Signals of quark combination at hadronization in \( pp \) collisions at \( \sqrt{s} = 200 \text{ GeV} \)

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We find signals of quark combination at hadronization from the experimental data of \( p_T \) spectra of hadrons at mid-rapidity in \( pp \) collisions at \( \sqrt{s} = 200 \text{ GeV} \). The first is the constituent quark number scaling property for \( p_T \) spectra of \( \Omega^- \) and \( \phi \) and that for \( p_T \) spectra of \( p \) and \( \rho^0 \). The second is that \( p_T \) spectra of \( \Lambda, \Xi^- \), and \( K^{*0} \) can be self-consistently described using the spectrum of strange quarks from \( \phi \) data and that of up/down quarks from \( p \) data in the equal-velocity combination mechanism. The third is that experimental data for \( p_T \) spectrum of \( D^{*+} \) are also well described using the spectrum of up/down quarks from \( p \) data and that of charm quarks from perturbative QCD calculations. These results indicate a similarity between hadron production in \( pp \) collisions at \( \sqrt{s} = 200 \text{ GeV} \) and that at LHC energies. We predict \( p_T \) spectra of single-charm hadrons and their spectrum ratios. We suggest systematic measurements in \( pp \) collisions at \( \sqrt{s} = 200 \text{ GeV} \) in future so as to better understand the property of small parton system created in \( pp \) collisions at different collision energies.

I. INTRODUCTION

Hadronization refers to the process of the formation of hadrons from final state quarks and gluons created in high energy reactions. Hadronization is a non-perturbative quantum chromodynamics (QCD) process and is described by phenomenological models at present. String fragmentation \(^1\), cluster fragmentation \(^2\) and quark recombination \(^3\) \( \)are three kinds of popular models which are often used to describe the hadron production in high energy reactions.

Experimental data of hadron production in high energy reactions often provide new inspiration on the understanding of hadronization. We recall that heavy-ion collision experiments at Relativistic Heavy Ion Collider (RHIC) in the 2000s found several surprising phenomena such as the enhanced ratio of baryon to meson \(^3\) \( \)– \(^7\) and number-of-constituent quark scaling (NCQ) property for hadronic elliptic flow \(^8\) \( \)– \(^10\) in intermediate \( p_T \) range. These observations prompt the study of quark (re-)combination or parton coalescence mechanism \(^11\) \( \)– \(^16\) for the hadronization of bulk quark matter created in relativistic heavy-ion collisions. On the other hand, the hadronization of parton jet with high \( p_T \) and small parton system is still usually described by fragmentation mechanism.

In the last decade, experiments of \( pp \) and \( pA \) collisions at energies available at Large Hadron Collider (LHC) found a series of new phenomena in hadron production in high multiplicity events such as ridge or long-range correlation \(^17\) \( \)– \(^18\), collectivity \(^19\) \( \)– \(^20\), enhanced ratio of baryon to meson \(^21\) \( \)– \(^24\). These phenomena have been observed in relativistic heavy-ion collisions and are usually regarded to be closely related to the formation of quark-gluon plasma (QGP). Observation of these phenomena in \( pp \) and \( pA \) collisions therefore invoke an interesting question, i.e., the possible creation of mini-QGP. This attracts intensive theoretical studies from different aspects \(^25\) \( \)– \(^30\). Our recent studies \(^31\) \( \)– \(^37\) found that an equal-velocity combination (EVC) mechanism of constituent quarks and antiquarks can systematically describe \( p_T \) spectra of light-flavor and single-charm hadrons. Compared with the traditional viewpoint that fragmentation mechanism is often applied to small parton system and usually successful, our studies indicate the new feature of hadron production in \( pp \) and \( pA \) collisions at LHC energies. This may be related to the possible formation of mini-QGP in \( pp \) and \( pA \) collisions at LHC energies.

The production of identified hadrons in \( pp \) collisions at \( \sqrt{s} = 200 \text{ GeV} \) was systematically measured by STAR collaboration in early years of RHIC experiments \(^38\) \( \)– \(^44\). Experimental data were usually compared with calculations of event generators such as PHThIA with tuned parameters. In view of our findings in \( pp \) collisions at LHC energies \(^31\) \( \)– \(^37\), it is interesting to study the performance of quark combination in \( pp \) collisions at \( \sqrt{s} = 200 \text{ GeV} \) so as to find the similarity or difference in hadron production in \( pp \) collisions at two collision energy scales. The study of \( p_T \) spectra of identified hadrons in this paper gives a surprising indication.

II. QUARK NUMBER SCALING OF HADRONIC \( p_T \) SPECTRA

In our EVC model \(^32\) \( \)– \(^33\), a hadron is formed by the combination of (anti-)quarks with the equal velocity. \( p_T \) distribution of a hadron \( (dN/dp_T) \) is the product of those of (anti-)quarks

\[
\begin{align*}
    f_{B_i}(p_T) &= \kappa_B f_{q_i}(x_{1p_T}) f_{q_i}(x_{2p_T}) f_{q_i}(x_{3p_T}), \\
    f_{M_i}(p_T) &= \kappa_M f_{q_i}(x_{1p_T}) f_{q_i}(x_{2p_T}),
\end{align*}
\]

Here, (anti-)quarks are constituent (anti-)quarks so that their equal velocity combination can correctly construct...
the on-shell hadron. Moment fractions satisfy $x_1 + x_2 + x_3 = 1$ with $x_i = m_i/(m_1 + m_2 + m_3)$ $(i = 1, 2, 3)$ in baryon formation and $x_1 + x_2 = 1$ with $x_i = m_i/(m_1 + m_2)$ $(i = 1, 2)$ in meson formation. $m_i$ is constituent mass of quark $q_i$. Coefficients $\kappa_B$ and $\kappa_M$ are independent of $p_T$ but dependent on numbers of quarks and antiquarks \[33\].

For hyperon $\Omega^-(sss)$ which only consists of strange quarks, its $p_T$ distribution has a simple expression

$$f_\Omega (p_T) = \kappa_\Omega \left[ f_u (p_T/3) \right]^3.$$ \label{3}

$p_T$ distribution of meson $\phi(ss)$ also has a simple expression

$$f_\phi (p_T) = \kappa_\phi f_s (p_T/2) f_s (p_T/2) = \kappa_\phi \left[ f_s (p_T/2) \right]^2,$$ \label{4}

where the approximation $f_s (p_T) = f_s (p_T/2)$ at mid-rapidity is taken. From Eqs. \ref{3} and \ref{4}, we obtain a relationship

$$f_{1/2} (2p_T) = \kappa_{\phi,\Omega} f_{1/3} (3p_T)$$ \label{5}

which is called the constituent quark number scaling of hadronic $p_T$ spectra. Coefficient $\kappa_{\phi,\Omega} = \kappa_{1/2} ^{1/3}$ is independent of $p_T$. For $p_T$ spectra of proton and $\rho$, we obtain a similar relationship

$$f_{p_1/2} (2p_T) = \kappa_{p,p} f_{p_1/3} (3p_T)$$ \label{6}

where approximations $f_u (p_T) = f_u (p_T)$ and $f_u (p_T) = f_u (p_T)$ at mid-rapidity are taken. We run PYTHIA 8 with default parameter values and find that calculation results do not exhibit properties in Eqs. \ref{3} and \ref{4}.

In Fig. 1(a), we test the scaling property Eq. \ref{5} using experimental data of $\Omega^- + \Omega^+ \phi$ and $\phi$ at mid-rapidity in inelastic $pp$ collisions at $\sqrt{s} = 200 \text{ GeV} \ [38, 41]$. $\kappa_{\phi,\Omega}$ is taken as 1.88. $\Omega^- + \Omega^+ \phi$ has only three datum points and we see that they are almost coincident with the scaled data of $\phi$. In Fig. 1(b), we test Eq. \ref{6} using experimental data of proton and $\rho \ [39, 42]$. $\kappa_{p,p}$ is scaled to be 1.10. Except for the first datum point at $p_{T,u} \approx 0.15 \text{ GeV/c}$, we see that other datum points of $\rho^0$ are very close to the scaled data of proton. We emphasize that values of two coefficients $\kappa_{\phi,\Omega}$ and $\kappa_{p,p}$ can be reproduced in our model by considering quark number distributions at hadronization. Therefore, these two scaling tests positively indicate quark combination mechanism at hadronization in $pp$ collisions even at $\sqrt{s} = 200 \text{ GeV}$.

III. $p_T$ SPECTRA OF MIXING-FLAVOR HADROS

Subsequently, we understand the experimental data for $p_T$ spectra of $\Lambda$, $\Xi^-$ and $K^{*0} \ [40, 41]$. These hadrons consist of strange quarks and up/down quarks. By Eqs. \ref{1} and \ref{2}, their $p_T$ spectra at hadronization are given as

$$f_\Lambda (p_T) = \kappa_\Lambda \left[ f_u \left( \frac{1}{2 + r_{su}} p_T \right) \right]^2 f_s \left( \frac{r_{su}}{2 + r_{su}} p_T \right),$$ \label{7}

$$f_\Xi (p_T) = \kappa_\Xi \left[ f_s \left( \frac{r_{su}}{1 + 2r_{su}} p_T \right) \right]^2 f_u \left( \frac{1}{1 + 2r_{su}} p_T \right),$$ \label{8}

$$f_{K^*} (p_T) = \kappa_{K^*} f_u \left( \frac{1}{1 + r_{su}} p_T \right) f_s \left( \frac{r_{su}}{1 + r_{su}} p_T \right)$$ \label{9}

where $r_{su} = m_s/m_u$ is the relative momentum ratio of strange quark to up quark. We take $r_{su} = 1.67$ by considering constituent quark masses $m_s = 0.5 - 0.55 \text{ GeV}$ and $m_u = 0.3 \sim 0.33 \text{ GeV}$ in constituent quark model. To calculate Eqs. \ref{7}-\ref{9}, quark distributions $f_s (p_T)$ and $f_u (p_T)$ at hadronization are needed. We obtain them by using our EVC model to fit experimental data of $\phi$ and proton \[38, 41\]. Here, the decay contributions of decuplet baryons in ground state to octet baryons are included. The detailed derivation of coefficient $\kappa_h$ in the EVC model can be found in Refs. \[33, 34, 35\].

In Fig. 2(a), we firstly show $p_T$ spectrum of $\rho^0$ based on $f_u (p_T)$ fitted from proton data. We see that $\rho^0$ result is in good agreement with experimental data \[39\]. We note that the consistency between $\rho^0$ and proton here is better than the scaling test in Fig. 1(b). This is because final-state protons receive certain decay contamination of decuplet baryons $\Delta$, which will weakly influence $p_T$ spectrum of proton. $\Omega$ and $\phi$ hardly contain decay contributions and therefore their $p_T$ spectra do not have this contamination.

In Fig. 2(b), we show results for $p_T$ spectra of $\Lambda$, $\Xi^-$ and $K^{*0}$. We see a good agreement with experimental data of three hadrons \[40, 41\]. Combining results of Figs. 1 and 2, we see that experimental data of $\phi$, $\Omega^-$, $\rho^0$, proton, $\Lambda$, $\Xi^-$ and $K^{*0}$ can be self-consistently explained by a set of quark spectra at hadronization $f_u (p_T)$ and $f_s (p_T)$ under equal-velocity combination mechanism. This is the explicit signal of quark combination
at hadronization in $pp$ collisions at $\sqrt{s} = 200$ GeV.

Figure 2. $p_T$ spectra of hadrons at mid-rapidity in $pp$ collisions at $\sqrt{s} = 200$ GeV. Lines are model results and symbols are experimental data [41, 42].

IV. $p_T$ SPECTRUM OF SINGLE-CHARM HADRON $D^{++}$

We extend the above study to the combination of charm quark and light-flavor quarks. Because constituent mass of charm quark is larger than those of light-flavor quarks, a charm quark with momentum $p_T$ will hadronize by combining a light-flavor antiquark or two light-flavor quarks with momentum $p_T/\rho_{ct}$ where $\rho_{ct} = m_c/m_l$ ($l = u, s$). We take $r_{cu} = 5$ and $r_{cs} = 3$ by considering the constituent mass of charm quark $m_c = 1.5 \sim 1.7$ GeV. In our EVC model, $p_T$ distribution of $D^{++}$ is

\[
 f_{D^{+}}(p_T) = \kappa_{D^{+}} f_c \left( \frac{r_{cu}}{1 + r_{cu}} \right) f_a \left( \frac{1}{1 + r_{cu}} p_T \right)
\]

where we assume $f_a(p_T) = f_a(p_T)$ at mid-rapidity.

Since $f_a(p_T)$ is already known by fitting data of proton, $p_T$ spectrum of $D^{++}$ can be calculated when $f_c(p_T)$ is also known. Here, we consider the calculation result of perturbative QCD for differential cross-section of charm quark in FONLL scheme [15, 40]. Because FONLL calculation has relatively large uncertainties at low $p_T$, we firstly fit the FONLL calculation in Fig. 3(a) with a Lévy-Tsallis function to get the normalized distribution $f_c^{(n)}(p_T)$ and then take $d\sigma_c/dy = 0.125$ mb at mid-rapidity which is located in the range of theoretical uncertainties.

In Fig. 3(b), we show model result of differential cross-section of $D^{++}$ and compare it with available experimental data [43, 44]. We see a good agreement. This provides a significant indication on the equal velocity combination of charm quark with light-flavor (anti-)quarks as an effective hadronization mechanism in $pp$ collisions at $\sqrt{s} = 200$ GeV.

Figure 3. The charm quark distribution at hadronization (a) and result for differential cross-section of $D^{++}$ (b) in $pp$ collisions at $\sqrt{s} = 200$ GeV. Symbols in panel (b) are experimental data of $D^{++}$ [43, 44].

V. PREDICTION OF SINGLE-CHARM HADRONS

Similarly, we study the combination of charm quark with a strange antiquark to form a $D_s^{+}$. The calculation results for differential cross-section of $D_s^{+}$ and the spectrum ratio $D_s^{+} / (D^0 + D^+) as the function of $p_T$ are shown in Fig. 4. Compared with $D^{0,+}$, production of $D_s^{+}$ is suppressed. As we known, in the light-flavor background the number of strange (anti-)quarks is smaller than that of up/down (anti-)quarks. Therefore, a charm has a relatively small chance to capture a co-moving $\bar{s}$ to form a $D_s^{+}$. We use a suppression factor $\lambda_s = N_s/N_{\bar{u}}$ to denote the relative abundance of strange quarks. In our model yield ratio of $D_s^{+} / (D^0 + D^+)$ has a simple expression

\[
 \frac{d\sigma_{D_s^+/dy}}{d\sigma_{D^0+D^+/dy}} = \frac{1}{2} \lambda_s.
\]

Since $\lambda_s \approx 0.29$ in $pp$ collisions at $\sqrt{s} = 200$ GeV, we see in Fig. 4(b) that the spectrum ratio $D_s^{+} / (D^0 + D^+)$ is located in the range [0.1, 0.2]. The ratio has a weak $p_T$ dependence, which is because relative abundance of strange quarks is $p_T$ dependent and combination kinematics is slightly different for $c\bar{s}$ and $c\bar{u}$ pairs.

Figure 4. Differential cross-section of $D_s^+$ (a) and the spectrum ratio $D_s^+/ (D^0 + D^+)$ (b) in $pp$ collisions at $\sqrt{s} = 200$ GeV.

We further calculate $p_T$ spectra of single-charm
baryons by the equal-velocity combination of a charm and two light-flavor quarks. In Fig. 5 (a), we present results for differential cross-sections of $\Lambda_c^+$, $\Xi_0^c$ and $\Omega_0^c$ as the model parameter $R_{B/M}^{(c)}$ is taken as $0.374 \pm 0.042$. In quark combination mechanism, a meson can form a baryon by picking up an antiquark or form a baryon by picking up two quarks. Since hadronization unitarity requires that a charm quark has to become a hadron at last, there exists a competition between baryon formation and meson formation. In our model, such a non-perturbative competition dynamic is parameterized by $R_{B/M}^{(c)}$ and is tuned by experimental data. We fit the latest experimental data of $\Lambda_c^+/D^0$ in $pp$ collisions at LHC energies \cite{17,18} and obtain $R_{B/M}^{(c)} \approx 0.374 \pm 0.042$. Then, we use it to predict the production of single-charm baryons in $pp$ collisions at $\sqrt{s} = 200$ GeV.

$\frac{d\sigma}{dy} \left( \frac{d\sigma}{dy} \right) = \frac{2}{2 + \lambda_s} R_{B/M}^{(c)}.$ (12)

Strangeness suppression factor $\lambda_s$ changes weakly ($0.25 \sim 0.35$) in $pp$ collisions and causes little contamination on the ratio. Therefore, the ratio $\Lambda_c^+/D^0$ is a sensitive probe of the relative probability of $ct$ combination against $\bar{c}l$ combination (here, $l = u, d$) at charm quark hadronization. Similarly, $\Xi_0^c(c\bar{s})/D_s^0$ denotes the relative probability of $c\bar{s}$ combination against $cs$ combination. Since the suppression influence of strange quark is canceled in the ratio, we have $\Xi_0^c/D_s^0 = \Lambda_c^+/D^0$ for yield ratios. In Fig. 5(c), we also see that the spectrum ratios $\Lambda_c^+/D^0$ and $\Xi_0^c/D_s^0$ have the same magnitude. The small difference in $p_T$ dependence between two ratios is caused by the combination kinematics, i.e., momentum fractions $x_u$ and $x_s$ are different in combination with charm quark.

In Fig. 5(d), we present ratios $\Xi_0^c/\Lambda_c^+$, $\Omega_0^c/\Lambda_c^+$ and $\Omega_0^c/\Xi_0^c$ as the function of $p_T$. In our model, they are related to the combination dynamics of increasing number of strange quarks involving the combination process. Statistical combination symmetry is mainly used in model and gives in yield ratios

\[
\frac{d\sigma_{\Xi_0^c}/dy}{d\sigma_{\Lambda_c^+}/dy} = \frac{d\sigma_{\Omega_0^c}/dy}{d\sigma_{\Xi_0^c}/dy} = \frac{1}{2} \lambda_s, \\
\frac{d\sigma_{\Omega_0^c}/dy}{d\sigma_{\Lambda_c^+}/dy} = \frac{1}{4} \lambda_s^2
\]

where $\lambda_s \approx 0.29$ in $pp$ collisions at $\sqrt{s} = 200$ GeV. We clearly see this flavor hierarchy property in spectrum ratios in Fig. 5(d). In addition, we see a $p_T$ dependence for three ratios, which is because the difference between $p_T$ spectrum of up/down quarks and that of strange quarks at hadronization.

**VI. SUMMARY AND DISCUSSIONS**

In summary, we have applied an equal-velocity quark combination model to understand the early RHIC data for $p_T$ spectra of hadrons in $pp$ collisions at $\sqrt{s} = 200$ GeV. We found explicit signals of quark combination at hadronization. First, we observed a constituent quark number scaling property for $p_T$ spectra of $\Omega$ and $\phi$ and that of proton and $\rho$. Second, based on the $p_T$ spectrum of up/down quarks extracted from proton data and that of strange quarks extracted from $\phi$ data, we found that data for $p_T$ spectra of $\Lambda$, $\Xi^{-}$ and $K^{*0}$ are also well described. Third, based on the obtained spectrum of up/down quarks and that of charm quarks from perturbative QCD calculations, we found that experimental data for differential cross-section of $D^{*+}$ are also well described.
Because these properties of hadron production are already found in pp collisions at LHC energies \cite{32-34, 36, 37}, the current study indicates a significant similarity between the hadron production in pp collisions at \( \sqrt{s} = 200 \) GeV and that at LHC energies. As we known, at LHC energies, some experimental phenomena such as ridge/long-range correlation \cite{13, 18}, collectivity \cite{12, 20}, enhanced baryon-to-meson ratio \cite{21, 24} were observed as the indication of possible formation of mini-QGP in pp collisions in high-multiplicity events. On the other hand, compared with fragmentation mechanism, quark combination mechanism is conceptually more suitable to describe the hadronization of QGP and actually works well in relativistic heavy-ion collisions. Interestingly, our recent works \cite{32, 37} suggest that an equal-velocity quark combination mechanism at hadronization can systematically describe the momentum spectra of hadrons in pp collisions. Therefore, signals of quark combination found in pp collisions at \( \sqrt{s} = 200 \) GeV in current study, which indicate the stochastic combination of quarks and antiquarks at hadronization, inspire us to consider the possibility of mini-QGP creation in pp collisions at RHIC energies!

We therefore suggest the systematic measurements in pp collisions at \( \sqrt{s} = 200 \) GeV in future. These measurements should include ridge/long-range correlation, collectivity, multiplicity dependence of hadron production and so on. By a systematic comparison with available LHC data, these measurements will greatly improve our understanding for the property of small parton system created in pp collisions at different collision energies.

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