

## Color Reconnection and Flowlike Patterns in $pp$ Collisions

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Increasingly, with the data collected at the LHC we are confronted with the possible existence of flow in  $pp$  collisions. In this work, we show that PYTHIA 8 produces flowlike effects in events with multiple hard subcollisions due to color string formations between final partons from independent hard scatterings, the so-called color reconnection. We present studies of different identified hadron observables in  $pp$  collisions at 7 TeV. Studies have been done both for minimum bias and multiplicity intervals in events with and without color reconnection to isolate the flowlike effect.

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For many years, the existence of something that is generically called flow has been taken as a proof of collective behavior of partons and hadrons. According to this interpretation, in central heavy ion collisions the transverse pressure gradient causes a transverse hydrodynamic expansion [1]. On the basis of hydrodynamic calculations the effect is transmitted to hadrons via a boost by the local velocity field  $u^\mu$  [2]. The transverse flow shifts the emitted particles to higher momenta, and this effect increases for heavier particles, because they gain more momentum from the flow velocity. It is important to stress that particles are not used for calculations, and a local thermal equilibrium is assumed as the starting point of the hydrodynamic evolution of the system. Therefore, hydrodynamics does not tell us what is flowing and how these underlying degrees of freedom hadronize. Among the problems of the hydrodynamical models are the initial temperature, thermalization, and the size of the system. Extending the hydrodynamical picture to  $pp$  and  $p$ -Pb [3–5] brings us in contradiction with the basic tenet of hydrodynamics, i.e., the mean free path of partons must be smaller than the size of the system.

In heavy nuclei collisions the proton-to-pion ratio exhibits an enhancement for transverse momentum ( $p_T$ ) below 8 GeV/ $c$  and the position of the peak is pushed to higher momenta when one goes from peripheral to central Pb-Pb collisions [6]. Surprisingly, Fig. 1 (see Ref. [7]) shows that in  $pp$  collisions at  $\sqrt{s} = 7$  TeV we also observe a small enhancement around 3 GeV/ $c$  [8] which is qualitatively well reproduced by PYTHIA version 8.17 [9] tuned to early LHC data, tune 4C [10]. For higher  $p_T (> 8$  GeV/ $c$ ) the description is poor, but for us this is not a major worry since we just use PYTHIA as a framework and we do not intend to tune it. In this Letter, our aim is to show that in PYTHIA the enhancement is attributed to color reconnection (CR). We argue that CR is another mechanism of flow

where the boost is introduced at the partonic state just before hadronization in events with several multipartonic interactions (MPI). The CR mechanism, which was originally introduced in PYTHIA [11], is microscopic and does not require a medium to be formed. This flow mechanism is very important because it could provide an explanation of the observed flowlike patterns in  $pp$  collisions [12] and the collective phenomena seen in  $p$ -Pb collisions [13].

Note that here we shall only show evidence for radial flow, but the discussion will mention how higher order flow, e.g. elliptic flow, could be produced by the same mechanism.

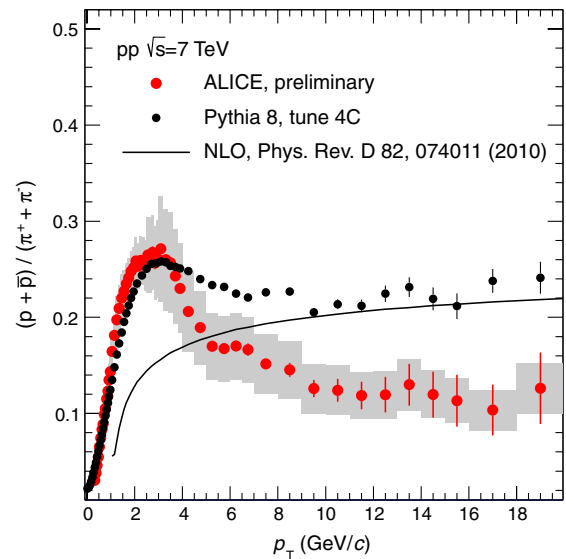


FIG. 1 (color online). Proton to pion ratio from  $pp$  collisions at  $\sqrt{s} = 7$  TeV. ALICE data are compared to results from PYTHIA 8 tune 4C, as well as next-to-leading order (NLO) QCD calculation [7].

In hadron-hadron interactions it is possible to have multiple parton-parton interactions in the same event, because beam particles contain a multitude of partons which can interact [14]. This is expected to happen in most hadronic collisions at high energies, since, for example, in  $pp$  collisions at LHC energies the inclusive jet cross section for  $p_{T\min}$  below  $\approx 4\text{--}5$  GeV exceeds the total cross section [15]. The inclusion of multiparton interactions has been supported by many experimental results [16–18]. This is an important assumption used in PYTHIA [11,19] which allows us to have a qualitatively good description of the multiplicity distributions as well as the correlation of observables like transverse sphericity with multiplicity in minimum bias (MB)  $pp$  collisions at the LHC energies [20]. But there are other issues, like the increase of the average transverse momentum with the multiplicity, which can be described through the so-called color reconnection.

Color reconnection was first studied in a quantitative way, in the context of the rearrangements of partons at the perturbative level [21]. More recently, different approaches to deal with CR have been developed [10,22,23]. All these models are based on the calculation of the probability to connect partons by color lines. The models of CR include the probability to join low and high  $p_T$  partons, so the mechanism is present in soft and hard QCD processes. However, at the perturbative level, CR is strongly suppressed [24].

Figure 2 shows a sketch of CR in the string fragmentation model as implemented in PYTHIA where final partons are color connected in such a way that the total string length becomes as short as possible [25]. Therefore, the fragmentation of two independent hard scatterings are dependent and induces the rise of  $\langle p_T \rangle$  with multiplicity. However, in this work we discuss another feature of the model. In PYTHIA one string connecting two partons follows the movement of the partonic endpoints. The effect of this movement is a common boost of the string fragments (hadrons). Without CR, for a parton being “knocked out” at midrapidity, the other string end will be part of the remaining proton moving forward so the boost is small [Fig. 2(a)]. With CR, two partons from independent hard scatterings at midrapidity can color reconnect and make a large transverse boost [Fig. 2(c)]. The last effect becomes more important in single events having several partonic subcollisions.

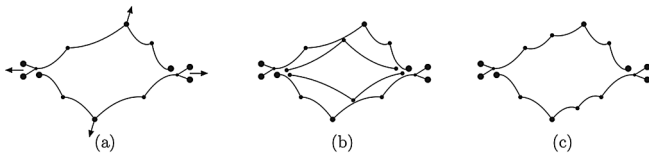


FIG. 2. Illustration of the color reconnection in the string fragmentation model (image reproduced from Ref. [25] with permission). The outgoing gluons color connected to (a) The projectile and target remnants. (b) The second hard scattering. (c) Color reconnected string.

This boost effect is similar to how flow affects hadrons in hydrodynamics, but the origin of the boost is clearly different in CR compared to hydrodynamics.

In order to pin down the effect, we calculated different baryon to meson ratios as well as heavy meson to light meson ratios with and without CR. The results were produced using primary charged particles defined as all final particles including decay products except those from weak decays of strange particles. This definition is similar to the one adopted by ALICE [26]. The identified particle yields were computed at midrapidity,  $|y| < 1$ , and the event multiplicity in  $|\eta| < 2.4$ . The parameter which controls CR is the reconnection range (RR) which enters in the probability to merge a hard scale  $\hat{p}_T$  system with one of a harder scale,  $(2.085 \times \text{RR})^2 / [(2.085 \times \text{RR})^2 + \hat{p}_T^2]$ . The tune 4C uses the value  $\text{RR} = 1.5$  which gives a good description of  $\langle p_T \rangle$  as a function of multiplicity [10].

The top panel of Fig. 3 shows the  $(p + \bar{p})/(\pi^+ + \pi^-)$  ratio in the  $p_T$  interval,  $p_T < 6$  GeV/c, for MB (PYTHIA 8 tune 4C)  $pp$  collisions at 7 TeV. The distribution shows a clear bump around 2.5 GeV/c. The result for simulations using  $\text{RR} = 0$  (without CR) indicates a completely different behavior, for  $p_T$  larger than  $\approx 1.8$  GeV/c the ratio stays flat. Therefore the origin of the peak is attributed to CR. The result also indicates that for  $p_T > 5$  GeV/c, the particles inside hard jets are not sensitive to color reconnection. The peak is enhanced if one considers events with increased MPI activity. In the figure, we plotted the results for events with more than 20 MPIs, in this case the peak is also pushed up to higher  $p_T$ , a characteristic effect of flow. The curve crosses the MB curve at  $\approx 1.8$  GeV/c and the maximum ratio reaches 0.3 at 3 GeV/c. On the contrary, in events with less than five MPIs the ratio behaves like in simulations without CR. The evolution of the ratio with the number of MPIs is qualitatively similar to the behavior of the ratio from peripheral to central Pb-Pb collisions [8]. To study the effect of CR, the bottom panel of Fig. 3 shows the double ratios with and without CR. For  $(p + \bar{p})/(\pi^+ + \pi^-)$  and  $(\Lambda^0 + \bar{\Lambda}^0)/(2K_S^0)$  one sees a bump at  $\approx 2.5\text{--}3$  GeV/c, similar to the one observed in the proton-to-pion ratio (top of the figure). The behavior of the double ratios indicates that we have a mass effect since the  $\phi/\pi$  and the  $(p + \bar{p})/(\pi^+ + \pi^-)$  ratios exhibit a much larger bump than the  $(K^+ + K^-)/(\pi^+ + \pi^-)$  ratio. Even though, in general, PYTHIA underestimates the production of strange particles [26,27], we observe a hierarchy in the effect; it increases with the hadron mass in a pattern reminiscent of the radial flow in heavy ion collisions. To distinguish it from the flow usually associated with hydrodynamic evolution, we call it flowlike. We also observe the decrease in the double ratios at higher momenta, a feature that seems to be proper of CR and not of hydrodynamical behavior.

At LHC energies, the CMS Collaboration has published  $p_T$  spectra for pions, kaons, and protons as a function of the

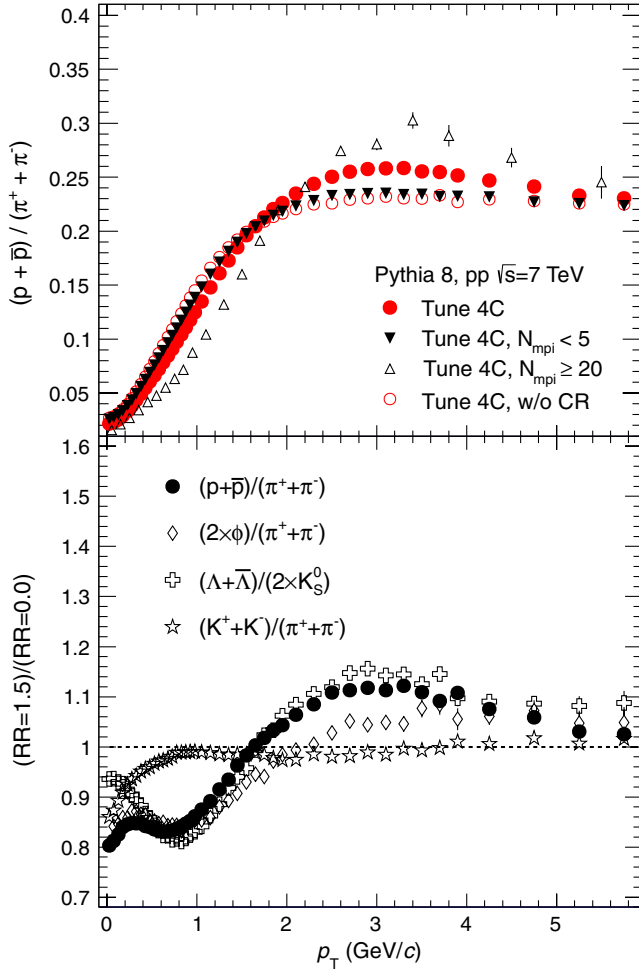


FIG. 3 (color online). Top panel:  $(p + \bar{p})/(\pi^+ + \pi^-)$  as a function of  $p_T$  in  $pp$  collisions simulated with PYTHIA 8 (solid circles), the ratio for events with low (solid triangles) and high (empty triangles) numbers of multiparton interactions are overlaid. Results without color reconnection ( $RR = 0.0$ ) are also shown (empty circles). Bottom panel: double particle ratios as a function of  $p_T$  for different hadron species.

track multiplicity [28]. They found that  $\langle p_T \rangle$  for protons increases from  $\approx 0.6$  to  $\approx 1.4$  GeV/ $c$  from their lowest multiplicity class to the highest one. The upper panel of Fig. 4 shows that this can only be accommodated by PYTHIA simulations when color reconnection is included. In the plot we observe an increase of  $\langle p_T \rangle$  with multiplicity when the color reconnection is turned on, while it looks flatter when color reconnection is turned off. This is the expected behavior that is used in PYTHIA to tune the amount of CR. However, our work offers an interpretation from a different point of view; with CR the  $\langle p_T \rangle$  of protons increases faster than the pion one, i.e., the effect increases with the hadron mass. This observation is consistent with the idea of the flowlike effect of string boosts.

We also made a combined fit of the pion, kaon, and proton  $p_T$  spectra with a blast-wave function [29]. From this fit one usually extracts the freeze-out temperature  $T_{\text{kin}}$

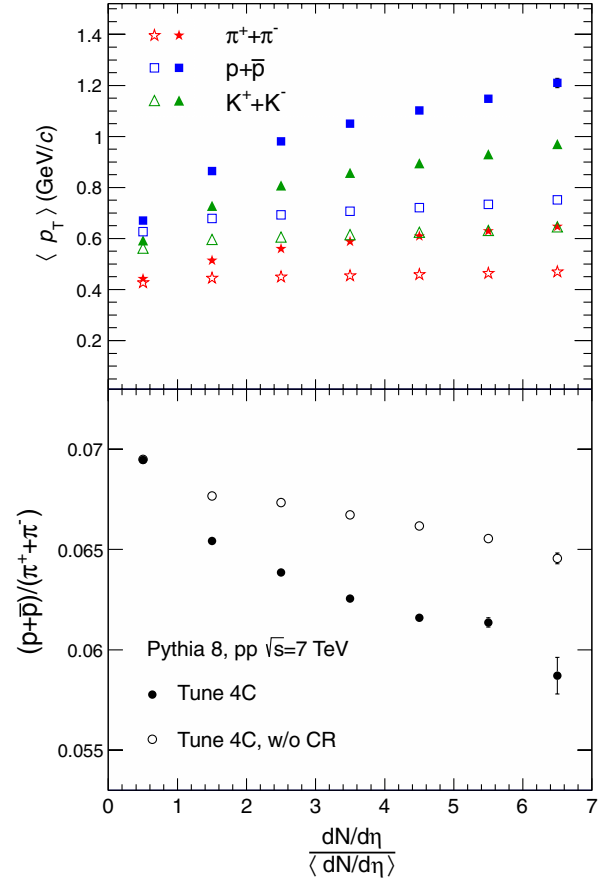


FIG. 4 (color online). Top panel: mean  $p_T$  as a function of the scaled event multiplicity for pions, kaons, and protons. Results with CR (solid markers) and without CR (empty markers) are shown. Bottom panel:  $p_T$ -integrated proton-to-pion ratio as a function of the scaled event multiplicity.

and the average transverse velocity  $\langle \beta_T \rangle$ . We found in CMS and PYTHIA data a  $T_{\text{kin}}-\langle \beta_T \rangle$  behavior as a function of multiplicity very similar to the one observed in heavy ion collisions [6].

The bottom panel of Fig. 4 shows that the  $p_T$ -integrated  $(p + \bar{p})/(\pi^+ + \pi^-)$  ratio decreases with the event multiplicity. It is interesting that Pb-Pb data at the LHC exhibits a similar behavior; a model assuming a baryon-antibaryon annihilation does the qualitatively best description of the trend [6]. In PYTHIA 8, this effect is caused by a change of the particle distribution in the phase space. Actually without any cut on  $y$  the  $\bar{p}/\pi$  ratio stays constant as a function of multiplicity with or without CR.

Finally, we want to say that the study was only focused on radial flow. However, we stress that the quantity used to minimize the string length  $l = \sqrt{\Delta \eta^2 + \Delta \phi^2}$  has a dependence on the azimuthal opening angle  $\Delta \phi$  between the two partons. For radial flow we can understand that the partons from two independent interactions select a preferred rapidity (minimizing  $\Delta \eta$ ) and therefore boosts in that direction. In a similar way one could imagine that they could select a

preferred  $\phi$  giving rise to higher order flow, e.g., elliptic and triangular. This point is very speculative and requires further theoretical investigations but here we want to point out that there is naturally a  $\Delta\phi$  relation in the CR picture.

We have demonstrated that the CR scheme used in the PYTHIA 8 event generator exhibits a qualitatively new feature that has a potentially important consequence on our understanding of the details of the  $pp$  collisions. The flowlike mechanism of PYTHIA does not require thermalization or a medium to be formed, and can hopefully lead to predictions that are different from hydrodynamics for small systems like  $pp$  and  $p$ -Pb. We also note that the CR mechanism introduced in PYTHIA is microscopic and could potentially lead to novel hadronization effects if applied in a much denser environment such as heavy ion collisions.

For the  $(p + \bar{p})/(\pi^+ + \pi^-)$  ratio as a function of  $p_T$  (Fig. 1) we have shown that even when hard and soft processes are combined, such as in PYTHIA 8, one needs to introduce a flowlike effect to obtain a peak. This suggest that this peak is a direct indicator of a flowlike behavior, i.e., collective phenomena. We also remark that CR produces the mass dependent rise of  $\langle p_T \rangle$  as a function of multiplicity; therefore, radial flow is an important effect which plays a role to explain the CMS results [28].

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