COLOUR INTERCONNECTION - NONPERTURBATIVE ASPECTS

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A short review is presented for nonperturbative aspects of colour interconnection effects. Different models are discussed, and also possible signals and the effect on a precision measurement of M_W at LEP2.

1 Introduction

A hard process like an e^+e^--annihilation event is successfully described in terms of two phases: First a short time ($t \lesssim 0.3$ fm) perturbative phase described by parton cascades. Here only planar diagrams are included in the MC programs. Secondly a long time ($t \sim 1 - 2$ fm) hadronization phase described by a string or a cluster chain, where the parton state is transformed to a hadron state with probability 1. In the $N_c = \infty$ limit only planar diagrams contribute and the string topology is completely fixed. With 3 colours many problems are encountered:

- The topology is not unique
- Full QCD states are *not* described by perturbative QCD
- Non-planar diagrams do contribute

Assume that a parton state is produced as in fig 1a. The partons can be connected in different ways as shown in fig 1b-d. Since different string topologies give different hadronic states, the topology is in principle an observable. Thus to describe a state in QCD, it is not enough to specify the colour, momentum and polarization of the partons. Also a topological quantum number has to be given, which describes the response of the vacuum condensate[1,2]. It has been proposed by 't Hooft[1] that this corresponds to gauge singularities, as in a superconductor. Thus we have a set of questions:

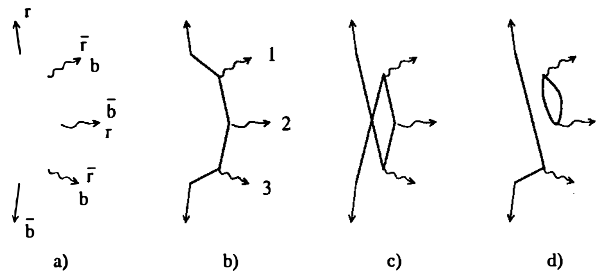


Figure 1: The partons in a) can be connected in three different ways as in b), c), and d).

- What mechanism fixes the topology in cases when it is not determined by perturbation theory?
- Is it a random choise between different possibilities, or are some topologies dynamically favoured?
- At which time is the topology fixed? Is only the soft phase involved, or does this process also interfere with the perturbative phase?
- Can these questions be answered by experimental observations?

Note that the commonly used term colour reconnection can be misleading. The colours are only *re*connected in the MC. In Nature they are just connected once.

If we compare with a superconductor we have two different cases. If vacuum is like a type I superconductor, the string should correspond to a flux tube as in the bag model, with a transverse size ~ 1 fm. In the analogue of a type II superconductor the string should correspond to a vortex line with a thin core. If the core determines the topology we might then expect an earlier fixation of the topology in this case [3,2,4].

Another interesting example is the reaction $\Upsilon \to 3g$. Here the amplitude M is proportional to the following colour factor (a, b, and c denote the gluon colours)

$$M \propto \frac{1}{2}d^{abc} = Tr[T^cT^bT^a] + Tr[T^aT^bT^c] \equiv A + B \tag{1}$$

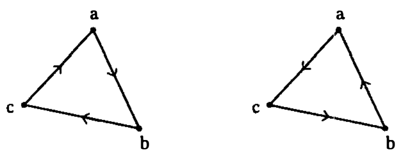


Figure 2: Two different string configurations are possible in the decay $\Upsilon \to 3g$. The direction of the string is defined as going from colour to anti-colour.

The two terms correspond to different orientations of the colour field, corresponding to the two situations shown in fig 2. (The direction is defined as going from colour to anti-colour, i.e. the direction in which a quark is pulled if the field breaks.) The problem is that the two terms in eq (1) are not orthogonal. Summing over colours we find

$$\sum_{colours} |A|^2 = \sum |B|^2 = \frac{(N_C^2-1)(N_C^2-2)}{8N_C}; \quad \sum AB^* = -\frac{N_C^2-1}{4N_C} \tag{2}$$

Thus for three colours the interference term equals 40% of the total result. Since the two "string states" in fig 2 are eigenstates to an observable with different eigenvalues, the full amplitudes have to be orthogonal. The interference term arises from situations when e.g. all gluons are $r\bar{r}$. In those cases the string direction is not determined by the perturbative calculations. Also here we have to ask: What determines the topology in cases when it is not fixed by perturbation theory?

2 Reactions

2.1 $e^+e^- \to q\bar{q}$

In e^+e^--annihilation one can look for special signals, like a gap in phase space obtained if a set of gluons form a separàte colour singlet system as in fig 3. (Note that if colour (re)connection is allowed in the simulation, the MC program has to be retuned.) If two gluons are emitted from the quark or antiquark legs (cf fig 4a) they form a colour singlet with probability 1/8. With many emitted gluons any connected system, as indicated in fig 4b, forms a colour singlet system with the approximate probability 1/8. Here the large number of possibilities can give a large total probability. If the gluons originate from a single initial gluon, as in fig 4c, they form, however, always a colour octet system. Thus for a correct estimate it is necessary to keep track of the emitting colour charge.

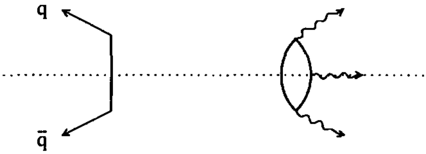
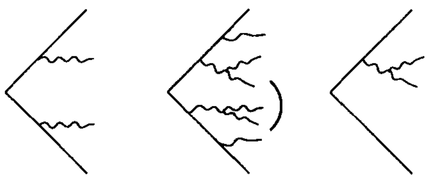


Figure 3: If an isolated gluon system moves away from the remaining system, a central rapidity gap can be obtained.



a) b) c)

Figure 4: a) A pair of gluons emitted from (anti-)quark legs are in a colour singlet system with probability 1/8. b) This is also approximately the case for any connected subsystem. c) An exception is two or more gluons originating from a single gluon parent. Such a system is always a colour octet.

2.2 $e^+e^- \to W^+W^- \to q\bar{q}Q\overline{Q}$

In this reaction the pair $q\overline{Q}$ (and $Q\bar{q}$) will form a singlet with probability 1/9, and also here a possible signal is a central rapidity gap[3]. We note, however, that gluons with energy larger than the width of W are emitted independently by W^+ and W^-[5]. Such gluon emission reduces the difference between "normal" states and recoupled states. However, as indicated in fig 5 it

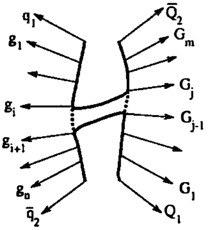


Figure 5: The gluons $g_1 g_2 ... g_n$ (with $E > \Gamma_W$) are emitted from the original $q_1 \bar{q}_2$ pair while $G_1 ... G_m$ are emitted from the $Q_1 \overline{Q}_2$ pair. The reconnected systems indicated with heavy lines are then colour singlets with probability 1/9 for each value of i and j. They may thus form independent hadron strings or chains.

also gives very many recoupling possibilities, which should increase the total recoupling probability. Interconnection effects in this reaction are of particular interest because they can affect a precision measurement of the W mass at LEP2 [4,6].

3 Models

3.1 *"Soft reconnection models"*

In these models the parton cascades are unaffected, and the topology is fixed when the partons move apart.

Sjöstrand and Khoze [4] have studied a set of models based on a geometrical picture in coordinate space. In Model I the confining field is assumed to behave like a flux tube. When two flux tubes (or different parts of one flux tube) overlap there is a possibility for reconnection. The probability for the reconnection is essentially a free parameter. In Model II the field behaves like a thin vortex line, and a crossing causes a reconnection with probability 1. In this model the probability for reconnection in WW production is around 30%.

In a model by Gustafson and Häkkinen [7,8] it is assumed that colour connection is dynamically favoured between nearby gluons. Reconnections which result in "short strings" are assumed to occur with a probability of the order of 1/9. This gives a total reconnection probability around 15 - 20% at LEP1.

In the Herwig model [9], at the end of the cascade the gluons split into $q\bar{q}$ pairs which form colourless clusters. Here new clusters can be formed by reconnection between the quarks and antiquarks, if they are close in coordinate space. The reconnection probability is also here assumed to be of the order of 1/9.

3.2 *Reconnection also in the parton cascade*

In a parton cascade, colour coherence implies that gluon emission is restricted to angular ordered cones or colour dipoles. In the Monte Carlos there is no interference between different dipoles. In a situation as illustrated in fig 6 it might be better to neglect interference between the original pairs. Such a model is studied by Friberg, Gustafson and Häkkinen [8] (called cascade reconnection model), and a similar model is implemented in the Ariadne MC by Lönnblad [10].

3.3 *Colour non-singlet models*

In these models it is assumed that a colour octet system relatively easily can be transfered into a colour singlet by emitting a soft gluon. Such a model is studied by Ellis and Geiger [11], where very large reconnection effects are obtained. An indication that such large reconnection

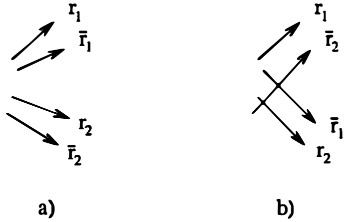


Figure 6: a) Usually a colour charge and its associated anti-colour are close in phase space. b) Occasionally a red charge can be closer to an anti-red charge from a different pair.

probabilities are not inconceivable is obtained e.g. in the decay $B \to \psi X$, where experimental data indicate around 20% probability for formation of a $c\bar{c}$ singlet.

4 Some results. Experimental signals and W mass shift.

4.1 LEP1

Generally soft particles are most affected by reconnection (*cf* the talk by Khoze). Therefore a natural signal to look for is a central gap in heavy quark tagged events, *cf* fig 3. Fig 7 shows results from the GH models for the rapidity distribution and for the multiplicity distribution in a central rapidity bin, for events with a cut in the angle between the tagged quarks of 110°. We note a clear difference, in particular for the cascade reconnection model. With the statistics accumulated at LEP1 it should be possible to determine whether or not reconnection occurs with this probability.

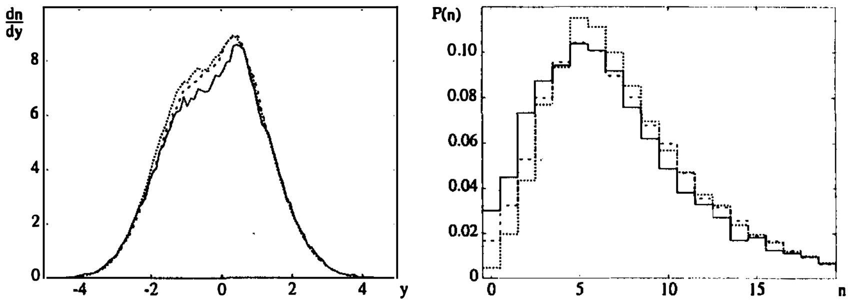


Figure 7: Rapidity distribution for charged particles and distribution of charged multiplicity in the rapidity interval [-1,0] for tagged events with less than 110° between the q and the $\bar{q}$. Dotted line: Default Ariadne, dashed line: GH soft reconnection model, solid line: GH cascade reconnection. Both reconnection models are retuned.

4.2 $e^+e^- \to W^+W^- \to q\bar{q}Q\overline{Q}$

The *signal* for reconnection between the two Ws should be a central hole in the particle distribution [3]. This should be emphasized by a cut in thrust, which selects events where the q and $\overline{Q}$ are relatively close. (The signal is reduced by the W polarization, which favours events where q and $\overline{Q}$ go in opposite directions.) Results from the GH model are presented in fig 8. The conclusion is that it ought to be possible to experimentally observe the recoupling if the recoupling probability is about 30% or larger.

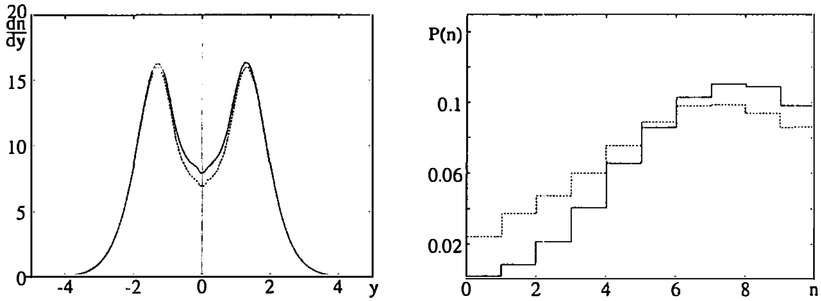


Figure 8: Comparison between "normal" events (solid lines) and recoupled events (dashed lines) for WW decays with a thrust cut $T > 0.84$ in the GH model. Left: Rapidity distributions. Right: Multiplicity distributions for a central bin $|y| < 0.5$.

As mentioned above colour interconnection in this reaction is also of special interest because it will affect a precision measurement of the *W mass* at LEP2[4]. Naturally the mass shift caused by this effect depends upon the method used for the mass determination. Results from different MC analyses are presented in ref 6, and for the colour singlet models one generally finds that the mass shift ΔM_W is of the order of 100 MeV times the recoupling probability.

This implies that we have one of two possibilities: If the recoupling probability is less than 30% we should have both a small signal and a small mass shift ($\Delta M_W \lesssim 30 MeV$). If the recoupling probability and the mass shift ΔM_W are large, this should also be accompanied by a visible experimental signal. For the "colourful" model of Ellis and Geiger the mass shift is very large, but also the signals should be clearly visible.

5 Conclusions

- (Re)connection is an essential problem in QCD, with relations to the properties of the vacuum condensate and the confinement mechanism.
- Possible signals involve in particular soft particles.
- If there is no observable signal, the W mass shift is expected to be small.

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