CERN-TH.6312/91

Some String and Coherence Phenomena*

Torbjörn Sjöstrand
Theory Division, CERN
CH–1211 Geneva 23
Switzerland

Abstract

A few aspects of semisoft or soft QCD phenomena are considered. It is shown that the CM energy dependence of the hadronic energy flow in three-jet events can be used to distinguish perturbative and non-perturbative explanations for the string effect. The possibility of colour flow reconnection in hard processes is reviewed. A method to quantify angular ordering in parton showers is studied.

---

*To appear in the proceedings of the EE500 Workshop on the physics of a 500 GeV e^+e^- linear collider, DESY, Hamburg, September 2 – 3, 1991

CERN-TH.6312/91
December 1991

1 Introduction

The large energies available at a 500 GeV linear collider will permit a number of interesting QCD tests to be carried out. Several examples are given in other contributions to these proceedings. Here we will concentrate on three aspects related to semisoft QCD, namely the distinction between perturbative and non-perturbative effects in energy flows in three-jet events, the possibility that colour flow reconnection in hard processes will affect event shapes, and a method to confirm the angular ordering of parton showers.

For each topic, Monte Carlo studies have been performed. These have been simplified, however, in the sense that issues of beamstrahlung, initial state bremsstrahlung, background processes and detector imperfections have not been considered. Based on the study of Bethke [1], e.g., we may expect an inclusion of such effects to lead to some small quantitative changes, but not to have a qualitative impact on the results presented here.

2 Strings versus Coherence

In the Lund model [2], a simple $q\overline{q}$ event gives rise to a single string, which connects the q and $\overline{q}$ as these move apart, and which fragments into the primary hadrons. The string may here be viewed as the simplest way to implement a linear confinement force in a Lorentz covariant manner. In a $q\overline{q}g$ three-jet event, the Lund model is based on having a string stretched from the quark via the gluon to the antiquark. The string piece between the quark and the gluon has a transverse motion out along a direction intermediate to the quark and gluon directions. The particles which are produced when the string piece breaks therefore receive a Lorentz boost, such that slow particles are systematically shifted slightly away from the origin. A corresponding boost in a direction intermediate to the gluon and antiquark directions is required for the string piece spanned by these two partons.

Since there is not a string piece spanned directly between the quark and the antiquark, no particles are produced in between these two partons, except by 'leakage' from the other two regions, i.e. by transverse momentum fluctuations and by particle decays. In the Lund string picture, there is therefore a direct prediction that the region between the quark and antiquark directions should be significantly less populated than the two other regions between jets [3]. This contrasts with the behaviour in independent fragmentation frameworks [4], where fragmentation takes place symmetrically around each of the three jet directions, and therefore none of the three regions between jets occupies a special position.

Comparisons with data have tended to favour the Lund scenario, and disfavour the independent fragmentation one [5]. The effects that are experimentally observed are actually much smaller than the ones predicted on the Monte Carlo level — it is difficult to know which jet is the gluon one, and therefore the true effect is reduced by the influence of events where the gluon is misidentified. So far, essentially all studies have been based on the assumption that the jet with lowest energy is the gluon one, which is typically true only 60% of the time.

The Leningrad group has shown that the 'string effect' appears as a natural consequence of coherence phenomena in the parton shower evolution [6]. In lowest order, this may be viewed as follows. Start out with a quark, an antiquark and a gluon, all three with approximately the same energy, and let the three partons act as antennae that emit soft gluons in a semiclassical pattern. Due to interference effects between the colour charges of

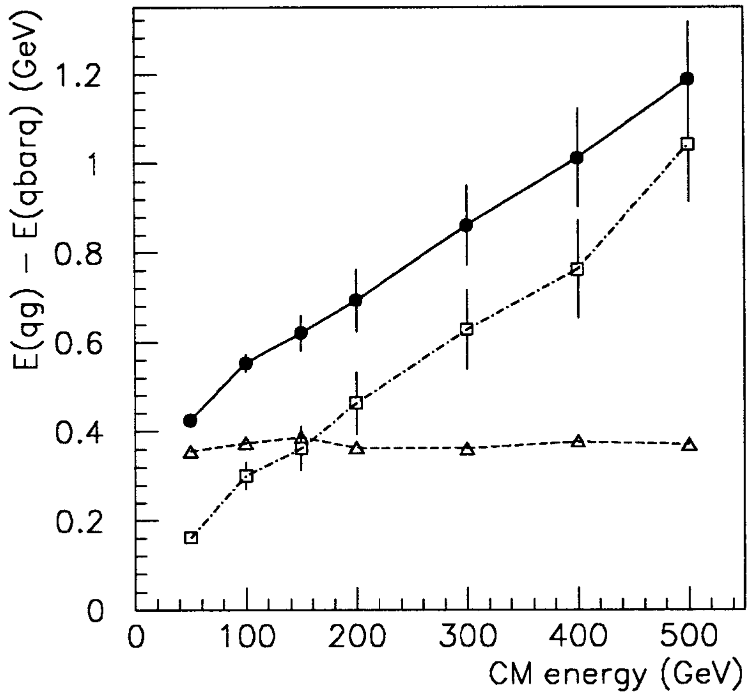

Figure 1: The difference ΔE of energy flows in the central 40% of the 'q–g' and 'q–$\overline{q}$' angular ranges, respectively. Only three-jet events with all jet-jet angles larger than 60° have been used, and the 'gluon' jet is defined as the jet opposite to the largest opening angle. Triangles (connected by dashed lines) show string fragmentation of three-parton events only, squares (dashed-dotted lines) parton level results in a parton shower approach, and the circles (full lines) parton shower followed by string fragmentation. Error bars are for 40,000 hadronic events before cuts.

the three partons, there is then a surplus of radiation in the q–g and g–$\overline{q}$ regions, and a depletion in the q–$\overline{q}$ one. If a term down in order by $1/N_C^2$ (i.e. a colour-suppressed term) is dropped, the two remaining terms may be interpreted as simple qg and $\overline{q}g$ dipole radiation, boosted from the the qg and $\overline{q}g$ rest frames into the overall $q\overline{q}g$ CM frame.

The scenario above literally repeats the explanation given in the string model, with the important difference that, where the string picture is based on purely non-perturbative deliberations, the colour antennae picture is purely perturbative. Despite the sharing of a common ideological basis, namely the importance of the colour flow in events, the two explanations are not describing quite the same physics. The perturbative and non-perturbative scenarios can be distinguished by more detailed tests, based on comparisons of data at different CM energies. In [7] some examples are given, making use of identified particles with different masses ($\pi/K/p$) or different transverse momenta: a boost effect is felt more by particles with a large transverse mass (with respect to the boost direction), while the coherent gluon emission picture makes no such distinction. In the following we will study another test [8], which would be made possible by data from high energy linear colliders.

Consider a three-jet event, with jets of about equal energy. Denote by E_{qg} ($= E_{\overline{q}g}$) the energy flow in the middle of the angular region between the q and g jet directions (e.g. integrated over the central 40% of this region), and by $E_{q\overline{q}}$ the corresponding energy flow between the q and $\overline{q}$ jet directions. In the string picture, E_{qg} and $E_{q\overline{q}}$ are essentially independent of the CM energy: as the energy is increased, more particles are produced along the three jet directions (at large momenta), but the centre of the string pieces between the jets remain the same. In the perturbative framework, on the other hand, it is the *fraction* of the CM energy radiated into gluons between the jets that stays the same, modulo the running of α_S and issues related to the cut-off of the shower evolution at low virtualities. One therefore expects $E_{qg}, E_{q\overline{q}} \propto \alpha_S E_{CM}$. In forming the ratio $E_{qg}/E_{q\overline{q}}$, as has traditionally been done, the energy dependence is factored out, so that both approaches predict a constant ratio as function of CM energy.

The energy difference, $\Delta E = E_{qg} - E_{q\overline{q}}$, however, preserves the contrast between the two approaches. Furthermore, it allows for a world in which not all is 'black and white', but where both perturbative and non-perturbative contributions coexist. One would therefore expect an energy dependence of the form

$$\Delta E(E_{CM}) = E_{qg}(E_{CM}) - E_{q\overline{q}}(E_{CM}) = c_1 + c_2 \alpha_S E_{CM}. \qquad (1)$$

The presence of both these terms in the data would thus demonstrate the complementary nature of the perturbative and the non-perturbative contributions, with the slope representing the perturbative piece and the constant term the non-perturbative one.

In Fig. 1 we show that the complete event generation scheme in JETSET [9], which is based on a perturbative shower followed by the non-perturbative string fragmentation, does indeed behave according to expectations. Three different scenarios are compared. In the first, three-parton events are generated according to first-order QCD and then fragmented, to give the 'pure' non-perturbative behaviour. In the second, a parton shower is generated instead, and the parton level energy flow is studied. In the third, finally, the events of the second scenario are allowed to fragment. All simulations are for 40,000 5-flavour events, with full γ/Z^0 exchange included. Exactly three jets are identified with the LUCLUS algorithm [9], and events with all opening angles between jets larger than 60° are accepted as *bona fide* three-jet events. The gluon jet is identified as the one opposite to the largest opening angle, i.e. the 'q–$\overline{q}$' angular range is the largest one and the 'q–g' range the middle one. This identification method is not very reliable, and therefore the true effect is significantly reduced. If prompt leptons or secondary vertices can be used to give a more reliable quark jet identification, the ΔE values would be much larger than the ones shown in Fig. 1.

In conclusion, it should be possible to use the energy dependence from LEP onwards to show the presence both of the constant non-perturbative term and the rising perturbative one. In the region below LEP 1, and in particular below 40 GeV, additional sources of experimental problems appear (e.g. fake 3-jet events from $b\overline{b}$ events), which means that comparisons between LEP and PETRA/PEP cannot be made very convincing. In addition, the need for a consistent analysis strategy at different CM energies could be ideally filled by a linear collider.

3 String Reconnection

In an event with several colour charges, new prospects open up. Consider, e.g., an event containing two quarks, q_1 and q_2, and two antiquarks, $\overline{q}_1$ and $\overline{q}_2$. The string picture allows those partons to be paired into colour singlets in one of two ways, either $q_1+\overline{q}_1$ and $q_2+\overline{q}_2$ or $q_1+\overline{q}_2$ and $q_2+\overline{q}_1$. A given event may be either one or the other, but not both at the same time. In a standard perturbative picture, on the other hand, the total emission rate of gluons is generated by a multipole containing all four charges. The multipole contains many terms, four of which may be related to the four dipoles above. All four dipoles are thus allowed to radiate in one and the same event.

Taken literally, the string picture therefore introduces additional 'quantum numbers', not present in the perturbative language, but related to the long-distance confinement force. In its logical extreme, this could even lead to a modification of the standard perturbative cross-sections by terms of order $1/N_C^2$ [10].

Leaving aside that possibility, one could still hope to observe some consequences of the string picture by a study of event shapes. One particularly attractive possibility is studied in [11], where WW pairs close to threshold are considered. Here each W decays to a quark-antiquark pair, which forms a colour singlet by itself, i.e. we are in the normal $q_1+\overline{q}_1$ and $q_2+\overline{q}_2$ situation of above. However, the exchange of a gluon would lead to the alternative $q_1+\overline{q}_2$ and $q_2+\overline{q}_1$ configuration. That such exchanges can and do happen is illustrated by the example of J/Ψ production in B meson decay, which would not be allowed otherwise. One would expect the alternative configurations to appear at a significant rate only close to the WW pair threshold, since otherwise the two W's will have time to travel apart some distance before they decay, and then gluon exchange should be suppressed.

In [11] it is shown how a gluon exchange would affect event topologies. Consider, e.g., events where the W^+ and W^- decays give small $q_1+\overline{q}_2$ and $q_2+\overline{q}_1$ invariant masses. If a colour exchange takes place, the fragmenting strings therefore produce few particles. By the string boosts, these particles are swept away from low momenta. The rapidity distribution (with respect to the thrust axis, for example) therefore has a deep dip at around $y = 0$. If no exchange takes place, on the other hand, both strings have the W mass, and connect a q on one side of the event with a $\overline{q}$ on the other. Therefore the total multiplicity is much higher and there is no significant rapidity dip (a shallow dip does develop just by trivial kinematics).

One would hope that these aspects can be studied at LEP II. By the time a 500 GeV linear collider is available, we should therefore already be in a position to say if these phenomena occur in nature or not. Presuming they do, what consequences would they have at higher energies? There are several additional processes where colour exchange could take place, like in triple gauge boson production, in $t\overline{t}$ pair production with hadronic t and $\overline{t}$ decays, especially close to top threshold, and in many processes involving new particles (e.g. supersymmetric ones) which cascade down by the emission of W's, Z's and quark pairs. Here we make the point for just one especially interesting possibility, namely an intermediate mass Higgs.

A standard model H^0 has a 10% branching ratio to W^+W^- or Z^0Z^0 at a 115 GeV mass (obviously with at least one W/Z off mass-shell), and thereafter this branching ratio rapidly increases to close to 100%. The other main decay channel is $b\overline{b}$. One is therefore in the unique situation that, whatever the Higgs mass is, in a range from 115 GeV to around 200 GeV, there is a significant rate of WW pair production close to threshold, where string reconnections could take place. As it happens, this is also the mass range where the minimal supersymmetric extension to the standard model predicts the presence of at least one neutral

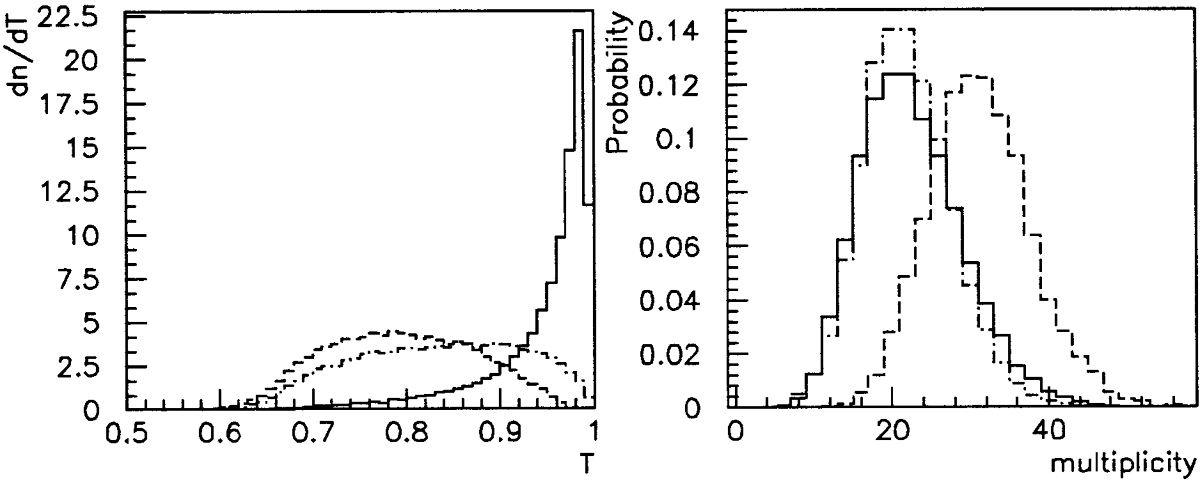

Figure 2: Thrust distribution (left) and charged multiplicity distribution for events with $T > 0.9$ (right). Full curve for Higgs decay to $b\bar{b}$, dashed for decay to W^+W^- (with subsequent hadronic decays) without string reconnection and dash-dotted ditto with string reconnection. Results are for a 150 GeV Higgs. Each curve is normalized to unit area, i.e. relative branching ratios have not been folded in.

Higgs particle [12]. If such a particle is indeed discovered, a measurement of its branching ratios would be essential to pin down the model. To do this, it would be necessary to understand the topology of WW events, and in particular how often a WW event could mimic a $b\bar{b}$ one (and vice versa).

In Fig. 2 we show the example of a 150 GeV Higgs, which either decays to $b\bar{b}$ or to W^+W^-, with W's assumed to decay hadronically. One should note that if string reconnection takes place, the thrust distribution of the W^+W^- event is shifted closer to unity, and thus forms a larger background under the $b\bar{b}$ peak. Note that a standard model Higgs with a 150 GeV mass would have a $b\bar{b}$ branching ratio of only 24%, compared to 71% for WW/ZZ; the thrust peak would therefore in absolute terms not be as impressive as it seems from Fig. 2. For events with $T > 0.9$, the multiplicity distribution of reconnected W^+W^- events closely agrees with that of $b\bar{b}$ ones, while normal W^+W^- events have a larger multiplicity. The separating power lost in the multiplicity distribution could be compensated by the deeper dip at around rapidity zero for reconnected W^+W^- events.

It should be admitted that effects of colour reconnection are as drastic as above only if both perturbative shower evolution and non-perturbative fragmentation take place within the reconnected systems. If the shower evolution is assumed to take place before the reconnection, the effects are much smaller, in particular in the thrust distribution.

4 Angular Ordering

In a coherent shower, the decay angle of a parton is restricted to be smaller than its production angle, where the former angle is defined between the two decay products and the latter

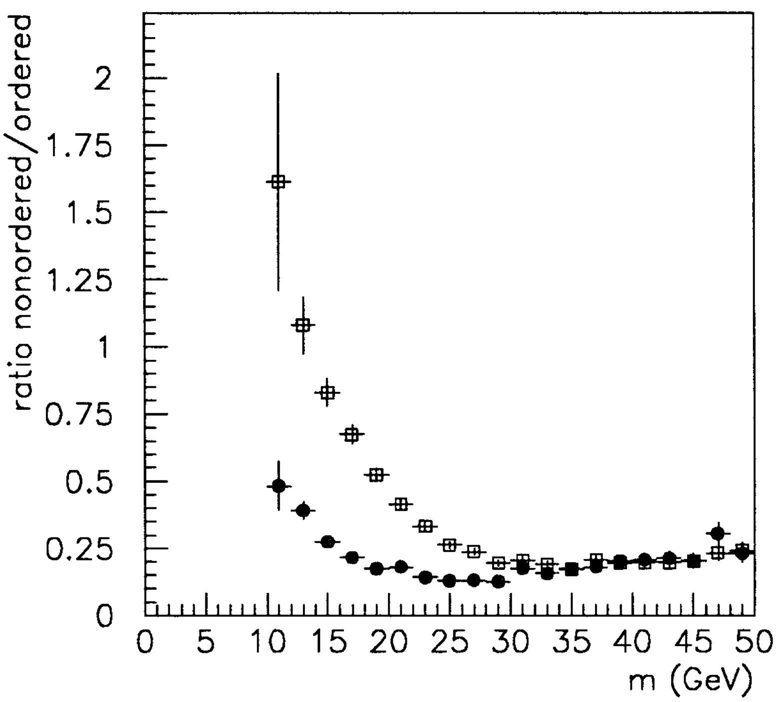

Figure 3: The ratio R_r, i.e. the ratio of ordered to non-ordered branchings (see text for details), as a function of the jet mass m. Coherent shower is marked by circles, non-coherent by squares.

between the parton and its sister in the preceding branching. This angular ordering requirement is a consequence of destructive interference [13]. The angular ordering requirement has a number of consequences, e.g. a reduced growth rate of parton multiplicity as a function of CM energy, and a suppression of parton production at small momenta [14], which are all in very good agreement with data.

The tests are mainly indirect, however. In particular, if one combines an incoherent shower (i.e. without angular ordering) with the standard string fragmentation picture, all existing data can be explained fairly well at any fixed CM energy. It is only when comparing different CM energies that the coherent showers are at an advantage, since they can describe all data with a fixed set of parameters, while the incoherent showers need to have parameters retuned. Over the currently explored range of CM energies the mismatch is not dramatic, however. So whereas the theoretical support for angular ordering is strong, it would be preferable to have a more direct experimental test.

One such test is proposed in [15]. Since it is based on the explicit reconstruction of many separate jets per event, LEP energies are not quite enough to provide a good separation between alternatives. The higher energies of a 500 GeV collider will allow the explicit reconstruction of more jets, and thus make this test feasible, as we will show below. Of course, we must remember that the comparison is based on only one set of incoherent and coherent showers, namely what is found in JETSET, and that further comparisons with other alternatives would have to be included in a definite analysis.

The first step is to reconstruct a number of jets, which is performed by the LUCLUS algorithm, with a maximum jet recombination scale of $d_{join} = 4$ GeV. This gives an average number of 4.6 and 4.8 jets per event for the coherent and non-coherent showers, respectively. (The average number of particles is 67 and 91, respectively, if π^0 decays are not included.) The jet resolution adopted is about as far as one can go and still not have too many 'spurious' jets, more determined by fluctuations in the fragmentation than by the parton shower structure.

Next the two jets with the smallest invariant mass are recombined into a 'mother' jet. This procedure is iterated until all jets have been recombined into one single one. At a recombination the angle between the recombined jets is also calculated. For each jet, except all the original ones and the single final one, a ratio $r = \theta_{decay}/\theta_{prod}$ can therefore be calculated, where θ_{decay} is the angle between the two daughter jets that were recombined to form the jet, and θ_{prod} is the angle to the sister jet when the jet itself is recombined. If this experimental definition of shower history agrees with the 'correct' one, the requirement of angular ordering simply means that $r < 1$ always.

Of course, the mass reconstruction above is not an exact tracing of the shower history: even in a coherent shower an $r > 1$ will sometimes be reconstructed. To quantify how often this happens we use the ratio $R_r = n(1.4 < r < 2.0)/n(0 < r < 0.6)$, i.e. the ratio of the number of clearly non-ordered opening angle ratios to the number of clearly ordered opening angle ratios. The ratio R_r is conveniently plotted as a function of the mass m of the jet considered, Fig. 3. This way, one obtains a direct normalization check of the two curves to each other at large masses, where one is mainly probing the three-jet structure (which is constrained by first-order matrix elements) and not so much the interference between several subsequent gluon emissions.

A difference therefore shows up in the mass range 10 — 30 GeV only, and there is of the expected kind, i.e a non-coherent shower picture gives more non-ordered branchings. The error bars refer to a statistic based on 40,000 multihadronic events, but clearly the separation would be visible with much less statistics than that, contrary to the case at lower energies.

5 Summary

Despite impressive progress in our understanding of QCD, there are many aspects where we still do not know the whole picture. In this report we have shown three such examples, where experiments at a high energy linear e^+e^- collider could help clarify the properties of QCD. Many of the uncertainties are reflected not only in the properties of the standard multihadronic γ/Z annihilation events, but in any event type where hadrons are produced. This includes most processes, within the standard model and beyond. Continued QCD studies are therefore essential.

References

[1] S. Bethke, these proceedings

[2] B. Andersson, G. Gustafson, G. Ingelman and T. Sjöstrand, Phys. Rep. **97** (1983) 31

[3] B. Andersson, G. Gustafson and T. Sjöstrand, Phys. Lett. **94B** (1980) 211

[4] For a review and references see e.g.:
T. Sjöstrand, Int. J. Mod. Phys. **A3** (1988) 751

[5] JADE Collaboration, W. Bartel *et al.*, Phys. Lett. **101B** (1981) 129; Z. Physik **C21** (1983) 37;
TPC/2γ Collaboration, H. Aihara *et al.*, Z. Physik **C28** (1985) 31;
TASSO Collaboration, M. Althoff *et al.*, Z. Physik **C29** (1985) 29;
OPAL Collaboration, M.Z. Akrawy *et al.*, Phys. Lett. **B261** (1991) 334

[6] Ya.I. Azimov, Yu.L. Dokshitzer, V.A. Khoze and S.I. Troyan, Phys. Lett. **165B** (1985) 147; Yad. Fiz. **43** (1986) 149

[7] V.A. Khoze and L. Lönnblad, Phys. Lett. **B241** (1990) 123

[8] T. Sjöstrand, *in* Z^0 Physics, Cargèse 1990, eds. M. Lévy *et al.* (Plenum Press, New York, 1991), p.367

[9] T. Sjöstrand, Computer Physics Commun. **39** (1986) 347;
T. Sjöstrand and M. Bengtsson, Computer Physics Commun. **43** (1987) 367

[10] G. Gustafson, Z. Physik **C15** (1982) 155

[11] G. Gustafson, U. Pettersson and P. Zerwas, Phys. Lett. **B209** (1988) 90

[12] See, e.g., the contribution by A. Brignole *et al.* in these proceedings

[13] A.H. Mueller, Phys. Lett. **104B** (1981) 161;
B.I. Ermolaev and V.S. Fadin, JETP Lett. **33** (1981) 269

[14] For a review and references, see e.g.:
Yu.L. Dokshitzer, V.A. Khoze and S.I. Troyan, *in* Perturbative QCD, ed. A.H. Mueller (World Scientific, Singapore, 1989), p. 241

[15] M. Bengtsson and T. Sjöstrand, Nucl. Phys. **B289** (1987) 810