Small and beautiful
–
the colourful world of quarks

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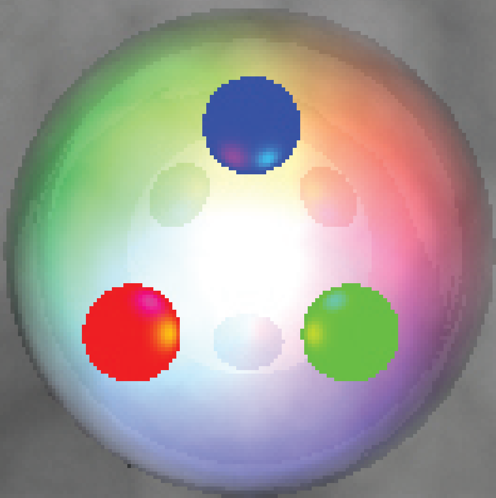
Inaugural speech in Utrecht, September 9, 2005



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I. Subatomic physics studies objects smaller than atoms, down to the smallest structure of nature, i.e. elementary particles. The paradigm underlying its scientific program is that isolating the fundamental constituents of matter and studying their interactions leads to a deeper understanding of nature.

Since the first atomistic ideas of Democrit we have gone a long way and have transcended the mechanistic view often associated with atomism. Knowing the building blocks of a system alone is not really sufficient to fully understand it. A system is often more than its parts. In particular, quantum mechanics has taught us to be careful to regard objects as "isolated", and quantum mechanics is indeed of utmost importance in understanding atomic and subatomic systems.

Keeping this in mind, the strategy of subatomic physics to "dissect" matter to understand its properties has proven to be extremely useful.

Let me illustrate the size of what we study with a series of pictures taken from a very nice book entitled "Powers of Ten". *(Illustration 1)* We start from our scale of everyday life, a metre and perform stepwise enlargements of a factor of ten.

The first three steps, a factor 1000 up to a millimetre are still familiar to us, but then we enter more and more unknown dimensions. At the seventh step, after 10 million-fold enlargement, we would start seeing the first hints of molecular structures like the DNA. Of course we do now rely on an artists view as no human eye has directly seen things like this. These are already small

structures, but we are not even half way on our trip to the scale of subatomic physics.
At a scale of 10 to the power of minus 10 (10 billion-fold enlargement) we would see single atoms, which appear to be relatively diffuse objects. Another factor of 10000 and we have the atomic nucleus in sight. One more step, and we are on a typical scale of particle physics, one “femtometre”, 10 to the power of minus 15 metres.
How close the relation of this picture to reality is, is debatable – I said that these are artists views. The dominating feature is that it’s colourful – and that is in fact a property of our subatomic world, although in a different sense of the word “colour”.

Matter consists indeed of atoms. These are, however, not the smallest objects existing, they are not “indivisible”. They are made up from a nucleus and a certain number of electrons bound together by the electromagnetic interaction and can be taken apart. The atomic nucleus itself is again a composite object with protons and neutrons as its constituents, and it can also be split. Finally it was found that protons and neutrons are also not true “elementary particles”, that means smallest building blocks, but have a substructure. Three still smaller particles, the quarks, can be found inside.
This may seem like a never-ending story: Advancement of physics leading to another more fundamental layer of nature, like Russian dolls being containers for yet another doll. Will we ever find the smallest doll? Or will we perpetually rewrite our book on elementary particles?
There are particles, which have stood the test of time – so far. The electron, one of the particles discovered earliest

is still believed to be elementary, that means it has no substructure, no further constituents.
Our current picture of the fundamental constituents is what we call the “standard model”, which knows a certain number of particles and describes their interaction. The particles are six different quarks and six other particles called leptons. Among these are the electron (one of the leptons) and the two quarks, which are necessary to build protons and neutrons. Those three particles make most of the matter that surrounds us.
The underlying theory has a striking beauty – striking at least to the scientist, because to a large extent it is related to the simplicity and the symmetries, which are most apparent when looking at the mathematical structure.

It may well be that this “standard model” of particle physics is very close to the deepest layer – or may be not, as the fact that we haven’t found another smaller substructure may also reflect our current inability to measure it. We should have learned the lesson from the turn of the other century, when many physicists were ready to declare their science “finished” – just before the advent of quantum theory and relativity. Most likely we will never be done, and as such we will never have a final theory, a final picture of “how the world is constructed”. And I should admit that we do actually appreciate that this is an open science, and we will not be out of work too soon.
But subatomic physics and the standard model of elementary particles is presently the closest we can get to the true nature of our physical world – that means the physics aspects of it. It may not be necessary to emphasize that there are many aspects of our world for

which physics has no answers and doesn't even attempt to find one. But may be it is useful to say that even some physicists know that themselves.
Even if the applicability of our science is limited, it has enriched our vision of the world around us. Atomic and subatomic physics have radically altered our understanding of matter.
A solid object is essentially mostly vacuum, a more or less regular assembly of tiny particles with a lot of space between them. Its solidity and stability that we perceive originate entirely from the dynamics of the particles, their forces, their interaction and the laws of quantum theory. An atom is again mostly vacuum, more than 99.9 % of its mass is concentrated in the nucleus, which occupies only an unbelievably small fraction of its total volume – in fact one quadrillionth.
So, shape as we know it, is defined by forces – gravitation on geological and cosmological scales and electromagnetism in our everyday world. And the vacuum that fills up most of this is also very different from what one thought earlier. Although there is no real matter in it, it is also not empty. It is filled with energy, with virtual particles reappearing and disappearing continuously.

This is a dramatic change in world-view: The stability or may be better the inertia of the "dead" world around us is due to our perception. On a deeper level it is entirely dynamic.
To use an example from a very different scale: Some people have said that the biggest achievement of space travel has been to enable humans to see earth as the small blue planet from outside, and by that to see how small we

really are in a cosmic context. The changes in perspective and sometimes paradigm that accompany science progress and surprises demonstrate that natural sciences, and in particular physics, are an important contribution to culture, beyond technological and other implications.

II. Let's continue with physics surprises. Here subatomic physics has a lot more to offer. In particular, quarks, the constituents of the proton and neutron, are a rich source of surprises.

How were quarks discovered? One had found early, that the proton has a certain size. It is an extended object, unlike for example the electron, which looks like a point down to the smallest scale reachable. This could be taken as a first hint that the proton is a composite object. Furthermore, in the experiments of particle physics more and more particles were discovered, which mostly seemed to be relatives of the proton, that means very similar particles. This was very much against the ideas of particle physicists, who had hoped that one could reduce the diversity of different objects on larger scales to just a few fundamental constituents. This didn't seem to work – there were far too many different particles to make for a "beautiful", that means simple theory.

In the 60's Murray Gell-Mann demonstrated how this "zoo" of particles could be explained by postulating that they were all made out of different combinations of three sorts of particles, which he called "quarks" (the first three of the six quarks we know now). Independently, experimentalists found, that deflections of high-energy electrons when hitting a proton could be explained by point-like constituents inside the proton. These were

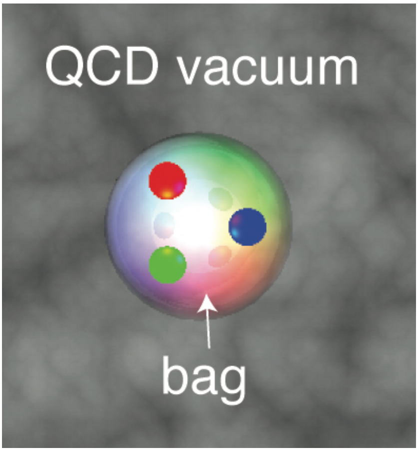
called “partons”, and people realized that these partons were identical to Gell-Mann’s quarks.
A theory of quarks and their interaction was formulated and tested successfully in many experiments. One of the necessary ingredients of such a theory is another particle, which mediates the interaction. In general an interaction, a force, can be understood as the exchange of such a particle. The electromagnetic interaction, like the repulsion between two positive charges, can be understood as being due to the exchange of photons. There is another exchange particle, analogue to the photon, for the interaction between the quarks, the so-called “strong interaction”. Those exchange particles are called gluons and they carry the strong interaction. They were predicted by the theory and were in fact discovered experimentally later.
The picture of the microscopic world had regained its simplicity and by that its beauty to the physicist.
But back to the surprises related to quarks: First of all, the quarks have a charge, and it appears to have a strange value. One had earlier found that electric charge comes in portions, for example as much as an electron carries. This was called “elementary charge” and was regarded as a fundamental constant and as the smallest possible unit. Now the charge of the quarks is either 1/3 or 2/3 the size of it. This is already against expectations.
Also, for a correct description in theory quarks should have a relatively small mass. However, when for example three of them are put together to make a proton, the resulting mass of it is much larger than just the sum of the masses of the three quarks.
But even more, although there is overwhelming evidence that quarks exist, one has never found one of them as a

single isolated particle. They seem to only appear in pairs (a quark together with one of the antiparticles, an anti-quark) or in groups of three, like in a proton. This is related to the behaviour of the interaction between them, the so-called strong interaction. Forces we know from the macroscopic world, like gravitation, reduce in strength for increasing distance and are negligible for very large distance. This is not true for the strong interaction we find between quarks: The force remains strong even for arbitrarily large distances. This implies that one would need an infinitely large amount of energy to free a quark from the attractive force of others. The force "confines" quarks in for example a proton.
Another aspect of this puzzle is that each quark seems to come in three versions, which are called colours. These colours have nothing to do with our colours in everyday life, the name was chosen because the properties of the quarks are very much analogous to them. There exist three colours, much like the ordinary base colours "red", "green", and "blue", and mixing the three together in equal amounts produces something neutral, that is "white".
An isolated coloured object, like a single quark, is not "allowed" to exist in nature. Only the colour-neutral combinations are allowed, and they make particles like the proton. It appears that these white objects do not experience the confining strong force.
Not only is the strong force extremely strong for large distances, but it is also getting much weaker than naïvely expected for small distances, so much that it is almost negligible.
These two properties of quarks in the extremes:

- confinement for large distances and

- asymptotic freedom for small distances

have inspired a simple picture of the proton (or other particles made of quarks).
The proton can be seen as a space, a hole, in some surrounding material, like a bubble in water, which contains the quarks. The surrounding material is responsible for the confinement of the quarks, it takes the role of the confining force. Inside the hole the quarks are free to move as they want – the force between them is negligible (see following illustration).
This may already seem like a strange description of the constituents of matter, but this is just the beginning of surprises. One may continue with asking: What is this surrounding material? In fact it is not really "material", but just the vacuum.
Vacuum is a peculiar thing. Our every-day notion of it is of course influenced by very early ideas of vacuum as "empty space". Vacuum is what you obtain, if you take everything out of a certain volume – like taking the air out of those metal spheres in the first "vacuum engineering" experiments performed by Otto van Guericke.



It is not necessarily empty space, but as empty as you can get. On macroscopic scales, for every-day life, vacuum may appear empty. On microscopic scales however, in subatomic physics, we realize that there is

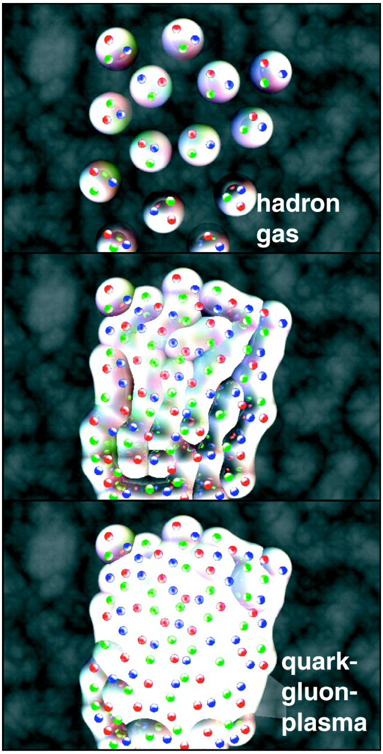
nothing like emptiness. If we take everything away that we can, that means we try to reach the most empty state, which to the physicist is the “true ground state”, the simplest possible state, space is not empty. There are certain things that we can never get rid of – not even theoretically.
Space is interwoven with virtual particles and fields. There is the so-called “vacuum polarisation”, particle-antiparticle pairs appearing and disappearing spontaneously, which cannot be observed directly, but which for example carry energy. Through them the vacuum has its own energy.
When looking at quarks, one realizes that there are even stranger components of the vacuum: There are so-called “condensates” both of quarks and of gluons (the carriers of the strong interaction), also consisting of virtual particles and thus not directly measurable, but much stronger in magnitude. These condensates, which are part of the vacuum, are responsible for the confinement of quarks into protons, a rather strong effect.

When quarks appear in a system, they can do so only in groups that neutralize each other. In addition, something in the vacuum surrounding them squeezes them together so that they can’t escape.

This phenomenon of confinement, which is unique to systems of quarks, is now well known and there exist theoretical descriptions of it. It is, however, not yet really fully understood. It is one of the puzzles that we are trying to investigate experimentally in our group at Utrecht and NIKHEF. The research we perform is in fact “vacuum engineering” on a very deep level.

These properties of the vacuum are so strange, that one is lead to ask whether they are so fundamental that they will always be there. Is there always this strong condensate as part of the vacuum that confines quarks, no matter what the conditions of the system are? And in fact this may be not so.

If one puts a very large number of quarks close together, that means one increases the density, the strange vacuum is "pushed away" between them. Theoretical calculations predict that at very high density or temperature the force between quarks changes its behaviour drastically – the confinement disappears. You can see this in the following illustration, which starts from a system of protons and neutrons with three confined quarks, and goes to a new deconfined state. Suddenly, quarks are no longer imprisoned in small volumes, but are essentially free. They do no longer need to combine to colourless (white) objects, such that this is truly a colourful world. This is an extreme example where you cannot just know the constituents and the force between them to predict their behaviour, because the conditions of the

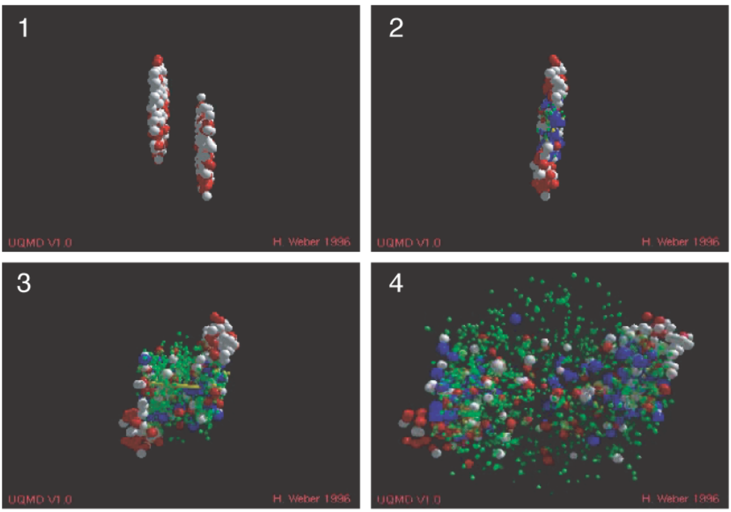


environment change the force itself.

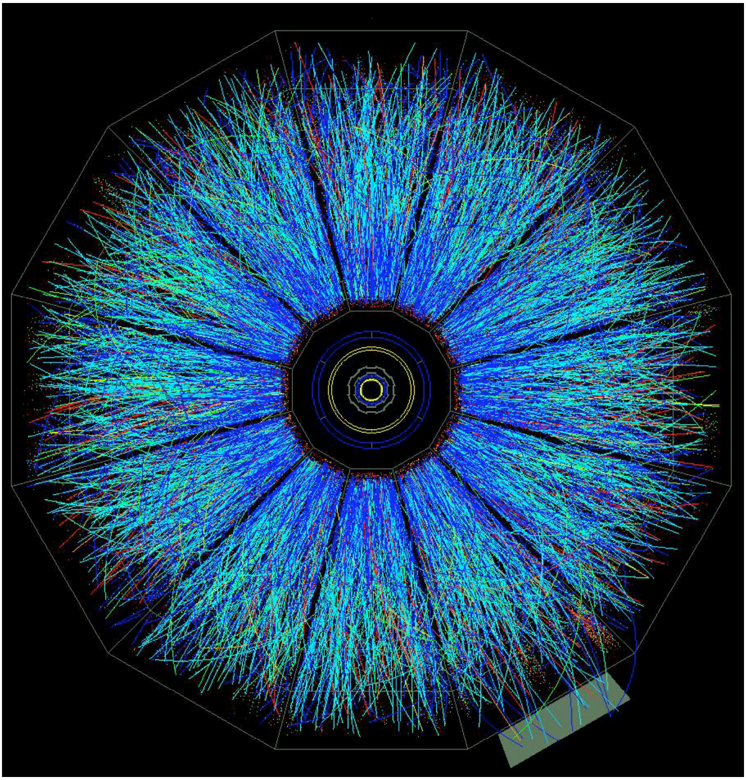
One does need really extreme conditions for this to happen, for example the temperature is much hotter than even in the centre of the sun. But once these conditions are there, one expects the phase transition of “deconfinement”. Quarks are liberated and the nature of the vacuum changes. The new state of matter that will be produced has been named the ”quark-gluon plasma”, a state of free quarks and gluons. The gluons that I mentioned above play a significant role here. They are accompanying quarks and are necessary for a correct description of these systems.
The extreme conditions needed have certainly existed at least once: Very shortly after the big bang the universe was so hot and dense that it must have been such a quark-gluon plasma. Only later when it had cooled down were quarks confined as we find them now. It is also believed that this state of matter exists in the core of very dense stars. And although the quark-gluon plasma may lead to observable consequences in these cases, they are not easily accessible to the researcher.

The only possibility to study this new state of matter experimentally is by colliding heavy nuclei with extremely high energies. The nuclei contain a large number of quarks, and they will be effectively heated and compressed when they collide, thereby providing the necessary conditions for the phase transition. But, as we have no container for this matter, it will not stay put, but fly apart almost immediately. We can produce it only as a transitory state for a very brief moment – this makes the study even more complicated. In the following illustration you can see four snapshots from a simulation of a collision between two high energetic nuclei.

How is this research done in reality? The atomic nuclei (for example gold or lead), with a size of a few femtometres – the scale you may remember from the beginning – are accelerated by huge machines, particle accelerators. They consist of tubes running in rings of several kilometre circumference in underground tunnels,



surrounded by thousands of magnets which both perform the acceleration and keep the particles on track in the rings. There are dedicated collision points, where the collisions take place inside huge detector setups, which are several storeys high and weigh thousands of tons.
When the experiment is running, thousands of collisions of nuclei take place every second, and each collision sends out a shower of thousands of subatomic particles, as in the following picture showing the measurement of a single such collision. Using the detectors we try to measure as many of these particles as possible and use them to reconstruct what has happened at the very



moment of the collision. The accelerators and the detectors use the most advanced technologies available, for example for their huge superconducting magnets, for their microscopically accurate silicon detectors and last not least for state of the art electronics and computers.
These extremely complex experiments cannot be built and exploited by single scientists or small groups. Hundreds to thousands of scientists from all over the world work together in large collaborations to achieve their goals. While this large scale may sometimes seem frightening for newcomers, those experiments are perfect examples of modern international collaborations with the required management and communication structures.
The challenges in such an experiment are enormous. Each particle produces electronic signals in up to hundreds of detector cells. Within microseconds one has to decide, whether the signals of the detector are worth measuring and then has to transform them in similarly short times into numbers stored in the memory of specialized computers. For every collision to be measured several 100 megabytes of measured data are produced, corresponding to several tens of gigabytes per second. Part of that data is pre-analyzed online to reduce the data volume to below 100 megabytes per second. To remind ourselves of the amount of information this contains – 100 megabytes is roughly 20 times the amount of text in the complete works of Shakespeare. In modern standards: A DVD would be filled in less than a minute. The total amount of data collected is enormous and requires specialized state-of-the-art computing resources. The analysis of these data also requires enormous resources and clever, efficient custom-made programs,

but it also challenges creativity and intuition of the scientists.

Although the problems are extremely complex, we are able to perform fascinating studies of these tiny, short-lived systems right after the collisions. To give just two examples:

- We are able to precisely determine the distance of the two-nuclei at the moment of impact and even to measure their orientation in space – on length scales a million times smaller than single atoms.
- We can use highly penetrating radiation, so-called jets, which are automatically produced in these collisions and can be theoretically predicted with good precision, to scan the produced system for regions of high or low density. This employs the absorption power of the matter, very much like in computer tomography.

Although a lot has been achieved in these studies – we are certainly producing matter of extreme density and temperature, which meets the necessary conditions for a quark-gluon plasma – the jury is still out on the exact properties of this state. A lot of open questions remain. We see that the interaction between quarks is altered in this state, but how strong or weak is it still? Are quarks still bound together or do they eventually become really free?

The mass of the protons and neutrons, which accounts for most of the known mass of the universe, is much larger than what we expect naïvely for the sum of the masses of the three quarks. Where does this come from? How is this mass generation related to confinement?

Do we really alter the state of the vacuum?

These are some of the fascinating questions that will keep us busy in the future, and which make fundamental research in subatomic physics so fascinating, especially for the researcher himself. It can also be fascinating for laymen, although we have to make it more accessible to them.

III. One of our strong motivations is to understand nature, and this curiosity is such a strong integral part of human beings, that this may already be sufficient as a motive. But I'm convinced that we have to ask ourselves about the real use of what we do for society.

Enlarging our knowledge, broadening our horizon and contributing to shape our world-view, as I have discussed in the beginning, is in fact important for society. But more concrete implications come via technology that originates from physics research.

Subatomic physics has only a few direct applications (like nuclear power, and medical treatment and diagnosis) and from the current fundamental research there are actually no direct applications in sight. In addition, one might argue that some of the applications are at least ambiguous in their use. Just because of the risks involved society has to maintain knowledge about these issues and continue to study them consciously. But this is the topic of a different talk, which I don't want to give today.

Fundamental research in subatomic physics has no direct applications. But physics is a systematic science, may be the systematic natural science. The success of physics originates from the complete system, and there is no completeness without the most fundamental parts of this science. To keep science alive we need physics, and to keep physics alive we need this foundation.

Then there are the indirect applications. Is there a “Teflon frying pan” of subatomic physics? This example has been frequently used and maybe overused in the context of space travel, so one should probably not overemphasize the importance of such singular products.
But there are in fact important developments in the context of subatomic physics. Maybe the “world wide web” is the ”Teflon” of subatomic physics. It was developed at the subatomic physics research centre CERN in Geneva in our scientific context as a communication means and has certainly evolved now into one of the most influential modern technologies of everyday life.
To name another example: The extreme electronics and computing requirements in our experiments push the current information technology beyond its limits. This is one of the driving forces behind the GRID concept, a new form of distributed computing, where every user can exploit computer resources all over the world transparently.
The ambition to solve the most challenging problems without the constraints to produce a specific result (like a marketable product) can lead to outstanding achievements. The combination of extremely focussed work with a very open attitude is unique to fundamental research, and it is a strength of subatomic physics. There are only few areas where such dedication and particular skills come together – and this even without the expectation of excessive salaries.

In our context developments can be undertaken that would be impossible in commercial environments. Just imagine: If something like the world wide web would have been invented by commercial enterprises, we would have communication systems with numerous different proprietary standards – nowhere near as useful as what we have now.

To come back closer to the main purpose of this talk: One of the most important influences of our field is in its deep connection between research and education. Students taking part in subatomic physics research have unique opportunities. They are trained in systematic, complex problem solving, which can be applied in many different areas. This is done in an open environment as in most fundamental research. They are taught to be open for surprises. The work is focussed, but not towards a particular outcome. Results are freely communicated to other scientists. They take part in developing equipment at the forefront of for example information technology.
A very unique feature is that this work is done in large international collaborations, which require and exercise modern management, communication, quality assessment and other techniques, which are extremely valuable in any modern work environment.
It is this particular combination of forefront technology, international collaboration and open-mindedness, which makes education in subatomic physics very valuable for society. Research and education going hand in hand is of course a necessary condition for this.
At the same time taking part in outstanding research of fundamental importance and contributing to the education of young people is what gives a position such

as this professorship the potential of a “dream job”, and makes this lecture an opportunity to celebrate.

Acknowledgements
At this point I would like to express my thanks to all people involved in this endeavour:

First, I would like to thank the University of Utrecht and the Faculty of Physics and Astronomy, now part of the Beta-Faculty, for appointing me as professor for subatomic physics. I would also like to thank the NIKHEF institute and FOM for supporting my installation. I hope I can further the interest of students in this fascinating and important research and help to provide a balanced, broad but also deep education program in physics.

I have profited enormously from my own physics education, which happened for a large part at the University of Münster. There I also had the opportunity to work with an inspiring, promoting, and last not least very pleasant teacher, Prof. Santo. I would like to thank all colleagues in our research group at Münster, and also my collaborators from all over the world in the various experiments at CERN, Geneva, and at Brookhaven National Laboratory near New York. I'd also like to express gratitude for the support from people at GSI, Darmstadt, over the years and in particular during my brief period as an employee.

I would like to also thank the colleagues of the subatomic physics group at Utrecht University and NIKHEF, and everybody else at the faculty and the FOM institute who has facilitated my work, for their warm hospitality and the positive working atmosphere, and for their dedication to our research projects.

Thanks to the students, who are the true employers and teachers. I hope I can pay back your confidence.

A thank you to all my friends and family for their help on my way, above all to my dear parents, who have made my education and career possible, and have always provided support.
Dear Beate, thank you for sharing with me this way of mine and being the other true centre of my life.

I’d like to thank everybody for the attention.

Ik heb gezegd.