Quark number scaling of $p_T$ spectra for $\Omega$ and $\phi$ in relativistic heavy-ion collisions

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We show that the experimental data of transverse momentum ($p_T$) spectra of $\Omega$ baryon and $\phi$ meson at mid-rapidity in heavy-ion collisions exhibit the constituent quark number scaling in a wide energy range from RHIC to LHC. Such a scaling behavior is a direct consequence of quark combination mechanism via equal velocity combination and provides a very convenient way to extract the $p_T$ spectrum of strange quarks at hadronization. We present the results of strange quarks obtained from the available data and study the properties in particular the energy dependence of the averaged transverse momentum ($p_T$) and the transverse radial flow velocity ($\langle \beta \rangle$) with a hydrodynamics-motivated blast-wave model.

I. INTRODUCTION

Precision measurements on transverse momentum ($p_T$) spectra of hadrons produced in high energy $pp$, $pA$ and $AA$ collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) in the intermediate $p_T$ region provide us a good opportunity to study the hadronization mechanism and in particular an efficient probe to the created quark matter system — the quark gluon plasma (QGP). We have in particular data for hadrons such as $\Omega^-$ (ssss) hyperon and $\phi$ (ss) \textsuperscript{[1–9]} that consist of only strange quarks and/or anti-quarks and are important probe to strangeness related dynamics of QGP in $AA$ collisions \textsuperscript{[10–13]}. Because they are expected to have relatively small hadronic interaction cross sections \textsuperscript{[11–14]}, they suffer from small distortion in hadronic re-scattering stage and therefore carry important information of QGP at hadronization.

In a recent Letter \textsuperscript{[15]}, we showed that the experimental data of $p_T$ spectra of hadrons at mid-rapidity in high-multiplicity events of $p$-Pb collisions at LHC energies exhibit a perfect constituent quark number scaling (QNS). Such a scaling behavior is a direct consequence of quark combination mechanism via equal velocity combination (EVC) and might be regarded as a clear signature for creation of QGP. Recently, QNS for hadronic $p_T$ spectra has shown also valid in high-multiplicity $pp$ collisions at $\sqrt{s}$ = 7 and 13 TeV \textsuperscript{[17,18]}. It is nature to ask whether it is also valid in $AA$ collisions.

The study in $AA$ collisions is in principle straightforward. However since in the intermediate $p_T$ region, for long lived hadrons such as pions, Kaons and protons, decay contributions are often important and contaminations from these decays and final-state hadronic interactions are difficult to remove. It is therefore very exciting to see that data on $\Omega$ and $\phi$ have been obtained \textsuperscript{[1,2]} at RHIC and LHC in a very wide energy range from $\sqrt{s_{NN}}$ = 11.5 to 2760 GeV.

The $p_T$ spectra of $\Omega$ and $\phi$ provide the best place to test QNS not only because there is little contamination from decay but also due to the fact that in these hadrons only constituent strange quarks and anti-quarks are involved so that QNS, if exists, takes the simplest form. It provides also an ideal place to extract the $p_T$ spectrum for strange quarks.

In this paper, we examine the experimental data of mid-rapidity $p_T$ spectra of $\Omega$ and $\phi$ in heavy-ion collisions \textsuperscript{[1–9]} and show that such a QNS also exists in the broad energy region from RHIC to LHC. We extract the strange quark $p_T$ spectrum just before hadronization in relativistic heavy-ion collisions and study the related properties within a hydrodynamics-motivated blast-wave model. These results are given in Secs. II and III. In Sec. IV, we present a short summary and an outlook.

II. THE QNS FOR HADRONIC $p_T$ SPECTRA

QNS was shown to be valid for hadronic $p_T$ spectra in high-multiplicity events in $pp$ and $p$-Pb collisions at LHC \textsuperscript{[16–18]}. We now examine whether it is also valid in $AA$ collisions by using data on $p_T$ spectra obtained at RHIC and LHC \textsuperscript{[1–9]}.

A. QNS for $\Omega^-$ and $\phi$ in $AA$ collisions

We recall that QNS for hadronic $p_T$ spectra in $pp$ and $p$-Pb collisions at LHC in the intermediate $p_T$ region refers to the number of constituent quarks and is formulated in the following way. For $p_T$ spectra $f_h(p_T) \equiv dN_h/dp_T$ of hadrons consisting of quarks and/or anti-quarks of the same flavor, we have,

$$f_h(p_T) = \kappa_h f_n^{q\bar{q}}(p_T/n_q),$$  \hspace{1cm} (1)

where $h$ denotes hadron, $n_q$ is the number of the constituent quarks and/or anti-quarks, $\kappa_h$ is a constant independent of $p_T$ but can be different for different hadron...
h. For a hadron consisting of different flavors of quarks, e.g., for a baryon $B$ consisting of $q_1q_2q_3$, we have,

$$ f_\Omega(p_T) = \kappa_\Omega f_{q_1}(x_1p_T)f_{q_2}(x_2p_T)f_{q_3}(x_3p_T), \quad (2) $$

where $x_1 + x_2 + x_3 = 1$, $x_1 : x_2 : x_3 = m_{q_1} : m_{q_2} : m_{q_3}$, and $m_{q_i}$ is the constituent quark mass of $q_i$. The function $f_{q_i}(p_T)$ of $p_T$ is universal for different hadrons and can be identified as the $p_T$-distribution of $q_i$ before hadronization.

It is obvious that for $\Omega^-$ and $\phi$, QNS takes the simplest form, i.e.,

$$ f_{\Omega^-}(3p_T) = \kappa_{\Omega^-} f_{s}^3(p_T), \quad (3) $$

$$ f_{\phi}(2p_T) = \kappa_{\phi} f_{s}(p_T) f_{s}(p_T) = \kappa_{\phi} f_{s}^2(p_T), \quad (4) $$

and it leads to the equality,

$$ f_{\phi}^{1/2}(2p_T) = \kappa_{\phi,\Omega^-} f_{s}^{1/3}(3p_T), \quad (5) $$

where the coefficient $\kappa_{\phi,\Omega^-} = \kappa_{\phi}^{1/2}/\kappa_{\Omega^-}^{1/3}$ is a constant that is independent of $p_T$ but can be dependent on collision energies, centralities or other parameters. Here we consider the mid-rapidity region and do not distinguish between the $p_T$ spectrum of strange quarks and that of strange anti-quarks.

Eq. (5) can be used to check whether QNS is valid for the $p_T$ spectra of $\Omega^-$ and $\phi$ in AA collisions. To do this, we take all of the available data on the $p_T$ spectra of $\Omega^-$ and $\phi$ in $\text{Au+Au}$ collisions at RHIC and in $\text{Pb+Pb}$ collisions at LHC [1–9]. We build up $f_{\phi}^{1/2}(2p_T)$ and $f_{\Omega^-}^{1/3}(3p_T)$ and plot them in the same figure. The obtained results are given in Fig. 1. The results for $\Omega^-$ are multiplied by an arbitrary $p_T$-independent constant that corresponds to $\kappa_{\phi,\Omega}$ in Eq. (5). This constant is adjusted in the way that the results for $\kappa_{\phi,\Omega} f_{\Omega^-}^{1/3}(3p_T)$ look to fall in the same lines as those of $f_{\phi}^{1/2}(2p_T)$. To guide the eye, we also present simple fittings with the Tsallis-Levy function [19] to guide the eye.

From Fig. 1, we see clearly that the results obtained from the data of $\Omega^-$ and those of $\phi$ are well coincident with each other at different energies and different centralities. These results clearly show that QNS exists also in heavy-ion collisions in such a wide energy range. Besides the normalization constant, the curve in Fig. 1 just corresponds to $f_s(p_T)$, the $p_T$ spectrum of strange quarks.
The result given by Eq. (9) is valid quite generally in the stochastic quark combination models. The parameters are all well determined by using the corresponding experimental data. The total number of quarks and antiquarks \( N_t \) and the net-quark fraction \( z \) are determined by the charged hadron multiplicity and anti-hadron to hadron yield ratios (see e.g., [20–22]). The parameter \( a \) is determined as \( a = 4.86 \) in the light-flavor sector [23]. The strange suppression factor \( \lambda_s \) is determined by yields of strange hadrons kaons and \( \Lambda \)'s relative to pions [21, 23]. If we take only vector and pseudo-scalar meson productions into account, \( C_\phi \) is determined by vector to pseudo-scalar meson production ratio. It can also be determined by the data of the yield ratio \( \phi/K^- \) [2, 4, 6, 9] using the relation \( \phi/K^- = \lambda_\phi C_\phi / (1 + \lambda_s C_\phi) \) in the quark combination model. As a test, we show in Fig. 2 values of coefficient \( \kappa_{s, \Omega} \) (full symbols) obtained in Fig. 1 and those obtained using Eq. (9) (open symbols). The model uncertainties come from those of the parameters, in particular those of \( C_\phi \) and \( N_t \). We see that the agreement with each other is quite satisfactory. We also see that there is a very good agreement with a logarithmic fit for the coefficient \( \kappa_{s, \Omega} \) as a function of \( dN_{ch}/d\eta \).

III. THE \( p_T \) SPECTRUM OF \( s \)-QUARKS

As described in Sec. II, QNS provides a convenient way of extracting \( p_T \) spectra for quarks before hadronization. Here, from the data on \( \Omega \) and \( \phi \) [16], we obtain the \( p_T \) spectrum of strange quarks. It is then interesting to study the related properties based on the extracted results. In this section, we present the results on the energy dependence of the averaged transverse momentum and the radial flow velocity within the blast-wave model [24].
that in particular those results at the energy dependence of $\langle p_T \rangle$

By fitting the data of $\Omega$ and $\phi$ as given in Fig. 1 in terms of the Tsallis-Levy function [19] of quark $p_T$ distribution, we calculate the averaged transverse momentum $\langle p_T \rangle$ of strange quarks in the soft region $0 < p_T < 2$ GeV/c. The results obtained are shown in Fig. 3 as a function of the charged-particle pseudo-rapidity density per pair of participant nucleons ($dN_{ch}/d\eta$) / (0.5$N_{part}$). The error bars are calculated from the uncertainties of the parameters of Tsallis-Levy function in fitting the data with quadratic sums of statistical and systematic uncertainties. The dashed line represents a logarithmic fit $\langle p_T \rangle = 0.476 + 0.159 \ln[(dN_{ch}/d\eta)/(0.5N_{part})]$ GeV.

From Fig. 3 we see that the transverse momentum $\langle p_T \rangle$ for $s$-quarks before hadronization depends approximately logarithmically on $(dN_{ch}/d\eta)/(0.5N_{part})$. The energy dependence is not significant. We note that in particular those results at $\sqrt{s_{NN}} = 19.6$ and 11.5 GeV are mixed up each other to the similar $(dN_{ch}/d\eta)/(0.5N_{part})$. The averaged transverse momentum of strange quarks under local thermal equilibrium [24] is about 0.45-0.5 GeV/c at the hadronization temperature ($T \sim 160$ MeV). The obtained $\langle p_T \rangle$ of strange quarks in Fig. 3 is significantly larger than this value. This might suggest a large collective transverse radial flow of strange quarks created in prior to parton phase evolution.

B. The radial flow velocity of strange quarks within the blast-wave model

Using the $p_T$-spectrum obtained in Sec. III A, we can further analyze the radial flow of strange quarks within the hydrodynamics motivated blast-wave model [24]. Here, in this model, it is envisaged that particles are locally thermalized and moving with a collective transverse radial flow velocity field. The $p_T$-distribution is obtained from the superposition of boosted thermal sources at a critical temperature $T$, i.e. [24].

$$
\frac{dN}{dp_T} \propto \int_0^1 d\xi \int m_T J_0 \left( \frac{p_T \sinh \rho}{T} \right) K_1 \left( \frac{m_T \cosh \rho}{T} \right),
$$

where $\rho = \tan^{-1} \beta(\xi)$ is the boost angle, $J_0$ and $K_1$ are modified Bessel functions, and $m_T = \sqrt{m^2 + p_T^2}$ is the transverse mass. The flow velocity profile is taken as $\beta(\xi) = \beta_s \xi^n$ where $\xi$ is the relative radial position, the form of the profile is controlled by the exponent $n$, and $\beta_s$ is the surface velocity. To be compatible with hydrodynamics simulations, we set $n \sim 2$. We take the temperature $T$, the averaged flow velocity $\langle \beta \rangle = 2\beta_s/(n+2)$ and the exponent $n$ as fit parameters.

We take the data on $p_T$-spectra of $\Omega$ and $\phi$ in central (0-10%) Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [3, 4] as an example, and show the fit results of blast-wave model in $(\langle \beta \rangle$-$T$) plane in Fig. 4. For comparison, we first make the direct fit at the hadron level for $\Omega$ ($p_T \leq 6$ GeV/c) and $\phi$ ($p_T \leq 4$ GeV/c) respectively, then make the fit for the strange quark distribution $f_s(p_T)$ obtained in Fig. 3. The results obtained are marked as direct-BW or QNS-BW fit in the figure.

![Figure 3. The average transverse momentum ($p_T$) of strange quarks at mid-rapidity in heavy-ion collisions. The dashed line is a logarithmic fit.](image)

![Figure 4. Contour plot of blast-wave model fit of data of the $p_T$ spectra of $\Omega$ and $\phi$ in central (0-10%) Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [3, 4].](image)
report of STAR collaboration [23], while at 39 GeV, it is lower in temperature and lower in \( \langle \beta \rangle \). In other collision energies, the relative position between \( \Omega \) and \( \phi \) is also variant. This means that one could not obtain an universal freeze-out picture for \( \Omega \) and \( \phi \) production from the direct blast-wave model fit in heavy-ion collisions at different collision energies.

From Fig. 3 we also see that the parameter space of strange quarks is a narrow band across relatively large \( \langle \beta \rangle \) or \( T \) range in the plane. This is because, in contrast to \( \Omega \) and \( \phi \), strange quark has a small mass that has small influences on the shape of the distribution given by Eq. (10). The \( \langle \beta \rangle \) and \( T \), in a complementary manner, determine to a larger extend the shape of the distribution. Compared to the direct fits to \( \Omega \) and/or \( \phi \), the parameter space of strange quarks has a shift toward to smaller \( \langle \beta \rangle \) direction. We observe the same behavior by fitting the data [1, 2, 5–7, 9] at other collision energies.

![Figure 5](image)

**Figure 5.** The averaged radial flow velocity \( \langle \beta \rangle \) of strange quarks at hadronization in central heavy-ion collisions extracted from \( p_T \) spectrum data of \( \Omega \) and \( \phi \) at mid-rapidity, compared with those obtained for fitting the \( \pi \), \( K \) and protons data [32, 33].

We can also extract \( \langle \beta \rangle \) of strange quarks at hadronization by taking a physical hadronization temperature. For this purpose, we simply take \( T = T_0(1-c_2\mu_B^2/T_0^2) \), where \( \mu_B \) is baryon number chemical potential and is taken as \( 29, \mu_B = 1.3075/(1 + 0.288\sqrt{\sqrt{S}}) \) GeV; the curvature \( c_2 = 0.0145 \) is taken from Lattice QCD calculations [21]; and \( T_0 \) is the temperature at vanishing \( \mu_B \) and is taken as \( T_0 = 164 \pm 5 \) MeV [2, 24, 28, 52]. Fig. 5 shows the results obtained. For comparison, we show also results for direct fit to the data of \( \pi \), \( K \) and \( p ' s [32, 33] \), which characterize the averaged radial flow at kinetic freeze-out. We see that \( \langle \beta \rangle \) of strange quarks increases monotonically with increasing energy. Compared with those for \( \pi \), \( K \) and protons, the difference seems to be smaller at the LHC energy implying smaller contributions from hadronic stage.

**IV. SUMMARY AND OUTLOOK**

To summarize, we show that the experimental data of \( p_T \) spectra of \( \Omega \) and \( \phi \) in \( AA \) collisions at both RHIC and LHC energies exhibit also the quark number scaling (QNS). This suggests that QNS of \( p_T \)-spectra found in [16, 18] is not only valid in \( pA \) and \( pp \) but also in \( AA \) collisions and hence is a universal property of \( p_T \)-spectra of hadrons in all three different kinds of hadronic reactions. The QNS is a direct consequence of quark combination under the rule of equal velocity combination (EVC). It provides a convenient way of extracting the \( p_T \)-distribution of quarks from the data for those of hadrons. We extracted in this paper the \( p_T \)-spectrum of strange quarks from the data of \( \Omega \) and \( \phi \) and studied its properties such as the average \( p_T \) and the radial flow velocity of strange quarks within the blast-wave model. We show that this may get deep insights into the properties of QGP and/or mechanisms of hadronic interactions in high energy collisions.

As discussions, we would like also to mention that QNS might be used as a test of different mechanisms. As mentioned, quark combinations under EVC provide the most direct and natural explanation. In contrast, we have also checked that, with default parameters, event generators where the fragmentation mechanism is adopted such as PYTHIA [34], Herwig [35], AMPT [36] and HIJING [37] show significant deviations from QNS. Including color reconnection and/or string overlap effects [38, 39] does not significantly improve the case. The QNS might also provide important constraints on details of quark combination mechanism. EVC at the constituent quark level provides the most natural explanations while others such as the Wigner wave function method in coalescence models [40, 42], the parton recombination [43] with recombination functions determined by the valon model [44, 45], and AMPT with string melting that adopts a coalescence mechanism via finite combination radius [46] and so on seem all have difficulties to reproduce such precise QNS for \( p_T \)-spectra of produced hadrons. Further studies along this direction, both experimentally and theoretically, should be worthwhile and encouraging.

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