Strangeness enhancement across collision systems without a plasma

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Abstract

We present novel rope hadronization results for strange hadron enhancement in pp, pPb, and PbPb collisions using PYTHIA/Angantyr at LHC energies. With the rope model for string fragmentation, we find that the strangeness and baryon enhancement has a coherent increase across all collision systems as a function of average charged central multiplicity, in qualitative agreement with LHC data. In AA collisions, we find that the baryonic yields overshoot data at high multiplicities, and we discuss how a combination of rope hadronization with other string interactions may tame this rise.
Strangeness enhancement in both small and large systems is usually interpreted as a signal of a dense and hot Quark-Gluon Plasma (QGP) \[1-3\]. However, the Lund strings physically represent colour-electric flux tubes, and in a series of papers \[4-7\] we have demonstrated that interactions between overlapping flux tubes are able to reproduce not only enhanced rates for strangeness and baryons \[4\], but also collective flow \[6\] in pp collisions. The Angantyr model \[8\], which is a generalization of the Lund string model in PYTHIA to nucleus-nucleus (AA) collisions, is able to successfully reproduce many features of hadron production in these collisions. We note that in this picture the initial energy density and temperature do not have to be very high \[6\], and that the string degrees of freedom therefore survive the initial, mainly longitudinal expansion, until hadronization sets in. In a dense environment, the overlap among these transversely extended strings naturally causes interactions between overlapping flux tubes.

The string-string interaction can be a repulsive interaction between a pair of overlapping flux tubes, called string shoving \[5, 6\], giving rise to a transverse collective flow in high-density systems. The interaction can also give the formation of "colour ropes" as discussed in ref. \[9\]. The increased energy density in a rope implies that more energy is released when a new $q\bar{q}$ pair is produced (or a diquark-antidiquark pair in case of baryon production). This corresponds to a higher effective string tension $\kappa (\kappa_{\text{eff}})$ during the hadronization of a rope, which modifies the fragmentation parameters entering the Lund fragmentation function \[4, 10, 11\]. Quark-antiquark production in a colour-electric field can be regarded as a tunnelling process \[12\], which gives a production probability for different quark flavours proportional to $\exp(-\pi \mu^2 / \kappa)$, where $\mu$ is the respective (di-)quark mass. An increased $\kappa$ will here mainly reduce the suppression of strange quarks (and diquarks), while heavier quarks typically are too suppressed to be relevant for the hadronization process, and are only produced in hard scattering processes. Thus the higher $\kappa_{\text{eff}}$ produces higher yields of both strange hadrons and baryons in pp collisions, as described in detail in ref. \[4\]. To use rope hadronization in Angantyr-generated pA and AA collisions, we require a common reference frame for every possible pair of strings. Such a reference frame would be a baseline for computing the interactions between every possible string pair. In this paper, we use a new implementation of the rope model, based on this so-called parallel frame \[7\], and show the resulting strangeness enhancement in pp, pPb, and PbPb systems. We conclude by examining our current approach and outlining possible improvements.

**Strangeness enhancement due to rope hadronization:**—Our original rope hadronization model, and the recent re-implementation of it, are presented in detail in refs. \[4\] and \[7\] respectively. When we now apply the model to collisions involving heavy ions we use the Angantyr \[8\] model. Parton-level nucleon–nucleon collisions generated by PYTHIA are here stacked on top of each other, after having selected nucleon sub-collisions using a Glauber simulation. When hadronizing a given set of such sub-collisions, it is in principle straightforward to apply our rope model, but there are a few caveats, and the main one of these is related to colour reconnections (CR). To understand this issue we need go through some of the basics of the rope model.

Consider two simple strings, each stretched between a quark and an antiquark. If they are completely overlapping and anti-parallel, the colours of the quark and anti-quark in each end can either combine into a colour-octet or a colour-singlet. Lattice calculations show \[13\] that the tension in a rope between any multiplet and the corresponding anti-multiplet...
charge is proportional the second Casimir operator. Denoting a multiplet corresponding to $p$ coherent triplet and $q$ coherent anti-triplet colours by \( \{p,q\} \), this gives
\[
\kappa^{\{p,q\}}/\kappa^{\{1,0\}} = C_2^{\{p,q\}}/C_2^{\{1,0\}} = \frac{1}{4} \left( p^2 + pq + q^2 + 3p + 3q \right),
\] 
where \( \kappa^{\{1,0\}} \equiv \kappa \) is the tension in a single triplet string. Thus for an octet, we would have a string tension of \( 9\kappa/4 \), while for a singlet, we would have no string at all. In pp collisions, all strings originate in a small region in coordinate space, and we have previously argued in ref. [7] that singlet case corresponds to the CR process in PYTHIA [14], where strings close in momentum space are allowed to reconnect, if the combined string length is thereby reduced. For high string densities we assumed that any combination of \( m \) triplets and \( n \) anti-triplets would then always combine into the highest possible multiplet [7].

For nuclear collisions, we must also account for the separation between vertices in coordinate space. In the Angantyr model, although there are CRs between strings formed in the same sub-collision, there are currently no reconnections between strings from different sub-collisions, since the current CR models in PYTHIA do not take into account the space-time separation.

To handle the space-time separation for rope formation, we here use the parallel frame formalism [7] to include separation between vertices in both coordinate and momentum space. It also accounts for strings with “kinks”, coming from strings stretched between a quark-antiquark pair via a number of gluons. It constructs a Lorentz transformation to a frame, where any two (straight) string pieces will always lie in parallel planes, moving away from each other with equal velocities.

To estimate the formation of a rope in the absence of CR, we now adopt a random walk in colour space combining elementary colour charges [9] where we add one overlapping string at the time. Adding a triplet to a \( \{p,q\} \) multiplet can give three possibilities:
\[
\{p,q\} \oplus \{1,0\} = \begin{cases} 
\{p+1,q\} \\
\{p,q-1\} \\
\{p-1,q+1\}
\end{cases}
\] 
and similarly for adding an anti-triplet. For each added overlapping string, we choose randomly among these, according to the number of states in the corresponding multiplet, \( N_{\{p,q\}} = (p+1)(q+1)(p+q+2)/2 \). Since we always assume that we have a string being hadronized (\( \{1,0\} \)) to begin with, we never let \( p \) go to zero, but otherwise the random walk is unconstrained.

To estimate the breakup of a rope we note that the tension in a rope \( \{p,q\} \) is given by the Casimir operator in eq. (1). In our model, the rope would break up one string at the time, and the tunnelling process implies that in each such a breakup, the effective string tension is given by the reduction of the rope tension due to the multiplet field being reduced from, e.g., \( \{p,q\} \mapsto \{p-1,q\} \):
\[
\kappa_{\text{eff}} = \kappa^{\{p,q\}} - \kappa^{\{p-1,q\}} = \frac{2p+q+2}{4} \kappa.
\] 

In our new implementation, for any given breakup in a string being hadronized, we can consider each of the other string pieces in the event, and boost to the common parallel
Figure 1: Production points of primary hadrons in impact parameter space produced in the central pseudo-rapidity bin in sample events from pp at 7 TeV (top row), pPb at 5.02 TeV (middle), and PbPb collisions at 2.76 TeV (bottom) for different intervals of central \(|\eta| < 0.5\) charged multiplicity: \(\sim 25\) (first column), \(\sim 50\) (second), \(\sim 100\) (third) and \(>1000\) (last column). The colour of the points indicates the \(\kappa_{\text{eff}}/\kappa\) used in the string breakup where the primary hadrons were produced. The impact parameter vector is along the \(x\)-axis.

In each of these breakups we can determine an effective string tension, \(\kappa_{\text{eff}}\). This will influence the flavour of the \(q\bar{q}\) pair responsible for the breakup via the tunnelling mechanism, notably increasing strange quark production. Also di-quarks can be produced in the breakups, giving rise to baryon production, and especially strange baryons are enhanced by an increase in \(\kappa_{\text{eff}}\). These effects are technically achieved by changing several parameters in PYTHIA8, as explained in ref. [4].

To illustrate the variations in \(\kappa_{\text{eff}}\), we show in figure 1 sample events from pp, pPb, and PbPb collisions. Each point in each figure represents the production point in impact parameter space of a primary hadron (a hadron produced directly in the hadronization) produced in the central unit of pseudo-rapidity, and the colour indicates the \(\kappa_{\text{eff}}/\kappa\) used.
to produce it. The size of the points correspond to the assumed width of the strings \( R \approx 0.5 \text{ fm} \). Since the number of produced hadrons per unit rapidity is approximately the same in all vertical columns, the figure also gives an indication of the difference in (transverse) density of strings for different systems.

We show events with a central charged multiplicity\[ \frac{dN_{ch}}{d\eta}|_{\eta=0} \sim 25 \] (leftmost column), for pp, pPb, and PbPb, and we see that the PbPb event is much more spread out, as expected. We note that also the pp event is quite spread out. This is because (mini-)jets cause the hadron production to occur away from the centre of the collision. This is in line with the expectation that the increase in multiplicity in pp collisions is driven by additional jet production while in pA, and especially in AA, the increase is due to additional nucleon–nucleon sub-collisions. Although there is only one event from each collision system, we see that there is no dramatic difference in the average \( \kappa_{\text{eff}} \). Also for \( N_{ch} \sim 50 \) (second column), we see no large difference in \( \kappa_{\text{eff}} \), and while we see the expected almond-like shape for PbPb, the pp event is clearly more jetty. At \( N_{ch} \sim 110 \) (third column), there are fewer pp events, and we only show samples from pPb and PbPb. Here we see that the pPb has jets, but the difference between \( \kappa_{\text{eff}} \) in pPb and PbPb is still not large. To get higher \( \kappa_{\text{eff}} \), we need extremely high multiplicities, available only in PbPb collisions, and we show such an event in the last column. The density of strings is here very large, but there are also large fluctuations in density, with hotspots spread out in the impact parameter plane.

**Results:** We now apply the rope hadronization mechanism to minimum bias events in the three systems with a canonical value of the string width \( R = 0.5 \text{ fm} \). The analysis for each system follows the procedure used by ALICE in ref. [3], where the event samples are divided in centrality bins, and the ratio of each of the strange hadrons to the pion rate are presented as a function of the average central charged multiplicity, \( \langle \frac{dN_{ch}}{d\eta} \rangle_{\eta=0} \), in each bin. We have used default PYTHIA/Angantyr, and the tuned hadronization parameters presented in ref. [10]. In figure 2 we show our result in all three systems, with and without rope hadronization compared to data [3].

We look at \( K^0_s, \Lambda, \Xi \) and \( \Omega \) hadrons to \( \pi \) ratio for \( |\eta| < 0.5 \). Overall, the yields of strange mesons and baryons are significantly increased due to rope formation compared to the baseline prediction of Lund string hadronization without any rope effects, which is a major improvement. The magnitude of enhancement is directly related to string density before hadronization sets in, giving an increased \( \kappa_{\text{eff}} \). The number of strings, in turn, is directly related to the average charge multiplicity at mid-rapidity, \( \langle \frac{dN_{ch}}{d\eta} \rangle_{\eta=0} \). Therefore, \( \frac{dN_{ch}}{d\eta}|_{\eta=0} \) is a perfect scaling variable to show the multiplicity dependence of \( \kappa_{\text{eff}} \), and hence also for strangeness and baryon enhancement. This scaling is in qualitative agreement with the data, and for \( K^0_s \) we also have quantitative agreement. However, we see that the increase with \( \langle \frac{dN_{ch}}{d\eta} \rangle_{\eta=0} \) is too steep, especially for the baryons, but also for \( K^0_s \) there is a tendency to overshoot the data at the highest multiplicity in PbPb. In our results for the rope model we have assumed \( R = 0.5 \text{ fm} \) for the string radius, and increasing it to 1 fm would improve the comparison with data for low multiplicities (see figure 3), but would overshoot even more at the highest multiplicity PbPb bins.

We notice that the yield ratios in pPb and PbPb lack saturation at high \( \frac{dN_{ch}}{d\eta}|_{\eta=0} \), while pp is much flatter. As discussed above, this can be expected since very high multi-

\[ \text{Note that } N_{ch} \text{ is not the same as the number of primary hadrons.} \]
plicities in pp are, to a large extent, driven by increased (mini-)jets production, while the high multiplicities in AA are driven by an increase in soft nucleon sub-collisions. Since hadrons that are produced in jets come from strings that are not parallel to the bulk of the soft strings along the beam axis, and are produced further away from these, the effective number of overlaps is smaller.

From figure 2, it may seem that the steep rise in yield ratios is mainly a problem for the baryon production, but this is not necessarily the case. In figure 3 where we show the $(\Lambda + \bar{\Lambda})/2K^0_s$ ratio for pp at $\sqrt{s} = 7$ TeV, we observe that the increase in $\Lambda/K$ follows the behaviour seen in data. There are, however, additional uncertainties in the string fragmentation for baryons. One such effect is the hyperfine correction [10] arising from spin-spin interactions between a quark and an antiquark or between two quarks. This especially affects the multi-strange particles, and there is room for further corrections to the baryon yields. However, this would mainly affect the overall yield of (multi) strange baryons, and would not affect the strong rise in figure 2 which is mainly driven by $\kappa_{\text{eff}}$.

Including colour reconnections between sub collisions, which are lacking in our current implementation will clearly affect the results. This would naively reduce the number of

Figure 2: Strange hadron to pion yield ratios in pp at $\sqrt{s} = 7$ TeV, pPb at $\sqrt{s_{NN}} = 5.02$ TeV, and PbPb at $\sqrt{s_{NN}} = 2.76$ TeV, vs. $\langle dN_{\text{ch}}/d\eta \rangle_{\eta=0}$. The data is taken from ALICE [3]. For clarity error bars are only shown for the rope model results.
Figure 3: $(\Lambda + \bar{\Lambda})/2K^0_s$ yield ratio vs. $\langle dN_{ch}/d\eta \rangle_{\eta=0}$, compared to pp minimum bias data at $\sqrt{s} = 7$ TeV \cite{3}. Effects of random walk with $R = 0.5$ fm and 1 fm, and highest-multiplet with $R = 0.5$ fm is shown.

strings ($n_s$), but it would not necessarily reduce the rise of $\kappa_{\text{eff}}$ since $N_{ch}$ is approximately proportional to $n_s$. Hence, $n_s$ would have to be increased again by modifying Angantyr parameters in order to fit data. Additionally, after that we would need to use the highest multiplet procedure which would increase $\kappa_{\text{eff}}$, although we see in figure 3 that this is not necessarily a large effect.

There is, however, one mechanism that can decrease the string density without decreasing $n_s$, and that is the repulsion between overlapping strings, which is addressed in the string shoving model \cite{5,6}. Owing to the technical difficulties outlined in ref. \cite{7} string shoving is not included in our current results. However, shoving would spread out the strings more in dense environments, possibly taming the rise for high multiplicities in figure 2.

To look further into rope effects on the baryon yield, we show in figure 3 the rope model for two values of the string radius with the random walk (rw) formulation. We also show the yield ratio using highest multiplet (hm) formulation for $R = 0.5$ fm, which we use in ref. \cite{7}. As discussed above, the highest multiplet is used together with CR in pp, assuming that the latter corresponds to the steps downward in eq. (2).

In figure 3, compared to default PYTHIA8, rope hadronization with random walk and $R = 0.5$ fm enhances the baryon vs. meson yields significantly in all multiplicity bins. However, following the highest multiplet procedure, the yield ratios are slightly higher, giving a better agreement with data. Here we note that with the random walk formulation, if $R$ has a higher value such as 1 fm, the effect is in better agreement to data as shown in the figure. Therefore, we conclude that string shoving and CR would have non-trivial effects on strangeness and baryon yields, especially at high the highest string densities.

Conclusions:– Based on the success of our previous rope model in explaining strangeness enhancement in small systems \cite{3}, we show here that our new implementation, based on the parallel frame, can model enhanced strange flavour production in all collision systems.
The enhancement of strange hadrons shown here is due to modification of the string tension $\kappa_{\text{eff}}$ in dense environments. The average $\kappa_{\text{eff}}$ in string fragmentation, as shown in figure 1, combines the effects of local fluctuations in overlap among ropes during hadronization. Clearly the current rope model lacks the saturation at high multiplicities seen in data, but we believe that this is due to the lack of repulsion between overlapping strings, which we can achieve by combining the ropes with our shoving model. It should be noted that our rope model is very different from the conventional picture based on the formation of a QGP, so even if the same strangeness enhancement can be achieved in both pictures, there are several other observables that would differ. In particular, it is central to the string model that there is a strong momentum correlation between strange and anti-strange hadrons, which should be completely lacking in a thermalized QGP.

String shoving would not only dilute a string system before hadronization via rope formation takes place, it can also give rise to final-state collective flow. Hence, in small systems, both string shoving and rope hadronization together give rise to two out of three typical QGP-like signals. On the other hand, hadronic rescattering [15,16] also gives rise to final-state collectivity for central collisions in pA and AA. In addition, modification of jet energy and topology can arise due to CR. Therefore, to arrive to a complete string-based physical picture in AA collisions in PyTHIA/Angantyr, the combined effects of colour recon-

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