Single string structure and multiple string interaction effect on strange particle production in pp collisions at $\sqrt{s} = 7$ TeV

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We present a systematic study on the strange particle production at the Large Hadron Collider (LHC) in proton-proton (pp) collisions at $\sqrt{s} = 7$ TeV based on PACIAE simulations. Two different mechanisms accounting for single string structure variations and multiple string interactions are implemented in the simulations. These modifications give rise to increased effective string tension in the Lund fragmentation model and generate more strange particles in the hadronic final state. By comparing the results with a wealth of the LHC data, it is turned out that the inclusion of variable effective string tension is capable to reach an improved agreement between theory and experiment, especially on the recently observed multiplicity dependence of strangeness enhancement in pp collisions. This approach provides us a new method to understand the microscopic picture of the novel high multiplicity pp events collected at the LHC in the string fragmentation framework.

I. INTRODUCTION

The production of strange hadrons plays an important role in the investigations of properties of the strong force and the de-confined quark-gluon matter. For the hadronic scatterings in vacuum, the strangeness content in the created particles is much smaller compared to the non-strange components due to the mass suppression effect in the particle production. If the quark-gluon plasma (QGP) is produced, the chemically equilibrated system generates a high number of strange quark pairs through the thermal gluon fusion process and also favors the formation of multi-strange hadrons [1, 2]. It is thus believed that the enhancement of strange particle production, especially for multi-strange baryons, observed in the heavy-ion collision experiments [3–5] is a characteristic signature for the presence of QGP matter [6].

Recently, striking commonalities between the high multiplicity pp, proton-lead (p-Pb) and heavy-ion collisions at LHC energies. The strangeness production, for example, has been systematically analyzed by the ALICE collaboration with a wide range of experimental data from pp, pPb to lead-lead (Pb-Pb) collisions [7]. A pronounced enhancement of strange particle relative to pion production is reported in Ref. [7]. The strangeness-to-pion ratio increases smoothly with the event multiplicity across all collision systems. The magnitude of enhancement relies on the strangeness content of the hadron. The particle ratios obtained in pp are quite similar to those found in p-Pb at the same event multiplicities. These intriguing results complement other observations showing similar features traditionally associated with the QGP formation and call for further theoretical investigations to understand the microscopic mechanisms that lead to these novel phenomena.

Different models are trying to interpret this universal strangeness-to-pion ratio as a function of the event multiplicities. The statistical-thermal model calculations are found to provide a reasonable quantitative description to the particle ratios observed in data and suggest the suppression of strange hadron production in pp may come from the explicit conservation of strangeness quantum number based on the canonical approach [13]. The EPOS model [14] assumes the QGP matter is partly formed in the pp collisions treating the interactions based on a core-corona approach. The prediction of this model agrees qualitatively with the observed increasing trend of the strangeness production [15]. Another model which qualitatively describes the data is the color ropes mechanism [16, 17] implemented in DIPSY [18] taking into account the color interactions between strings. Other interesting extensions to the Lund string fragmentation model are implemented in PYTHIA8 [19] by considering thermodynamic features of strings in a dense environment [20] and used to explain some of the changing flavor composition on multiplicity. As various models can describe some key features of the data, the fundamental origin of enhanced strangeness production in pp collisions is still largely unknown.
In this work, we introduce an effective string tension stemmed from the single string structure variation and multiple string interaction effect to reduce the strange quark suppression in pp collisions based on the tunneling probability in Lund string fragmentation model. These two mechanisms of obtaining the effective string tensions are implemented in the PACIAE Monte Carlo event generator [21] to study the strange hadron production in \( \sqrt{s} = 7 \) TeV pp collisions at the LHC. Systematic studies are performed to compare the effects of different effective string tensions on the multiplicity dependence of strange flavor composition.

The remainder of the paper is organized as follows: in Sec. II we give a short introduction on the approaches to construct the effective string tension in the string fragmentation model. Detailed implementations of the effective string tension mechanism in the PACIAE model are illustrated in Sec. III. The results and comparisons to data are provided in Sec. IV. In the end, we summarize in Sec. V.

II. EFFECTIVE STRING TENSION

In the Lund string fragmentation model, particles are produced mainly through the iterative breakups of the color singlet string pieces created during the multiple parton-parton interactions in a pp collision [22]. Given an initial string object consisting of \( q_0 \) and \( \bar{q}_0 \) endpoints moving apart from each other, it is assumed that the original string system can break up into two with the production of a new \( q_1 \bar{q}_1 \) pair in the middle of two end quarks. Therefore, one can find a new hadron formed from the \( q_0 \bar{q}_1 \) object, leaving \( q_1 \) behind which may at a later stage pair with other iterative creations or with \( q_0 \) directly. The hadronization is then determined by the parton flavor and kinematic configurations of its quark components. If a diquark-antidiquark pair is generated at the breakup point instead of the \( q\bar{q} \) pair, a baryon can be created in the same formalism. As required by the local flavor conservation, the new \( q\bar{q} \) pair is always produced at a common vertex. Similar to the Schwinger particle production model in electric field [23], virtual particles only hadronize when the \( q\bar{q} \) pair tunnels out a distance \( d = m_{\perp}/\alpha \). The tunneling probability can thus be obtained as

\[
P(m_{\perp}) \propto \exp\left( -\frac{\pi}{\alpha} m_{\perp}^2 \right)
= \exp\left( -\frac{\pi}{\alpha} m_q^2 \right) \exp\left( -\frac{\pi}{\alpha} p_{\perp q}^2 \right),
\]

where \( \alpha \) is the string tension representing the color force acting on the quarks in the linear confinement field.

This formula suggests the relative production of different quark flavor depends on the effective quark mass involved in the tunneling probability. As it is practically hard to give the mass values theoretically, the relative production probabilities are usually treated as empirical model parameters tuned to data. The string tension value is often assumed to be \( \alpha = 1 \) GeV/fm [24, 25] for a pure \( q\bar{q} \) dipole string hadronized without interactions to its close-by neighbors. However, for the strings created in the pp collisions at LHC energies, the structure of a string can be much more complicated than the pure dipole state and the hadronization of each string may not be treated independently when the interaction between neighboring strings becomes non-negligible. To quantitatively account for these impacts, one can apply an effective string tension in the tunneling probability Eq. [1] for the estimation of flavor compositions.

In this work, the effects of gluon wrinkling in the string structure and the multiple string interactions in the densely populated environment are included in the effective string tensions, individually and taken together. The first scheme follows the reduction of strange quark suppression mechanism [26] modeled in PACIAE [27] which enhances the string tension when radiated gluons exist on a string piece. The parameterized effective string tension responsible for the single string structure change can be given as:

\[
\kappa^\text{eff}_{\perp} = \kappa_0 (1 - \xi)^{-\alpha},
\]

where \( \kappa_0 \) is the pure \( q\bar{q} \) string tension usually set to 1 GeV/fm, \( \alpha \) is a parameter to be tuned with experimental data while \( \xi \) can be calculated by

\[
\xi = \frac{\ln\left( \frac{k^2_{\perp}}{k_{\perp 0}} \right)}{\ln\left( \frac{r}{r_0} \right) + \sum_j \ln\left( \frac{k^2_j}{k^2_{j,0}} \right)},
\]

with \( k_{\perp} \) being the transverse momentum of the gluons inside a dipole string. \( \sqrt{s} \) and \( \sqrt{s_0} \) give the mass of the string system and a parameter related to the typical hadron mass, respectively. This \( \xi \) quantifies the difference of a gluon wrinkled string to a pure \( q\bar{q} \) string. The value of this string tension changes on a string-by-string basis in the current implementation and takes the stringwise fluctuations into consideration.

On the other hand, we consider the multiple string interaction effects from the correlation of strings overlapped in a limited transverse space by parameterizing the effective string tension in a similar spirit of the close-packing strings discussed in Ref. [28] as follows:

\[
\kappa^\text{eff}_{\perp} = \kappa_0 \left( 1 + \frac{n_{MPL} - 1}{1 + p_{T,\text{ref}}/p_{0}} \right)^r,
\]

in which \( n_{MPL} \) indicates the number of multiple parton interactions in a pp collision event and \( p_{T,\text{ref}}/p_0 \) shows the transverse scale of a typical string object relative to the proton size. The exponent \( r \) is then treated as a free parameter. Again, \( \kappa_0 \) provides the string tension without any modifications and takes the same value as used in Eq. [2]. This multiple string interaction triggered effective tension applies globally to all the string objects in the same event and thus serves as an event-wise effective string tension moderator. It is expected that the effect
of inter-string interactions can be modeled in this functional form without considering the details of individual string dynamics.

Additionally, the string-wise single string structure change and event-wise multiple string interaction effect can be combined together by replacing the \( \kappa_0 \) in Eq. \( \text{[1]} \) with \( \kappa_{eff} \). Assuming \( \kappa_0 = 1 \text{ GeV/fm} \), one can derive a combined effective string tension as a product of the two:

\[
\kappa_{s+m}^{eff} = \kappa_{eff}^{s+m}(1 + \frac{\eta_{s+m}^{pref-1}}{1 + \eta_{s+m}^{pref-2}})^r
= \kappa_{eff}^s \times \kappa_{eff}^m. \quad (5)
\]

By introducing the effective string tension, the quark relative production ratio parameters can be modified by a scaling relation as implied in the tunneling probability accordingly.

III. THE SIMULATION FRAMEWORK

The variational string tension study is performed with the PACIAE simulations in this work. The PACIAE model is a multi-purpose Monte Carlo event generator developed to describe a wide range of collisions including hadron-hadron interactions, hadron interactions off nuclei and nucleus-nucleus collisions. It is built based on PYTHIA-6.4 [28] and incorporates the parton and hadron rescattering stages to take care of the nuclear medium effects. For pp collisions, the PACIAE model is different from PYTHIA with the capability to carrying out parton cascade before hadronization and hadron rescattering after hadronization. We follow the strategy in Ref. [21] and Ref. [18] which introduce a modification on the relevant string fragmentation parameters to account for the string tension alterations. The following relevant string fragmentation parameters are supposed to evolve as the string tension directly:

- \( \rho \), strange to light quark ratio \( P(s)/P(u) \), PARJ(2) in PYTHIA;
- \( x \), extra suppression on diquarks with strange content, PARJ(3) in PYTHIA;
- \( y \), spin 1 to spin 0 diquark ratio, PARJ(4) in PYTHIA;
- \( \sigma \), Gaussian width of the transverse momentum distribution for primary hadrons in fragmentation, PARJ(21) in PYTHIA.

The overall diquark to quark ratio \( P(qq)/P(q) \), \( \eta \) (PARJ(1) in PYTHIA), relies on the above parameters and changes with the string tension indirectly. We take the pre-tuned parameters based on the inclusive measurements as the reference values at \( \kappa = \kappa_0 \) and modify these parameters according to a simple scaling indicated by Eq. \( \text{[1]} \). This means if \( \kappa = \kappa_{eff} \), then \( \rho_{eff} = \rho_0^{\kappa_{eff}/\kappa_0} \), \( x_{eff} = x_0^{\kappa_{eff}/\kappa_0} \), \( y_{eff} = y_0^{\kappa_{eff}/\kappa_0} \), \( \sigma_{eff} = \sigma_0^{\kappa_{eff}/\kappa_0} \). However, the diquark to quark ratio needs to be revised as \( \eta_{eff} = \eta_0^{\beta_{eff}/\beta_0} \), where \( \beta_{eff} = \frac{1+2x+9y+6xy+3x^2y^2}{2+r} \) depicts the weighting factor from all different kinds of diquark or quark combinations. As diquarks in the model are effectively generated through a stepwise popcorn mechanism [29] from the successive production of several \( qq \) pairs, \( \beta \) is introduced for the probability to have a \( qq \) fluctuation at the first place which is independent of the string tension.

The reference values for the above pre-tuned string fragmentation parameters are taken from Perugia2011 tune [30] (PARJ(1)=0.087, PARJ(2)=0.19, PARJ(3)=0.95, PARJ(4)=0.043, PARJ(21)=0.33), which provides a reasonable description of the inclusive measurements at the LHC energy. To describe the charged particle density, a factor \( K = 0.82 \) needs to be introduced in PACIAE for the hard scattering cross sections. The fraction of diquarks from two step quark anti-quark pair productions \( \beta \) is found to be important for the multiplicity dependence of the baryon to meson ratio. We fix \( \beta = 0.05 \) to give a flat \( \Lambda/\bar{K}/p/\pi \) ratio dependent on event multiplicity. The single string structure effective string tension \( \kappa_{eff}^{s+m} \) related parameters are set as \( \alpha = 3.5 \) and \( s_0 = 0.8 \text{ GeV} \). For the multiple string interactions, we set \( p_T^{ref}/p_T^0 = 1 \) and \( r = 0.2 \).

Figure 1 shows different particle over \( \pi \) ratios varying with the string tension based on the parameter setup discussed above for pp collisions at \( \sqrt{s} = 7 \text{ TeV} \). The result is given by the combined effective string tension \( \kappa_{eff}^{s+m} \) simulation with both string structure change and multiple string interactions shown in Eq. \( \text{[5]} \). We find a rapid increase with \( \kappa_{eff}^{s+m} \) in strange particle relative production especially for the multi-strange particles. Due to the choice of a small \( \beta \) value, \( p/\pi \) ratio barely changes with respect to the string tension.

We also explore the string tension varying with the
To investigate the effects of the different effective string tension scenarios, we focus on the pp collisions with \( \sqrt{s} = 7 \) TeV. The inclusive measurements on the charged particle pseudo-rapidity, transverse momentum and multiplicity distributions are presented in Fig. 2. Model predictions with default string tension \( \kappa_0 \), single string structure change \( \kappa_{eff}^s \) and multiple string interactions \( \kappa_{eff}^m \) are shown in the solid, dashed and dotted lines, respectively. The combination of two varying string tension scenarios \( \kappa_{eff}^{s+m} \) is shown with the dash-dotted line. It is shown in this comparison the charged density decreases as the effective string tension increases. This is not beyond expectations in the model as increasing string tension makes a particle more difficult to tunnel out. This effect can also be identified in the mid-rapidity event multiplicity distribution that high multiplicity events become rare in \( \kappa_{eff}^s \) and \( \kappa_{eff}^{s+m} \) simulations. However, the impact on the charged particle transverse momentum distribution is hardly visible with the inclusion of different string tension parameterizations indicated by Fig. 3(b).

The multiplicity dependent studies are made with the event classifier counting charged particle number accepted in the pseudo-rapidity region \(-3.7 < \eta < -1.7 \) and \( 2.8 < \eta < 5.1 \) (following the ALICE analysis convention) in pp collisions at \( \sqrt{s} = 7 \) TeV for single string structure change \( \kappa_{eff}^s \) (a), multiple string interaction effect \( \kappa_{eff}^m \) (b) and combined string tension \( \kappa_{eff}^{s+m} \) (c), respectively. Solid line shows the average value of the effective string tension dependent on multiplicity in each scenario.

![Figure 2](image_url)

FIG. 2. (Color online) Correlation of the effective string tension and the number of charged tracks accepted within the region \(-3.7 < \eta < -1.7 \) and \( 2.8 < \eta < 5.1 \) (following the ALICE analysis convention) in pp collisions at \( \sqrt{s} = 7 \) TeV for single string structure change \( \kappa_{eff}^s \) (a), multiple string interaction effect \( \kappa_{eff}^m \) (b) and combined string tension \( \kappa_{eff}^{s+m} \) (c), respectively. Solid line shows the average value of the effective string tension dependent on multiplicity in each scenario.

IV. RESULTS

The event-wise track numbers at forward rapidities are used as the event activity estimator. In this comparison, one can observe that there is a correlation between the effective string tension and the event multiplicity. For the single string structure related effective string tension \( \kappa_{eff}^s \), a rapid increase of string tension is expected in the low multiplicity region due to stronger gluon radiations. The maximum gluon radiation energy is constrained by the allowed phase space. For the events with high multiplicities, the effects from the single string structure change may not be important any more. Accordingly, if we switch to the multiple string interaction case, the average string tension \( \kappa_{eff}^m \) of an event is rising as the multiplicity with rather small variations. By combining the effects of the two modifications in the effective string tension \( \kappa_{eff}^{s+m} \), we get an even larger average tension as the coupling of two scenarios will amplify this effect.
To begin with, we perform an examination on the multiplicity dependence of charged pion and proton yields as shown in Fig. 4. The results suggest that the total pion production in each event class only slightly decreases with the increasing string tension. It is then not surprising to see the $\pi$ yield from all four scenarios are in reasonable agreement with the experimental data. On the other hand, the integrated proton yield from model is higher than data even with the constant string tension $\kappa_0$. All effective string tension variation scenarios introduce a negligible increase to the integrated proton yield comparing with the constant string tension result. It is due to our setup of the small $\beta$ parameter which determines how strong the diquark to quark production ratio relies on the string tension.

In Fig. 5 we show a comparison of simulation results on multiplicity dependence of strangeness production with experimental data. As can be seen in Fig. 5(a) $K^0_S$ production is enhanced with the inclusion of a stronger string tension. Comparing the $K^0_S$ production in the events with largest charged particle density between the $\kappa_0$ and $\kappa_{eff}^{++}$ scenario, the yield is increased by a factor of 50%. The impact of the string tension change on strange baryon productions is much more pronounced.
FIG. 4. (Color online) Pion (a) and proton (b) integrated yield varying with event multiplicity in pp collisions at $\sqrt{s} = 7$ TeV for different scenarios showing: constant string tension setup ($\kappa_0$, solid line), single string-wise tension setup ($\kappa_{s, \text{eff}}$, dotted line), multiple string interaction tension setup ($\kappa_{m, \text{eff}}$, dashed line) and combined string tension setup ($\kappa_{s+m, \text{eff}}$, dash-dotted line). The experimental data are taken from [7].

FIG. 5. (Color online) Strange particle integrated yield varying with event multiplicity in pp collisions at $\sqrt{s} = 7$ TeV for $K_S^0$ (a), $\Lambda$ (b), $\Xi$ (c) and $\Omega$ (d). Four different scenarios are shown with constant string tension setup ($\kappa_0$, solid line), single string-wise tension setup ($\kappa_{s, \text{eff}}$, dotted line), multiple string interaction tension setup ($\kappa_{m, \text{eff}}$, dashed line) and combined string tension setup ($\kappa_{s+m, \text{eff}}$, dash-dotted line). The experimental data are taken from [7].

than that on $K_S^0$. In the strange baryon comparisons, the slope change due to string tension variation shows
FIG. 6. (Color online) Baryon over meson ratio varying with multiplicity in pp collisions at $\sqrt{s} = 7$ TeV. Four different scenarios are shown with constant string tension setup ($\kappa_0$, solid line), single string-wise tension setup ($\kappa_{\text{eff}}^s$, dotted line), multiple string interaction tension setup ($\kappa_{\text{eff}}^m$, dashed line) and combined string tension setup ($\kappa_{\text{eff}}^{s+m}$, dash-dotted line). The experimental data are taken from [7].

FIG. 7. (Color online) Strange particle over pion ratio varying with event multiplicity in pp collisions at $\sqrt{s} = 7$ TeV. Four different scenarios are shown with constant string tension setup ($\kappa_0$, solid line), single string-wise tension setup ($\kappa_{\text{eff}}^s$, dotted line), multiple string interaction tension setup ($\kappa_{\text{eff}}^m$, dashed line) and combined string tension setup ($\kappa_{\text{eff}}^{s+m}$, dash-dotted line). The experimental data are taken from [7].

a clear hierarchy depending on the strangeness number. The difference between the slope of minimum string ten-
sion case ($\kappa_0$) and maximum string tension case ($\kappa_{sff}^{+m}$) in $\Lambda$ production is the smallest, while the $\Omega$ slope changes most dramatically from $\kappa_0$ case to $\kappa_{sff}^{+m}$ case. This strangeness dependent slope change is a direct outcome as our implementation involves the variation of the effective string tension which determines the relative production of strange sector in $q\bar{q}$ pair, diquark anti-diquark pair and spin 1 diquark anti-diquark pair at string breakups.

Aside from examining the integrated yield of particles as a function of event multiplicity, it is of more interest to understand the relative production of strange particles. Figure 6 shows the baryon to meson production ratio in strange ($\Lambda/K_S^0$) and non-strange ($p/\pi$) sector. In the constant string tension scenario represented by the solid line, we observe no dependence of baryon to meson ratio on event multiplicity. The inclusion of effective string tension results in a mild increase on both $\Lambda/K_S^0$ and $p/\pi$ ratios. This is consistent with observations in the experimental data. If we set the $\beta$ parameter to higher value, the variational string tension assumptions may lead to a stronger increasing trend with event multiplicity.

The strange particle relative to $\pi$ production is shown in Fig. 7 for $K_S^0$, $\Lambda$, $\Xi$ and $\Omega$. The rising trend on event multiplicity of the strange particle to $\pi$ ratio can be explained by the inclusion of string tension variational scheme in the simulation, while a constant string tension assumption gives a flat ratio over the whole event multiplicity range. It is also observed that the gluon wrinkled string structure modification and the multiple string interaction coordinated method implemented in $\kappa_{sff}$ and $\kappa_{eff}$ predict different event multiplicity dependence of the strange to pion ratio. The relative strange production in $\kappa_{eff}^m$ curve grows monotonously with the event multiplicity, while the $\kappa_{sff}$ curve increases dramatically in low multiplicity events and then saturates if the mid-rapidity charged density becomes larger than 4. This observation is consistent with our knowledge to the multiplicity dependent string tension change in two scenarios as described in Fig. 2. The $\kappa_{sff}$ curve shown with the combined effective string tension change is thus divided into two domains. The rapid increase in low multiplicity region is dominated by the impact of gluon wrinkle effect as in $\kappa_{sff}^m$. The inter-string interaction takes over and leads to a mild increase of the strange to pion ratio in high multiplicity events. Taking account of the strangeness number of the particles analyzed in this comparison, one can also find the relative production of multi-strange particles are more sensitive to the event multiplicity variation than $K_S^0$ and $\Lambda$. Additionally, one may also find the multiple string interaction caused effective string tension modification becomes very small in low multiplicity events. Thus, strange to pion ratios at $<dN_{ch}/d\eta>$ 2 are grouped into two categories, “$\kappa_{eff}^m \approx \kappa_0$” and “$\kappa_{sff}^{+m} \approx \kappa_{sff}^m$”. The single string structure relevant effect comes from the gluon radiations inside a string object, thus the impact is going to be stronger with the growth of collision energy $E_{\text{cm}}$. It is therefore natural to see the modifications introduced by $\kappa_{sff}^m$ or $\kappa_{eff}^{+m}$ to the pure dipole string structure $\kappa_0$ scenario are still visible even in the low multiplicity events at the LHC energy scale. This multiplicity dependent strangeness enhancement feature can be well understood with the tunneling effect mediated by the string tension change in Lund string hadronization framework by taking the single string structure variation and multiple string interaction mechanisms into consideration.

V. DISCUSSIONS AND CONCLUSIONS

The multiplicity dependent strangeness enhancement observed in pp or p-Pb collisions is an intriguing finding which triggers a lot of theoretical interest and continuing experimental investigations for a wider range of energy dependence. We provide a systematic study on the strange particle productions in high energy pp collisions based on several variational string tension in the string fragmentation framework. It turns out that in the $\kappa_{eff}^m$ case, the strange particle yields are generally in agreement with the experimental data. However, the $p/\pi$ ratio is still overestimated with the current parameter setup for all different string tension cases. The multiplicity dependent strangeness enhancement can be naturally included in the string tension change mechanism. The multiple string interaction caused effective string tension change can offer a reasonable starting point for the observed increasing trend of strange flavor composition, suggesting the multi-string interactions are of great interest to explain the multiplicity dependence.

In addition, the effective string tension in Eq. $\kappa_{eff}^m$, can also be extended to other collision types by revising the relevant term to include the nuclear size dependence explicitly. We will leave the comparisons of the extensions to p-Pb and Pb-Pb to the next work. It must be noticed that only flavor composition which can be directly handled by the tunneling mechanism is considered in the current framework. Other collective-like effects such as the near side ridge in two particle correlations or the radial flow observed in the transverse momentum distribution of the high multiplicity pp collisions still require the inclusion of other mechanisms to deal with the kinematic effect of string dynamics in the high density environment.

In the end, this study provides a solid comparison between theoretical and experimental results of the flavor composition relevant collective behavior in pp collisions based on the string fragmentation scheme. It is a starting point for further exclusive studies combining different mechanisms in a more detailed modeling with microscopic tracing of the parton and hadron evolution history.

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