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'Beauty in things exists in the mind which contemplated them.' An aphorism by David Hume.

#### Accelerators in physics

Accelerators are our approach to the beauty present in the heart of matter. It is hidden to our senses but not to our mind. We are looking into the deep structure of matter in order to find Unity and Simplicity in a world that surprises us by its seemingly vast complexity and diversity. At present we can probe the structure of matter with a resolution of  $10^{-18}$  m. The reward has been enormous. At the quark and lepton level thus met, the strong force, which is responsible for the binding of nuclei, and the weak force, which is responsible for the dominant features of radioactivity, present a universality and a basic simplicity that are to a large extent hidden at the nuclear level, with a resolution limited to  $10^{-15}$  m, which is where we were 40 years ago.

Increasing our resolution from  $10^{-15}$  to  $10^{-18}$  m, we have understood the strong force. And we have understood the weak force. In the latter case, our understanding is achieved in a framework where weak and electromagnetic interactions are but two facets of a unique phenomenon, the electroweak interaction.

In quantum physics, which is overwhelming as one probes beyond atomic dimensions (<  $10^{-10}$  m), the price to pay for resolution is energy. This can be understood in analogy with diffraction in optics, noting that a quantum of light has an energy inversely proportional to the wavelength. It takes 100 MeV of collision energy to analyse a structure with a resolution of  $10^{-15}$  m. It takes the 100 GeV, which we have today at LEP, to scrutinize it with a resolution of  $10^{-18}$  m. This is also the type of resolution achieved with our present pp̄ colliders, granting the fact that what matters is the energy available in quark, antiquark, or gluon collisions with, accordingly, a typical loss by an order of magnitude as compared with the nominal machine energy given at the proton-antiproton level.

The understanding of the physical world has clearly followed the development of instrumentation. Ever since Galileo, scientific research has relied extensively upon the knowledge collected from the detailed observation of nature, using instruments that greatly extend the power of our senses.

Progress over the past 40 years—during which we could extend the exploration made possible with synchro-cyclotrons to that accessible with our present colliders—has been spectacular. Is it not wonderful to be able to understand all forces as resulting from a unique invariance principle, namely the invariance of the laws of physics under gauge transformations. We like symmetries and the invariance properties with which they are associated. To quote S. Chandrasekhar: 'It is, indeed, an incredible fact that what the human mind, at its deepest and most profound, perceives as beautiful, finds its realization in external nature.'

In order to meet with this beauty we have to look in depth. Accelerators are our tools for doing this.

In our atavistic longing to know the deep structure of matter, we have always striven to have higher and higher energies communicated to the smallest probes (protons or electrons) that we can find. At each stage there have been technological and financial limits, but with physics ingenuity and technological developments they could be overcome. In this context it is striking to consider the so-called Livingston plot, which shows the growth of accelerator beam energy as a function of time. Changing techniques from rectifier generators to alternating gradient synchrotrons, an overall exponential increase could be sustained from the thirties to the seventies. This is shown in Fig. 1a [1].



Fig. 1 The Livingston plot of the development of accelerators with time: a) as it looked in the late seventies, b) as it looks today, now that colliders hold the centre of the stage.

Note, however, that the growth rate that is at first sight read from the Livingston plot represents a too optimistic view, since relativistic kinematics imposes that the centre-of-mass collision energy-that is, the energy that is actually relevant to the resolution achieved-increases only as the square root of the beam energy. Moreover, we know now that when it comes to the deep structure of matter, the proton is but a broad-band beam of quarks, antiquarks, and gluons. Only a fraction of the incident proton energy (say 10%) is to be found, on the average, with each constituent. However, the advent of colliders-and one already sees the ISR point on the 1979 plot of Fig. 1ahas vindicated the sustained exponential growth! It is seen at work in Fig. 1b, now considering a centre-of-mass energy at the constituent level and no longer a proton beam energy, with new points associated with recent machines and projects that are already under way or merely just being talked about [2]. We can reasonably well anticipate a sustained growth in our resolution power for many years to come. Indeed, we hope that by the year 2000 we will already have gone beyond  $10^{-19}$  m (1 TeV).

We shall come back later to the physics met at 100 GeV, or with a resolution of  $10^{-18}$  m, and to the questions that make us so eager to explore the TeV (1000 GeV) energy range, which is possible with the SSC and the LHC. Proton colliders are the present key projects in particle physics. They are designed to gain over an order of magnitude in collision energy at the constituent level.

However, before doing this, it is first worth while to mention a cosmic connection that makes accelerators and telescopes highly complementary instruments for helping us to understand the cosmos at large. We live in an expanding Universe, and the density and the temperature are the higher the more one probes deep into the past to reconstruct what happened at the beginning of the Universe. It all started with a Big Bang about 15 billion years ago and, as the Universe expanded, the temperature (energy per particle) first fell as the inverse square root of time. When the Universe was one second old, the temperature was 1 MeV. This was a time of a carnage for electrons and positrons, leaving only the small electron excess that was present at earlier times, namely  $10^{-9}$  of the initial electron population, and which can be compared with the photon population that is still around today in the low-temperature radio-wave background. This was also the time when deuterons could make their first attempt at binding-a nucleosynthesis process that was over when the Universe was 200 seconds oldleaving the overwhelming constituents, helium and hydrogen, in the 1 to 3 mass ratio which stellar evolution has hardly changed since.

With our present 100 GeV, we can probe the early Universe down to  $10^{-10}$  s after the Big Bang. This was a time when the W and Z (the latter being now produced at an industrial level at LEP) had just acquired their heavy mass through a phase transition of the prevailing vacuum, and were soon to disappear entirely from the cosmic scene.

Understanding the physics that prevailed in the early Universe (physics in an ever-increasing energy range) is the only way to tackle important questions raised by our study of the cosmos, which we can probe with telescopes to further and further distances—and therefore also to earlier times.

Take a specific example: the neutrino plays a very important role in astrophysics. Its physics could be understood thanks to accelerators, which have since a long time provided intense high-energy neutrino beams. The counting of families of quarks and leptons through the counting of neutrino species, as has recently been done at LEP and the SLC, is directly

related to the analysis of nucleosynthesis, since the cooling rate of the early Universe depends on the number of neutrino species, and since neutrinos—through their weak interactions—were the only agents to enforce thermic equilibrium between neutrons and protons, although only for a limited while.

We shall come back to the high-energy frontier later, and to our need for higher-energy accelerators, but in the meantime we shall concentrate on other machines. Particle physicists, with their drive to unravel hitherto unknown phenomena, always look for new grounds, and at higher energy. It is clear, however, that whilst the march towards higher energies has advanced, with its gathering of new phenomena and its many successes, a large number of unsolved riddles have been put aside. There is a certain type of physicist who prefers to keep working on these still unsolved and difficult questions rather than explore the fully unknown top energy frontier. One may, of course, argue that the new insight collected from high energy may eventually make the lower-energy riddles easier to solve, but this can in no way exclude a direct approach, with its specific demand for new instruments.

Thus there is also a demand for lower-energy machines, for which the intensity, the duty cycle, and the dedicated production of specific beams are more important than sheer energy [3].

At CERN, two examples of such lower-energy facilities are the Low-Energy Antiproton Ring (LEAR) and the heavy-ion complex, where ions up to sulfur are at present accelerated to 200 GeV/A in the PS and the SPS. Later, in 1994, when the new dedicated injector becomes operative, lead ions will be accelerated. Both facilities are used by a community of over 500 physicists. At stake in the former case is a detailed study of hadron spectroscopy and, in the latter case, a search for evidence of a new state of matter: a quark-gluon plasma where colour is no longer confined to hadronic dimensions, and which should exist at temperatures in excess of 200 MeV. This should have been the state of our Universe up to a few microseconds after the Big Bang.

Encouraging results after exploratory heavy-ion runs [4] support not only the construction of the lead source at CERN but also the extension of this research to much higher collision energies. This extension could be possible with the RHIC, a heavy-ion collider of 100 GeV/A which should soon be built at BNL, and later with the LHC, which could accelerate the then available lead ions through the CERN machine complex, with colliding beams of 3.5 TeV/A! We should thus be able to reproduce, over the volume of the colliding ions, the conditions that prevailed in the early Universe, and gain much insight into the dynamics of colour confinement.

I shall now briefly mention two types of machines that are at present under much discussion. If, as seems likely, the physics case is strong enough to fuel the enthusiasm of a large enough constituency (three to four hundred physicists in each case), the construction of such machines should become a must, funding permitting.

The first machine is a  $b\bar{b}$  factory. This would be an electron-positron collider with a collision energy of the order of 10 GeV, but with a much higher luminosity than anything achieved so far (close to  $10^{34}$  cm<sup>-2</sup> s<sup>-1</sup>). Such a machine would produce B mesons (mesons with beauty) abundantly. This would offer a great opportunity to study CP violations in the  $B\bar{B}$  system when all our present results are confined to the  $K\bar{K}$  system.

The second machine is a 100% duty cycle electron accelerator that would cover the initial energy range of SLAC, where the quark structure inside the proton was first discovered. It would extend the energy domain soon to be covered by CEBAF, reaching energies where the dynamics behind the EMC effect could be studied [5]. The present pulsed machines do not allow for coincidence experiments where the complex system which recoils against the scattered electron could be studied. In order to do this, a high duty cycle is a must.

Despite their relatively low energy by present standards, such machines are quite hard to build. Achieving very high intensities—which in both cases is a must—is not an easy matter!

It is worth while to mention that such lower-energy initiatives are supported by a physics community that is often composed of both nuclear and particle physicists. Nuclear physicists have indeed also been pushing for higher energies as their understanding of nuclear structure has become more refined. One of the present giants of nuclear physics, the SIS at GSI Darmstadt, with intense heavy-ion beams of energy of the order of 1 GeV/A, would have been called a high-energy facility 30 years ago. It will now extend to much higher energy work on high-intensity heavy-ion collisions, for which GANIL has had the monopoly for several years. At stake with this research is the formation of exotic and 'hot' nuclei and the study of the equation of state of nuclear matter. This is very relevant to astrophysics, as well as to nuclear physics proper.

I shall next touch, in very general terms, on the questions of polarization. Particles have spin and collision amplitudes depend on polarization. Therefore, having polarized beams is a significant plus. Polarization effects usually originate from an interference between different spin amplitudes. Thus the rate of a small and poorly known amplitude can be emphasized by its interference with large and better known ones. One can thus obtain relatively easy access to effects that would be much harder to see—or might even simply be hidden—with unpolarized results alone. However, there is usually an imposed trade-off between polarization and intensity, and this often muddles the case. When weak processes are of key importance (HERA) or when the Standard Model may demand still more precise tests, or show its limitation (LEP, SLC), polarized beams should be an asset.

I conclude this survey of accelerators in physics with a few words on synchrotron radiation.

Accelerated particles radiate, and the more so the lighter they are. The relevant factor for a circular machine is  $(E/m)^4/r$ , where E and r are the machine energy and radius, respectively, and m is the particle mass. With 10 to 100 GeV electron machines, cost optimization leads to a radius increasing as the square of the energy. LEP is therefore probably the largest electron-positron collider ever to be built. Reaching higher energies, much in excess of 200 GeV, requires linear colliders, where the needed luminosity has to be achieved through single-passing-bunch collisions. With protons, the limit for circular machines is at a much higher energy. However, the eventually powerful synchrotron radiation has now to be removed from a magnet structure at very low temperature, since superconducting magnets become a financial must. It is even possible that the SSC will be the largest circular proton-proton collider ever to be built. At its design luminosity, synchrotron radiation represents already half of the power that has to be taken away from the cryogenic system.

Such synchrotron radiation was first seen as a serious hindrance to accelerating electrons. However, it was soon realized that the intense fluxes of X-rays—and eventually gamma-rays—that are produced, could be of great potential use. Some machines have thus been optimized for synchrotron radiation, with wigglers and undulators that enhance the radiation and tailor it to specific purposes. The radiated Xray fluxes are put to use in research (solid state, molecular, ... studies) or for industrial applications (gradings, ...). For instance, the ESRF in Grenoble, which has the size and overall aspect of a high-energy machine of two decades ago, will soon be a powerful instrument for condensed matter and molecular studies. Accelerators have found a great many uses in physics. Many machines built for particle physics research (electronpositron colliders) or for nuclear physics research (tandems) have not been shut down when deserted by their initial community of users, but have kept working for basic research in other fields of physics—not to speak of chemical, biological, and medical research.

After this overview of physics with accelerators, I would now like to explain in greater detail the 'why' of this type of research, focusing on the high-energy domain, and to try to convey the enthusiasm felt by particle physicists for the study of the structure of matter to increasing depth and therefore with accelerators of ever increasing energy.

## To the heart of matter with accelerators

As I have already said, we probe matter to increasing depth in order to find unity and simplicity in a world that strikes us as a place of apparent diversity and complexity. Physicists have never been deceived in their hopes and great progress has been made as the atomic, the nuclear, and the hadronic levels-and now the quark level-were reached in the structure of matter, as the available resolution overtook, in turn, the values of  $10^{-10}$ ,  $10^{-14}$ ,  $10^{-15}$ , and  $10^{-17}$  m, respectively. With a resolution of  $10^{-8}$  m, accessible with collision energies of 100 GeV, we can clearly see the quarks inside the proton which they build. A proton is made of two u-quarks and one d-quark. This should, of course, not be taken as a static view. Quarks continuously exchange gluons. These gluons may break into quark-antiquark pairs which may fuse back into gluons. As a proton collides, we can pick up one of these many configurations. This continuous ballet obeys a now well-known choreography: quantum chromodynamics (QCD). Quarks and gluons carry 'colour', which plays the role of charge for QCD, but the proton is globally neutral under colour. Reactions among quarks and gluons can be predicted quite accurately when a proton and an antiproton collide in the CERN or the Fermilab collider. A quark and an antiquark may fuse into a W or a Z or, more frequently, they may scatter violently, producing spectacular hadronic jets. The Lego plots of collisions at the  $p\bar{p}$  colliders represent the modern version of the Rutherford experiment. They bear witness to the presence of point-like hard constituents within the colliding particles. At the quark level, and only at that level, strong interactions reveal their deep simple structure. QCD is a beautiful theory relying on a gauge-invariance principle [6]. Even though working out its consequences still presents impressive difficulties, the theory is basically simple. It can be used in a straightforward way at short distances, or with collision energies in excess of 20 GeV. It then meets with spectacular success.

Figure 2a shows the jets seen in  $p\bar{p}$  collisions at the CERN Collider. Spectacular jets of  $\pi$  mesons bear witness to the attempted escape of scattered quarks, antiquarks, and gluons inside the colliding particles.

With Fig. 2b, we have the modern view of the 'hydrogen atom'. This figure shows the transition lines between the levels of charmonium, a system formed by a charmed quark and its





Fig. 2 The quark structure of matter. a) The Rutherford experiment at the quark level: jets in  $p\bar{p}$  collisions. b) The hydrogen atom at the quark level: the energy spectrum of charmonium.

antiquark. The discovery in 1974 of the  $J/\psi$ , and in particular the way it appeared at SPEAR, was the first time that such a system had been seen. The spectrum of Fig. 2b was obtained with the Crystal Ball detector, which was used first at SLAC and then at DESY. Benefiting then from the heavy mass of the quark, we understand quark dynamics well enough to be able to calculate these levels and the electromagnetic transitions between them.

We can, in principle, reconstruct all known stable objects in terms of two quarks, the u-quark and the d-quark, and an electron. This may seem *a priori* to be only a small step forward, if any, from the situation of 40 years ago, when the no more numerous basic constituents—the proton, the neutron and the electron—were the building blocks of matter. However, it is well known that with quarks we have also the basic elements for the host of hadrons that were discovered in the meantime, in particular in the sixties with the first big synchrotrons (the Bevatron, the PS, and the AGS). More important is the fact that strong interactions are simple at the quark level, whereas at the proton-neutron level they were very complicated. It is like comparing complicated molecular forces, relying on atomic polarization, with the universal simplicity of the Coulomb law acting on point-like particles.

At the quark level also, the unity of the weak and electromagnetic interactions reveals itself to the full. The discovery of the W and the Z particles at the CERN pp Collider was the last spectacular result in the verification of the unified theory of electromagnetism and the most frequent aspect of radioactivity.

The W and the Z are the grains of heavy light imposed by the unification of electromagnetic and weak interactions, in much the same way as the photon was the grain of massless light required in the unified theory of electricity and magnetism.

The electroweak theory relies also on a gauge-invariance principle. The great similarity between QCD and the electroweak theory indeed suggests a larger synthesis whereby all interactions among particles would proceed from a unique invariance principle. The expected realm in which such a Grand Unified Theory can be given full rein is of the order of  $10^{15}$  GeV. We cannot expect our accelerator colleagues to lead us there, whatever the support given by the taxpayers. Nevertheless, we do expect many prominent indirect elements to be found as they reach the TeV domain—something which is within their power today.

We see that our quest for unity and simplicity has already been greatly rewarded by our descent to the level of  $10^{-18}$  m. The Standard Model of fundamental particles and fundamental interactions [7] sums up, in a compact and powerful form, the whole of particle physics at our present level of scrutiny.

The Standard Model, which shows in a simple, elegant, and neat way how nature works down to the level of  $10^{-18}$  m, is a relatively recent achievement. It still deserves a thorough testing and, despite its relative simplicity, it is certainly not expected to be the ultimate in physics. LEP, HERA, and the Tevatron Colliders are ideal instruments for conducting such tests, and for continuing with greater accuracy the exploration started with the CERN pp̄ Collider. In another context, the study of rare decay modes, neutrino properties, etc., using the intense beams of lower-energy machines also offers interesting tests of the Standard Model.

As the study of the structure of matter with a resolution of  $10^{-18}$  m is now fully under way, and as the first phase of LEP is now operative, it is quite legitimate to prepare for the next big step, which should take us at least one order of magnitude further in resolution power. This is TeV physics at the constituent level, something for which the SSC and the LHC are designed. They are proton-proton colliders of 40 and 16 TeV respectively, with luminosities of, or in excess of,  $10^{33}$  cm<sup>-2</sup> s<sup>-1</sup>, a much needed property for the study of quark and gluon crosssections, which typically decrease as the inverse square of the collision energy [8].

What are the main present motivations for this type of physics. First, one may recall that the Standard Model is based on symmetries or on invariance properties. However, these symmetries deep inside our theory are broken when they are applied to the inescapable stage offered by the vacuum. In quantum theory, the vacuum—which is by definition the lowest energy state of the world—could have all the complexity of scalar fields. The vacuum seems to use this possibility to the full. This is why the W and the Z acquire their heavy masses whilst the photon remains massless. This is why the vacuum is opaque to colour, forcing quarks and gluons to remain confined constituents of colourless hadrons, and transforming their escape attempts into jets of colourless mesons.

The vacuum behaves in the manner of a medium. Its properties are actually similar to those of superconductors although in a more involved, relativistic, and non-commutative way. Indeed, the electroweak theory of Glashow, Salam and Weinberg can be viewed as an extension of the Landau-Ginzburg theory of superconductivity.

However, whilst in the case of superconductivity it is the complexity of the medium—the superconducting metal—that provides the relevant dynamics, in the Standard Model we have merely 'twists' in the vacuum, with hitherto mysterious dynamics to explain the symmetry breaking. This can be described successfully in terms of Higgs fields, but we may then wonder what the Higgs fields actually are. This is one of the great open problems in physics.

A medium changes phase at critical temperatures, and we are led to expect that at about 200 MeV the vacuum is no longer opaque to colour (this is what we are after with heavyion collisions), and that at about 200 GeV the W and the Z mass should disappear, in much the same way as the effective photon mass—which prevents a magnetic field from permeating a superconductor—disappears at the critical temperature, when the behaviour of the metal returns to normal.

In order to understand this dynamics, we have to study interactions much above this critical temperature. A highly promising ground is the study of ZZ interactions up to and beyond the TeV range, using Z's, which quarks easily radiate at very high energy. This is one of the key motivations for the SSC and the LHC. We are thus after the dynamic origin of mass.

Another important reason was already mentioned in connection with the Grand Unified Theory, which could be operative above  $10^{15}$  GeV. The great unity of the Standard Model is such that we are naturally led to envisage this still greater symmetry, which would combine quarks and leptons, all coupled through a unique interaction mode. At our present 100 GeV, we can see only the broken remains of such a full symmetry. Its realm may seem very far away, but we may then wonder why we meet so much order at 100 GeV when it could be upset by quantum fluctuations involving this very high energy domain—unless, of course, there are compensating mechanisms.

These mechanisms, with probably new basic particles and interactions, should involve actors showing up not too much in excess of 200 GeV; their role is to protect what is happening at lower energies from perturbations from much higher energies. We definitely expect these mechanisms to manifest themselves by the time 1 TeV is reached. We have only ideas and scenarios and not the feeling of near certainty that we had about the W and Z. It is all the more interesting to go and see.

These questions, together with our natural curiosity to explore new ground, are the main motivations for physics in the TeV range, as is possible with the SSC and the LHC.

One can but emphasize the challenge raised by the present great complexity of the vacuum, which now seems to behave, in two different ways, as a superconductor. Such a complication of the vacuum, which we intuitively associate with nothingness, has occurred in the past. The ether presented great challenges before the advent of Einstein's theory of relativity. More recently, before quantum field theory could provide the proper understanding of antimatter, the vacuum seemed to behave as a semiconductor in order to circumvent the problem raised in Dirac theory by negative-energy states. As was previously the case, we may now expect the present complexity to stand for more new physics once the corresponding phenomena are properly understood, and we expect clues as we reach the TeV energy range.

## How far with accelerators?

Our present goal is to overtake the TeV at the constituent level. This is possible with proton-proton collisions, and with the technology at hand. It would be very interesting to do it also with electron-positron collisions, thus avoiding the complexity of hadronic collisions where information has to be extracted from a large background and where the interesting events have to be selected from a very high intake of uninteresting ones. Yet  $e^+e^-$  machines, which are at present the subject of much discussion, have to be linear colliders in order to escape the forbidding synchrotron radiation of very high energy circular machines. The required high luminosity has then to be achieved through the single crossing of very high density bunches. We do not yet know how to build such TeV electron machines at an acceptable cost, but the R & D is continuing, to meet the very great technological difficulties.

We cannot predict the distant future. Extrapolating our Livingston plots (shown in Fig. 1) is as good a guide as any. There are very powerful accelerators in the heavens. They have names such as Cygnus X3 and Hercules X1. Can we emulate them on Earth, as new ideas are discovered and exploited and new techniques are mastered?

Whilst new machines are built to explore new grounds, it is interesting to note that the older ones seldom die. They often merge into new and better complexes, and there are many such examples. CERN offers the most striking one, with its old PS now the hub of a complex system where it serves as an injector to the SPS and then to LEP, whilst providing fixedtarget users with protons and heavy-ion beams and feeding ACOL. It accelerates antiprotons for the SPS and decelerates them for LEAR.

In other cases, such latter-day uses imply an actual reincarnation. As an example, one may quote the thirdgeneration 'g - 2' ring at CERN--a muon storage ring with which the value of the anomalous magnetic moment of the muon could be measured with a precision of the order of one in a billionth, thus matching the eighth-order calculation in quantum electrodynamics. The 'g -2' magnet ring was later used for the Initial Cooling Experiment (ICE), in 1978, in order to conduct tests on stochastic and electron cooling before the former method was chosen. One could then embark on the construction of the Antiproton Accumulator (AA), which was a prerequisite for the CERN pp Collider. After this second glorious stage of its career, the magnet ring has gone to the Svedberg Laboratory at Uppsala, where it now provides the basic structure for the CELSIUS ring. It is coupled to the Uppsala cyclotron in a combined accelerator storage ring and cooler complex, ready for a third brilliant round of its career. Of particular importance is the study of meson production in cooled ion-ion collisions. and, through the decay of such abundantly produced mesons, the study of rare modes.

All this illustrates the great power and versatility of physics with accelerators. They are wonderful tools for exploring the physical world where, again quoting David Hume, 'All talk of a realm beyond experience has no content'.

#### **References and Notes**

- W. Paul, Early days in the development of accelerators, in Aesthetics and Science, International symposium in honour of R.R. Wilson, Batavia, 1979 (Fermilab, Batavia, Ill., 1979), p. 25.
- [2] C. Rubbia, CERN/SPC/593 (1990).
- [3] Discussing 'Accelerators in physics', I shall not touch the important questions of accelerators in medicine or in industry. The giant physics machines of 40 years ago are now widely used tools in many walks of our modern life.
- [4] For a review, the reader may consult M. Jacob, Opening Talk, Quark Matter '88, Lenox, Mass., 1988 [Nucl. Phys. A498 (1989) 1c], and Closing Talk, Quark Matter '90, Menton, 1990.
- [5] The EMC effect, discovered by the EMC Collaboration at CERN, is that quark distributions in nuclei are different from those found in free protons.
- [6] In a gauge theory, the physics is assumed to remain invariant under transformations of the basic fields, which can be applied differently as different points of space-time. Such an invariance property requires the presence of extra vector fields, the couplings of which are specified. The exchange of the vector fields is at the origin of the interactions among the basic particle fields. Forces then result from an invariance principle! In this way, all basic forces can be understood.
- [7] The Standard Model is at the core of physics. It describes the interactions of the fundamental building blocks (quarks and leptons) in terms of QCD and the electroweak theory, both of which are derived from a unique gauge invariance principle.
- [8] A high luminosity may compensate for a lower energy. One can then make use of the infrequent collisions where constituents enter with much above average fractions of the energy of the particle to which they belong.