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COHERENCE EFFECTS IN PARTON SHOWERS

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Abstract

A model for gluon emission based on the colour dipole approximation is presented. Gluons are radiated from dipoles that are stretched from one colour charge to the corresponding anti-charge, with probability distributions given by generalizations of the Altarelli-Parisi equations. The model agrees very well with experimental data on e^+e^- annihilation. For the reaction $e^+e^- \to W^+W^- \to q\bar{q}'Q\bar{Q}'$ it is pointed out how to extract information about the QCD vacuum and the confinement mechanism by varying the CM energy. Finally the model is applied to deep inelastic lepton scattering. When a quark is kicked out in the lepton-proton interaction, separation of the colour charges leads to gluon emission. Since the proton remnant is not a pointlike object, coherence conditions lead to an asymmetry between gluons emitted in the forward and in the backward region. The asymmetry is controlled by the energy distribution in the force field. Experimental data are reproduced with a linear energy distribution, which is consistent with the proton behaving as a vortex line in a type II superconductor.

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QCD, coherence effects, parton showers, colour dipoles, vortex lines, e^+e^- annihilation, deep inelastic scattering

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Signature Ulf Pettersson **Date** October 16, 1988

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I. G. Gustafson and U. Pettersson
Dipole Formulation of QCD Cascades
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II. U. Pettersson
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in the Colour Dipole Formulation
LU TP 88-5 (1988)

III. G. Gustafson, U. Pettersson and P.M. Zerwas
Jet Final States in WW Pair Production and
Colour Screening in the QCD Vacuum
Phys. Lett. B209 (1988) 90

IV. B. Andersson, G. Gustafson, L. Lönnblad and U. Pettersson
Coherence Effects in Deep Inelastic Scattering
LU TP 88-14 (1988)

V. L. Lönnblad and U. Pettersson
ARIADNE 2. A Monte Carlo for QCD Cascades in
the Colour Dipole Formulation. An Update.
LU TP 88-15 (1988)

"...é pur si muove"
Galilei

I. Introduction

Since ancient times, people have tried to understand the world around them and to answer the questions about "life, universe and everything". The attempts to answer these questions gave rise to many different philosophies and religions, a few of which are still around today. It is obvious that we still cannot answer many of the really interesting questions - those about ethics and the meaning of life, for instance. It is also obvious that we know a lot more about other things than people did before. In my opinion, the most important reason for the progress in science is that we have learned to distinguish between those questions that concern an objective reality (i.e. questions that can be answered by observations) and questions that can only be given subjective answers. Some readers may object to this statement - how do we know that there exists an objective reality? This is certainly a legitimate question, and one of the classical philosophical problems. The only answer I can give is that the alternative would lead to several absurdities. For example, when Johannes Kepler analysed the huge amount of astronomical data he had obtained from Tycho Brahe, he found that the orbit of Mars was elliptical. When astronomers today observe Mars, they also find that the orbit is elliptical. The only reasonable explanation for this seems to be that there really <u>is</u> a planet out there, and that it moves in a certain way independent of us down here.

Actually, Kepler did not like the result of his calculations. He tried to interpret the result in many different ways, but found no way around the conclusion that the orbit really was elliptical. This fact clashed completely with the old Aristotelian tradition (promoted by the Church), and it was at that time a very ugly fact. This was the first important example of one of the fundamental principles of physics - even the most beautiful theory does not stand a chance against an ugly fact. We will see more examples of this later.

At about the same time (beginning of the 17th century), Galilei started to observe falling stones. He found that all stones fall to the ground with the same acceleration, independent of their masses. This was also contradicting the Aristotelian philosophy, but - more importantly - he had just invented experimental physics. He asked a specific question, observed the answer that nature gave, and found that it was the same every time he made an observation. This is the most important principle in experimental physics - that the results are reproducible. Physics would be impossible if nature behaved differently from day to day.

From this moment on, physics became an empirical science. Physicists make observations (measurements) and these measurements result in numbers. If there are regularities in nature (i.e. physical laws), these should correspond to relations between the measured numbers. Simply stated, the aim of physics is to find the formulae that give the relations between the numbers that come out from the observations. If we find these formulae we can also calculate what will happen under given circumstances. It is actually quite exciting that we are able to make predictions about what will happen in nature - and it is certainly in favour of the existence of an objective reality. (Let me add here, to avoid misconceptions, that physics only deals with things that are measurable. There may be lots of phenomena in nature that are not liable to measurements. If so, physics says nothing about these. Let us hope that the human mind is not governed by physical laws.) The really exciting thing, however, is when we find relations between the formulae.

If Galilei was the inventor of experimental physics, then we may call Isaac Newton the inventor of theoretical physics. In the end of the 17th century, he showed that the elliptical orbit of Mars and the uniform falling of stones were in fact governed by the same physical law! This very simple law (that all material bodies attract each other in proportion to the product of their masses and inversely proportional to the square of the distance between them) accounted for the motion of stones as well as for the motion of planets. This unification of mechanics and astronomy finally shattered the old conception of the world. It was also the first example of what has become the principal aim of all theoretical physics - to find unified descriptions of seemingly unrelated phenomena, and, in the end, to find a unified description of all physical phenomena.

The next important unification was accomplished by Michael Faraday and James Clerk Maxwell. Through extensive experiments, Faraday made clear the connection between electricity and magnetism. Maxwell succeeded inexpressing all these results in a few concise equations, thereby giving a unified description of the two phenomena. But not only that - he found that there were solutions to the equations corresponding to electromagnetic waves moving with the velocity of light. In fact, light itself turned out to be an electromagnetic phenomenon.

This was the situation at the end of the 19th century. Newton's theory accounted for mechanics and gravitation, Maxwell's theory accounted for electricity, magnetism and optics. And these were all the phenomena that were known.

"So long as big and small are merely relative concepts,
it is no help to explain the big in terms of the small."
P.A.M. Dirac

II. Physics in the Twentieth Century

We must remember that physics is an empirical science. All theories are based on the experimental facts that are known at the time, and the theories should not be mistaken for what is actually true about nature. There is always the possibility that we will discover new phenomena. This is in fact what happened around the turn of the century. First it was discovered that the speed of light was always constant, independent of the motion of the observer. This was downright absurd from the common sense point of view, and it was entirely inexplicable within Newton's theory. Furthermore one found that the atoms seemed to consist of a negatively charged electron orbiting around a positively charged nucleus. According to Maxwell's theory an orbiting charge should emit radiation and thereby lose energy. thus no atoms would be stable. But they are.

It turned out that these facts required a complete revision of our concepts about nature. The first problem led Albert Einstein to formulate the special theory of relativity. This is a generalization of Newtonian mechanics, valid also for very large velocities. Among its many consequences are that space and time no longer are described as separate entities, and that mass is just another manifestation of energy. Einstein had arrived at this theory by considering the relation between measurements made by two observers that are in uniform motion relative to each other. The natural generalization of this problem is then to consider observers in non-uniform (accelerated) motion relative to each other. Thus Einstein demanded that all physical laws should hold good for all observers, independent of their state of motion. In mathematical language, this is the same as demanding that we are free to choose, at any point in space-time, our system of coordinates. This idea led to the general theory of relativity, with all its amazing consequences. According to this theory there are no gravitational forces. Everything moves in straight lines (falls freely), but in a four-dimensional space-time that is curved due to the presence of matter. Newton's theory of gravitation is just a special case, valid when the velocities are low and the gravitational fields are weak.

Nevertheless, there were still problems to be solved. The theory of relativity said nothing about the nature of matter. What are the building blocks of matter? How do they behave?

In order to explain the stability of atoms, we have to assume that the electrons behave differently from macroscopic objects. Niels Bohr postulated that there were only certain allowed orbits for an electron in an atom. When an atom was in the ground state the electron could not loose any energy since there was no allowed orbit closer to the nucleus, and thus the atoms would be stable. From this assumption grew the theory of quantum mechanics. According to quantum mechanics, the motion of electrons is described by a wave equation - the Schrödinger equation - and in the Bohr model the allowed orbits correspond to standing waves. This wave equation gave a very good description of microscopic phenomena, but it caused a great deal of confusion concerning the interpretation. Particles were endowed with wave properties, and the electromagnetic waves were found to sometimes behave like particles. We should, however, not expect that the microscopic world behaves exactly like our everyday world. On the contrary; if the elementary particles were exactly like macroscopic bodies, then they would also be just as divisible as these and there would be no elementary particles! So the only way to learn about the microworld is then to make detailed observations and try to find the relations between the measured numbers.

The characteristic constant in quantum mechanics is called Planck's constant and is denoted by $\hbar$. It has (in ordinary units) an extremely small value, which means that we do not observe any quantum effects in everyday life. The essence of quantum mechanics is that observables (energy, momentum etc.) are represented by operators (usually derivatives) acting on the wavefunctions. (I apologize to those of the readers who do not like mathematics, but now the subject is getting a bit more technical.) For example, energy is represented by the operator $E=i\hbar d/dt$ and momentum is represented by $p=-i\hbar d/dx$. The Schrödinger equation is simply the classical equation $E = p^2/2m + V$ where E and p are substituted with the quantum operators and the whole equation is acting upon the wavefunction. The obvious thing to do now is to unify quantum mechanics and the special theory of relativity, i.e. to make the same substitutions in Einstein's equation $E^2 = p^2c^2 + m^2c^4$. This resulted in a second derivative in time, which caused some problems. Dirac then made the ingenious move of replacing this equation with a linear equation: $E = \alpha p + \beta m$, and required that the square of this equation should reproduce the original equation. This meant that the parameters α and β, as well as the wavefunction could not be ordinary numbers, but had to be matrices (arrays of numbers). The wavefunction turned out to have four components - corresponding to particles and antiparticles with spin up and spin down! The electron spin had already been observed, and shortly after Dirac had written down his equation one also observed antiparticles. The existence of antiparticles was also a beautiful confirmation of Einstein's result on the equivalence between energy and matter. If a particle and an antiparticle meet they annihilate each other, and the matter converts into energy.

Now it was possible to treat the electromagnetic interactions within the quantum theory. Electrically charged particles interact with each other, and the interactions are mediated by photons (the electromagnetic quanta). The particles obey Dirac's equation and the photons obey Maxwell's equations. This theory is called quantum electrodynamics (QED), and it has been enormously succesful in describing the atomic world.

Now one had a theory for the interaction between electrons and the atomic nuclei. But what happened inside the nuclei? It was discovered that the nuclei consist of protons (with positive electric charge) and neutrons (that are electrically neutral). But in order to hold particles with the same charge together within a small region there has to be some other kind of interaction, much stronger than the electromagnetic. This interaction was for a long time quite problematic to describe, and the problem was not solved until one had met with several other difficulties. In high energy interactions lots of new particles were produced that in many ways resembled the proton and the neutron (these particles are called hadrons). Soon there were so many of them that one realized that they must have some substructure, i.e. that they are composed of other particles. (This was quite analogous to the periodic table for the chemical elements. Both the huge number of elements and the regularities among them was explained in terms of the substructure of the atoms.) These particles which are called quarks are, as far as we know today, elementary and do not have any substructure. The other particles that are considered elementary are the electron and the neutrino (plus a few exotic particles that are similar to these).

Today we know of four different types of interactions - gravitation, electromagnetism, weak interaction and strong interaction. I will not go into details on the weak interaction here, suffice it to say that it is responsible for certain types of radioactivity and that there today exists a successful unified theory of the weak and the electromagnetic interactions. This unified theory is built on a principle that is called local gauge invariance. The principle of local gauge invariance requires that the equations of motion should be invariant when we change the phase of the wavefunction arbitrarily from point to point. This is in fact exactly the same principle as the one Einstein used to formulate general relativity - local gauge transformations correspond to changes of the coordinate system in the internal space of the particle.

The theory (called quantum chromodynamics, QCD) for the strong interaction was then constructed as a gauge theory for the interaction of quarks. Certain properties of the hadrons required that there should be three different charges (generalizations of the electric charge) with the corresponding anticharges. The mediators of this interaction are the gluons. These are analogous to the photon in the electromagnetic interaction - with one important difference. It turns out that the gluons themselves carry charge, and therefore interact with each other. This has some profound consequences. If we look upon the force field between two quarks, this does not spread out (like it does in the electromagnetic case), but gets compressed into a flux tube between the quarks. Although it has not been proven mathematically, this seems to prevent the quarks from appearing as free particles. If one tries to separate two quarks, the flux tube stretches out, and there is more and more energy stored in the field. Eventually there will be enough energy to produce a quark-antiquark pair. These will combine with the original quarks into new hadrons. Thus no matter how hard we try to release a quark from a hadron, the result will only be more hadrons.

The Lund string model is a (successful) phenomenological model for this process. The flux tube between the quarks is approximated by a one-dimensional string, and the production of quark-antiquark pairs is described by a fragmentation function giving the probability for the string to break. Since this is a stochastic process resulting generally in lots of new particles, the only possibility is to make computer simulations of the process.

One peculiar feature of QCD is that the strength of the interaction decreases when the distance between the charges gets smaller. Thus it is possible to use perturbation theory when dealing with short distances (i.e. large momentum transfers). When an electron annihilates with a positron, for example, the energy may be converted into a quark-antiquark pair. When these still are very close together they may emit bremsstrahlung (gluons), and this process should then be possible to calculate in perturbation theory. When the quark, the antiquark and the gluons move apart from each other the force field will, as described above, be compressed into a flux tube. Therefore we make a separation between the initial perturbative phase, and the non-perturbative phase where the string (flux tube) fragments into hadrons.

"There is nothing cuter,
than my little computer."
Anonymous

III. The papers

In paper I we present a model for the bremsstrahlung of gluons in e^+e^--annihilations. The probability distribution for gluon emission is in principle given by the QCD equations. However, even for the emission of just two gluons, it is very difficult to calculate the probabilities analytically. It has been shown that experimental data are not accurately described by perturbative calculations to second order in the coupling constant (with subsequent fragmentation in the non-perturbative phase). Therefore one has to use some kind of iterative scheme, using repeatedly the probability distribution for the emission of one gluon. Using this method, however, one does not take the interference effects fully into account. In our model we start from the idea of the colour charges being connected by a stringlike force field (flux tube). In this picture the gluons act as kinks (transverse excitations) on the string. The radiation of one more gluon (in the perturbative phase) thus corresponds to one more kink on the string (in the non-perturbative phase). It is then natural to consider a gluon as being emitted by colour dipoles, and not by the individual colour charges. The calculation of the probability distributions that we use and a description of the computer program are presented in paper II.

In paper III we apply our model to the reaction $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}'Q\bar{Q}'$. We point out the possibilities to distinguish between the case where each of the W's independently decay to colour singlet strings, and the case where the colour singlets result from quark exchange pairing. If the total energy of the system is increased, the W's will decay farther away from each other, and the probability for quark exchange pairing should be reduced. Thus future experiments may give information about the distances at which this recoupling occurs, information that may tell us something about the QCD vacuum and the confinement mechanism.

In paper IV we present a model for gluon radiation in deep inelastic scattering of leptons on protons. The proton is assumed to behave like a one-dimensional colour flux tube (similar to a vortex line in a type II superconductor). When a quark (or antiquark) is kicked out in the interaction there is formed a colour dipole between the quark and the proton remnant. This dipole will radiate gluons, but the radiation has to satisfy certain coherence conditions. Since the dipole has a finite extension, gluons with (transverse) wavelengths shorter than the dimension of the dipole will be suppressed. Furthermore, only a fraction of the vortex line will in general be involved in the emission, due to destructive interference. This leads to an asymmetry between gluon emission in the backward and in the forward region, just as observed in experiment. In the usual approach to deep inelastic scattering, backward moving gluons are suppressed owing to constraints from the structure functions of the proton. In our model , the parameters are a mass scale of the order of a hadronic mass and a parameter related to the energy distribution in the vortex line. It turns out that we get a good description of experimental data when using a linear energy distribution. In paper V, finally, we describe the computer program used for this model.

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