Physics – Uspekhi **52** (6) 541 – 548 (2009)

ORAL ISSUE OF THE JOURNAL "USPEKHI FIZICHESKIKH NAUK"

PACS numbers: **12.10.–g**, **12.60.–i**, 29.20.db

Physics at the Large Hadron Collider

I M Dremin

DOI: 10.3367/UFNe.0179.200906c.0571

Contents

Abstract. The goals of the physics to be studied at the Large Hadron Collider (LHC) are very impressive. Four major experimental installations are ready to compete in obtaining and analyzing the data from high-energy hadron collisions. The main hope is to answer the most intricate questions ever asked concerning the most fundamental problems of matter and its fundamental forces and space structure. The design of the LHC and its four detectors is briefly described. We then review the main facts revealed previously by experimentalists at other accelerators. The most pertinent topics and the stage-by-stage plans for LHC investigations are discussed. Further prospects for high-energy physics are outlined.

1. Introduction

The highest energy frontier ever reached in particle collisions at accelerators will be moved further to the entirely new region of energies of several tera-electron-volts (TeV) with the advent of the Large Hadron Collider (LHC) at CERN. High energies allow studying the properties of space at small scales. Each step in this direction has led to new fundamental discoveries, which is why the data of experiments at the LHC are awaited with such impatience.

The modern theory of the forces of Nature, called the Standard Model, is very powerful. It is able to describe many experimental observations and has predictive power. New ways beyond the Standard Model are also being sought, however. Experiments at the LHC may show which way has actually been chosen by Nature and, moreover, reveal something that has not been predicted. The principles of symmetries and invariance are at the heart of all approaches. Among the most disputable problems are the origin and variety of masses, the structure of the physical vacuum, the abundance of types of matter particles in the Universe, a unified description of fundamental forces, including gravitation, and the possible existence of supersymmetric partners of all observable particles and of extra dimensions of space–time.

Here, we briefly review the design of the LHC and its detectors, the major physics findings at previous accelerators, the principal goals of LHC experiments and their initial and further steps, and the general prospects for high-energy physics.

We give no reference to the existing literature because the number of papers is enormous and they can be easily found on the Internet and in physics journals, starting, for example, with popular articles in *CERN Courier* (especially in the September–November 2008 issues).

2. The LHC design

The LHC is designed to collide head-on beams of protons, each with the energy 7 TeV or the total energy 14 TeV in the center-of-mass system (equivalent to about 10^{17} eV in the rest frame of one of the protons), and ion beams with the total energy 5.5 TeV per nucleon. The beams circulate in opposite directions around the 27 km circumference tunnel 50 to 175 m underground, crossing the Swiss–French border near Geneva.

The 1232 superconducting dipole magnets with the length 14.3 m and weight 3.5 t, each with two apertures inside (one for each of the counterrotating beams), bend the beams. They are to produce a magnetic field up to 9 T. The maximum magnetic field imposes the upper limit on the particle energy in a given geometry. The magnetic lines surround the two apertures in the shape of a figure eight to guide the bunches in opposite directions. The magnetic fields are created by electric currents up to 11.7 A in superconducting cables with the total length 7600 km and weight 1200 t. Each cable is made of 36 strands of superconducting wire, each of which contains 6300 superconducting niobium–titanium filaments. The total

---

I M Dremin Lebedev Physical Institute, Russian Academy of Sciences,
Leninskii prosp. 53, 119991 Moscow, Russian Federation
Tel. (7-495) 783 37 19
E-mail: dremin@lpi.ru

Received 23 December 2008
Uspekhi Fizicheskikh Nauk **179** (6) 571 – 579 (2009)
DOI: 10.3367/UFNr.0179.200906c.0571
Translated by I M Dremin; edited by A M Semikhatov

length of filaments is about 10 times the distance to the sun (10 AU). The magnets must be fixed well because at the full magnetic field, the force loading 1 m of a dipole is about 400 t.

The magnets operate at the very low temperature 1.9 K and pressure 10^{-10} Torr. Liquid helium and a high vacuum are necessary to operate at the designed temperature and pressure values. Up to 1.2×10^7 liters of liquid nitrogen are needed for the initial cooling of the machine and up to 7×10^5 liters of liquid helium for further operation. About 40000 leak-proof pipe junctions must be well controlled. Moreover, the machine also incorporates more than 500 superconducting quadrupole magnets and more than 4000 superconducting corrector magnets.

Building the LHC was a very challenging and unprecedented technological project. It is also at the frontier of characteristics important for experimentation. In addition to the highest energies, the LHC project is aimed at a very high luminosity 10^{34} cm^{-2} s^{-1} (with the initial operation at a luminosity about 5 times lower).

To appreciate the importance of high luminosity, we consider a simple example. A collider usually operates about 10^7 s a year, and hence the integrated luminosity per year is estimated as 10^{41} cm^{-2} or 100 fb^{-1}. The total cross section of the interaction of colliding protons is estimated at about 80 mb $= 8 \times 10^{-26}$ cm^2 (and about 60 mb for inelastic collisions). Therefore, in principle, there could be 8×10^{15} events per year. Thousands of particles will be created in most of them. It is clear that no electronic or computer system will be able to read all the data and store it. However, the high luminosity is crucial for studies of rare events with very small cross sections. It is precisely such events that will become the most important for new physics searches. With good triggers (i.e., selection of events according to the prescribed features), it will be possible to obtain about 100 events with a very low cross section of 1 fb per year. Therefore, the detector systems should contain very good triggers that reduce the original crossing bunch rates to a rate of much less abundant but more interesting events, rejecting all others. Hence, the high LHC luminosity is required for studying processes with low cross sections. For processes with larger cross sections, a lower luminosity is sufficient. It can be achieved by different methods (e.g., by defocusing the beams at the collision points as is done at the LHCb).

A schematic of the LHC layout is shown in Fig. 1. The twin-pipe structure is clearly indicated. The arrows show the directions of the two beams. As we see, there are four major LHC detectors placed at four points where the bunches are brought into collision.

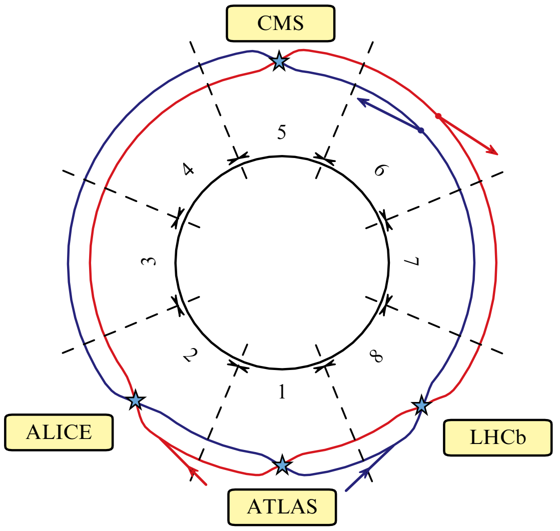


Figure 1. General layout of the LHC. The beam directions are shown by the arrows. The four interaction points where the four major detectors are installed are seen.

3. Detectors and collaborations

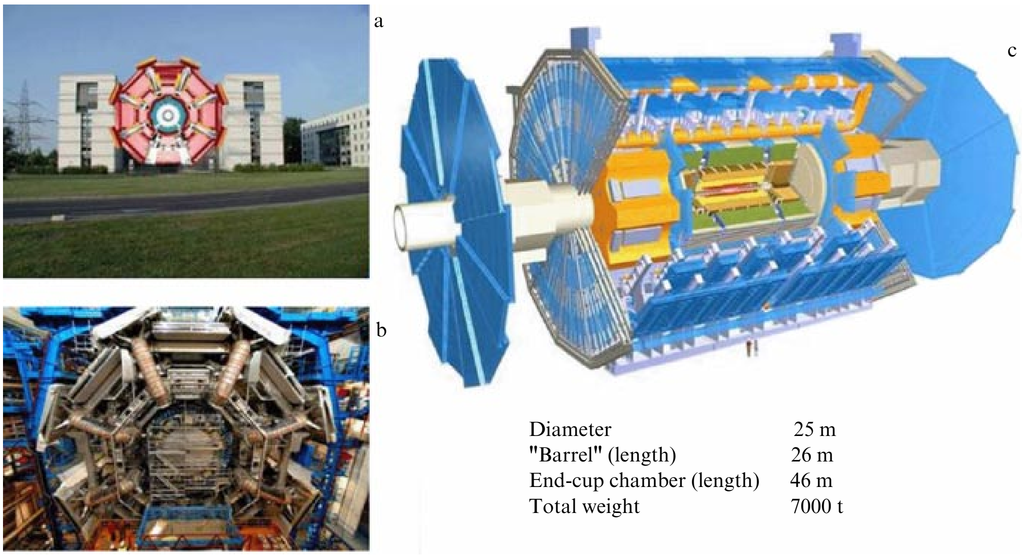
Four major detectors, named ATLAS, CMS, ALICE, and LHCb, will register the products of beam collisions created at the interaction points. Correspondingly, there are four main international collaborations of physicists dealing with them. The number of participants in the biggest ATLAS collaboration exceeds 2000. These detectors and collaborations are both competitors and allies in the search for new physics. Time will tell which choice was best.

The largest detectors, ATLAS and CMS (see Figs 2 and 3), have been designed to record both pp and AA collisions. ALICE is more specialized in AA interactions, although some work on pp will be also done there. The LHCb detector has a special design aimed at the registration of events with b quarks involved. Besides the four major detectors, there are smaller subdetectors called LHCf, TOTEM, ZDC, FMS, roman pots, CASTOR, and FP420 (the last one is still awaiting approval). They will work in combination with some of the main detectors and are aimed at recording particles produced at small angles. Therefore, they are placed at large distances, up to several hundred meters from the collision points of the main detectors along the beam direction.

The sizes of the main detectors are quite impressive. The height of ATLAS is 25 m (about the height of an 8-story building), its length is 46 m, and it weighs 7000 t. It is necessary to host all the trackers and calorimeters and cover as large a region of angles as possible to record the produced particles. With the uniform azimuthal coverage, it will be attempted to detect particles produced at polar angles θ as small as a fraction of a degree with respect to the incoming beams. In terms of the pseudorapidity $\eta = -\log(\tan\theta/2)$, this means that the region up to $\eta = 5$ will be accessible. However, the different detector elements can cover different regions in pseudorapidity, and particular physics measurements can be done with varying accuracy depending on the physics selection. The forward subdetectors extend the available range of angles up to the pseudorapidities as large as 9, i.e., to angles of the order of 10^{-2} degrees. It is important to detect these particles, not allowing them to be captured inside the accelerator tube with the main stream of protons. This requires special technical solutions.

The detectors are shaped like cylinders ('barrels') to surround the interaction regions by uniform magnetic fields. Their segmentation should be fine to avoid overlapping signals: no charged particle should escape unseen. Many paticles move almost along the beam direction. 'End-caps' of the major detectors and 'forward' subdetectors provide the coverage of this region. There are several trigger levels.

There are some special features in the beam structure. The beams are not homogeneous streams of protons inside a pipe but are composed of bunches following each other at time intervals of 25 ns or at the distance about 7.5 m, which is much shorter than the lengths of the detectors. Therefore, the bunch



Diameter	25 m
"Barrel" (length)	26 m
End-cup chamber (length)	46 m
Total weight	7000 t

Figure 2. The ATLAS detector. A cutaway view and the detector image imposed on building 40 (hosting the ATLAS and CMS collaborations) at CERN are shown.

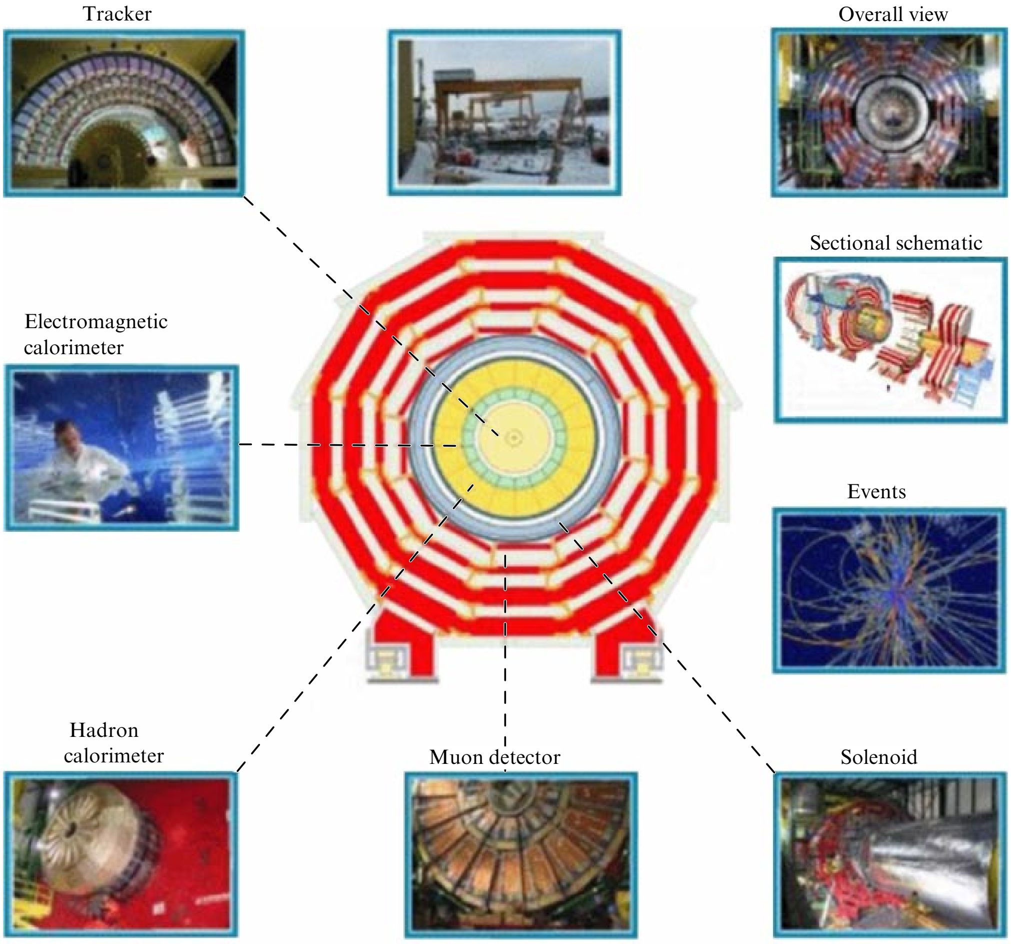


Figure 3. The CMS detector. A cutaway view and the inner structure indicating different tracker and calorimeter regions are shown.

crossing rate is 40 MHz, which will be effectively reduced to about 30 MHz. Most protons in a bunch do not interact at the crossing point and continue their motion along the accelerator pipe. Even then, each bunch crossing gives rise to about 20 – 40 proton–proton interactions within a very short distance along the beam trajectory inside the detector. The trigger systems should distinguish separate scatterings and, moreover, choose those that are of physical interest. Due to the limits imposed by electronic and computer systems, 100 – 200 events per second should be left to record and store. Thus, the triggers must be very fast, specialized, suitable for detection purposes, reprogrammable in the case of changing physics requirements, and radiation resistant due to the huge flux of charged particles.

The magnetic fields in the detectors are necessary to bend the charged particles produced. They are up to 2 T in ATLAS and up to 4 T in CMS. The curvatures of particle trajectories tell us about their momentum and nature (masses). This is the main information to be obtained about a particular process. The detection technique is based on the properties of interactions of charged particles with matter inside a detector. The overall design of the ATLAS, CMS, and ALICE detectors is somewhat similar, while LHCb is more forward-oriented to give special attention to the forward-moving b quarks. The central region closest to the beam interaction point is filled with tracking systems to determine particle trajectories and measure particle momenta. Then follows an electromagnetic calorimeter that absorbs electrons and photons and measures their total energy. Because hadrons are absorbed at larger lengths, the hadronic calorimeter is placed at ever larger distances from the interaction point. Muons are even more penetrating particles. Therefore, the layers of muon detectors are positioned at the outskirts of the whole system.

The inner detector systems are based on silicon pixel detectors covering about 2 m^2 at radii as small as 4.5 cm and silicon microstrip detectors at larger radii (20 – 55 cm). They are well segmented to accurately follow the particle motion and provide enough precision in detecting the track position. ATLAS additionally has a transition radiation tracker (TRT) that uses the effect of transition radiation of charged particles (at radii greater than 56 cm). It is effective in separating electrons from pions and provides a large number of tracking points (about 30 – 40 per track). This system allows continuously following tracks, identifying the nature of produced particles, measuring their momenta, and reconstructing primary and secondary vertices of decays and interactions. Special effort has been made that the materials used in this system be radiation resistant in view of the huge fluxes of charged particles, especially dense at small radii. This is also crucial for the electronic system that collects all the information from the detector system and transfers it to computers.

Then follow the calorimeters that absorb and measure the energies of electrons, photons, and hadrons. They contribute to triggering signatures of events suspected, in particular, for new physics signatures. The ATLAS electromagnetic calorimeter consists of layers of lead and liquid argon, while high-density crystals are used in CMS. The energy of electromagnetic showers developing in high-density matter is measured. Hadron calorimeters surround the electromagnetic calorimeters and measure the energy and directions of hadronic showers (especially jets) as well as the missing energy that can be related, for example, to neutrinos and undetected neutral particles. The last outposts of the detectors are the large-area gas-based detectors used in muon systems at the periphery to identify muons and measure their momenta. Their work is synchronized with the entire trigger system. Moreover, some systems provide independent momentum measurements and allow cross-checking.

Dealing with such elaborate systems requires physicists with the highest qualifications, who must understand and calibrate the various parts of the detectors. Surely, there will be some specific problems with each of them. For example, the high priority in LHCb is given to a very precise determination of the decay vertices, which defines the accuracy of the data on B mesons. Similar problems exist in each detector. A common feature of the detectors is that they must be initially tested with cosmic ray showers for the calibration of their response to the passage of particles; this calibration is currently underway.

A vast amount of computer power is needed to select, store, distribute, and analyze the information that will come from the LHC (tens of petabytes per year). Therefore, a special project (GRID) including sites all over the world is being developed. It relies on many 'Tiers'-levels (0, 1, 2) that compile, process, and reconstruct the raw data (0), share it with the experimental physics analysis groups (1) with definite trigger paths, and use it for comparison with Monte Carlo simulations and further analysis (2).

All this shows how complicated the problems confronting engineers and physicists are even before the experimentation starts. This became especially clear in September 2008. The very first attempt to operate the LHC was on 10 September. It appeared to be extremely successful. The first interactions in the detectors were recorded (shown in Fig. 4 for the CMS detector). Even some preliminary data on distributions at lower energies were compiled. More impressive for experts was the demonstration of the well-controlled shape of the beam bunches. A perfect longitudinal bunch profile demonstrates that the bunches are keeping in time with the system that provides the accelerating electric fields (see Fig. 5). The

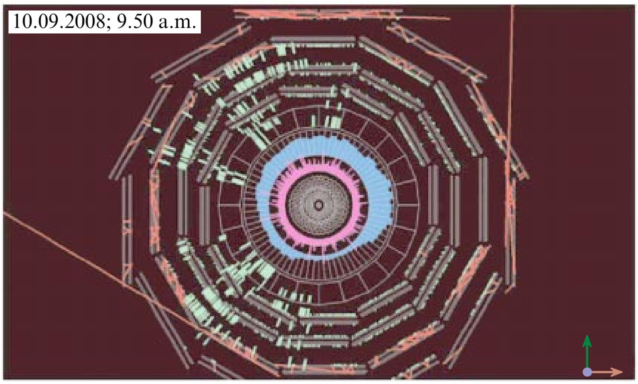


Figure 4. The first beam-induced events recorded by the CMS detector. The particle trajectories are seen in the tracking system and calorimeters.

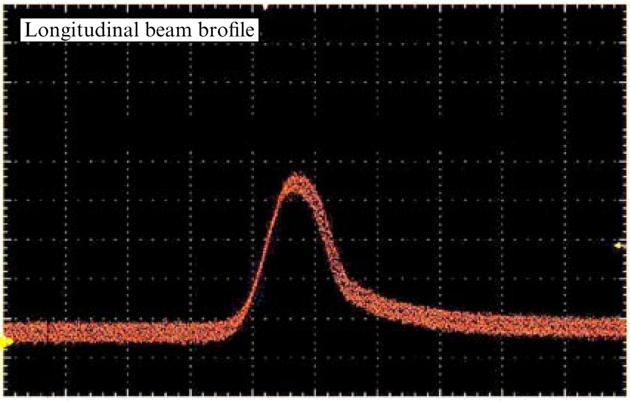


Figure 5. A perfect longitudinal beam profile demonstrates the stability and synchronization of the accelerating systems.

ability to operate the LHC at somewhat lower energies and intensities was demonstrated. However, a further attempt to reach higher energies and luminosities on 19 September failed. An incident occurred because of a large helium leak in the LHC tunnel. According to the *CERN Courier* "preliminary investigations indicate that the most likely cause of the problem was a faulty connection between two magnets, which probably melted at high current, leading to a rupture of the helium vessel and the release of high-pressure gas into the cryostat. The gas then discharged into the tunnel through the pressure-relief valves designed for this purpose." It would be very unlikely if no problems appeared at all because "the LHC ... has been built at the cutting edge of technology ... with unprecedented complexity."

A restart of the LHC is planned in the second half of 2009 after the tunnel is warmed up and everything repaired. Surely, the initial energy and luminosity values will be lower than the prescribed ones. Pragmatic physicists are not very disappointed, however; according to the spokesman of ATLAS, P Jenni, "this will already give us a lot of data to calibrate, as well as understand all the subdetectors and the chain of data preparation and analysis. Before any discovery can be claimed we first have to show that the known physics is reproduced and that the detector performs well." The inauguration of the LHC was held at CERN on 21 October 2008.

The 20 member states of CERN and 5 nonmember states (including Russia) with observer status are contributing to the LHC project. Russian institutes are participating at each stage of this work. This includes the design and construction of the accelerator and detectors, transfer line from the SPS to the LHC, equipment and material supply, radiation studies, programs of detector calibration, development of programs of physics research, on-line and off-line processing of forthcoming data, participation in all LHC experimental collaborations, and contacts among theorists.

4. What has been learned from earlier studies

Before discussing the scientific program of the LHC, we briefly discuss what has been done at major particle accelerators built earlier.

The SPS accelerator at CERN now mostly serves as an injector of beams with the energy up to 450 GeV into the LHC. Among the major observations made with it are precise measurements of the general characteristics of hadron interactions at energies up to 540 GeV (total cross sections, real parts of the forward scattering amplitudes, diffraction processes, inclusive distributions, correlations, etc.), as well as the first indication of collective effects in ion–ion collisions, which led to the notion of quark–gluon plasma (QGP). Nowadays, it is also the source of the neutrino beam sent to Gran Sasso National laboratory in Italy, and some experiments on fixed targets are still ongoing at CERN (e.g., measurements of dilepton spectra).

We note that the LHC uses the tunnel first built for the Large Electron–Positron (LEP) accelerator to produce colliding electron–positron beams with the energy up to 200 GeV. The LEP accelerator was extremely successful. The quark and gluon jets were first observed and studied in detail there, the QCD coupling constant α_S and its scale dependence were precisely measured (at the present accuracy $\alpha_S(M_Z) = 0.1176 \pm 0.002$), the carriers of weak forces, W and Z bosons, were discovered and studied, the lower limit on the mass of the Higgs boson (114 GeV) was imposed, not to mention many other achievements. It is now closed and is to be superseded by the LHC.

Another recently closed accelerator, HERA, in Hamburg used electron–proton colliding beams with the 27.5 GeV energy of electrons and the 920 GeV energy of protons. This enabled physicists to study the so-called structure functions of protons, i.e., to dissolve the quark–gluon content of high-energy protons. The most important findings concern the increase in the number of soft gluons contained in the proton cloud and its energy dependence (scaling behavior and its violation).

Closest to the LHC in energy and the nature of colliding partners is the TEVATRON at the Fermilab near Chicago. The proton and antiproton beams collide there with the center-of-mass energy up to about 2 TeV. Each of them can itself be considered a bunch of quarks, antiquarks, and gluons distributed according to the structure functions. Thus, it is the source of $q\bar{q}$, gg, $\gamma\gamma$, and γ-Pomeron processes. Studies of masses and widths of W and Z bosons and the top quark were especially intensive and fruitful (the approximate values of their masses are correspondingly 80.4, 91.2, and 172 GeV). Limits on the mass of the Higgs boson were imposed. QCD jets and large-p_T processes were studied in detail. Some surprises are coming from there even now (recently recorded multimuon events?). All these processes will be studied at the LHC with better precision. Statistics on similar events (e.g., jets with the same energy) will be about 10^3 times larger at the LHC than at TEVATRON during the same sampling time.

Another accelerator, RHIC (Relativistic Heavy Ion Collider), operates at Brookhaven. Its main goal is to study ion–ion collisions at energies up to 200 GeV per nucleon, comparing them with analogous effects in pp collisions. The properties of the matter formed during the ion–ion collision were carefully investigated and gave further arguments in favor of ideas about QGP. It turns out that they are closer to those of an ideal fluid than to those of gases (in particular, the nuclear refractive index is about 2 or 3 according to the interpretation in terms of Cherenkov gluons). Collective effects such as the azimuthal asymmetry and jet quenching are clearly seen. The success in having both beams polarized is also very impressive.

A somewhat different stream of research is provided by B-factories at KEK (Japan) and SLAC (USA). The high intensities of beams allow carefully measuring the properties of the Υ boson and other processes with b quarks produced. This allows clearer understanding the CP violation and the matrix elements of the CKM matrix and the origin of the differences between matter and antimatter, learning much about rare decays, and imposing some limits on the masses of supersymmetric partners of the existing particles.

The length of this paper does not allow us to discuss other numerous achievements of experimental studies at these accelerators, to say nothing about the revolutionary theoretical ideas developed in connection with these data, which have often determined the areas of experimental searches. However, the major background and inspiration for LHC experiments is already rather clear from what was said above.

5. The main goals of LHC experiments

As always, the major task for LHC experimentalists will be to find something yet undiscovered. The theory provides some hints.

Most attention is presently given to searches for the so-called Higgs boson. It underlies the ideas about the origin and variety of mass. Theoretically, the origin of mass is ascribed to exchange by the Higgs boson. We do not yet understand why the masses of the most 'elementary' constituents of matter differ so strongly. The mass of the top quark is 10^{14} times larger than neutrino masses(!), not to mention the zero mass of the photon.

The ways to search for the Higgs boson are determined by the various production channels and decay modes of this particle. The most probable interval of masses of the Higgs boson is 120 ± 6 GeV, as given by modern theory. The forward subdetectors would allow studying the central exclusive processes of Higgs boson production (in this range of its mass) by separating events with large pseudorapidity gaps between the final two protons. The 'golden' decay mode of the Higgs boson into two Z bosons, each of which decays into two muons, is preferred at masses above 200 GeV. Just the search for this mode in the early days determined the design of the ATLAS and CMS detectors and their proportions. ATLAS is longer than CMS but has a much lower magnetic field. This is determined by the requirement to measure the muon momenta with at least 10 percent accuracy. The relative error in measuring the momenta is inversely proportional to the magnetic field and to the square of the track length inside the detector. Photons, bottom quarks, and tau leptons must also be recorded in order to obtain a convincing signature. If it happens that the Higgs mass is of the order of 1 TeV, then decay modes with the production of W and Z bosons and jets in various combinations must be considered. The increase in the number of available channels leads to a noticeable increase in the Higgs boson width. We do not yet know whether one or several Higgs bosons exist, whether they have any internal structure, or whether they overlap in masses with a general increase in the widths, which might lead to problems in distinguishing them from the background.

Another important line of searches is supersymmetric partners (sparticles) of the already observed particles. They are predicted theoretically as a corollary of the statement about possible supersymmetry in the world. These particles must be very heavy due to some violation of the supersymmetry and have not yet been recorded. Their experimental signatures are defined by their heaviness. Cross sections for processes beyond the Standard Model are estimated to be in the range of femtobarns to picobarns.

In general, new, very heavy resonances must be sought.

The experimental program of the LHC also includes 'old' QCD processes such as inclusive processes, jets, top quarks, B mesons or mesons containing both bottom and strange quarks, dilepton spectra, and collective effects in ion–ion collisions. The LHC can be called a 'heavy-quark' factory because the $b\bar{b}$ pair production cross sections are of the order of 1 μb and top-quark production cross sections are of the order of 1 nb. The forward detectors can help clarify cosmic ray problems, e.g., by calibrating the hadron interaction models used for the description of extremely high-energy cosmic rays.

Certainly, we are especially waiting to find something completely new and unexpected, as often happened previously when a new energy region became available.

From the theoretical standpoint, the most intriguing problem is the structure of the physical vacuum. It is believed that broken symmetries play a crucial role in our world. The ideas widely used in superconductivity (recall the Ginzburg – Landau potential!), ferromagnetism, and many other problems of condensed matter are actually at the origin of the Higgs boson, supersymmetry, CP violation, etc. in particle physics. The complicated structure of the physical vacuum with many minima (like an old-fashioned washboard) and special asymmetries determine numerous effects and is not well understood presently. It is believed that the physical vacuum is not empty but filled by scalar Higgs fields.

There are many unexplained facts in the framework of the Standard Model. In particular, we do not have answers to questions such as why exactly three generations of the quark–lepton families exist, what lies at the origin of their masses, and where the major forces converge.

The registration of the Higgs boson decays at the LHC would imply that we are on the correct path to revealing the mass puzzle. At the same time, it will open up many new questions such as either it is single (nowadays, this possibility is considered rather unrealistic and disappointing) or there are other Higgs bosons, or there are composite Higgs fields. The proportionality of the Higgs coupling to masses should be carefully tested by searching for different decay modes. Higgs fields are related to astrophysical observations such as dark energy (or to the cosmological constant of the gravitation theory, in theorists' terms).

The fundamental supersymmetry can be revealed at the LHC by recording the lightest sparticles, such as the neutralino or gravitino. Supersymmetry pairs fermions with sbosons and bosons with sfermions. The radiative corrections due to pairs of virtual fermions and bosons cancel in supersymmetric theories. Such a pairing does not exist in the Standard Model and requires going beyond it. It demands that sparticles exist. This is a completely new world. If found, it will prove a natural candidate for explaining dark matter and facilitate the unification of the fundamental forces of Nature.

Another way beyond the Standard Model is opened by the idea about extra dimensions of space. These additional dimensions can be curled up such that they have been unobservable up to now, but may become noticeable at energies exceeding 1 TeV. This happens in some variants of string theory. In particular, gravity might become strong and microscopic black holes might be created in collisions at LHC energies. The new world of Kaluza–Klein particles[1] might appear.

Concerning CP violation, we are sure that our description in terms of the 3 × 3 CKM matrix is generally correct. However, we should understand more deeply why precisely 3 generations of quarks and leptons have been chosen by Nature. More precise measurements of the angles of the unitarity triangle are needed. There should exist additional sources of CP violation to explain the cosmological matter–antimatter asymmetry. These might be the yet undiscovered heavy particles. The data from ATLAS, CMS, and LHCb can contribute to the solution to this problem by measuring the rare B-meson decays. For ATLAS and CMS, this is one of the experiments where the high luminosity of the LHC is crucial. At the LHCb colliding point, on the contrary, the bunches are even somewhat defocused. If the new particles are very heavy, it might happen that they are not directly seen at ATLAS and CMS but their virtual effects are discovered by LHCb.

---

[1] The theorists Kaluza and Klein were the first to publish a paper with the idea of extra dimensions in the 1920s.

New properties of hadronic matter might show up in the new region of densities and temperatures provided by the high energy of colliding nuclei at the LHC. The jump in energy density at the LHC is huge (the energy is 28 times higher than at the RHIC and 300 times higher than at the SPS). This is important for understanding the behavior of matter under these conditions and, therefrom, of the processes in the early universe when quarks and gluons were 'free' and were not yet confined inside hadrons. The evolution of collective effects with energy (when compared with RHIC data) might indicate the nature of the transition from hadrons inside the nuclei to the quark–gluon matter during the short time of overlap of colliding nuclei before the final hadronization started. Besides the hot and dense quark–gluon plasma, the search for cold and dense color glass condensate (CGC) is very promising for discovering new aspects of the fields described by QCD.

The problems of very small and very large distances intermingle in the LHC studies. Our understanding of the fundamental forces and their unification at very high energies and very small scales is crucial for theories of the Universe both at the initial stage and at present. Topics such as dark matter, dark energy, and black holes are widely discussed in connection with the LHC experiments.

6. The initial period of LHC experiments

After the incident with helium leakage, the LHC schedule was changed. New attempts to produce beams of protons at the designed energy and somewhat lower luminosity will start in the middle of 2009. If they are successful, the experimentation will start soon afterwards. Some time will be needed to check all the systems of the detectors, and to understand and calibrate them. Their response at low intensities has already been checked with cosmic rays since 2006. The response to physical signals at high luminosity will first be tried with effects well known from minimum-bias events with relatively low-momentum particles in the final state and jet events where a single high-momentum jet is produced, with other remnants of a proton forming the underlying event. Inclusive characteristics will be measured. Then other Standard Model processes like W, Z, and top-quark production will be studied. More accurate values of the W, Z, and t masses obtained by ATLAS and CMS might enable estimating the Higgs mass with high precision within the Standard Model. It will be confronted with results on radiative corrections supplied by LHCb. All this is also needed to establish the correspondence to results obtained at lower energies.

Only then must the search for the Higgs boson begin. It will require very careful separation of special signals (like two-photon modes of its decay) from many different signatures coming from other sources. Various channels of its production have also been considered. Estimates show that for the smallest masses, the integrated luminosity about 5 fb^{-1} suffices, and hence the Higgs boson can be detected soon, but the analysis will take more time.

The situation with sparticles depends very much on the values of their masses. For example, if the gluino mass is less than 1.2 TeV, then even 0.1 fb^{-1} of integrated luminosity will be sufficient for discoveries after careful analysis. Clear indications might be obtained by LHCb, where measurements of processes strongly influenced by virtual radiative corrections due to supersymmetric particles might go ahead of their direct detection. Optimists say that we can wait for important news coming after several months of stable running of the LHC if we are lucky with mass values being low enough.

We hope that b quarks studied in greater detail at the LHC will tell us about intricate features of CP violation. This might solve the puzzle of the baryonic asymmetry of the Universe.

Because a proton can be considered a wide-energy-band source of partons, various exclusive processes can be studied. For example, quark–quark, gluon–gluon, and quark–gluon scatterings can be distinguished. The mutual interaction of Pomerons and their interactions with these fields are especially interesting. Strong electromagnetic fields of ions can lead to special effects like unexpected asymmetries in $\gamma-\gamma$ processes.

Above all, there are expectations for new unpredicted effects.

7. Next steps

Further areas of investigations at the LHC strongly depend on discoveries at the initial stage. If found, the Higgs boson will become the major attractor. Its characteristics like the mass, spin, flavor, and coupling strength and its dependence on masses, CP-properties, etc. will be intensively studied with enlarged statistics.

The same will happen, for example, if the gluino or gravitino is discovered. The LHC luminosity allows studying sparticles as heavy as 3 TeV, according to some estimates. The cascade decays of such heavy sparticles can lead to lighter ones (among them, the stau might be especially interesting). The different spins of the cascade partners can lead to special correlations and help in distinguishing between various possible theories (supersymmetric or invoking extra dimensions) by observing correlations of final particles. However, these are tiny effects and they will place a heavy burden on Monte Carlo models.

Physicists will be disappointed if no principally new effects are found. Nevertheless, there are many interesting problems to be solved. They appear even now, for instance, from TEVATRON experiments with the detection of unexpected and yet unexplained muon bunches far from the collision axis. The traditional QCD physics must become more accurate with higher-order corrections understood and compared at higher energies. More precise determination of the CKM matrix elements might reveal some new puzzles. The behavior of hadronic matter in ion collisions at the LHC energies can be very far from simple extrapolations. In general, it is difficult to predict which way Nature will choose — one chosen by us or an absolutely new one in this new energy region. We have to wait for experimental data coming from the LHC to obtain the answer.

8. Prospects for high energy physics

Will the run to ever higher energies stop after the LHC? Surely not, even though each new stage becomes more and more expensive and demands fundamental technological and engineering improvements. This can be done only within large international collaborations.

The most likely possibility is to increase the LHC luminosity by an order of magnitude. This proposal is known as the SLHC. This will become especially appealing if some signatures of heavy Higgs particles are found during the nominal LHC running and it would be necessary to enlarge the statistics to arrive at more definite conclusions. In general, it would extend the region of masses where the Higgs particles, supersymmetry, and extra dimensions are sought. The electroweak effects and CP violation could also be studied with greater precision.

Another ambitious project is the International Linear Collider (ILC). Electrons and positrons moving along straight trajectories will collide head-on with the total energy 1 TeV. These collisions are simpler for theoretical treatment because electrons and positrons do not have such a complicated internal structure as protons. The supersymmetric world can be studied with good accuracy and at larger masses. The need for energies of several TeV (the CLIC project) may arise if sparticles with ever higher masses must be studied.

These projects will compete with the existing proposals for doubling the LHC energy (DLHC) or even enlarging it by a factor of three (TLHC).

The discussion and comparison of these possibilities is going on already now. The conclusions can be finalized only after the LHC experimental information about all the key questions raised above becomes available. The future of high-energy physics strongly depends on the LHC results. Sooner or later, these possibilities will become a reality (maybe in a somewhat different form) because it is in the nature of human beings to try to learn as much as possible about the structure of the surrounding world and its major forces.