in high energy heavy ion collisions is the enhanced production of strange hadrons, which is absent in elementary particle collisions. In relativistic heavy

ion collisions, enormous amounts of energy are deposited in the collision region to create a deconfined hot and dense quark matter. The multiple scatterings between partons in the hot and dense quark matter will cause the large production rate of strangeness by $gg \rightarrow s\bar{s}$ [27]. The high strangeness of the hot and dense quark matter, after hadronization, finally leads to the abundant production of the strange hadrons. This phenomenon is regarded as a signal of QGP creation. As we know, the enhancement of strangeness production at the top RHIC energy is quite obvious [62], and it is generally believed that the QGP has been created at RHIC energies. When the collision energy drops to the SPS and AGS energies, it is found that the strangeness production peaks at about 30A GeV and turns into a plateau at higher collision energies [14]. It is an indication of the onset of deconfinement.

In our model, the strangeness of the hot and dense quark matter is characterized by the suppression factor $\lambda_s = N_{\bar{s}}/N_{\bar{u}} = N_{\bar{s}}/N_{\bar{d}}$, i.e., the ratio of s quark number to newborn u (or d) quark number. By fitting the experimental data of identified hadrons, we use the model to extract the λ_s of hot and dense quark matter at midrapidity in central AA collisions at four energies $\sqrt{s_{NN}} = 17.3, 62.4, 130,$ and 200 GeV, and the results are shown in Table III. The data of midrapidity dN/dy and the calculated results with minimum deviations at different collision energies are shown also. The statistical uncertainty of λ_s is fixed by the twice minimum deviation. The model reproduces the hadron yield in a reasonably good way, and the χ^2 fit seems to indicate that with increasing collision energy, the agreement with data significantly improves.

One can see that λ_s in such a broad energy range is nearly unchanged within statistical uncertainties, exhibiting an obvious saturation phenomenon. The results of λ_s are consistent with the grand canonical limit (≈ 0.45) of strangeness [15]. Using the Bjorken model, one can estimate that the primordial spatial energy density of the hot and dense quark matter produced in collisions at top RHIC energy is about 6.0 GeV/fm^3 [15], which is double that in Pb + Pb collisions at top SPS energy. The difference in primordial energy density

TABLE III. Strange suppression factor λ_s and the calculated hadron dN/dy at midrapidity in central AA collisions at different energies. The experimental data are taken from Refs. [32,36,37,53,63–70].

	Pb + Pb 17.3 GeV		Au + Au 62.4 GeV		Au + Au 130 GeV		Au + Au 200 GeV	
	Data	Model	Data	Model	Data	Model	Data	Model
π^+	$170.1 \pm 0.7 \pm 9$	168.3	$212 \pm 5.8 \pm 14$	211	$276 \pm 3 \pm 35.9$	268.7	286.4 ± 24.2	287.3
π^-	$175.4 \pm 0.7 \pm 9$	183.5	$204 \pm 7.4 \pm 14$	217	$270 \pm 3.5 \pm 35.1$	272.4	281.8 ± 22.8	288.3
K^+	$29.6 \pm 0.3 \pm 1.5$	27.3	33.35 ± 2.15	36.3	$46.7 \pm 1.5 \pm 7$	46.6	48.9 ± 6.3	48.35
K^-	$16.8 \pm 0.2 \pm 0.8$	15.7	28.16 ± 1.76	29.9	$40.5 \pm 2.3 \pm 6$	43.1	45.7 ± 5.2	46.48
p	$29.6 \pm 0.9 \pm 2.9$	25.9	$27 \pm 1.8 \pm 4.6$	26.17	$19.3 \pm 0.6 \pm 3.3$	16.45	18.4 ± 2.6	17.41
\bar{p}	$1.66 \pm 0.17 \pm 0.16$	1.53	$11.5 \pm 1.5 \pm 2.9$	11.15	$13.7 \pm 0.7 \pm 2.3$	11.63	13.5 ± 1.8	13.48
Λ	$9.5 \pm 0.1 \pm 1$	13.3	$14.9 \pm 0.2 \pm 1.49$	13.42	$17.3 \pm 1.8 \pm 2.7$	14.99	$16.7 \pm 0.2 \pm 1.1$	15.76
$\bar{\Lambda}$	$1.24 \pm 0.03 \pm 0.13$	1.35	$8.02 \pm 0.11 \pm 0.8$	6.77	$12.7 \pm 1.8 \pm 2$	11.4	$12.7 \pm 0.2 \pm 0.9$	12.6
Ξ^-	$1.44 \pm 0.1 \pm 0.15$	1.43	$1.64 \pm 0.03 \pm 0.014$	1.63	$2.04 \pm 0.14 \pm 0.2$	1.99	$2.17 \pm 0.06 \pm 0.19$	2.12
Ξ^+	$0.31 \pm 0.03 \pm 0.03$	0.26	$0.989 \pm 0.057 \pm 0.057$	0.96	$1.74 \pm 0.12 \pm 0.17$	1.67	$1.83 \pm 0.05 \pm 0.2$	1.72
$\Omega + \bar{\Omega}$		0.17	$0.356 \pm 0.046 \pm 0.014$	0.369	$0.56 \pm 0.11 \pm 0.05$	0.551	$0.53 \pm 0.04 \pm 0.04$	0.539
χ^2/ndf	10.7/7		6.2/8		1.6/8		0.88/8	
λ_s	0.48 ± 0.09		0.44 ± 0.02		0.44 ± 0.04		0.42 ± 0.025	

is large, while the final strangeness is nearly equal. The hot and dense quark matter created in heavy ion collisions is shown to be very close to a perfect fluid [71]. It means that the local relaxation time toward thermal equilibrium is much shorter than the macroscopic evolution time of the hot and dense quark matter. When the hot and dense quark matter evolves to the point of hadronization, the strangeness abundance should be mainly determined by the current temperature, irrelevant to the initial energy density and temperature. The same strangeness is an indication of the universal hadronization temperature for the hot and dense quark matter with low baryon chemical potential.

VI. SUMMARY

In this paper, we have systematically studied the longitudinal and transverse production of various hadrons at the top SPS energy in the scheme of quark combination. Using the quark combination model, we first calculated the yields and rapidity distributions of various hadrons in most central Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The calculated results agree with the experimental data. This indicates that the quark combination mechanism is applicable to describing longitudinal hadron production at this collision energy. Second, the p_T distributions of various hadrons at top SPS energy were calculated and compared with the data. We found

that the light hadrons and the single-strange and multistrange hadrons are well reproduced by the same quark distributions. This indicates that the hadronization of the hot and dense quark matter is a rapid process. The well-reproduced baryon/meson ratios in the intermediate p_T range at different collision energies are indicative of the universality for the quark combination mechanism. By fitting the extracted constituent quark distributions at hadronization with the hydrodynamic scenario, we further obtained the longitudinal and transverse collective flow of the hot and dense quark matter produced at the top SPS energy. We found that the strange quarks have a stronger collective flow than light quarks, which is consistent with that observed at RHIC energies. The strangeness in the hot and dense quark matter produced at $\sqrt{s_{NN}} = 17.3, 62.4, 130, \text{ and } 200$ GeV was extracted. The almost unchanged strangeness may be associated with a universal hadronization temperature for the hot and dense quark matter with low baryon chemical potential.

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