Aspects of the QCD Cascade

Magnus Olsson

Department of Theoretical Physics
University of Lund
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Department of Theoretical Physics
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Magnus Olsson

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Abstract

A model is proposed for the production of transverse jets from diffractively excited protons. We propose that transverse jets can be obtained from gluonic bremsstrahlung in a way similar to the emission in DIS. Qualitative agreement is obtained between the model and the uncorrected data published by the UA8 collaboration.

Perturbative QCD in the MLLA approximation is applied to multiple jet production in e^+e^--annihilation. We propose modified evolution equations for deriving the jet cross sections, defined in the "k_t" or "Durham" algorithm. The mean number of jets as a function of the jet resolution is studied, and analytical predictions are compared to the results of MC simulations.

We also study a set of differential-difference equations for multiplicity distributions in e^+e^--annihilations, supplemented with appropriate boundary conditions. These equations take into account nonsingular terms in the GLAP splitting functions as well as kinematical constraints related to recoil effects. The presence of retarded terms imply that the cascade develops more slowly and reduces the fluctuations. The solutions agree well with MC simulations and experimental data.

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Paper I:

G. Gustafson and M. Olsson: Transverse Jets in High Mass Diffractive Excitation
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Paper II:

Yu. Dokshitzer and M. Olsson: Jet Cross-Sections and Multiplicities in the Modified Leading-Logarithmic Approximation
LU TP 92–17, to appear in *Nuclear Physics B*

Paper III:

G. Gustafson and M. Olsson: Hadron and Jet Multiplicities in QCD Cascades
LU TP 93–1

Foreword

This thesis is divided into three parts. In the first part, called *'An introduction to the subject for humanists, lawyers, and other innocents'*, I give a very brief overview of particle physics; as the title says, I have tried to make it understandable to non-physicists. All too often, we physicists resign ourselves to the fact that nobody except other physicists (and sometimes not even them) seem to understand – or even care – what we're doing; this part can be seen as at least an attempt to do something about this. I hope that I have not failed totally in this regard, but that the non-physicist should be able to extract at least some interesting information from what I've written.

The second part is a short introduction, written for other physicists, to the third and main part of the thesis: the three papers that contain the results of my research.

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Lund, February 1993

The Author

Part I:
An introduction to the subject for humanists, lawyers and other innocents

A physicist is an atom's way of knowing about atoms.
George Wald

When a non-scientist is introduced to a particle physicist, he or she will perhaps most commonly react by rapidly changing the subject to some more interesting topic (after all, most of us are taught in school that physics is *boring*, aren't we?). It is more gratifying to the physicist when the other person shows some interest, and asks about his* work, and what particle physicists really do. Unfortunately, such a question isn't easily answered in a few sentences. If the physicist tries to be brief, he runs the risk of confusing the layperson by using lots of funny-sounding words like 'quarks', 'intermediate vector bosons', 'chiral anomaly', 'running coupling constants' and 'anomalous dimensions'. If he, on the other hand, tries to explain everything properly, the result will probably be such a long-winded lecture that it will *bore* the poor non-physicist to death. If he or she survives this ordeal, some very relevant follow-up questions are "Why on earth do you want to work with particle physics?" and "Is there any practical use for it?"

In this introduction to my thesis I will first make an attempt to throw some light on what particle physics is all about, and then to state my personal views on the last two questions. I'll not go into the gory details of my work here – it's very technical and not very likely to interest non-specialists – but rather explain some of the general concepts of particle physics, with the goal of at least giving an idea of the problems I've been involved in trying to solve.

Since there is often a lot of significance in names, let's start with the name of the subject: theoretical particle physics - a rather formidable-sounding name that can make one wonder if there's any difference between theoretical and 'practical' physicists. The word 'theoretical' of course doesn't mean that we theoretical physicists are less practical than other physicists**. Also, it absolutely doesn't imply that what we are doing is "just theories" with no connection to reality. What it does mean is that there's a division of labour among physicists - some of us try to understand nature by performing actual experiments, while others use theoretical methods (mathematics and computer simulations) to achieve the same goal. The reasons for this are practical; modern particle physics experiments are so large and complicated, and the theories so mathematically difficult, that it is virtually impossible for a single individual to master both.

As for the 'particle physics' part: Particle physics is the study of the smallest objects we know - known as *subatomic* (because they are smaller than atoms) or *elementary particles* (because they are believed to be the building blocks of which all matter is constructed) - and the ways they interact with each other. This is a rather young science; it didn't become a separate discipline until the 1950's. It is also one of the areas of science that attract the most interest, people and money; we will discuss the reasons for this below.

* I will in the following write just "he" about particle physicists in general, rather than the 'politically correct' "he or she"; this is done for pure convenience, even if it does reflect the unfortunate circumstance that there are very few women in particle physics.

** of course, *some* are - it used to be said about the famous theorist Wolfgang Pauli that he could cause experiments to fail just by being in the same town!

As mentioned above, the experiments of particle physics are very large and complicated. They are also very expensive - in fact, the big particle laboratories, like CERN outside Geneva, are huge industries with thousands of employees and correspondingly large budgets. The reason for this is, paradoxically, that elementary particles are so small; it is a fundamental fact that one needs more energy to study an object the smaller this object is. In almost all the experiments, one takes a large number of easily produced particles, such as electrons, give them a large energy by accelerating them to speeds very close to the speed of light (300 000 km/s; the fastest any material object can move) and then lets them collide. The acceleration is done in machines called, very logically, accelerators. In the accelerator, the particles are made to go round in circles with the help of magnets; to be efficient, these circles - and hence the accelerator - must be very large. The biggest accelerators today are several tens of kilometres in circumference, and even bigger ones are being constructed.

When the particles collide, some of their energy is converted into new particles - as predicted by Einstein, energy can be converted to mass according to the famous formula $E = mc^2$. Many of these particles are of kinds never seen outside the laboratory; they very quickly* decay into more familiar particles, and the physicists have to deduce from these decay products the properties of the new particles - usually a very difficult task. The higher the collision energy, the more exotic particles will be created. Therefore, particle physics is often also called high energy physics.

It is the study of these particles - with strange names such as quarks, leptons and hadrons - that constitutes particle physics. In the next two chapters, we will describe them more in detail; but before we do that, let's ask ourselves the question what makes them so interesting that thousands of people want to spend large parts of their lives studying them.

Firstly, the particles are rather interesting creatures by themselves, and the world they inhabit (which is of course the same world as that of humans, but viewed at an incredibly small scale) is a weird and wonderful place indeed. Several thousands of different particles are known; their classification into families is a fascinating new kind of 'zoology', the study of their properties is an enormous challenge to the experimentalists, and the construction of the needed experimental apparatus requires the development of new, exciting technology at a large scale.

A more important reason, however, is that the laws of nature seem to reveal themselves in their simplest, most fundamental form in the world of elementary particles. As we study nature at a smaller and smaller distance scale (that is, at higher and higher energies), much of the complexity we see in nature seems to disappear: seemingly disparate phenomena turn out to have a common origin and to be described by a common law. There is no *a priori* reason why this should be so, but at least so far, the fundamental laws of nature seem to become fewer and in a sense simpler at higher energy. Some physicists hope that this trend will continue and that we will sooner or later be able to write down one final 'Theory of Everything' that unites all the aspects of nature in one fundamental law. Let me hasten to add that there is also an opposite trend: the simpler and more fundamental our description of nature becomes, the harder it seems to get actually to calculate anything from the equations. One day, we may be faced with the paradoxical situation that we have a Theory of Everything, but that we can't solve its equations!

* "very quickly" means very quickly indeed - in particle physics, a billionth of a second is considered a very long time

Searching for the indivisible - about atoms, quarks and such things

Quark! Quark!
The quantum duck

Nature, as we see it, is incredibly varied. We are surrounded by an enormous number of different material things: from stars to bacteria, from glaciers to telephones; none of them exactly like the other, and most of them constantly changing, growing, dying.

As we all learn in school, all these things are built out of less than a hundred different kinds of atoms (actually, more than a hundred different atoms are known, but some of these are unstable and fall apart so quickly that we never see them in nature). All atoms of one kind seem to be identical, and all the diversity of nature is due to the different ways the atoms are arranged. This is not a new thought; it goes back at least to the Greek philosopher Democritus, who lived in 5th century B.C. The word 'atom' itself was also introduced by Democritus; it comes from the Greek words for 'impossible to divide'. In Democritus' philosophy, the atoms are the smallest possible parts of matter - what we today would call fundamental particles.

Even though the actual existence of atoms wasn't proved until the late 19th century, atomism (the idea of atoms) has been popular among philosophers* ever since Democritus, and (in modern times) among scientists. In a way characteristic of scientific thought, atomism 'gets rid of' the complexity in nature - on the fundamental level of atoms, nature is very simple; the complexity we experience is due to the many possible ways of putting the atoms together, not to any inherent complexity of the fundamental laws of nature. Of course, saying that all matter is made of atoms leaves an open question: what are the atoms themselves made of? While such questions may be irritating to the philosopher, scientists in general are content to leave them aside, at least temporarily.

A more troubling problem is that there are so many different atoms. One of the driving beliefs behind modern physics is that the laws of nature are *simple* (in some not quite well-defined manner) - a simple theory is almost always preferred over a more complicated one, as long as both agree with experiments. Now, if nature really is simple, and atoms really are the fundamental building blocks of matter, we would prefer that there be only a small number of different atoms - and certainly not over a hundred.

What's inside the atom

This problem was solved around the turn of the century when it turned out that atoms aren't fundamental. The first such particle to be discovered was the *electron* - a tiny (almost 2000 times lighter than the lightest atom, hydrogen) particle with a negative electric charge.

During the following decades a picture was developed of the atom as a miniature solar system: in the centre of the atom is a tiny *nucleus*, and the electrons move around it like the planets move around the sun. The nucleus is in turn built up of particles called *protons* and *neutrons*. These are much heavier than the electron; each of them weigh almost 2000 times as much, and almost all the mass of the atom is concentrated in the nucleus. In spite of this, the nucleus is very much smaller than the atom, so in fact mat-

* though far from all philosophers liked the radical materialism of Democritus at all - which may explain why his writings have been almost totally lost.

ter consists (by volume) almost exclusively of empty space! An atom is about a tenth of a millionth of a millimeter in diameter, but the nucleus is 10 000 times smaller still. These numbers are so small that they are difficult to imagine; but a useful analogy is to say that if an atom were as big as a house, the nucleus would be as a tiny insect flying inside the house. (On the same scale, a human being would be as tall as the distance between the earth and the sun.) Like the electron, the nucleus is electrically charged, but whereas the electron's charge is negative, the nucleus has a positive charge (together, these charges neutralize each other, so the atom as a whole isn't charged). In school, we learn that positive and negative charges attract each other, and it is this attraction that keeps the atom together and prevents the electrons from flying away on their own.

Quantum mechanics

The discovery of the atom's internal structure was one of the things that started one of the greatest intellectual revolutions ever – the introduction of *quantum mechanics*. This is not the place for a long discussion of this fascinating subject; suffice it to say that it was clear already from the beginning that an atom that was built like a solar system in miniature could never work. When an electron moves in circles it sends out radiation, so all atoms should be constantly radiating (which of course they aren't). What's even worse is that the radiation would carry away the electron's energy, causing it to slow down and fall into the nucleus in a tiny fraction of a second. It seemed as if atoms couldn't exist at all!

To solve this problem, a new kind of physics was required. The new theory, quantum mechanics, was developed during the first 30 years of this century, and proved to be an enormous success. Not only could it explain why atoms were stable (the answer is that the electron's orbit can only have certain sizes, and when the electron is in its smallest orbit it can't radiate any more energy), but it could be used to explain a lot of phenomena that were impossible to explain with classical physics. In fact, everything that is smaller than a few hundred times the size of an atom must be described by quantum mechanics.

The price to be paid for this success was heavy, though: quantum mechanics has some consequences that seem to be contrary to common sense. For example, an electron can behave not only as a small, pointlike particle, but also as a wave. On the other hand, light, which is normally thought of as consisting of waves, can also be viewed as consisting of particles called *photons*. This may sound impossible, but it is a fact that if you perform certain experiments on a light beam (or on a beam of electrons), you will get clear indications that you're dealing with waves; and if you perform another experiment, you'll 'see' individual particles.

This may sound strange, and it *is* strange. The microscopic world of atoms and particles is quite different from what we're used to. We can use quantum mechanics to calculate things, but nobody 'really' understands what's going on in the quantum level. What we can do is to make simplified pictures of things – saying that the atom is like the solar system is such a picture – but we must accept that these pictures are misleading. The only way we know of to describe accurately how an atom works is by using the mathematical formulas of quantum mechanics. In this introduction, however, I will stick to the simple pictures.

More particles, more trouble

Apart from the fact that quantum mechanics takes some time to get used to, this new picture of the world seemed to be a simple one. Everything was built not of more than a hundred different kinds of atoms, but of just three different kinds of particles: electrons, protons and neutrons. These were called the elementary particles, since they were believed to be the elements out of which everything was built. The photon also is regarded as elementary, but it is a different kind of particle, that doesn't build matter but light.

Soon, however, things began to get more complicated again. First, it was discovered that for every particle, there is a corresponding *antiparticle*. The antiparticle is in a sense a mirror image of the particle – but made by a mirror that reverses not only left and right, but all the properties of the particle, except its weight. The electron, for example, has an antiparticle called the *positron;* it has the same weight, but has a positive rather than a negative charge. When a particle and its antiparticle meet they annihilate each other, leaving only energy (which turns into other particles). This almost doubled the number of particles (some particles, like the photon, are their own antiparticles).

The number was increased again when Wolfgang Pauli, to explain certain features of radioactivity, had to assume that there existed yet another elementary particle, which he called the neutrino. Then a totally unexpected particle called the muon was found in cosmic rays. (This is radiation consisting mostly of atomic nuclei, that continuously bombards the earth from space. Fortunately, most of it is stopped by the atmosphere.) Muons seem to be exactly like electrons, but 200 times heavier and unstable - when left to itself, a muon will turn into an electron and two neutrinos in only a few millionths of a second.

The situation became even more complicated in the 1940's, when people started building accelerators powerful enough to create new particles (as described in the previous chapter). During the following decades many new particles, all unstable and very rapidly decaying, were discovered. Most of these particles share many properties with the proton and the neutron; they are grouped together in a family called *hadrons*. The electron, muon and neutrinos (it was later found out that there are actually three different kinds of neutrino) belong to another group called *leptons*. This group also contains a particle called the *tauon,* which is very much like the electron and the muon, but much heavier.

While there are only six leptons, there are literally hundreds of hadrons. This is not a good situation if we want to believe that hadrons are elementary - why should there be so many of them, when only the proton and neutron seem to be needed in nature?

Quarks – bringing order to chaos

The solution to this problem turned out to be that the hadrons aren't elementary, but are built up of smaller particles, called *quarks*. In the mid-sixties, when quarks were first proposed, it looked as if three different quarks were sufficient to build up all the different hadrons; since then, the number of quarks has increased to six, which is still a much more comfortable number of fundamental particles than the hundreds of hadrons.

According to our current knowledge, which is summarized in a theory known as the *Standard Model,* the truly elementary particles are the quarks and the leptons. There are six leptons: the electron, muon, tauon, each with a neutrino 'partner'; and six quarks, called the up, down, charm, strange, top and bottom quarks. Each of these also has its antiparticle. There is also a set of particles similar to the photon, that we will discuss in the next chapter; the role of these particles isn't to serve as the building blocks of matter, but to be the 'carriers' of the forces that hold matter together.

The top quark hasn't been discovered yet, but we have many indirect signs of its existence, and almost all physicists are confident that it does exist. The reason that it hasn't been discovered yet is that it is very heavy, so heavy that today's biggest accelerators are just barely able to produce it. The same theory that says it should exist also puts a limit on how heavy it can be, and if it isn't found the current theories would need a major reworking.

The quarks and leptons are organized in 'generations'. The first generation consists of the the up and down quarks, the electron and its corresponding neutrino. The other two generations seem to be heavier copies of the first one. Only the first generation is needed to build all the matter we see in nature; the other two are only found for very brief times inside particle accelerators. Nobody knows why nature should repeat itself three times in that way. One explanation could be that the quarks and leptons themselves are composed of still smaller particles; however, it seems very difficult to make a working theory for such 'subquarks', and so far the experiments seem to show that quarks and leptons are pointlike, with no internal structure. The philosophically minded may find comfort in the fact that the Standard Model wouldn't work with less than three generations, so the 'extra' generations aren't wasted after all.

It should be mentioned at this point that nobody has ever observed a free, isolated quark. At first, this was (very naturally) taken as a sign that there weren't any quarks, and that the quark theory was wrong. However, we now have lots of indirect evidence that quarks actually do exist; for example, if one collides electrons with protons, the electrons behave just as if they were bouncing off particles inside the proton, and these particles behave just as the theory says the quarks should behave. Very few physicists today doubt the existence of quarks. The probable reason we don't see any free quarks is that the force that keeps the quarks together inside hadrons is so strong that the quarks are forever trapped. If one tries to free a quark, one has to supply so much energy that a lot of new particles are created; and instead of producing a free quark, one gets a *jet* of dozens of hadrons. It has not yet been conclusively proved that the theory really forbids free quarks, but it seems increasingly likely and most physicists would be very surprised indeed if a free quark was found. The particle jets mentioned above are observed in experiments, and they look just as they should according to the theory of the forces between quarks. In the following chapters we will return to this theory, which is called QCD.

What makes things stick together, and how physicists search for a Holy Grail of their own.

Felix qui potuit rerum cognoscere causas.
(He is fortunate who has been able to learn the causes of things.)
Virgil

The four forces

So far, we've discussed what the material world is made of, but we haven't said much of what holds it together. If nothing prevented the various particles from flying off in separate directions the world would be a very different place indeed, but fortunately, there are various forces that keep the particles organized. On the largest, macroscopic, level, there is the force of *gravity*, which keeps the planets in their orbits, and prevents us from drifting off the earth when we sneeze. Clearly, gravity is the most important force in our daily lives.

On the microscopic scale, however, gravity is far too weak to have any noticeable effects. In the world of atoms and molecules, the most important force is instead the *electric* force. Electrons inside an atom are kept in their orbits around the nucleus by electric forces: electrons have a negative and the nucleus a positive charge, and (as we learn in school) negative and positive charges attract each other. The forces that cause atoms to stick together to form molecules are also electric. *Magnetism* is caused by electric currents, so the electric and magnetic forces together are called *electromagnetic* forces.

Electromagnetism and gravity do not suffice to explain what keeps an atomic nucleus together, however. The nucleus consists of protons, which have a positive electric charge, and neutrons, with no electric charge at all. Since positive charges repel each other, and the neutrons only dilute the positive charge a bit, a nucleus should really fall apart by itself (gravity is far too weak to keep it together). Since it doesn't, there must be another force that causes the protons and neutrons to stick together, a force that is stronger than the electric force. This force is called (not very imaginatively) the *strong force*, and it is also responsible for keeping the quarks together inside hadrons. The reason we don't feel the strong force in our daily life is that it has a very short range - it can't be felt at distances much larger than the size of a nucleus (a millionth of a millionth of a millimeter).

There is also a fourth force, which has an even shorter range than the strong force. It is called the *weak force*, and plays an important role in radioactivity and in the nuclear reactions that make the sun shine.

Just as the quarks and leptons are the fundamental particles, from which all matter is built, these four forces (gravity, electromagnetism, the strong force, and the weak force) are the fundamental forces: as far as we know, all change in nature can be attributed to them. You may object to the word 'change' here - weren't we just discussing how the forces keep things together, and thus prevent them from changing? But if one thinks about it a little, it is clear that what forces really do is change things. The way the force of gravity keeps the moon moving around the earth, for example, is by continuously changing the direction of its motion, so that instead of flying away along a straight line it moves in an ellipse around the earth. Forces can also change the identity of things: apply enough force to a rubber band, and it snaps. The weak force can even cause one kind of quark to change into another (this is what happens in the so-called beta decay of atomic nuclei). To a physicist, the most important thing about a force is that it causes things to change, and therefore one often speaks about *interactions* rather than of forces.

The problem of action at a distance

When Newton discovered the law of gravity, he was bothered – as were many other people – by the fact that gravity seemed to be acting at a distance. In other words: what is it that causes the apple to fall to the ground? The law of gravity simply states that any two bodies will attract each other, no matter how far apart they are. It is hard to believe that, say, the moon just *knows* that the earth is sitting there, 380 000 km away, and that the moon should feel a force pulling it in that direction. The same problem exists for the other forces.

The modern theories of the forces, known under the imposing name of *quantum field theories*, explain this by saying that all the forces in nature are caused by the exchange of particles. For each force there exists one or several particles that act as 'carriers' of the force. In the case of electromagnetic forces, this carrier is the photon, the particle that light consists of. According to the quantum field theory of electromagnetism, which is called QED (quantum electrodynamics), any electrically charged particle can emit and absorb photons.

This gives us a way to explain for example the force between two electrons. Suppose both electrons are at rest. When one of them emits a photon, it will recoil in the opposite direction, just as a gun bounces back when a shot is fired. If the photon is absorbed by the other electron it will give the electron a push and make it move away from the first electron. By exchanging a photon, the two electrons have started to move apart. An observer who can't see the exchanged photon will draw the conclusion that there is a force between the electrons that pushes them apart.

Actually, this is an over-simplified picture, which runs into difficulties already when it comes to explaining an *attractive* force. What we must remember is again that this is just a simplified picture of what's really happening. We're dealing with quantum mechanics here, and it is not possible to describe in words exactly how the exchange of photons can lead to an attractive force. When one studies the equations of QED, however, one sees that the force can be interpreted as the exchange of photons, in a mathematically well-defined way – and that's really the best explanation we have.

Other forces, similar theories

The other forces of nature, with the exception of gravity, are also described by quantum field theories. Most physicists think that there should be such a theory for gravity also, but so far all attempts to invent one have failed. For the strong and weak forces, things work better, however.

The strong force is described by a theory called QCD, which stands for *quantum chromodynamics*. This theory is in some ways very similar to QED, but more complicated. There is for example just one sort of electric charge (which can be positive or negative), but in QCD there are several kinds of charges, called *colours*. The 'chromo' in 'chromodynamics' comes from the Greek word for colour. Quarks come in three different colours: red, green and blue. (These 'colours' have of course nothing to do with ordinary colours, but we have to call them something.) The particles that carry the force are called *gluons*, and come in eight different colours.

In the case of the weak force, something interesting happens. It turns out that one can't make a theory for the weak force alone*, but one has to include electromagnetism in the same theory. What one gets is a *unified* theory, that describes the two different forces as consequences of just one law of nature. At very high energies, the weak force and electromagnetism behave very similarly, but

* or, rather, one can create such a theory, but its results don't agree with experiments.

in everyday phenomena, which take place at low energies, they have very different properties. This is an example of why it's important to study things at very high energies (or at very small scales, which is the same thing): raising the energy reveals the hidden symmetry of nature.

The Holy Grail of physics

This is only the most recent example of unification of the laws of physics. As early as in the 17th century, Galileo did something similar, when he showed that the same laws of nature were valid for the heavenly bodies as for things on earth (Aristotle, who was the great authority from antiquity until Galileo's time, taught the opposite). In the 19th century, electricity and magnetism were unified; maybe the finest achievement of classical physics was when Maxwell could derive one set of equations that describe all aspects of electricity and magnetism.

Today, the search for unity in nature has been intensified; the search for a Theory of Everything, that would summarize all the laws of nature into one, has been called the Holy Grail of physics. The most logical first step toward this would probably be to find a theory that unifies the strong, weak and electromagnetic forces. One such theory was rather popular a few years ago; however, it didn't agree with experiments* and had to be discarded. There exist several modified versions of the theory that may work; they predict interesting phenomena (such as entirely new types of particles) at energies that should be within reach of the next generation of accelerators. Unifying gravity with the other forces seems to be much harder; one kind of theories known as superstring theories seem promising, but are tremendously difficult and nobody knows whether they will work or not.

The Theory of Everything, if it exists, will probably not be found for several decades. If it is eventually found, will that be the end of physics? I don't think so. It will only be a theory of everything in the sense that all the laws of nature can ultimately be derived from it, but we will almost certainly not be able to use it to explain everything. One reason is that the equations of quantum field theories are extremely difficult to solve, and we will only be able to handle very simple problems mathematically.

But, more fundamentally, even if we can handle the mathematics the very complexity of the world makes it necessary to have different levels of description for different phenomena. Just to take an example: a computer works by sending electrons through silicon crystals and copper wires. All this can be described, on the fundamental level, with quantum mechanics (or, if one is really ambitious, with QED), and this description is used, for example, when designing new computer chips. However, it would be foolish to try to use quantum mechanics to explain why the government's computers insist that you pay twice your income in tax. That problem is properly described in terms of the program the computer is running.

The reductionist method used by physicists is a marvellous tool for deducing the fundamental laws of the universe; but lots of information is irretrievably lost on the way down to the fundamental principles.

* it predicted that there would be a very small chance that a proton would decay into other particles. Experimentalists watched a very large number of protons for several years and didn't see any decays; if the theory had been right, they should have seen several.

About cascades, and the usefulness of particle physics

[The true constitution of the universe] is such a great and noble problem that it deserves to be considered before any other question.

Galileo Galilei

We have now – finally – reached the point where I might explain a little of my own work. Very briefly stated, I've been involved in using QCD, and methods derived from QCD, to compute the results of particle collisions in accelerators.

The largest part of my work (papers 2 and 3, written together with Yuri Dokshitzer and Gösta Gustafson; there are also some connections to this in paper 1) concerns what is known as the *QCD cascade*. To explain what this is, we consider what happens when an electron and a positron are made to collide (this is done, for example, in the big LEP accelerator at CERN outside Geneva). Since the electron and positron are each other's antiparticles they will annihilate each other, and their energy will turn into new particles. One possibility is that a pair of a quark and an antiquark are formed. These will move away in opposite directions with high speed. Some of their energy will be radiated as gluons. The gluons, in turn, will also send out other gluons, or turn into quarks and antiquarks. Within a very short time, the initial quark-antiquark pair has turned into a large number of gluons, quarks and antiquarks, all moving apart at high speed. Since quarks and gluons can't exist by themselves, but only inside hadrons, they must sooner or later join together to form hadrons — a process that is known as *hadronization.*

This process is what we call the QCD cascade. It is governed by the equations of QCD, that say how large the probabilities are for each particle to be created. Unfortunately, these equations are (as far as we know) impossible to solve exactly. For the first part of the cascade we can find approximate solutions, using a technique known as *perturbation theory.** Even using perturbation theory the problem is very hard, and people at many institutes, including our department, are working on finding better approximations. Many problems remain in this area, and our contributions are just one small step towards the goal.

In the case of the hadronization process, perturbation theory doesn't work. Solving the QCD equations for hadronization, even approximately, seems to be beyond our current ability. Instead, one can construct simplified computer models of what happens in hadronization. One very successful such model is called called the Lund model, since it was developed by people at my department. I have not done any work on the Lund model myself, but like many other physicists all over the world I have been using it quite a lot.

I will not go into further details about my work here and now, since that would make the discussion too technical for this general introduction; the interested reader is referred to the next part of the thesis, "Introduction to the papers". Instead I'd like to turn to the questions of why I (and other people) do this, and if there is any practical use for these results.

Our results on QCD will hopefully be useful to other particle physicists. They can be used by other theorists both as a way of testing if QCD really is the correct theory of the strong force and as a way of exploring other aspects of QCD; and by experimentalists as

* To make things worse, in many very important problems one can't even use perturbation theory. One way to solve these problems is called lattice QCD and uses enormous amounts of computer time; in fact, to get really good results one needs much faster computers than we have today, and new, faster, computers are being developed specifically for this.

a help in analyzing their results and a way of planning new experiments. For example, to be able to discover a new particle (such as the top quark), one must know what will come out of an experiment where such a quark is produced, and what will come out if it is *not* produced.

However, when people ask if particle physics is useful, they usually mean whether it can be applied to any practical purposes. Can it be used to feed the hungering, to cure the sick, to free the oppressed? And, if not, how can we justify investing enormous amounts of money in particle accelerators, when the money could be used for so many other purposes?

To be honest: there is no *practical* use for particle physics – at least not today. One could of course say that there are many areas of human culture where the government invests money despite the fact that there is no practical use; for example, the government subsidizes artists, even though nobody can eat works of art. And is the study of the fundamental laws of nature any less noble or worthwhile than, say, the creation of a new piece of sculpture? However, this argument may not be enough for particle physics, since the cost for a single accelerator is many times higher than the money any government spends on culture.

Personally, I feel that one can still justify spending money on particle physics, for the reason that there will in all probability be applications in the future. This is not just idle wishing. Our whole industrial culture – and with it all the advances in health care, food production, and general standard and quality of living – is ultimately built on basic science. When people began studying electricity in the 18th and 19th centuries, it was first seen as a novelty or a game, and later as something very abstract and unapplied. Maxwell didn't write down his equations to enable coming generations to build radios, but to try to understand nature. Building accelerators now might in the long run very well help more people than would using the same amount of money on welfare today. Of course there are limits, and experiments are becoming dangerously expensive. However, I feel that a world that can spend as much money as it does on drugs, cosmetics and weapons can afford to invest in future progress as well.

However, I would be a hypocrite if I said that I was doing particle physics because there may be practical applications in the future. Instead, what drives me (and, I suppose, many other physicists) is that physics is *fun*, and that there is a strong sense of beauty, order and logic in the way the universe works. To extend an old simile: we're reading the the Creator's plans, and to our surprise we find that the text is not an incomprehensible cipher, but a poem. We may never be able to read all of it, but the parts we've managed to read so far are indeed beautiful.

Part II: Introduction to the papers

It is a capital mistake to theorize before one has data.
Sherlock Holmes

Paper I concerns the possibility of producing transverse jets in diffractive hadron-hadron scattering. Diffractive scattering, in which process one of the incoming hadrons is broken up, while the other emerges unharmed, can be described by the exchange of an object called the pomeron. It has been hypothesized that the pomeron has a partonic structure, like a hadron. If that is the case, there could be a possibility of hard scatterings between partons inside the pomeron and partons inside the diffracted hadron. Based on such a model, Ingelman and Schlein predicted that transverse jets (jets with large momentum components perpendicular to the direction of the initial hadrons) should be produced in diffractive scattering. Such jets were later found by the UA8 collaboration at CERN.

In paper I, we propose a different explanation for these jets. The idea is that the jets can arise from gluons radiated from the excited proton, without any need to invoke any internal structure of the pomeron. The situation is analogous to the one in deep inelastic scattering: experimental data indicate that one of the quarks of the excited hadron is torn loose, and dragged away in the direction of the other hadron. We thus get a system of two separating colour charges. According to QCD, such a system will emit gluons in the same way as an accelerated electric dipole will radiate photons. If the radiated gluons have large enough transverse momenta, they will be observed as transverse jets. Unlike the colour charges produced in e^+e^- annihilation, which are pointlike quarks and antiquarks, one can expect that the pieces of the diffracted proton will have a finite extension; this will lead to a suppression of the emission of hard gluons.

To study this gluon emission, we performed Monte Carlo simulations of the process with the Ariadne program. This program, which is based on the colour dipole formulation of QCD (see below), simulates the gluon emission from the the excited proton, and the following cascade process in which gluons emit further gluons or split into quark-antiquark pairs. Ariadne also takes care of the finite size of the emitting charges. The final state of the Ariadne simulation consists of quarks and gluons; this was used as input to the Jetset program, which simulates the production of colourless hadrons according to the Lund model. The output from Jetset was then analyzed with a jet finding algorithm similar to the one used in the UA8 experiment. Our results agreed fairly well with the results published by the UA8 collaboration.

Paper II is about calculating jet multiplicities in e^+e^- annihilation from perturbative QCD. The number of jets found in an e^+e^- event depends of course on the way a jet is defined. This is often done in terms of a resolution parameter y, which specifies for example which is the largest difference two particles can have in transverse momentum and still be considered as belonging to the same jet.

If for example the average jet multiplicity is computed in perturbation theory, the coupling constant α_s will appear multiplied with large powers of $\ln y$ in the perturbation series. This means that for small y, it will not be possible to ignore higher-order terms in α_s; in fact *no* finite-order calculation is sufficient as long as one uses α_s as the expansion parameter.

However, it is possible to re-sum the perturbation series and absorb the large logarithms of y in the expansion parameter. If one chooses a suitable definition of jets, this resummation can be done analytically to leading and next-to-leading logarithmic order (this is known as the modified leading-logarithmic approximation, MLLA). One such definition of jets is known as the 'Durham algorithm'.

In this paper we have derived expressions for the mean jet multiplicity and n-jet rates as a function of the jet resolution parameter, and compared these results with Monte Carlo simulations (performed using the Ariadne and Jetset programs). We have also been able to improve the approximation compared to earlier work, reducing the size of the term needed to correct for non-leading-logarithmic effects.

Paper III is about the computation from QCD of multiplicity moments in e^+e^- annihilation. Earlier results have given good agreement with experimental data for the mean multiplicity, but too large values of the higher moments. On the other hand, Monte Carlo simulation programs based on QCD, such as Herwig, Jetset and Ariadne, give good agreement with experiments.

We study the solutions of a set of evolution equations for the multiplicity moments, supplemented by a set of boundary conditions that fix the behaviour at low energies. These equations were derived from the dipole formulation of the QCD cascade. They generalize, and improve on, earlier DLLA results by taking into account, in a combined way, both kinematical constraints and the effects of non-singular terms in the GLAP splitting functions.

The evolution equations are differential-difference equations, i.e. they are differential equations containing retarded terms. These terms, together with the boundary conditions, have the important effect of slowing down the evolution of the cascade, which limits the fluctuations and gives smaller values for the higher multiplicity moments.

We solve the improved equations for the multiplicity moments numerically, and compare our results with Monte Carlo simulations (which agree well with experimental data) and with some earlier QCD results. Our results are very similar to the MC results, and differ significantly from earlier QCD results.

To compare the partonic distributions given by perturbative calculations with the hadronic distributions from experiments, one can use the principle of local parton-hadron duality. This principle says that the hadronic distributions should be directly proportional to the parton distributions. However, in the parton multiplicity soft and hard gluons are counted equally, but soft gluons are not expected to produce as many hadrons as the hard ones.

Therefore, we also study the moments of another multiplicity measure called λ, that gets a smaller contribution from soft gluons than from hard ones. We confirm earlier results that this measure is better correlated than the number of partons to the hadronic multiplicity.