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Effects of Colour Reconnection on Hadron Flavour Observables [1]

Christian Bierlich and Jesper Roy Christiansen

Dept. of Astronomy and Theoretical Physics, Lund University, Sweden

E-mail: `christian.bierlich@thep.lu.se`, `jesper.christiansen@thep.lu.se`

Abstract: We present a comparison between two recently developed colour reconnection models, the new colour reconnection model in Pythia and the dipsy rope hadronization model. Specifically we investigate ratios of identified hadron yields as a function of the final-state activity, as measured by the charged multiplicity. Since both models have a nontrivial dependence on the final-state activity, the above observables serve as excellent probes to test the effect of these models. Both models show a clear baryon enhancement with increasing multiplicity, while only the dipsy rope model leads to a strangeness enhancement. Flow-like patterns, previously found to be connected to colour reconnection models, are investigated for the new models. Only Pythia shows a $p_\perp$-dependent enhancement of the Λ/K ratio as the final-state activity increases, with the enhancement being largest in the mid-$p_\perp$ region.

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1 Introduction

The first run of LHC has provided a large number of measurements probing both soft and hard QCD, and thereby a large number of tests for the Monte Carlo event generators. Even though the overall performance of the event generators have been quite good, there are still some phenomena that are insufficiently understood [1]. One of the more intriguing soft QCD deviations is the observed enhancement of Λ production [2, 3]. No model has been simultaneously able to describe the identified hadron spectra at both LEP and LHC. This has led to the development of several phenomenological models [4–6], partly aimed to address this problem. With the planned low pile-up runs at the beginning of the second LHC run, it is now an ideal time to test these models further, and thereby probe the physical origin of the Λ enhancement. In this study we consider two of the models: the new colour reconnection (CR) model in the PYTHIA event generator [5, 7] and the colour rope model in the DIPSY event generator [4, 8, 9]. The models have previously been compared to pp data at $\sqrt{s}$ of 200, 900 and 7000 GeV. In this paper new possible observables to test the models are suggested, and predictions are made for collisions at $\sqrt{s} = 13$ TeV. Both colour reconnection models are built upon the Lund model for string hadronization [10]. Nonperturbative differences can therefore be ascribed to differences in the new phenomenological ideas.

One of the key ideas for the two models in question is *jet universality*. Stated in terms of the string model, it essentially means that fragmentation of a string does not depend on how the string is formed. Free strings at both lepton and hadron colliders should thus hadronize in a similar fashion. Fragmentation parameters are therefore tuned in the clean $e^+e^- \rightarrow Z \rightarrow q\overline{q}$ environment, and then directly applied to hadron colliders. Any discrepancy has to be due to physical phenomena not active at lepton colliders. For all the models attempting to describe the Λ enhancement, the enhancement is linked to the increased density of quarks and gluons in the final state at hadron colliders[1]. It would therefore be of natural interest to measure the Λ enhancement as a function of this density. The quark-gluon density is experimentally ill-defined, however, and we suggest to use the number of charged tracks in the forward region as a measure of final-state activity. A similar idea for using the hyperon-to-meson ratio to search for indications of a miniQGP was suggested in ref. [11]. We suggest ratios that allows for separation of strangeness enhancement from baryon enhancement, which both could be present in the hyperon-to-meson ratio.

Another puzzling observation is the indication of collective effects in high-multiplicity pp collisions [12, 13], often interpreted as the presence of flow. These effects were only expected in the dense medium of heavy ion collisions, where the pressure gradients give rise to flow effects. A study of the models for pp collisions showed that CR generated similar effects even without the introduction of a thermalized medium [14]. We therefore consider one of the standard observables in heavy ion physics, that of identified particle ratios as a function of $p_\perp$, separated into bins of centrality, and compare the model predictions for pp collisions. Since centrality is not experimentally well defined in pp collisions, the number of charged tracks in the forward region is used as a measure of activity.

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[1] Sometimes also referred to as string density, colour density, or energy density.

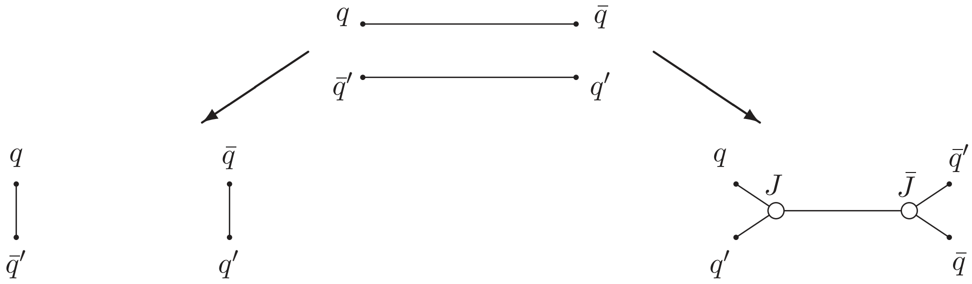

Figure 1. Sketch of how two $q\bar{q}$ dipoles (top) can be reconnected to different colour topologies (left and right). The right connection gives rise to a double junction, which in turn will produce baryons. Notice that the placement of the pairs differs in the junction figure.

The outline of the paper is as follows. In section 2 we will briefly recap the most important features of the two models considered. The event selection and model setup is described in section 3. In section 4, the predictions at $\sqrt{s} = 13$ TeV, for the second run of LHC, are presented. Finally, in section 5, we summarize and present an outlook.

2 The models

Both models for colour reconnection are built upon the Lund string model for hadronization. In this model, outgoing partons are connected with stringlike colour fields, which fragment into hadrons when moving apart. The model contains two main parameters relevant to this study, which determine the suppression of strange quarks and of diquarks (giving baryons) in the break ups. Assuming jet universality, these parameters are tuned to LEP data.

Baryons can in addition be created around string junctions, which can arise as a consequence of colour reconnection. Consider the simple configuration of two $q\bar{q}$ dipoles in figure 1, which for example could have originated from a decay of two W-bosons in a LEP environment, as described in ref. [15]. What essentially could be described as a quadrupole configuration is instead described as either the original (on top) or the left configuration in figure 1. Without CR only the original configuration is considered. Extending this type of colour reconnection to hadron colliders has been shown [16] to be a necessary condition to describe the rising of $\langle p_\perp \rangle(N_{ch})$ distributions. The QCD ε-tensor gives rise to the rightmost configuration, containing two junction connections, depicted as empty circles. Since such junctions constitute proto-baryons, in the same way string segments constitute proto-mesons, they become an additional source of baryons.

2.1 Colour reconnection in Pythia

The new CR model in Pythia is situated just prior to the hadronization. It takes the leading-colour ($N_c \to \infty$) strings and transform them to a different colour configuration based on three principles: firstly the SU(3) colour rules from QCD determine if two strings are colour compatible (*e.g.* there is only a 1/9 probability that the top configuration of figure 1 can transform to the left configuration purely from colour considerations). Secondly a simplistic space-time picture to check causal contact between the strings. Finally the λ measure (which is a string-length measure) to decide whether a possible reconnection is actually favoured. Since the model relies purely on the outgoing partons, it is in principle applicable to any type of collision. So far it has only been tested for pp [5] and ee collisions [17]. The main extension compared to the other CR models in PYTHIA is the introduction of reconnections that form junction structures. From a pure colour consideration the probability to form a junction topology is three times larger than an ordinary reconnection. The junction will introduce additional strings, however, and it is therefore often disfavoured due to a larger λ measure. Given the close connection between junctions and baryons, the new model predicts a baryon enhancement. It was shown to be able to simultaneously describe the Λ production for both LEP and LHC experiments, which neither of the earlier PYTHIA tunes have been able to.

The new CR model essentially contains two new parameters: a parameter that constrains the overall strength of the CR, and a parameter that controls the baryon enhancement. Both of these parameters were tuned to data [3, 18] from the LHC experiments at 7 TeV.

2.2 Rope hadronization in DIPSY

The DIPSY model for rope hadronization and final-state swing [4] is a (partly) dynamic model, implemented as corrections during the evolution of the final-state parton shower and also during the hadronization, depending on the local configuration of the density of quarks and gluons.

The model is based upon the idea that when several parton pairs are next to each other in geometric space, they can act together coherently to form a colour rope. Each string is treated as a flux tube with a fixed radius, and the amount of overlap between strings, in impact parameter space and rapidity, can be directly calculated.

If such an overlap is found to exist, it can have different effects, determined by SU(3) colour rules. The overlapping strings can end up in a colour singlet configuration. This is handled by a final-state ”swing”, that reconnects colour dipoles, in the final-state parton shower as the transformation from the top to the bottom left configuration in figure 1. In all other cases, the strings end up forming a ”rope”. This is hadronized with a higher effective string tension, reflecting the fact that more energy is available for the fragmentation, in accordance with results from lattice QCD. In some cases, the strings forming the rope end up in a junction structure. In such cases the junction pair is handled using a simple approach, where the two junctions collapse to either two diquarks or two quarks, with a probability controlled by a tuneable parameter. The resulting strings are then hadronized with the appropriate effective string tension.

An increased string tension results in more strange quarks and diquarks produced in string breakups. Since the effect increases with the density of quarks and gluons in the final state, the expected outcome is more baryons and strangeness among the resulting hadrons. The model includes two free parameters; the string radius and the probability for a junction to resolve to diquarks. Both are tuned to LHC data [3] at 7 TeV.

3 Model setup and event selection

Before studying exclusive observables, it is necessary to verify that the baselines for the two models agree reasonable well. Normally this is achieved by tuning the models to the available data. But with no available data at 13 TeV, the DIPSY model was tuned to the PYTHIA predictions for $\mathrm{d}N_{ch}/\mathrm{d}\eta$, $\langle p_\perp \rangle (N_{ch})$ and the multiplicity distribution. Both models will have to be retuned when the first data at 13 TeV becomes available.

An event and particle selection was implemented to mimic a possible experimental setup. Each particle is required to have $p_\perp > 0.15$ GeV. Two different η regions are used; a forward region ($2 < |\eta| < 5$) to measure the activity, and a central region ($|\eta| < 1$) to measure the identified hadron yields. The reason for the split is to avoid any potential bias, which otherwise happens at low N_{ch}, in particular for ratios involving both charged and non-charged hadrons. Since DIPSY does not have a model for diffraction, only non-diffractive events are considered for both models. To reflect this in the event selection, only events with at least six forward charged particles are considered.

All particles with $c\tau > 10$ mm are treated as stable. In practice this means that[2] π, K, Λ, Ξ and Ω are all stable whereas ϕ (which decays strongly) is not. This introduces some double counting in the ϕ/K-ratio, where a ϕ can potentially be counted in the numerator and its decay products in the denominator.

4 Predictions for 13 TeV

Differences between the colour reconnection models are best determined using observables controlled by hadronization effects. Ratios of identified particles is exactly such an observable, since particle species production is determined by the quark and diquark content in string breaks. In the first part of this section, ratios of identified particles are shown as a function of N_{ch} in the forward region, as a measure of event activity. Then flow-like effects are considered, by showing $(\Lambda/K)(p_\perp)$ in four different bins of N_{ch} in the forward region.

4.1 Particle ratios

Ratios of hadrons with different strange and baryon numbers as function of event activity, measured as functions of N_{ch}^{fwd}, are shown in figure 2. The strangeness enhancement in meson production is probed by the K/π and ϕ/K ratios, for which the numerator always contains one more strange quark than the denominator. As expected, only the DIPSY rope model shows an enhancement relative to the baseline, since it contains a strangeness enhancement. The new PYTHIA CR model lies slightly below the baseline, but a slight difference in tuning can potentially explain this. It should be recalled that both the new as well as the old models are capable of describing the total K_s^0 yield at 7 TeV. Thus, the limited effects in this ratio is somewhat expected. The ϕ/K ratio shows more promise

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[2] We denote a particle and its antiparticle with just a single letter such that *e.g.* p means both proton and anti-proton. Special cases are π with denotes $\pi^+\pi^-$, K which denotes $K^+K^-K_s^0K_L^0$ and Ξ which denotes $\Xi^+\Xi^-$.

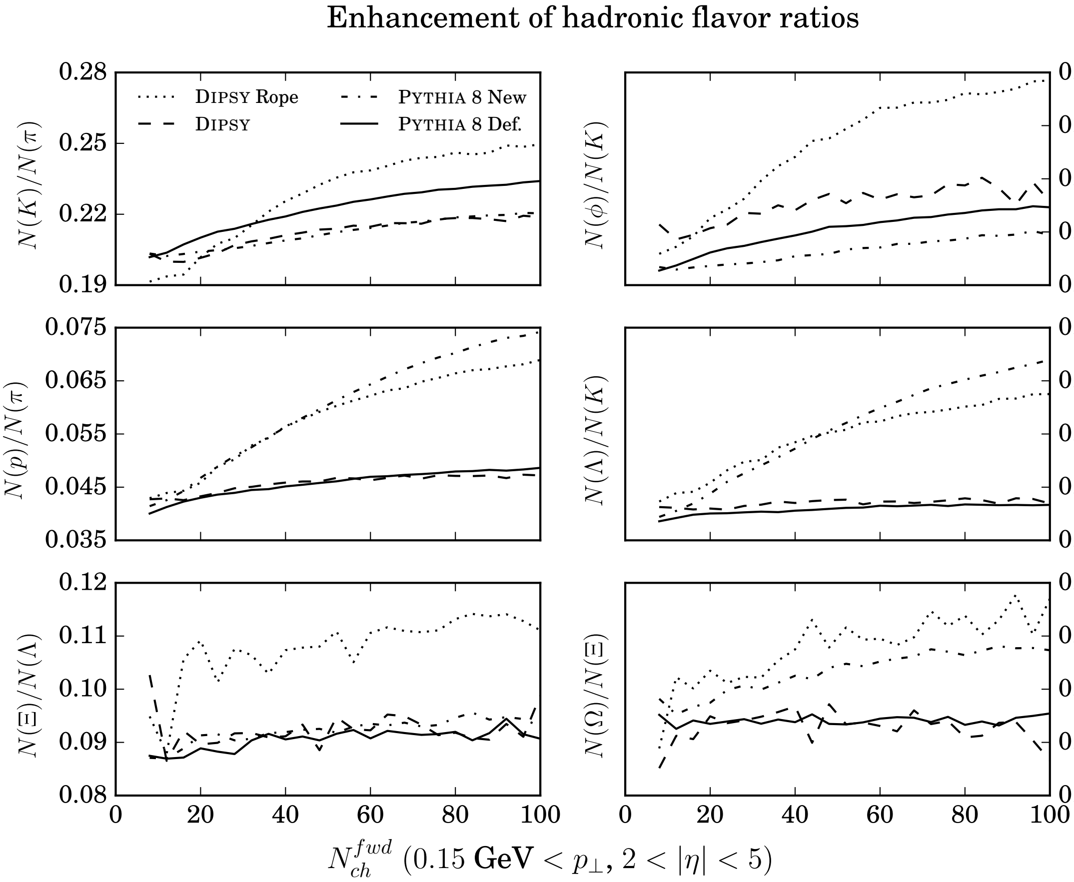

Figure 2. Ratios of identified hadrons as functions of N_{ch}^{fwd} at $\sqrt{s} = 13$ TeV. The top row shows meson ratios with the numerator having one more strange quark than the denominator. The middle row shows baryon to meson ratios, with same amount of strange quarks. The bottom row shows baryon ratios with the numerator having one more strange quark than the denominator. Note that the vertical axis differs between the figures and that zero is suppressed.

as a means to distinguish between the two models, since the DIPSY model shows a larger enhancement. It is, however, more experimentally challenging.

The baryon enhancement is tested for both hadrons containing zero or one strange quark, p/π and Λ/K. For both ratios, and both models, clear enhancements are expected and seen. For the Λ/K ratio both models agree quite well, which is not surprising, given that both models are tuned to describe the inclusive Λ/K distributions at 7 TeV. A similar picture is seen for the p/π ratio, indicating similar predictions for the baryon enhancement from both the models.

The multistrange baryon enhancement is tested in the same way as the strange-meson enhancement by considering the ratios Ξ/Λ and Ω/Ξ. The large variations at low multiplicity for both distributions are due to statistical fluctuations. For Ξ/Λ the DIPSY rope model shows a clear enhancement as opposed to the new PYTHIA CR model. It was already noted at 7 TeV that the inclusive Ξ/Λ ratio was underestimated by the default PYTHIA tune [3]. As such, the lack of enhancement for the new Pythia CR model can be taken as an inadequacy. The Λ/p ratio is not shown, but the enhancement is similar to the enhancement of Ξ/Λ. An enhancement is seen for both models in the Ω/Ξ, with the enhancement factor being around 2.5 for the DIPSY rope model in the highest multiplicity bins. This is larger than any of the other enhancements seen. The enhancement for the new Pythia CR model is somewhat surprising, as the increased junction production should be equal for both Ξ and Ω. The production of Ω in the standard Pythia fragmentation is, however, significantly suppressed, as the production of ss-diquarks is disfavoured. This suppression is not present in the junction handling, since it takes two already formed quarks and combine into a diquark. The enhancement in the new Pythia model should therefore not be interpreted as a "real" strangeness enhancement, but more as an absence of suppression of ss diquarks. For the DIPSY model the above effect is also present, but there is an additional enhancement of strangeness and diquarks. It should be noted that the Ω baseline from LEP is not that well constrained, due to a large experimental uncertainty, and the model predictions are below the actual measurements [19]. A measurement of $(\Omega/\Xi)\,(N_{ch})$ would cast light on whether an actual activity-based enhancement takes place.

Increased hyperon production in high activity pp events have previously been associated with production of a miniQGP [11]. The hyperon-to-pion ratio is only indirectly shown in figure 2, but the rise is similar to the one predicted by miniQGP. The new models therefore provide an alternative explanation, if such an enhancement is observed.

4.2 Flow-like effects

The Λ/K ratio as a function of $p_\perp$ for different N_{ch}^{fwd} ranges is shown in figure 3. The two models show different behaviours for the different multiplicity ranges: the DIPSY rope model only gives a small enhancement ($\sim 10\%$ at maximum) between the lowest and highest multiplicity regions. Even though the differential enhancement is generally below 10 %, the enhancement of the ratio of integrated yields is about 20 %, which is in good agreement with figure 2. It should be noted that the DIPSY model is inadequate in describing the high $p_\perp$ tails ($p_\perp >\sim 4$ GeV). This was observed for 900 GeV and 7 TeV in ref. [4].

The new Pythia CR model shows a clear change in $p_\perp$ with increasing multiplicity. The enhancement is largest in the mid-$p_\perp$ region ($p_\perp \sim 2-6$ GeV), leading to a "peak" structure. This structure looks qualitatively similar to what is observed in $PbPb$ and pPb collisions [20, 21]. The peak also moves towards larger $p_\perp$ with increased multiplicity, an effect normally attributed to radial flow in heavy ion collisions [22]. That the new CR model predicts a qualitatively similar effect in pp collisions is quite intriguing and strengthens the hint at a potential connection between flow and CR effects already observed [14].

5 Conclusions

The new CR models can be separated by measuring the identified hadron yields as a function of the multiplicity. The new CR model in Pythia only contains a baryon enhancement with increasing multiplicity, while the DIPSY rope models contains both a baryon and a

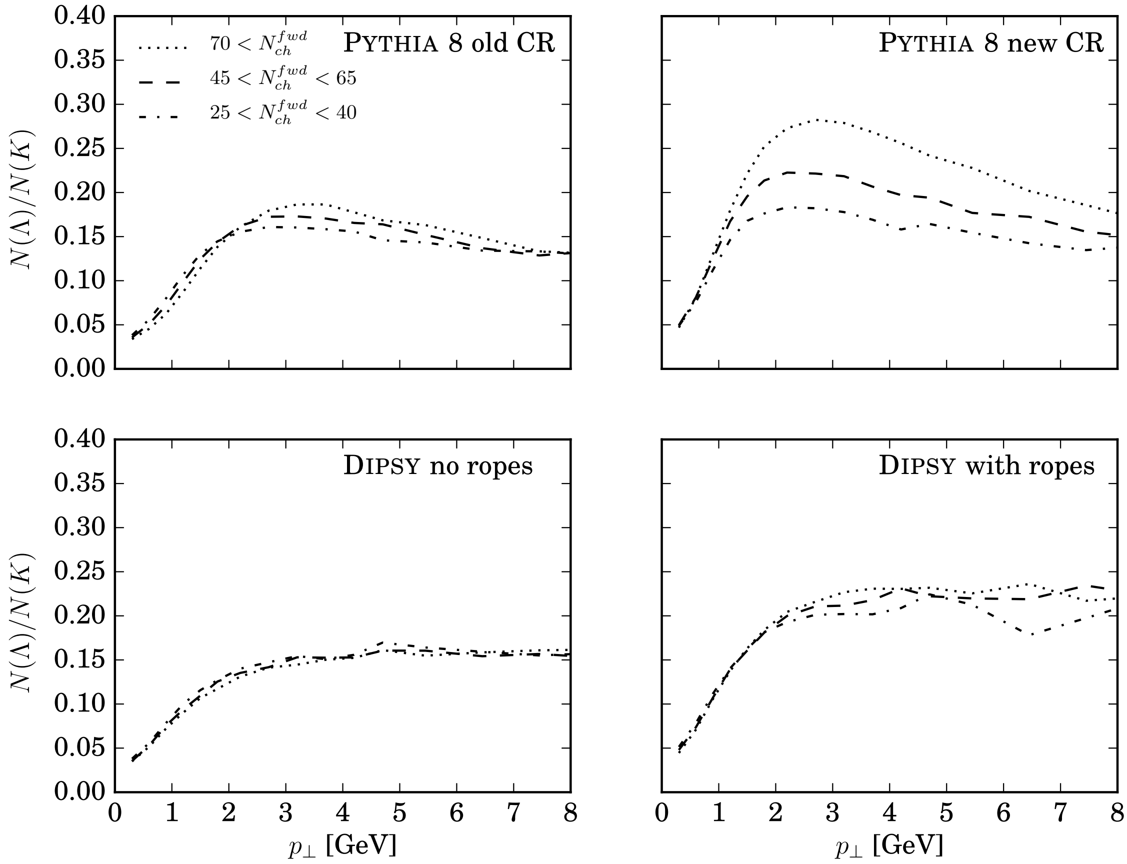

Figure 3. Ratio of Λ/K as a function of $p_\perp$ in three bins of N_{ch}^{fwd}. In the right column the new colour reconnection models are shown, and in the left column the old ones.

strangeness enhancement. The multistrange hyperon ratios, as well as the ϕ/K ratio, provide clear observables for distinguishing between the two models. It should be mentioned that this is already possible to observe in inclusive measurements, but the separation into different multiplicity regions highlights the enhancement.

One of the most important points is the power to distinguish, not only between the two new models, but also between the new models and the old models. Both new models are based on interactions between strings in the hadronization phase, and confirmation of the common predictions made by the two models is a direct hint that colour reconnections among strings are of physical importance. Both baseline models show almost no dependency on multiplicity for the identified hadron yield ratios. Therefore, any observed dependency would provide a clearer indication that the old models miss a feature, better than an inclusive measurement alone could provide. We therefore strongly suggest that these observables should be measured at the LHC experiments. In this paper we only studied the effects at a center-of-mass energy of 13 TeV, but the effects should also be visible in the already collected data at 7 TeV.

We have also shown that one of the CR models predicts effects similar to those normally attributed to radial flow in heavy ion collisions. This is in agreement with earlier indications that also hint at a connection between the two phenomena. It should however be recalled that neither of the models provide a satisfactory description of the individual $p_\perp$ spectra for the identified hadrons. And before these are fully understood, claims of connections between flow and CR may be premature.

6 Acknowledgments

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