PHENOMENOLOGICAL STUDIES
ON JET FRAGMENTATION

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Abstract

This thesis is centered on the development of and studies with a phenomenological model for the fragmentation of jets in high energy particle physics - the Lund model. Whereas QCD provides a description of quark and gluon interactions at high Q^2, it is at present not known how to apply QCD to describe the confinement phenomenon. We have developed a model based on the dynamics of the massless relativistic string with no transverse excitations. The string may break by the production of quark-antiquark (or diquark-antidiquark) pairs in the field, and a quark from one pair may combine with an antiquark from an adjacent pair to produce a hadron. In a $q\bar{q}g$ event the gluon is considered as a (momentum-carrying) kink on the string stretched between the q and the $\bar{q}$. We study the structure of jets in different processes, particularly in e^+e^- annihilation and in leptoproduction. To allow detailed studies we develop a Monte Carlo computer program that simulates the whole event chain. Problems considered include: the identification of gluon jets, the production of baryons and modifications to the energy flow from soft gluon emission. Comparisons, which generally show good agreement, are made with existing data and predictions are made for further tests.

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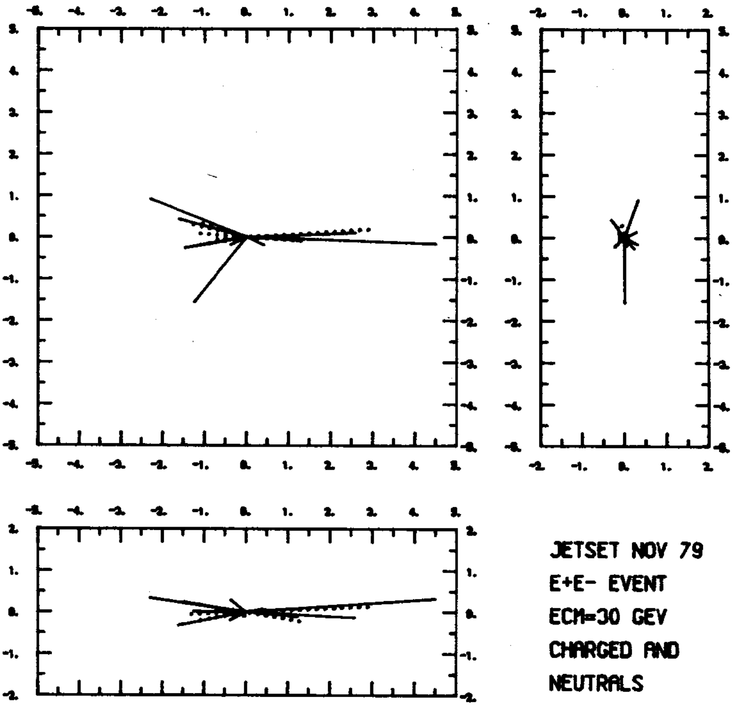

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Phys. Lett. 94B (1980) 211

III. B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand
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IV. B. Andersson, G. Gustafson, T. Sjöstrand
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V. B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand
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VI. B. Andersson, G. Gustafson, T. Sjöstrand
On Soft Gluon Emission and the Transverse Momentum Properties of Final State Particles
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VII. G. Ingelman, B. Andersson, G. Gustafson, T. Sjöstrand
Transverse Momentum Effects and Angular Energy Flow in Leptoproduction
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VIII. T. Sjöstrand
The Lund Monte Carlo for Jet Fragmentation
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Introduction

The human search for the truly elementary constituents of matter and their interactions is a long and arduous one. It is however only in the last few hundred years that real, systematic progress has been made. The development of chemistry lead to a picture of a limited number of different atoms building up the variety of our everyday world. The atom is however not indivisible. In the beginning of this century it was shown to consist of a small central nucleus surrounded by a cloud of electrons, which rather easily could be "kicked out". Later it was demonstrated that the different possible nuclei consisted of protons and neutrons, harder bound than the electrons, but still possible to liberate e.g. in nuclear reactions.

In the beginning of the thirties the basic building blocks were thus down to three: the electron, the proton and the neutron. In order to describe interactions between them another two were required: the photon, mediator of the electromagnetic force, and the neutrino, which was created in weak nuclear decays. This simplicity was however somewhat deceptive, since it left the forces binding the nucleus together unexplained. (Properly also the gravitational force should be taken into account, but gravity is so weak that it is normally neglected in the microscopic world.) The existence of a "pion" was postulated to account for these strong nuclear forces, and the search to find it began.

The pion was found, but so were a lot of other particles that were neither expected nor wanted. Although very short-lived, these particles did not seem to be any less fundamental than e.g. the proton. Eventually the total number counted in the hundreds. A small group called leptons, including the electron and the neutrino, are still today generally considered fundamental and pointlike particles. The vast majority, called hadrons, are related to the proton, neutron and pion in that they can interact via the strong force. Although inconceivably small by human standards, they can still be shown to have a size in the order of 1 fm = 10^{-15} m.

In 1963 it was suggested that the hadrons are built up from more fundamental objects, called quarks. The proton, the neutron and other "baryons" are then assumed to consist of three quarks while the pion and other "mesons" consist of one quark and one antiquark. Again a great simplification could take place, hundreds of hadrons could be described just in terms of three different kinds, later dubbed flavours, of quarks.

If quarks really exist, it is natural to assume that they can be kicked out and observed free, just like e.g. neutrons. Since the quarks were predicted to have some distinct properties, like charges one or two thirds of the electron charge, they should stand out rather easily. When experiments failed to detect them, it was a setback for the quark concept. On the other hand, in the late sixties an inner "grainy" structure was observed in the proton (by ep scattering experiments at SLAC). It was tempting to associate these grains, "partons", with quarks.

At about the same time so-called non-abelian gauge theories became popular, and were eventually shown to have nice mathematical properties, like e.g. renormalizability. They were applied to provide a unified theory of weak and electromagnetic interactions, the SU(2)×U(1) theory, popularly called QFD. Another theory of this type, suggested in 1972, is the SU(3) theory of strong interactions called QCD, in which quarks are taken seriously as dynamical entities. For the following it should be made clear that, although QCD (and similarly QFD) in principle gives a closed description of the forces it is constructed to explain, with a limited number of parameters as input, it is mathematically too difficult to be solved explicitly. Instead perturbation theory and other different approximation schemes are used to extract important features.

In QCD each quark flavour is supposed to come in three different varieties, whimsically called colours: red, green and blue. Each particle observed in nature would then be white (more precisely, a colour singlet), for a baryon corresponding to the three quarks being red, green and blue, respectively, for a meson e.g. to the quark being blue and the antiquark yellow (=antiblue). The forces between the quarks are mediated by eight different "gluons", each carrying a colour and an anticolour (colour octets), e.g red+yellow.

QCD also suggests, although it has so far not been proven, that quarks should be absolutely confined to hadrons, i.e. that no object with nonzero colour charge could exist free. The reason for this would then be that the force acting between two coloured objects does not fall off with distance in the same way as e.g. the force between two electrical charges. In QCD the effective coupling constant α_s can be shown to depend strongly on the energy scale squared Q^2, in lowest order

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln(Q^2/\Lambda^2)} \tag{1}$$

with n_f the number of different quark flavours (3-5 depending on energy regime) and Λ a parameter in the order of 100-400 MeV. Hence, at small distances, corresponding to large Q^2, the coupling constant becomes small and the quarks behave essentially as free, "asymptotic freedom". Conversely, at large distances and small Q^2, α_s becomes large and perturbation theory breaks down. It may then be that the force stays constant with distance, corresponding to the field between two colour charges being compressed (by gluon field self-couplings) into a tube of essentially constant cross section and constant energy density per unit length, a colour flux tube. A quark which is "kicked", i.e.

imparted with some energy, will thus draw out a flux tube when it recedes, and so stretch the field to a length proportional to the energy imparted, but will not be able to move beyond this.

On the experimental front, the inner structure observed in the proton could now be well explained by the existence of quarks and gluons. The pivotal point was however the "October Revolution" in November 1974, when a particle was found which contained quarks of a new, fourth flavour. This quark had in fact already been predicted within the theory for weak interactions. From then on quarks have become commonly accepted, with QCD and QFD considered as strong candidates for the description of their interactions.

Jet Phenomenology

If we thus no longer expect to see quarks coming out from a high-energy collision, what is really observed experimentally and how does that compare with theory? The answer is that, broadly speaking, whenever one would have expected to see a quark or a gluon emerging, one instead observes a cluster of particles going out in the same general direction - a jet.

More precisely, the particles in a jet seem to have a limited transverse momentum $\langle p_t \rangle \approx 300$-$400$ MeV with respect to the jet direction, whereas the distribution in longitudinal momentum roughly scales with the jet energy. Therefore a jet structure will only be visible above some minimum energy and will become more pronounced at higher energies.

Most clearly this is seen in e^+e^- annihilation events in the continuum, where we expect the creation of a quark and an antiquark going out in opposite directions, and where experimentally a two-jet structure is prominent at PETRA and PEP energies, around 30 GeV. Before that, jets were observed at SPEAR at much lower energies, ≈ 5 GeV, but then only after a careful analysis of the data. The jets also have the $1+\cos^2\theta$ distribution in angle characteristic for spin 1/2 objects, specifically quarks. In a smaller fraction of the events, three or more jets appear, within QCD readily explained as the bremsstrahlung of one or more gluons off the original quark and antiquark.

Another important process is lepton-nucleon scattering, where (in leading order) one quark is kicked out of a target proton, leaving behind a diquark target remnant. In this case one forward jet is observed. A fraction of the events (down in magnitude by one factor of α_s) is of the gluon emission or photon-gluon fusion type and contains two forward jets. Other processes where jets may be studied include onium decays (Υ, toponium?), lepton pair production (Drell-Yan events etc.) and high-p_t and low-p_t events in hadron-hadron collisions. In this connection, the high energies obtained in the SPS $p\bar{p}$ collider have recently provided us with pictures of the most complicated jet structures observed to date.

If we look closer, a typical event can phenomenologically be separated into three phases. The first phase contains the hard primary interaction and e.g. hard gluon bremsstrahlung in immediate connection herewith. This part is characterized by small distances and large momentum transfers, and a process-dependent description can be given in terms of perturbative QCD, where quarks and gluons are considered essentially free. In the second phase, the quarks and gluons are receding from each other. Confinement forces begin to dominate and eventually lead to a breakup of the system into a number of primary hadrons. The third phase consists of the decay of unstable hadrons into the observable particles. The transition between the first and the second phase should of course be continuous, yet it is for practical purposes convenient to draw a line somewhere and consider the subsequent jet fragmentation and particle decays as independent of the primary interaction.

Whereas the QCD formalism for the hard interactions can be considered with some degree of confidence, although with many questions unanswered, any quantitative description of the confinement force and hence of jet fragmentation can at present not be given within the QCD framework. Phenomenological models have instead been formulated to describe the fragmentation process. Many different schemes have been suggested, too many to be reviewed here. Most of them are of an iterative and probabilistic nature, i.e. the basic process is jet → hadron + remainder-jet, where the hadron will be produced with given flavour and momentum according to some probability distribution which depends on the jet flavour and momentum, and where the remainder-jet fragments just like an original jet with scaled-down energy. The perhaps first model of this type is by Krzywicki and Petersson [1], while the perhaps most generally known is by Field and Feynman [2]. This thesis centers on the development of a more comprehensive model in the same spirit, the Lund model.

Phenomenological models are valuable for two reasons. One is that the results obtained from QCD about the primary interaction are smeared by the hadronization process, so that detailed comparisons between perturbative QCD and experiments are almost impossible if the jet fragmentation is not taken properly into account. The other is that comparisons between experiments and models will help us understand the workings of the confinement mechanism better, specifically help us extract the important features even out of jets with large particle multiplicities, complicated geometries and large statistical fluctuations.

Even simple phenomenological models may become difficult (i.e. in practice impossible) to solve analytically, in particular when correlations between many particles are involved. One convenient way out is here offered by computer simulation of complete events: matrix elements from perturbative QCD (maybe together with structure functions etc.) are used to give an initial jet configuration, phenomenological models are called on to describe the fragmentation of these jets, and particle data tables are consulted for the decay of unstable particles. All the different phases involve probability distributions which are sampled with Monte Carlo techniques. In the end complete events are obtained that can be compared with the jets observed in nature.

Experimental groups often take the process one step further and run Monte Carlo-generated events through special detector-simulation programs to see what would actually be observed in their detector, and to compare directly with raw data without the need to make corrections for detector acceptance etc. Similar methods may also be used in planning new detectors, to check what phenomena one could hope to study with a given detector design.

Thus, in parallel with the Lund model we have developed the Lund Monte Carlo, to study the model, compare with data and make predictions. This program has also found widespread use among experimental groups at CERN, DESY, SLAC, FNAL, Cornell and other places. In addition to comparisons with existing data it has also been used to study events at higher energies, e.g. at LEP [3] and CHEER.

The Lund Model

In a jet event like e.g. $e^+e^- \rightarrow q\bar{q}$, the picture is of a q and a $\bar{q}$ going out in opposite directions, with a colour flux tube, an elongated colour bag, being stretched between them. We assume that the potential between the q and $\bar{q}$ is linearly rising, with the energy stored per unit length of the colour flux tube called κ, where phenomenologically $\kappa \approx$ 1 GeV/fm $\approx$ 0.2 GeV^2. A causal and relativistically invariant description of the kinematics can then be given in terms of the massless relativistic string with no transverse excitations [4], where the momentum-carrying endpoints correspond to the q and $\bar{q}$ and the string in between to the flux tube [5].

This string is allowed to break up, the breakups corresponding to the production of new $q'\bar{q}'$ pairs in the field. The pairs are pulled apart by the field and a quark from one pair may join the antiquark from the adjacent pair, giving mesons. On the average the $q'\bar{q}'$ pair production vertices will appear along a hyperbola of constant proper time, however with rather large fluctuations.

In any given Lorentz frame, the breakups that produce the slowest hadrons (in that frame) are also those that take place first. Hence formally we have an "inside out" cascade. It is however always possible to go to a frame in which one of the endpoint quarks q is low-energetic. In that frame the meson closest to this quark will be produced first, then the next closest, etc. With the q going out along the +z axis, a lightcone variable $W_+ = E+p_z$ is introduced to describe the longitudinal fragmentation. Each meson will take a random fraction z_+ of the W_+ remaining from previous steps, where z_+ is distributed according to [5]

$$f(z_+)\,dz_+ = 1\,dz_+ \tag{2}$$

If the quark and antiquark of a $q'\bar{q}'$ pair have mass and/or transverse momentum, they must classically be produced at a certain distance so that the field between them can be transformed into the transverse mass m_t. This can be treated as a tunneling phenomenon and the production probability will, in an infinite-length field, be proportional to [6]

$$\exp(-\tfrac{\pi}{\kappa}\,m_t^2) = \exp(-\tfrac{\pi}{\kappa}\,m^2)\,\exp(-\tfrac{\pi}{\kappa}\,p_t^2) \tag{3}$$

This leads to a suppression of heavy quarks and also to a flavour-independent Gaussian p_t spectrum.

In <u>paper I</u> pair production is studied for the case of finite field lengths, as relevant in jet fragmentation. To produce a heavy q' and $\bar{q}'$ at a certain distance from each other, we must wait until the original $q\bar{q}$ pair has come sufficiently far apart. On the other hand, to produce an energetic meson in the jet, the field must break very early. A simple quantum mechanical treatment suggests that the probability in eq. (3) should be multiplied by a factor $|g(\kappa\tau/m_t)|^2$ where τ is the proper time of the $q'\bar{q}'$ breakup vertex. This leads to a softer z_+-spectrum than eq. (2) and also introduces a correlation between the longitudinal and the transverse fragmentation properties. While the exact form of g is model-dependent and is not derived explicitly, it is shown that different, reasonable parametrizations give very similar results. Comparisons with existing data and some experimental predictions are also presented.

In the massless relativistic string formalism it is possible for a pointlike part of the string to carry a finite amount of energy and momentum. Such a "kink" mode is acted upon by twice the force acting upon an endpoint quark. This gives features very similar to those of a gluon in QCD, where the corresponding force ratio is expected to be $2/(1-1/N_C^2)$ with N_C the number of colours. The picture of e.g. a $q\bar{q}g$ event is thus that of a string stretched from the q *via* the g to the $\bar{q}$ [7].

This scenario for the gluon jet structure in e^+e^- annihilation events is studied in *paper II*. The probability for hard gluon emission is taken from first order perturbative QCD and the Lund model is used to describe the hadronization of the original $q\bar{q}$ and $q\bar{q}g$. For $q\bar{q}g$ events two features of this model are of particular interest. Firstly, since the gluon energy is shared between two string pieces rather than given only to one, a gluon jet will contain more particles at smaller momenta than a quark jet. Secondly, the particles produced in the qg and $g\bar{q}$ string pieces will in momentum space appear along two hyperbolae, typically with a distance from the hyperbolae to the origin of around 300 MeV/c for primary hadrons, i.e.

comparable to typical p_t within a jet. We thus predict more particles in the angular ranges between the gluon and the quark or antiquark than between the quark and the antiquark. Combining the two features above, an asymmetry is defined which should be ≈ 16% if the model is correct and 0% if a gluon jet fragments just like a quark one. If the model is correct, it is also possible to identify the gluon correctly in 70-80% of the three-jet events.

The jet structure expected in leptoproduction events is the subject of paper III. In addition to the lowest-order process $\gamma_V q \rightarrow q$ we also include the two first-order processes $\gamma_V q \rightarrow qg$ (gluon bremsstrahlung) and $\gamma_V g \rightarrow q\bar{q}$ (photon-gluon fusion). The Lund model is again used to describe the hadronization, but the fragmentation of the target remnant is not studied. Compared to e^+e^- events we have the advantage of knowing the jet axis, although a smearing is introduced by the primordial k_t, corresponding to the Fermi motion of the quarks inside the target proton. We compare z and p_t spectra with experimental data, and find good agreement. Suggestions are made for ways to study the structure of events which contain two forward jets, both for properties arising naturally from perturbative QCD, such as the appearance of an event plane, and properties specifically related to the fragmentation scheme, such as differences in gluon and quark jet fragmentation. In particular, we study the consequences of using a high-p_t particle as trigger for gluon emission and photon-gluon fusion events.

Up to this point, we have only considered the fragmentation of jets into mesons. However, experiments at e^+e^- storage rings also show a non-negligible production of baryons. In paper IV we formulate a simple model for baryon-antibaryon production. Our main assumption is that a pair of virtual quarks, in a colour antitriplet state, can tunnel out the same way as an antiquark, so that eq. (3) also determines the relative production of the different diquarks. This does not mean that we consider a diquark to be a pointlike object, only that at the small momentum transfers involved we feel that also an extended object will have an effective coupling to the colour field in the flux tube. For the production of baryons we weight the different diquark-quark flavour and spin combinations by the probability that they form a symmetric three-quark state. This model is in some sense a minimal scheme for baryon production, and as such a good starting point for further studies. Comparisons are made with data from SPEAR and PETRA, and a number of predictions are presented, e.g. for single particle spectra (baryons are essentially uniformly produced over the whole rapidity range), baryon-antibaryon pair correlations (they are to be found within ≈ 1 unit of rapidity from each other, with slightly opposite transverse momenta) and baryon production in gluon jets (somewhat larger than in quark jets, but not much).

In leptoproduction events two sources for baryons are present: target fragmentation and baryon pair production in the field. These are studied in paper V. Baryon pairs are produced just like in paper IV, while the model of [8] is used, in slightly modified form, to describe the fragmentation of a diquark target remnant. We also consider the somewhat more complicated situation when e.g. a gluon is kicked out of the proton (photon-gluon fusion) leaving behind a remnant of three quarks in a colour octet state. We compare with data and also present a number of predictions. In particular, in a leptoproduction event the parton kicked out is normally a colour triplet, leading to a harder baryon than antibaryon spectrum. The correlation in individual pairs may however be difficult to see, since we e.g. also have a target baryon.

In papers II and III only the effects from hard gluon emission were taken into account. The effects coming from the emission of soft or collinear gluons are considered in paper VI. For QCD the physical observables of the asymptotic final state are the hadron momenta whereas the quark and gluon momenta do not correspond to observable quantities, a different picture from the one encountered in QED. A meaningful description will require infrared stability, i.e. the effects of a soft or collinear gluon emission on the observable hadron momenta should vanish when one approaches the singularity. Since this requirement is satisfied in the Lund model, we may treat soft gluons as perturbations on a simple two-jet event. Using the lowest order matrix element for gluon emission in e^+e^- events, we show that the effect of soft, central gluons can be summed up e.g. to one effective gluon per pseudorapidity unit, distributing its transverse momentum to neighbouring particles, with the recoil taken up by the endpoint quarks. Collinear gluons, on the other hand, give a negligible contribution to transverse momentum properties. The resulting event structure is discussed.

One of the problems in leptoproduction is the unphysically large primordial k_t, ≈ 800 MeV, required to reproduce the transverse momentum distributions. In paper VII we show that, with the inclusion of soft gluon effects, the necessary primordial k_t is reduced to ≈ 450 MeV. A true primordial k_t should be compensated in the target fragmentation region whereas a soft gluon k_t is balanced in the central plateau. This offers ways to distinguish the two contributions experimentally. We also study the energy flow in leptoproduction, which on the parton level exhibits a characteristic forward-backward asymmetry. Unfortunately, when hadronization is taken into account, this asymmetry is almost entirely washed out. At the same time an asymmetry is introduced by the target jet fragmentation, which is different from that of the current jet. Hence the asymmetry observed experimentally is mainly due to this and not to QCD effects. We discuss how a high-p_t trigger may be used to improve the situation, and also how higher energies (ep colliders) would change the picture.

All comparisons with and predictions for experimental results presented in papers I-VII above have been based on the ability to simulate the hadronization of jets with

Monte Carlo methods. As the physical model has become more sophisiticated, so has this Monte Carlo. Previous versions have been presented in [9] and, for leptoproduction, [10], the present one is described in paper VIII. The theoretical background in the Lund model is presented briefly, and all practical details are considered. The main emphasis is put on a detailed description on how to use the Monte Carlo program, which is available in FORTRAN 77 code. To help study the importance of different assumptions in the hadronization model, alternative schemes not properly part of the Lund model have been included at some crucial points.

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