Colour reconnections in pp collisions

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Abstract: We discuss phenomenological results relating to Colour Reconnection, and review the Rope Hadronization formalism, including the ARIADNE/DIPSY final state swing. In this formalism, corrections to hadron flavour ratios in pp, have previously been calculated. We suggest new flavour ratio observables, based on event shapes, which are well suited for e^+e^-, and show that Colour Reconnection corrections can feasibly be measured at a new FCC-ee.

Introduction

LHC have provided many interesting results related to Colour Reconnection (CR), here understood as an umbrella term for colour supressed corrections to final state parton shower and hadronization. We will discuss such phenomena in the context of the Lund string hadronization model [1][2]. In proton–proton collisions at the LHC, multiparton interactions (MPIs) are ubiquitous, leading to substantial space–time overlap of strings. At the same time effects, which in heavy ion collisions are linked to the formation of a Quark Gluon Plasma (QGP), have been observed in pp, such as enhanced production of strange hadrons [3] or ridges in the two–particle correlation function, linked to flow [4]. Common to these effects is that they are more pronounced in "central" collisions, *i.e.* collisions where a large number of particles in the forward direction are observed, since many produced particles correlates with many MPIs.

Corrections to the hadronization mechanism, with the aim of explaining QGP effects in pp, includes for example the core–corona model in EPOS [5], which imposes a macroscopic hydrodynamic model on dense events, QCD–based junction formation [6], a "microscopization" of hydrodynamics, by incorporating a thermal spectrum [7], as well as the Rope Hadronization model [8], the latter being the focus of these proceedings. Since the different models are based on quite different physical ideas, they can be reasonably expected to give different results for pp observables to which they are not tuned. In this way one can discriminate between the models. This was done *e.g.* for hadronic flavour ratios [9] and measured by ALICE [10], as well as several new underlying event observables [11], which are yet to be measured. It is clear from these studies that the models give different results, and that none of the models can yet fully describe soft pp collisions.

A future e^+e^-–collider could further illuminate the situation. Since CR effects require the presence of many strings in a small space–time volume to be visible, large effects are hard to come by in existing LEP data, due to limited statistics. With the large statistics expected from the new collider, one should be able to open up for new types of precision measurements.

DIPSY and Rope hadronization

The DIPSY event generator [12] is built on an initial state cascade, based on Mueller's dipole formulation of QCD in impact parameter space and rapidity [13]. As such, full space–time information at the partonic level is accessible. After the initial state evolution and (multiple) interaction(s) between projectile and target, a final state shower is carried out by ARIADNE [14], where the space–time information is pertained. In figure 1, an example pp event (after final state shower) at $\sqrt{s} = 7$ TeV is shown in impact parameter space and rapidity. The coloured tubes are strings, and all string ends are quarks. Kinks on the strings are gluons. The event is finally hadronized by PYTHIA 8 [15], modified to include rope corrections.

When a number of string segments overlap, the colour charges of the string ends can act together coherently to form a "rope", which is conveniently described as an SU(3) multiplet, with two quantum numbers p and q, given by the amount of overlapping segments with colour flow in each direction. Several possible multiplets can arise from combining strings. Following the work by Biro et al. [16], we let each individual rope form using a random walk procedure in colour space. Such a random walk can lead to three qualitatively different endpoints. Junction formation, singlet formation and the highest multiplet. We will only treat the two latter here, and refer to ref. [8] for a description of the junction treatment.

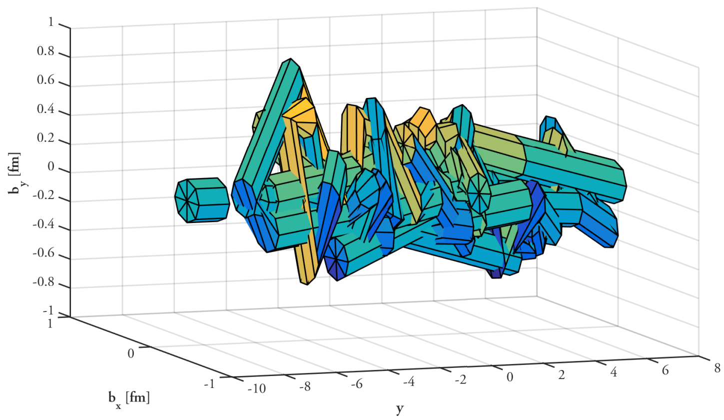

Figure 1: Example event from DIPSY in impact parameter space and rapidity, shoving sizable overlap of strings. Note that the transverse string radius in the picture is set to 0.2 fm, as opposed to 0.7 fm in the simulation, in order to improve readability of the figure.

Singlet formation

We address the possibility of singlet formation (*i.e.* the $\mathbf{1}$ in $\mathbf{3} \otimes \overline{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$) using a final state swing already in the shower. In the shower, a dipole emits with a probability:

$$\frac{d\mathcal{P}_e}{d\ln(p_\perp^2)} \approx dy \frac{C_F \alpha_s}{2\pi}. \tag{1}$$

If there are colour compatible dipoles present in the event, they are allowed to recouple, competing with the emission, with a probability of:

$$\frac{d\mathcal{P}_r}{d\ln(p_\perp^2)} = \lambda \frac{(\vec{p_1} + \vec{p_2})^2 (\vec{p_3} + \vec{p_4})^2}{(\vec{p_1} + \vec{p_4})^2 (\vec{p_2} + \vec{p_3})^2}, \tag{2}$$

where p_i are the parton momenta and λ is a parameter. The swing greatly affects $\langle p_\perp \rangle (N_{ch})$, which in pp collisions is often linked to CR between different MPI systems (see also T. Sjöstrand, these proceedings). In figure 2 we show this observable as measured by ATLAS [17]. We see that the swing increases the $\langle p_\perp \rangle (N_{ch})$ dependence, as expected. For comparison, PYTHIA 8 with CR is included. In Pythia, which does not include any correlations between the MPIs from the initial state, CR is necessary to get any $\langle p_\perp \rangle (N_{ch})$ dependence. Since DIPSY already includes such correlations from the initial state model, it shows such a dependence even before including CR in the form of the swing.

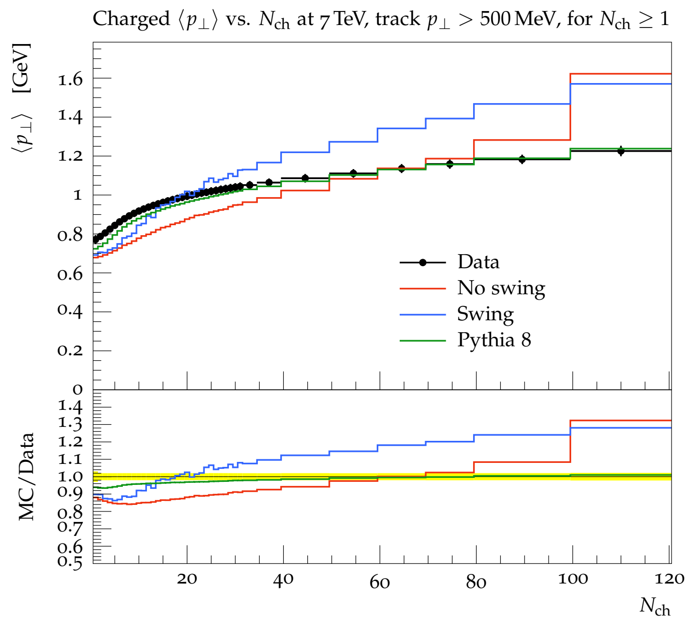

Figure 2: Average $p_\perp$ as function of N_{ch}, as measured by ATLAS, compared to DIPSY with and without swing, as well as Pythia 8.

Highest multiplet

The string tension of the rope has been calculated on the lattice [18], and is given by the secondary Casimir operator of the multiplet. The enhancement of string tension in a multiplet is thus:

$$\frac{\tilde{\kappa}}{\kappa} = \frac{C_2(p,q)}{1 \text{ GeV/fm}}. \tag{3}$$

In the string hadronization model, the string breaks by tunneling of a new $q\bar{q}$ pair with a tunneling probability of:

$$\frac{1}{\kappa}\frac{d\mathcal{P}_q}{d^2p_\perp} \propto \exp(-\pi m_{\perp q}^2/\kappa) = \exp(-\pi p_\perp^2/\kappa)\exp(-\pi m_q^2/\kappa). \tag{4}$$

From the latter part, it is clear that production of heavier quarks will be suppressed with respect to lighter quarks. When the string tension is enhanced, the suppression vanishes. In the case of strange quarks with respect to up and down we call the suppression factor ρ, and one obtains directly for the modified suppression factor ($\tilde{\rho}$):

$$\tilde{\rho} = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\tilde{\kappa}}\right) = \rho^{\frac{\kappa}{\tilde{\kappa}}}. \tag{5}$$

We therefore expect an increase in the amount of strange hadrons relative to non–strange with increasing string tension – and thus increasing event activity – which is also observed in pp data [10].

New observables for e^+e^-

It would be interesting to repeat the measurements of flavour ratios as function of event activity in e^+e^-. We focus here on $Z \to q\bar{q}$ events. Due to the absence of MPIs, a large number of produced particles in a $Z \to q\bar{q}$ event does not necessarily correspond to large overlap of strings, but can just as well correspond to a very long initial dipole. We suggest instead to look at event shape observables as a proxy for string overlap, also suggested for CR studies [19], not related to strangeness, in pp. The sphericity is defined as the linear combination $\frac{3}{2}(\lambda_2 + \lambda_3)$ of the second and third eigenvalues of the sphericity tensor. The sphericity approaches 1 for an isotropic event, which consists of many small gluon emissions, rather than two jets. With many small emissions, some strings are bound to be on top of each other, giving rise to rope hadronization effects.

In figure 3 we show the ratio of K_s^0, ϕ and Ω respectively to pions, in $e^+e^- \to Z \to q\bar{q}$, plus shower, with ARIADNE/DIPSY and Rope Hadronization. We ran 10^9 events, roughly similar to the expected statistics of a new FCC-ee machine.

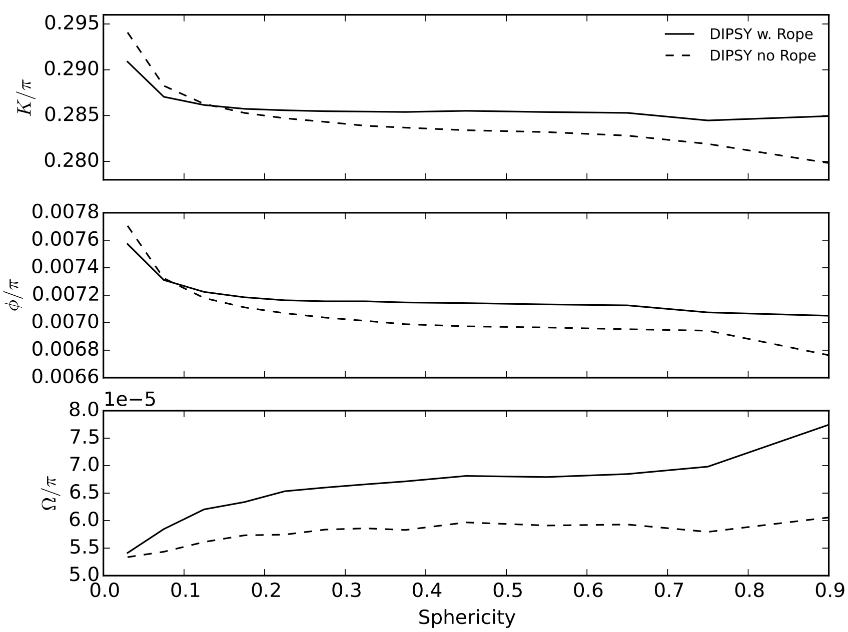

Figure 3: Hadron flavour ratios as function of sphericity in $e^+e^- \to Z \to q\bar{q}$. We show K_s^0 (single strange), ϕ (double strange) and Ω (triple strange) compared to pions.

It is seen that Rope Hadronization gives a sizeable effect in all three observables.

Outlook

We have briefly reviewed Rope Hadronization and the final state swing in DIPSY/ARIADNE, and how these mechanisms lead to increased $\langle p_\perp \rangle (N_{ch})$ and increased strangeness as function of N_{ch} in pp collisions. We have argued that N_{ch} cannot be directly translated to a proxy for string overlap in e^+e^-, and suggest the use of event shape observables instead. We show that effects on flavour composition from Rope Hadronization could feasibly be measured at an FCC-ee.

We expect that more interesting measurements relating to CR at an FCC-ee will surface, as CR is still an active, and not yet fully understood, topic in pp. New developments of the Rope Hadronization model [20] indicates that features similar to those observed in long–range near–side angular correlations (the ridge) can be obtained by allowing the excess energy in string overlaps generate a transverse pressure. If such a model can explain QGP–like features in systems as small as pp, it would not be far fetched to suggest a dedicated QGP programme at a new FCC-ee.

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