Colour Reconnections from LEP to Future Colliders

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Abstract: The phenomenon of colour reconnection (CR) is introduced, together with a selection of CR models and CR-related phenomena and observations.

Introduction

Colour Reconnection (CR) was first discussed in the context of charmonium production [1],[2],[3], notably in weak B decay to J/ψ, e.g. $\overline{B}^0 = b\overline{d} \to W^- c\overline{d} \to s\overline{c}c\overline{d} \to J/\psi\overline{K}^0$. In such decays the c and $\overline{c}$ belong to two separate colour singlets, but ones that overlap in space–time, with the possibility of soft gluon exchange. Alternatively, colour algebra gives accidental $c\overline{c}$ colour singlets 1/9 of the time, but a dynamical principle would still be needed to override the original singlets.

The first large-scale application of CR was in the Pythia multiparton interaction (MPI) model of hadronic collisions [4], notably to explain the increasing mean transverse momentum $\langle p_\perp \rangle$ with increasing charged multiplicity n_{ch} observed at the S$p\overline{p}$S [5]. If all MPIs draw out strings and fragment in the same manner, $\langle p_\perp \rangle(n_{\mathrm{ch}})$ would be essentially flat. CR was therefore introduced in such a way that the total string length is reduced. Each further MPI then on the average increases n_{ch} less than the previous one, while giving the same $p_\perp$ from (mini)jet production, resulting in an increasing $\langle p_\perp \rangle(n_{\mathrm{ch}})$.

The string length is conveniently described by the λ measure [6], which is constructed such that $\lambda \propto \langle n_{\mathrm{hadrons}} \rangle \propto \langle n_{\mathrm{ch}} \rangle$ within the string model. For a simple $q\overline{q}$ string $\lambda = \ln(m_{q\overline{q}}^2/m_0^2)$, with $m_0 \approx 1$ GeV a measure of hadronic mass scale. The λ measure becomes more difficult to evaluate for more complicated string topologies, and usually approximate expressions are used, like

$$\lambda \approx \sum_{i=0}^{n} \ln\left(1 + \frac{m_{i,i+1}^2}{m_0^2}\right) , \quad m_{i,i+1}^2 = (\epsilon_i p_i + \epsilon_{i+1} p_{i+1})^2 , \ \epsilon_q = 1 , \ \epsilon_g = \frac{1}{2} , \tag{1}$$

for a string $q_0 g_1 g_2 \cdots g_n \overline{q}_{n+1}$, where $\epsilon_g = 1/2$ because gluon momenta are shared between two string pieces.

LEP 2 offered a good opportunity to search for CR effects. Specifically, in a process $e^+e^- \to W^+W^- \to q_1\overline{q}_2q_3\overline{q}_4$, CR could lead to the formation of alternative "flipped" singlets $q_1\overline{q}_4$ and $q_3\overline{q}_2$, and correspondingly for more complicated string topologies. Such CR would be suppressed at the perturbative level, since it would force some W propagators off the mass shell [7]. This suppression would not apply in the soft region, and a number of models were developed.

The main Pythia ones were scenarios I and II [7], which take their names from the analogy with type I and II superconductors. Strings are viewed as elongated bags in the former, and reconnection is proportional to the space–time overlap of these bags. In the latter, strings are instead imagined as vortex lines, and two cores need to cross each other for a reconnection to occur. In either case it is additionally possible to allow only reconnections that reduce λ, scenarios I′ and II′.

Among other models, the Ariadne ones were based on λ reduction in combination with colour algebra restrictions [8],[9], whereas the Herwig model acted to reduce the space–time size of clusters [10].

Based on a combination of results from all four LEP collaborations, the no-CR null hypothesis is excluded at 99.5% CL [11]. Within scenario I the best description is obtained for ∼50% of the 189 GeV W^+W^- events being reconnected, in qualitative agreement with predictions.

As an aside, it was also proposed [12] that Bose–Einstein correlations between identical pions produced in the two W systems could lead to further interconnection effects. Only 0.17 ± 0.13 of the predicted effect was observed [11], i.e. consistent with no effect at all, and at most giving a 7 MeV mass shift.

CR studies spread to HERA. Specifically, the Uppsala group described diffractive production in DIS, i.e. the presence of rapidity gaps in the hadronic system, in terms of CR [13]. This model was later extended also to other processes in e^+e^- and $pp/p\bar{p}$, including rapidity gaps between jets and the production of gauge bosons. One main difference to the Lund approach is that minimization is imposed in terms of a string "area" $A \approx \sum m^2$ [14] rather than the $\lambda \approx \sum \ln m^2 = \ln \prod m^2$.

CR models at the LHC

The concept of CR has been well established also at the Tevatron and the LHC, e.g. by the same $\langle p_\perp \rangle(n_{\mathrm{ch}})$ behaviour as at the S$p\bar{p}$S. Over the years, as the MPI modelling in Pythia has evolved, also new CR scenarios have been added. The detailed space–time picture of the LEP 2 models has been deemed too complicated and uncertain to apply to hadron collider events, so instead the reduction of the λ measure has played a key role. In total Pythia 6 [15] came to contain twelve models, many of them involving annealing strategies to reduce λ.

In Herwig++ [16] the default Plain CR considers all quark ends of clusters, and reconnects clusters A and B into C and D by a swap of the antiquark ends if $m_C + m_D < m_A + m_B$. If there are many possibilities open for cluster A, the one is picked which reduces the mass sum the most. The reconnection rate can be reduced by a probability p_{reco} that an allowed reconnection is done. As an alternative, the Statistical CR minimizes the $\sum m^2_{\mathrm{cluster}}$ by simulated annealing.

The current Pythia 8 [17] initially only contained one model. In it two MPIs can be merged with a probability $P = r^2 p^2_{\perp 0}/(r^2 p^2_{\perp 0} + p^2_{\perp \mathrm{lower}})$, where r is a free parameter, $p_{\perp 0}$ is the standard dampening scale of MPIs, and $p_{\perp \mathrm{lower}}$ is the scale of the lower-$p_\perp$ MPI. Each gluon of the latter MPI is put where it increases λ the least for the higher-$p_\perp$ MPI. The procedure is applied iteratively, so for any MPI the probability of being reconnected is $P_{\mathrm{tot}} = 1 - (1 - P)^{n_>}$, where $n_>$ is the number of MPIs with higher $p_\perp$.

A new QCD-based CR model [18] implemented a further range of reconnection possibilities, notably allowing the creation of junctions by the fusion of two or or three strings. A junction is a point where three string pieces come together, in a Y-shaped topology. The relative rate for different topologies is given by $\mathbf{SU(3)}$ colour rules in combination with a minimization of the λ measure. The many junctions leads to an enhanced baryon production, although partly compensated by a shift towards strings with masses too low for baryon production. The model can explain some data but fails in other respects, see next presentation, by C. Bierlich.

Interestingly t, Z^0 and $W^\pm$ all have widths around 2 GeV, i.e. $c\tau \approx 0.1$ GeV. This means that their decays happen well after the (Lorentz-contracted) "pancakes" of the two incoming beams have passed through each other, and after the perturbative activity at scales above 2 GeV, but inside all the hadronization colour fields. The $t/Z/W$ decay products therefore have every chance of experiencing CR with the rest of the event.

Top mass determinations therefore have to take into account the uncertainty from our limited understanding of CR. As an example, the CMS measurement $m_t = 172.35 \pm 0.16 \pm 0.48$ GeV [19] involves an estimated systematic CR error of ±0.10 GeV, based on a comparison of the CR and noCR Pythia 6.4 Perugia 2011 tunes [20].

In order to provide an independent estimate, several new CR models were implemented in the Pythia 8 framework [21]. These fall in two classes. In the late t decays one, ordinary CR is first carried out by the default description, with t considered stable. After the subsequent t and W decays, the gluons from these can reconnect with the gluons from the rest of the event, using separate models. Some of these are intended to be straw-man ones, e.g. where random reconnections can occur, also when λ increases. In the early decays class, the t and W decay products undergo CR on equal footing with the rest of the event. A gluon may be moved from one location to another, or two gluon chains may flip, i.e. reconnect with each other, or two gluons may be swapped. In either case a reduced λ is required.

It is easy to shift the top mass downwards, by reconnecting the top decay products to particles outside the jet core and thereby broadening the jet profile, but more difficult to shift it upwards, since parton showers tend to select minimal λ values from the onset. Extreme values can be excluded, however, since they would give too broad jet profiles and other problems. Restricting the models to acceptable parameter ranges, the resulting reconstructed mass range is around 0.5 GeV, i.e. ±0.25 GeV. This is in line with previous studies for the Tevatron [22], but now with a broader range of models.

CR at future e^+e^- colliders

The CR issues already noted for LEP 2 will reappear at any future high-energy e^+e^- colliders. It will be especially relevant for the FCC-*ee*, with its high luminosities and resulting high precision. With the W mass determined to better than 1 MeV by a threshold scan [23], the hadronic and semileptonic WW channels can be used to probe the impact of CR. Some examples of how Pythia 8's CR scenarios shift the average reconstructed W mass are shown in Table 1. A common trend is that effects are reasonably small near the threshold, then initially increase with energy, but eventually decrease as the W's decay further apart. Most models also tend to shift the W mass upwards, when away from the threshold region, but GM-I offers an interesting counterexample. The GM variants also nicely illustrate that different aspects of a CR model may go in opposite directions and partly cancel. The CS model, finally, is an example where mass shifts are tiny.

E_{cm}	$\langle \delta \overline{m}_{\text{W}} \rangle$ (MeV)						
(GeV)	I	II	II′	GM-I	GM-II	GM-III	CS
170	+18	−14	−6	−41	+49	+2	+7
240	+95	+29	+25	−74	+400	+104	+9
350	+72	+18	+16	−50	+369	+60	+4

Table 1: Reconstructed average W mass shift for different CR models, relative to the no-CR baseline, at three different e^+e^- CM energies [24]. The first three are the I, II and II′ models from LEP 2 days [7], the next three the "gluon move" model introduced for top mass studies [21], where I is only move, II is only flip and III is both, and finally CS is the new QCD-based model [18].

It should be stressed that this is for one (simple) mass reconstruction algorithm. Variations in the algorithm give somewhat different outcome, and thereby probe details of the models. Other measures can also be used, such as the particle flow between jets, or changes in the charged multiplicity as a function of topology. The prospects for pinning down the CR mechanism at the FCC-*ee* therefore are good.

An understanding of the CR not only is of interest in itself, but also for all kinds of precision studies. As an example we take the study of Higgs properties. In the Standard Model the 125 GeV Higgs is a pure CP-even state, but in various extensions there can be an CP-odd admixture, and an important task is to set stringent limits on this. One possibility is to study angular correlations in $H^0 \to W^+W^- \to q_1\overline{q}_2q_3\overline{q}_4$ decays. The catch here is that CR also can shift jet directions, since the particle flow around a parton is biased in the direction towards its colour partner, by standard string effects. This can give rise to deviations that could be misinterpreted, unless CR is well understood [24]

Summary and outlook

CR has been with us for 30 years, as a building block in the picture of multihadron production at high-energy colliders. Its existence has been convincingly demonstrated at LEP 2, but statistics was too small to allow any quantitative studies. The FCC-*ee* would allow detailed tests of the CR phenomenon, especially in the hadronic WW channel, and the experience gained would help constrain the potential errors in other studies.

The picture is less clear for *pp* collisions, be it at the LHC or a future FCC-*pp*, where the busy environment not only allows much larger CR effects than in the relatively clean e^+e^- setup, but also opens the way for many further poorly understood effects. Indeed, the LHC studies have revealed patterns more commonly associated with heavy-ion physics and quark-gluon-plasma formation, from the ridge effect [25] to the increase of strangeness production in high-multiplicity events [26]. These are not explained by the standard PYTHIA framework, with or without CR. A solution could be the fusing of several strings into colour ropes [27], as further described in the presentation by C. Bierlich. One consequence of the changing landscape is that what used to be considered a key proof of CR in *pp*, namely the rising of $\langle p_\perp \rangle(n_{\mathrm{ch}})$, now could find alternative explanations, e.g. in terms of an increased string tension for closely-packed strings, or hadronic rescattering in a dense hadronic gas [28]. This does not mean that CR as such is in doubt, only that we may be faced with a cocktail of poorly understood effects, making further progress more challenging, but also invigorating the whole field of soft physics studies at hadronic collisions. To be continued ...

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