The quest of the Large Hadron Collider

Prof. Dr. Jorgen D'Hondt
Vrije Universiteit Brussel – Pleinlaan 2 – 1050 Brussel - Belgium
jodhondt@vub.ac.be

Abstract:

At CERN scientists and engineers are finalizing the last construction stage of the Large Hadron Collider. Later in the year this facility will collide for the first time protons to centre-of-mass energies of 14 TeV reaching energy densities equal to a fraction of a second after the Big Bang. Several multi-purpose detectors are being installed around the collision points to study the particle interactions which will occur every 25 ns building up a huge collection of information. The accumulated data will be used to test the consistency of the Standard Model of elementary particle physics. For example they will give a final answer on the existence of the yet undiscovered Brout-Englert-Higgs boson which is supposed to be responsible for the spontaneous symmetry breaking in the Standard Model. Although this model has been successfully tested over the last decades, it describes only about 4% of the matter content of the Universe. The high energetic proton collisions will give us insight in the remaining 96%, via the possible discovery of phenomena related to theories beyond the Standard Model. These models usually incorporate new concepts within our theory describing the micro-cosmos, for example supersymmetry or extra space-dimensions.

Revealing the secrets of the micro-cosmos

Millennia ago humanity first learned to interpret our place within the macro-cosmos governing the world around us. Only after this usually experimental endeavour, people have started to study the smaller building blocks of Nature. Originally due to an apparent similarity, many insights obtained in the macro-cosmos were consulted to shed light into the structure of the micro-cosmos. The search for a thorough understanding of the most elementary particles and their interactions has lead scientists through several fundamental revolutions based either on fundamental insights supported by experimental evidence or by adapting a problem solving attitude to incorporate new concepts in our theoretical reasoning.
The current Standard Model of particle physics has evolved on the basis of empirical observations and our build-in motivation to describe them in our process to understand Nature. After the quantum revolution early last century and with the invention of the first cyclotrons, scientists started to collide particles at high energies. This revealed a large zoo of new particles in which symmetrical structures were observed. Assuming a composite nature of these new particles the quark model arose by Gell-man and Zweig which was experimentally confirmed in deep-inelastic electron scattering experiments on protons in the sixties. Among others, these particles are today still at the basis of the Standard Model.

Aesthetics has always been a driven force to model Nature and which particle physicists have found in the mathematical concept of symmetry related by Noether to conservation laws. Theoretical physicists have incorporated this beauty in the models they build to describe the observed phenomena by constructing Lagrangian theories which are invariant under symmetry group transformations. This allowed experimentalists to search for the effects of yet unknown symmetry relations or invariances in Nature. Many of the symmetries are however broken at low energies shortly after the Big Bang. What remains to be observed today are the phenomena of spontaneously broken symmetries. By reaching higher energy densities in our experiments we might find glimpses of more fundamental symmetries hidden underneath. The SU(3) symmetry was for example introduced for the classification of mesons and baryons. Later Weinberg introduced the SU(2)xU(1) symmetry for the lepton sector spontaneously broken by the Brout-Englert-Higgs mechanism.

The currently most accurate description of the phenomena of electromagnetic, weak and strong interactions is based on a relativistic quantum field theory. This has evolved from solving the divergences in Fermi's theory for the weak interactions at high energies by introducing intermediate bosons exchanging the momentum between interacting particles.
By lots of theoretical work by 't Hooft and Veltman the proof came in the seventies that Yang-Mills theories are renormalizable and gave a boost to the development of theories based on gauge groups. The Standard Model of elementary particles is a quantum field theory with a Lagrangian density invariant under Lorentz and local SU(3)xSU(2)xU(1) transformations based on the well-known Yang-Mills theory. The model was confirmed by the discovery in the second half of last century of the charged and neutral currents (the gauge fields), and all particles of the three and only three families of fermions (the matter fields).

Particle physics in the 21^{st} century

The success of the Standard Model became very clear in the nineties with the observations and precise measurements in the electron-positron collisions of the LEP accelerator at CERN (Geneva, Switzerland). Precision measurements of the Z and W boson masses and the strong coupling constant α_S can be compared to theoretical predictions only when radiative corrections were taken into account based on the model. Also the top quark mass, measured by the Tevatron proton anti-proton collision experiments at Fermilab (Chicago, US), can only be predicted consistently when these loop corrections are included. When entering the 21^{st} century, we can state that the Standard Model is a solid theory rather than merely a model at the current energies we can probe.

Although the Standard model allows us to make accurate predictions, it has important fundamental weaknesses. The mechanism for a spontaneous breaking of the electroweak symmetry calls for a new scalar particle, namely the Brout-Englert-Higgs boson responsible for the masses of the Z and W bosons. From the precise measurements of the parameters of the Standard Model we can constrain the mass of this scalar. Nevertheless we have never made a conclusive direct observation of this scalar particle. Also cosmological observations, like those made by the WMAP satellite, have indicated that with the current particle content in the Standard Model we can only describe about 4% of the matter content in the Universe, the other 96% being dark or not interacting for us. The list of unresolved mysteries is long and requires the introduction of new concepts beyond the Standard Model.

Up to now we have studied particles and their interactions in our laboratories up to energy densities equivalent to about 10^{-12} seconds after the Big Bang. In the never-ending search for deeper underlying symmetries in Nature, we ought to see new phenomena at higher energy densities to help solving the puzzling problems of the Standard Model. These symmetries would have been present in the very early Universe, but where broken spontaneously once the energy density decreased, like the phase transition from a symmetric crystal state to a liquid state. By introducing for example supersymmetry in our equations, we can relate fermions to bosons in a unique way. Clearly this symmetry is broken in Nature at lower energies as we did not observe superpartners of the fermions at the same masses as the Standard Model fermions. With this problem solving attitude theorists have introduced new concepts beyond the Standard Model to tackle these mysteries. Either new symmetries have been proposed resulting into supersymmetry, grand unification theories (embedding the SU(3)xSU(2)xU(1) gauge groups into a large one like SU(5)) and finally string theory, or new interactions are introduced creating compositeness, condensates and technicolor models. If the hypothesis is correct the phenomenological effects of these models beyond the Standard Model are predicted to be visible in particle collisions at higher energies.

Although scientists try, it is not so easy to capture the high energetic particles from outer space to study their properties. In order to solve the mystery of the abundant dark matter for example, we need to create high energy densities in the controlled settings of our laboratory by means of particle accelerators. The Large Hadron Collider (LHC) at CERN is being completed in the old LEP tunnel of 27 km circumference. This facility will collide protons to a centre-of-mass energy of 14 TeV which is a factor of 7 higher than the current Tevatron accelerator at Fermilab. The first workshop on the need for the LHC happened already in 1983, followed by years of careful design, research and feasibility studies. Early this century the project entered into a construction phase. This unique experiment involves a worldwide collaboration of the experience of thousands of scientists and engineers, and will finally start colliding protons for about 10 years in 2008 after about 25 years of preparation. The scientific collaborations therefore ask for long term planning, and span usually over one decennium for the design, one decennium for the construction and one decennium to run the facility. They are only possible within the framework of strong international settings like CERN.

The brave new quest

During the last decennia particle physics research has witnessed a range of large scale experiments at particle colliders. The colliders can in general be classified in two main categories. For the first category scientists want to create a laboratory exploring physics at a new energy frontier, reaching collision energies never reached before. In these particle collisions people predict to observe the standard processes they have seen in previous experiments at lower energies, but with properties extrapolated to higher energies. The motivation to construct these facilities is to search for signals of new phenomena present in models beyond the standard theory confirmed at lower energies. These hypothetical models are build to answer some of the puzzling pieces of the current theory and are predicted to show their effects in the higher energy regime accessible by the new particle collider. Most of these new phenomena are however to be searched for in an overwhelming background of already know processes. Therefore these colliders aim to produce a large particle collision rate and need an online trigger system to decide which collisions are to be readout from the detector and saved on disk for further analysis. To keep the collision particles on their path in the accelerator strong magnetic field are used. When charged particles are bend in a magnetic field they loose energy due to synchrotron radiation. The lost fraction of energy is inversely proportional to the mass of the particles. To reach high energies, composite particles with larger masses are chosen, like for example protons. Of course the energy of the composite particle is the sum of the energies of the elementary particles which build-up the composite particle. As it is the elementary particle which collide in the end and not the composite particle, we do not have a fixed collision energy between the elementary particles for this type of colliders.

A second category of collider infrastructures aims to create particle collisions in which already known phenomena discovered by an experiment of the first category, can be precisely measured. This usually requires a clean initial state of the collision, provided by elementary particles like for example electrons and positrons. Because these particles have relatively low mass, they will loose a large fraction of their energy when bended in a magnetic field. Therefore the colliders in this second category often reach lower centre-of-mass energies in the collision and are therefore not always primarily designed to search for new phenomena.

To test the consistency of the phenomena with the experimental data precisely measured however, often new concepts have to be introduced in the current standard theory. These indirect hints are the motivation to create a new collider facility of the first category to confirm the hypotheses.

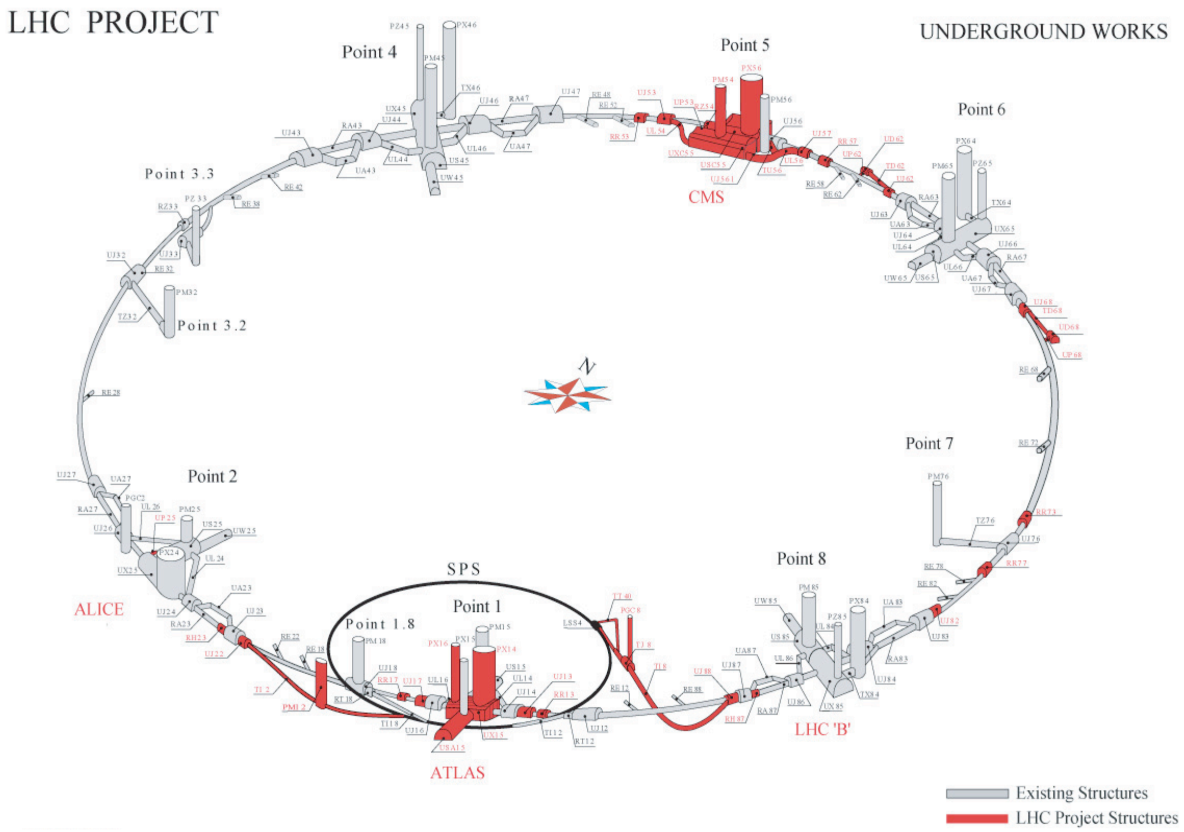
This demonstrates the natural sequence of search and precision measurement at collider experiments. The Standard Model has survived a large number of those sequences. The Large Hadron Collider at CERN is part of the first category and searches for new phenomena predicted to explain previous observations. The phenomenon related to the spontaneous symmetry breaking requires the presence of a scalar boson, the so-called Brout-Englert-Higgs boson according to its inventors. Although not directly observed, the mass of the Brout-Englert-Higgs boson has an indirect but important role in the calculations performed to understand the electroweak interactions at previous colliders. The radiative or loop corrections needed to explain the precision measurements performed at the LEP collider, the Stanford Linear electron-positron Collider and the Tevatron collider, indicate at the 95% confidence level this boson to have a mass between the LEP exclusion limit of 114.5 GeV and an upper limit of 190 GeV. Theoretical arguments motivate the mass to be smaller than 1000 GeV. Beyond this value the Standard Model becomes inconsistent as unitarity is violated in some scattering processes. The LHC and its detector experiments have been designed and it has also been demonstrated from simulations that the proton collisions will finally reveal us if this scalar boson exist in Nature or not. The Brout-Englert-Higgs boson can also help us to explain why the gravitational force is so much weaker compared to the other forces in particle interactions. The hypothetical supersymmetrical behaviour of Nature discovered theoretically in the early seventies is the most commonly studied concept to go beyond the Standard Model. By introducing this symmetry in the equations it allows to solve two major puzzles, namely the hierarchy problem and the unification of the gauge coupling constants of the weak, strong and electro-magnetic force. One of the main problems in the Standard Model are the quadratically divergences when calculating the mass of the Brout-Englert-Higgs boson or the so-called hierarchy problem. These divergences in the quantum mechanical interactions cause large renormalization corrections to the mass and require a fine-tuning of the parameters involved. With supersymmetry the quantum loop corrections are cancelled between the Standard Model fermion loops in the bosons propagator and the loops induces by the superpartners. As superpartners are not yet observed, the supersymmetry must be spontaneously broken. Several models are constructed to incorporate this. Within the Standard

Model the gauge couplings of the weak, strong and electromagnetic force do not unify at higher energies. The evolution of these couplings via the renormalisation group to higher energies is however sensitive to the particle content of the theory. By including the supersymmetrical particle spectrum the coupling constants apparently match at higher energies. Both collider and cosmological data indicate that the lowest energy scale to observe the phenomena induced by this new symmetry is within reach of the LHC. If supersymmetry is present in Nature there should be new particles, the superpartners of the Standard Model particles, which can be created in the proton collisions at the LHC. In most supersymmetric models a heavy stable particle or a Weakly Interacting Massive Particle (WIMP) is predicted which could help scientists to explain the dark matter in the Universe. Although the LHC laboratory still has to produce physics results, scientists are preparing the design of the next collider. This will probably be a linear electron-positron collider hence from the second category able to measure precisely the phenomena observed in the proton collisions at the LHC. The final parameters of this linear collider will be defined by the discoveries or the lack of discoveries of new phenomena at the LHC.

Picture of the installation of the dipole magnets and their connection to the cryogenic system in the LHC tunnel. (courtesy CERN)

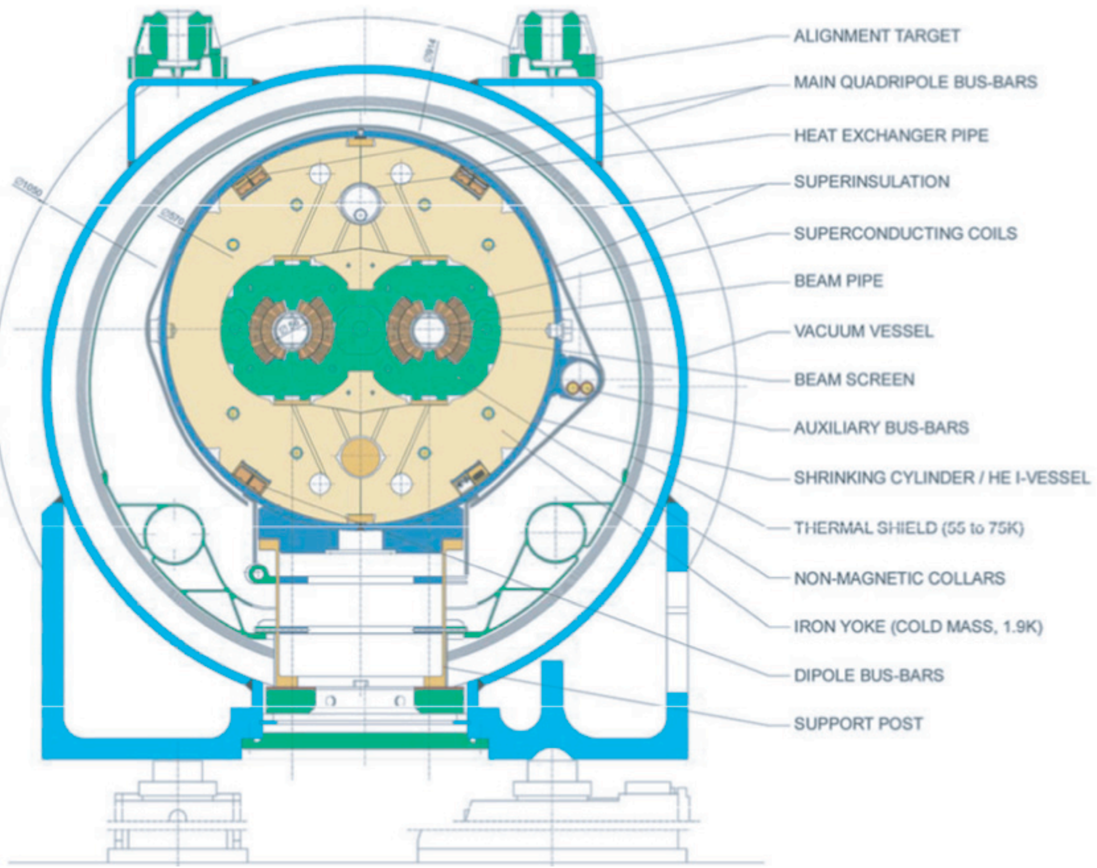
Reaching new energy frontiers

The Large Hadron Collider is in its final stage of construction and commissioning. Two proton beams will travel in opposite direction around the 27 km circumference ring hosted about 50 to a 175 meter below ground in the old LEP tunnel. In total 1232 superconductive dipole magnets will keep the charged protons on their path, while 392 quadrupole magnets will keep the beams in the ultrahigh vacuum pipe focussed towards the four collision points where the detector experiments are build. The Niobium-Titanium magnets will operate at a temperature of 1.9 K in superfluid Helium and conduct electricity without resistance at this temperature opening the possibility to create 8.3 Tesla magnetic fields. It is expected that about 100 tons of superfluid Helium is needed to cool all magnets which is unprecedented. The protons will be bunched in about 2800 packages to get a crossing of two bunches each 25 ns at the interaction points. Before injecting the protons in the LHC, they will be prepared by CERN’s accelerator complex consisting out of a series of systems and reaching proton energies of 450 GeV. After that the machine ramps up to its full 7 TeV beam energy in about 28 minutes.



Schematic overview of the underground infrastructure of the LHC laboratory. The main experiments will be hosted in caverns indicated by point 1, 2, 5 and 8. The other areas will be used for accelerator components like collimators and RF cavities. (courtesy CERN)

Although the energy stored in one single proton collision is tiny on macroscopic scales, this energy becomes large when integrated over all protons in the beam. The total amount of energy stored in each of the proton beams in the ring is about 360 MJ which is equivalent to a high speed train at about 150 km/h. While the beam is radiating off billions of particles, the magnets few centimetres away need to be kept at 1.9 K. These energetic particles could quench or even destroy a magnet. The energy of few particles could already quench a magnet and change its superconductive nature to a normal phase releasing a huge amount of energy within a second. The magnet would heat up from -271^{o}C to about 700^{o}C. To protect the magnets and the detector experiments at the interaction points from damage, a detailed beam dump system is being developed to protect the LHC from itself. When a quench begins the heat of that magnet is being dissipated over the whole 35 ton magnet of 14.3 m. Also energy is send to large resistors where about 8 ton of steel in heated to 300^{o}C in 2 minutes. If really the whole beam crosses a dipole magnet, the magnet will be destroyed and has to be replaced with one of the about 30-40 spares. Dumping the whole beam can happen on the request of the operators by using fast kicker magnets which redirect the beam. Before dumping the beam in an 8 m long and 1 m in diameter cylinder of graphite composite its intensity is diluted by magnets. Graphite is chosen for its high melting point and therefore the block can hold for the whole duration of the experiment.



Cross section of an LHC dipole magnet, indicating both beam pipes surrounded by the superconducting coils. All is contained in a vacuum vessel and a thermal shield in which the iron yoke of the magnets is cooled to 1.9 K. (courtesy CERN)

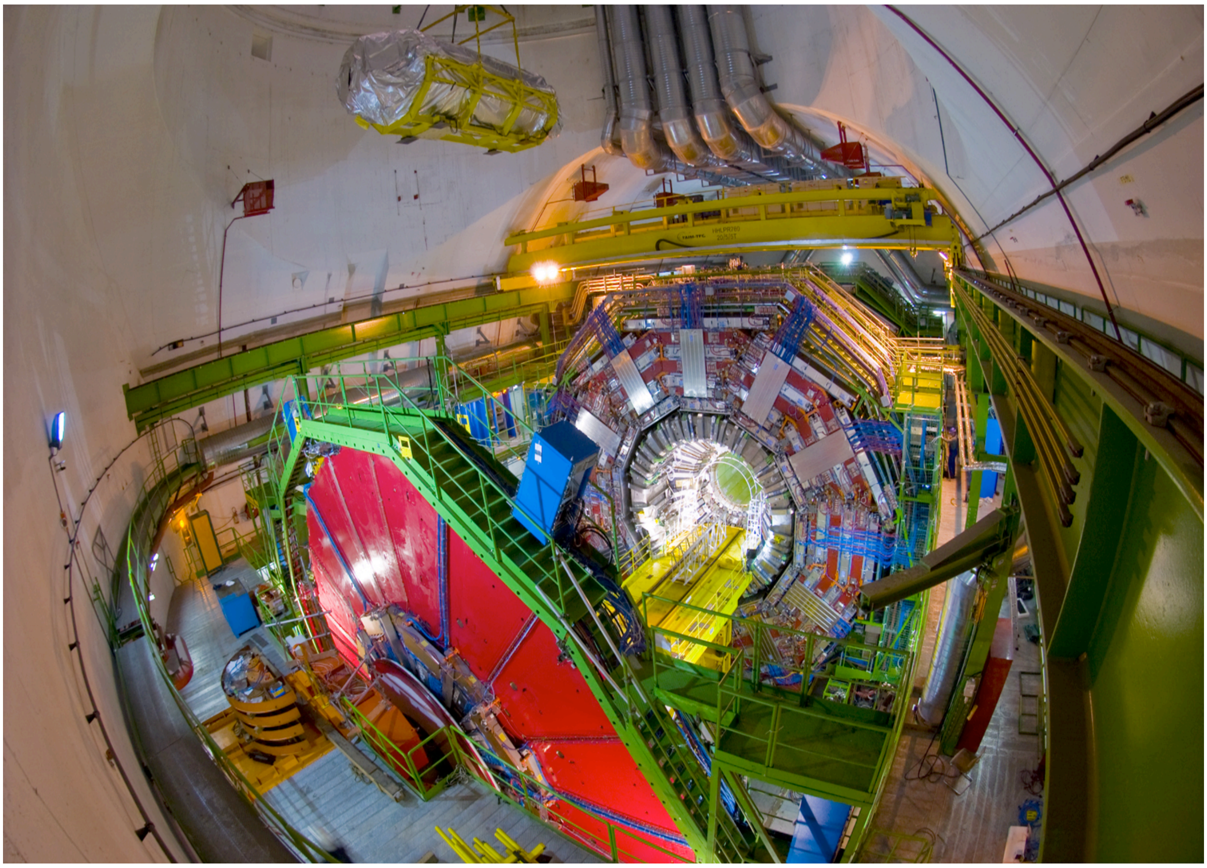
The LHC is divided in 8 arc sections connected with straight lines to host experiments and accelerator equipment. At one of the straight sections (point 4) two independent sets of radio-frequent superconducting cavities operate at 400 MHz. For each beam there are 8 single cell cavities providing 2 MV and therefore a field gradient of 5.5 MV/m. All sections are expected to be cooled down to the operation temperature by the end of June 2008. Mid July 2008 the access to the experimental caverns and the tunnel will be closed after which protons can be injected and the commissioning of the accelerator with proton beams will start. It is expected that this commissioning stage will take about 2 months before first collisions will be achieved, starting safely at centre-of-mass energies of 10 TeV rather than the designed 14 TeV. During the winter shut-down the magnets will be commissioned to their full current such that in 2009 we will reach collisions at 14 TeV. It is aimed to reach luminosities of 10^{32} $cm^{-1}s^{-1}$ in 2009 scaling up over the years to 10^{34} $cm^{-2}s^{-1}$.

Zoom into the collisions

In order to study the physics of the interactions several experiments are build to detect and reconstruct the particles present in the final state after the proton collisions. Their design is guided by the predicted phenomena to be discovered, for example the Brout-Englert-Higgs boson. Two general purpose experiments ATLAS and CMS are build with a precise inner tracking system, a calorimeter with a high energy resolution certainly for its electromagnetic component and a good muon reconstruction and identification system. Both experiments deploy a strong and uniform magnetic field. The CMS experiment has the worlds largest magnet of 6 m in diameter and 13 m in length producing a uniform 3.8 Tesla magnetic field. The detectors should be as hermitic as possible to get information on the energy of non interacting particles present in the Standard Model (neutrinos) or in models beyond the Standard Model. This information is obtained from the momentum balance of the collision in the transverse plane. Prior to the collision there is no transverse momentum as the protons collide frontal. Therefore also posterior to the interaction this transverse momentum balance should be true unless particles have escaped detection. The missing transverse energy in this balance can be connected to the momentum of these missing particles. For this technique to work, the hermiticity of the detector is of uttermost importance.

A third experiment, LHCb, is designed to study the apparent asymmetry between matter and anti-matter in the Universe. By studying the difference between matter and anti-matter the experiment will shed light on why a second after the Big Bang while the Universe cooled down and expanded, the anti-matter disappeared leaving the Universe as it is today. In the b-sector it will measure the properties of CP violation in the interactions of b-hadrons. The LHC will also allow heavy ions (Pb) to be collided to centre-of-mass energies of 1150 TeV. The

ALICE experiment will study these heavy ion collisions for which the collision energy is expected to be large enough to create a quark-gluon plasma in which quarks and gluon are deconfined. Two other experiments, TOTEM and LHCf, aim to study the forward physics which happens at very small scattering angles. TOTEM will measure for example the total cross section in the accessible scattering angle range and look at elastic scattering and diffractive processes, while LHCf has a special astro-particle physics purpose by measuring the energy and number of neutral pions in the collisions to help explaining the origin of ultra high cosmic rays. The FP420 experiment is proposed to study forward physics at 420 m from the interaction region.



Construction of the CMS detector about 100 m below surface with the CMS central tracking device flying in from the top to be installed in the centre of the detector. The diameter of the CMS detector is about 16 m and its length is about 21 m. (courtesy CERN)

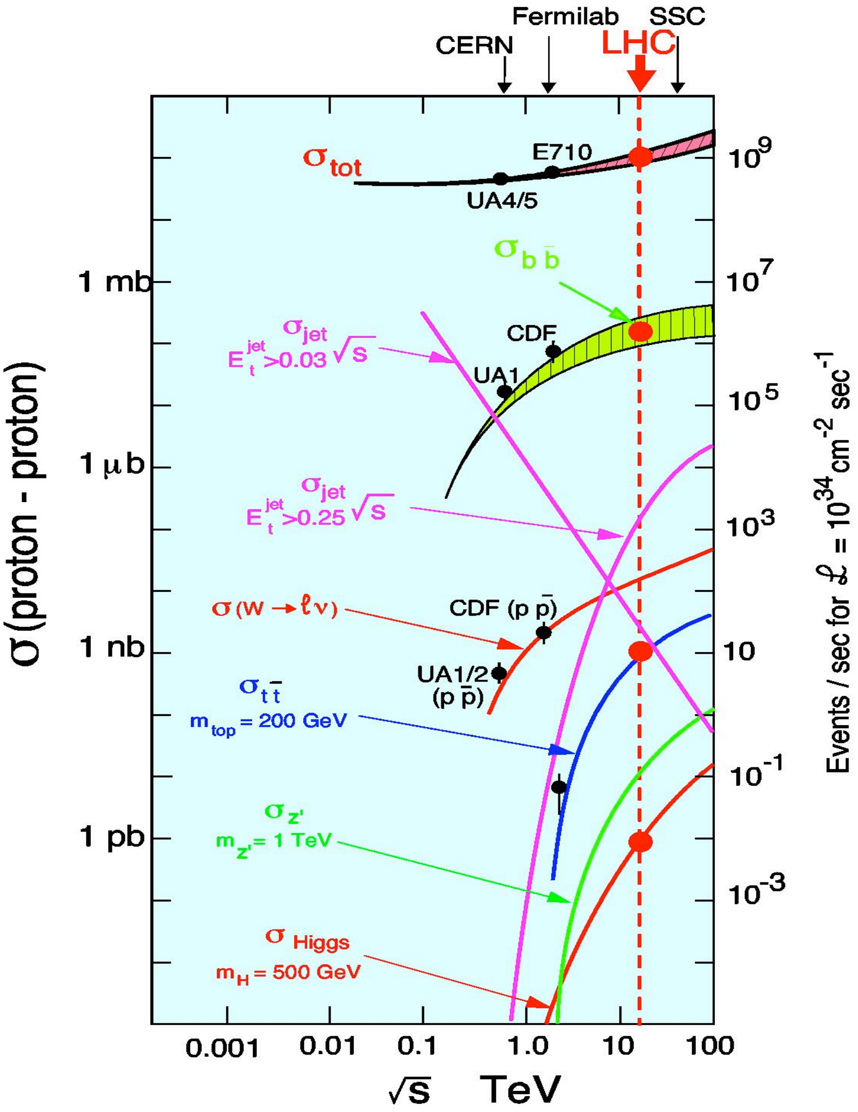
Several Belgian universities, namely UA, UCL, ULB, UMH and VUB, worked together within a consortium of about 35 laboratories around the world for the construction of the main tracking device of the CMS detector. They achieved major contributions to the design, the

R&D, the assembly and the testing phase of this front-line device. During the operational phase of the experiment, they will continue to have important responsibilities in the maintenance and operation of the CMS tracking device and in the studies for the upgrade of the detector to higher luminosities. In the spirit of the upgrade to higher luminosities the mentioned universities are joined by UGent in a project to create extra layers of muon detectors in the forward region of the CMS detector. They aim to achieve an essential improvement in the reconstruction of the tracks of muons, both in the so-called online trigger and in the offline analyses of the collisions.

God does play dice!

Particle interactions have a probabilistic nature reflected into the quantum mechanical properties of our interpretations. Although the Standard Model describes the interactions between the elementary particles to great precision, we cannot predict the path to be travelled by an individual neutrino or other particle through matter. The model makes average predictions over larger ensembles. For an infinite ensemble of W bosons, 1/3 will decay into leptons while the other 2/3 will decay into quarks, but we cannot know the decay mode of an individual W boson prior to its decay.

Similarly the proton collisions at the LHC will happen according to some predefined probability pattern in Nature which is for scientists to reveal. God will however have to call for assistance in throwing dice as we are going to collide bunches of protons every 25 ns. In each bunch crossing we are expecting moreover a Poisson distributed number of protons collisions with expectation values between 3 and 20 depending on the machine settings. Hence each 25 ns there will be about 10 proton collisions with properties according to the predefined particle interaction pattern in Nature but with otherwise random occurrence. All proton collisions happening together during the single bunch crossing constitute the event in the detector which is to be read out.



Cross section of several processes in proton-proton collisions as a function of the centre-of-mass energy. The event rate is indicated per second for a luminosity of 10^{34} $cm^{-2}s^{-1}$. The cross sections of the accessible processes which are measured at previous accelerators are shown. Clearly the probability to create an interaction to produce a Brout-Englert-Higgs boson is orders of magnitude smaller than the one to produce to processes with jets or top quarks.

Particle detectors evolved to very complex multi-layer systems with several millions of read-out channels. The data acquisition (DAQ) systems have evolved accordingly with the main reason for evolution the ever increasing particle rate in the final state of the collisions together with the usual custom detector electronics. More events to be looked at in less time and also more complex event topologies, gives strong requirements on the read-out and trigger systems of our detectors. The DAQ system of the detector collects all the signals of the millions of detector channels and allows the trigger system to analyze this data. In general the cross section of Standard Model processes is increasing when going to higher centre-of-mass energies. The processes of interest to be discovered (eg. Brout-Englert-Higgs boson, supersymmetry, etc.) have a much lower cross section compared to the Standard model processes. But as they require the creation of particles at higher mass scales their cross section usually increases more rapidly compared to Standard Model processes with the centre-of-mass energy. In general only 1 out of 10^{11} events exhibits the effect of a particle interaction beyond the Standard Model, see Figure.

The length of the ATLAS detector is more than 40m, hence with every 25 ns a bunch crossing (equal at the speed of light to 7.5 m of traveled distance) there are on average three trains of particles flying through the detector originating from the final state of three (or more) different collisions. The granularity of the detectors is very fine with small occupancy per collision. This allows the electronics to sample at a smaller rate compared to the collision rate because for most of the bunch crossings only interactions with negligible transverse activity will happen. Although the detector electronics will sample over several bunch crossings at the same time, the detector cannot be fully read out every 25 ns. This introduces the important concept of triggering events.

The trigger system consists out of several layers of consecutive online rejection of events. At a bunch crossing rate of 40 MHz and an average of about 3-20 collisions per bunch crossing, about 0.1 to 1 GHz of collisions will be produced in the detector. The total size of one event is on average about 1 MB. In the CMS experiment a two step approach is being deployed. The first Level-1 hardware trigger will select only those events for which locally in the detector a pattern is present of particles with relatively large transverse momentum or with a clear identification of interest. The parameters of these trigger algorithms have to be tuned to select only a rate of 100 kHz of events. The electronic delay buffers are finite and require the Level-1 decision to be made in 3 μs time, therefore relying on simple algorithms, small amounts of data and local decisions. During this time the signal cannot be transported to far. The control room with all processors is located underground very nearby the detector, but shielded however from the radiation. Most of the latency time of 3 μs is used for the transportation of the signal through cables. Upon a positive decision from the Level-1 trigger algorithms the full event is read-out and build by the DAQ system. At this stage there is still 1 TB/s of information. To reduce this, all these events are being processed in a second stage High-Level Trigger by a farm of thousands of commercial processors. More complex algorithms can be explored to reduce the event rate to 100 Hz, which is finally put on disk for further analysis. The processing time allowed for these algorithms depends on the amount of processors deployed in the computing farm. It is an important challenge to define optimal settings for this triggering process because it will decide which data we will be able to analysis and which will be rejected and therefore lost for ever. With only a tiny fraction of interesting events featuring new phenomena, the trigger thresholds have to be well studied prior to the first collisions.

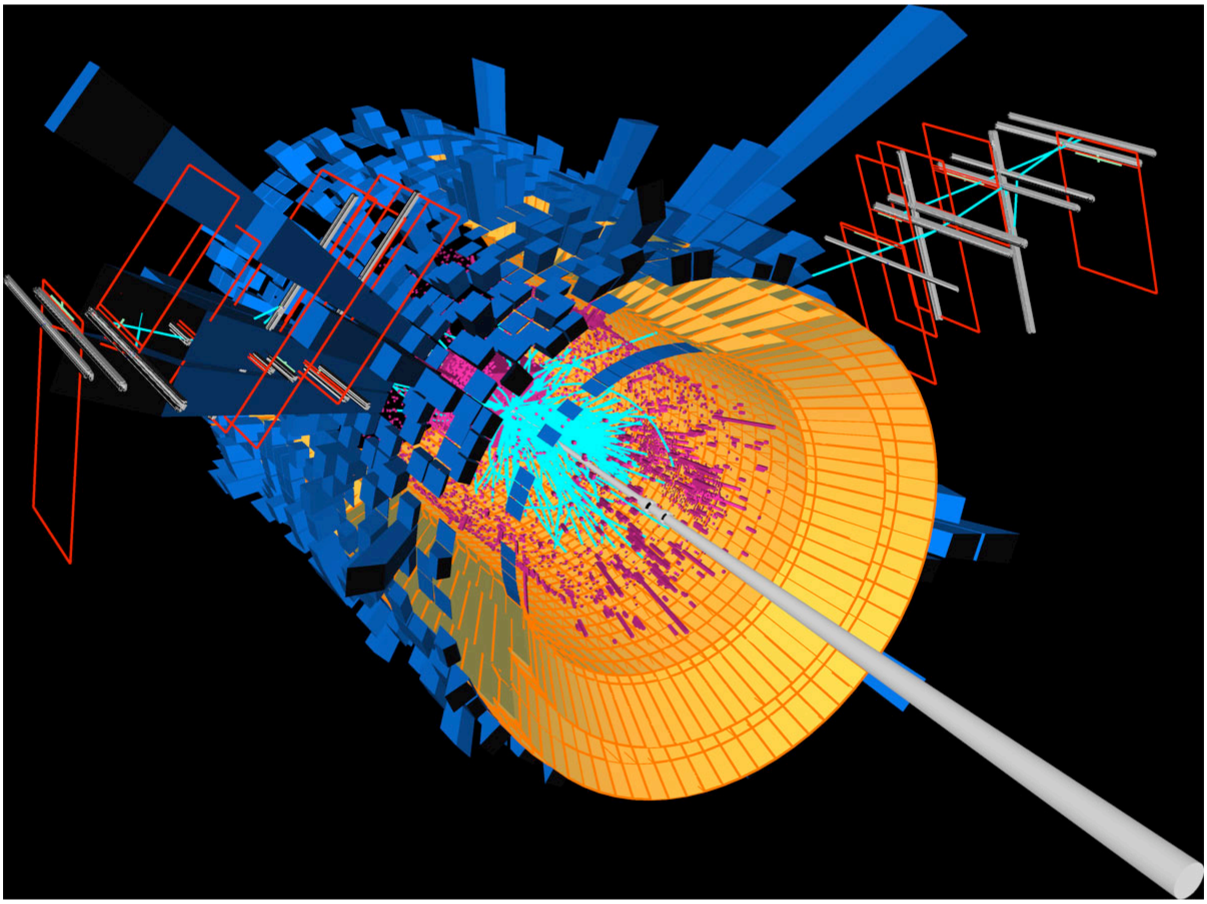


Illustration of the complexity of a proton-proton collision in which a pair of top quarks is produced, CMS detector simulation. (courtesy Steven Lowette)

The data which will make it to the disks will be distributed in a worldwide hierarchical network of computing infrastructures. The offline analyses themselves will be performed at the computing centre which will host the particular dataset the analysis is intended for. To allow the physicist to run his or her software analysis within this distributed system, GRID related tools are being used. The LHC Computing Grid (LCG) has been developed to support the experiments at the LHC to handle huge amount of data and large data rates.

Preparing to unfold Nature…

Once they have the triggered collision data on disk physicists can start exploring complex algorithms to find out the underlying interaction in each collision. It is again very difficult and even impossible to envisage to unfold a single detected event and to assign hereafter a unique identification of the underlying process. The resolution of the detector is finite and of course we cannot follow the outgoing particles down to the first fraction of a second after the interaction, leaving always ambiguities to assign in a multi-particle final state which particles originates from the same mother particle to complete the Feynman diagram picture of the interaction. Therefore statements on physics phenomena are usually made on the basis of several events together. The appearance of a signal of supersymmetric particles in one particular collision could still be, within the detector resolution, the result of a normal Standard Model interaction. To differentiate between interactions of interest and so-called background interactions physicists study by means of Monte Carlo simulations of the underlying physics and detector responds, the distributions of variables related to the observed events. The challenge is to find variables which exhibit different distributions for signal and background processes. With advanced selection algorithms based on all information reconstructed in the detected event they are able to purify the selected event sample to isolate particular signal events of interest. From a combination of detector simulations and extrapolations from previous experiments, a prediction can be made for a fixed integrated luminosity how many events should be present in the selected sample. By comparing this prediction with the actual observed number of selected events, new phenomena can be discovered or exclusions limits can be set on the parameters governing the physics beyond the Standard Model. For example the Standard Model is predicting a total cross section to produce two W bosons in the final state of proton collisions at 14 TeV. But this amount of events can be increased in the true data sample if Brout-Englert-Higgs bosons are produced which subsequently decay into two W bosons.

The race to Stockholm

The Brout-Englert-Higgs boson which gives mass to vector bosons is a massive scalar particle and is the only Standard Model particle not yet discovered. Because it is supposed to be responsible for the mass of microscopic matter, its experimental verification is critical for our understanding of Nature. The mechanism was created in 1964 by Peter Higgs, François Englert and Robert Brout, and later proposed by Steven Weinberg and Abdus Salam to explain the electroweak symmetry breaking in the Standard Model. The mass of matter particles is introduced by a non-zero vacuum expectation value of the so-called Higgs field in empty space, which breaks the electroweak gauge symmetry spontaneously. Hence after the Big Bang they suggested that elementary particles had no mass. Only when the Universe cooled and expanded beyond a critical value the symmetry was broken and the scalar field created. Clearly the hunt for the first glimpses of the Brout-Englert-Higgs boson and therefore understanding the mass of matter around us is a hot issue. It would reveal answers to an important puzzle in our quest and maybe define the theme of a future Nobel laureate speech. The Belgians Brout and Englert have performed their research at the ULB, hence it would put Belgium in the spotlights.

The mass of the Brout-Englert-Higgs boson is however not predicted by the Standard Model. The boson can be created via different interactions in the proton collisions at the LHC. Subsequently this scalar can also decay in different modes. Therefore not just one single analysis will try to unfold the collision data in search for the signs of underlying interactions with Brout-Englert-Higgs bosons, but several analyses will be specialized to look for a particular production process and decay mode. For some of them the signals will be outstandingly clear because few background events is expected from other Standard Model processes. An example is the process where one Brout-Englert-Higgs boson decays into two Z bosons which on their turn decay into muons. Both the ATLAS and CMS experiments will identify these muons with high efficiency and reconstruct their kinematics with high precision. This will allow physicists to reconstruct the mass peak of the four muon system with high precision. Therefore when enough collision data is collected this resonant peak will be very clear in an otherwise non-resonant background spectrum. For some other production and decay choices the hunt for the signals of the particle is transformed into a quest to understand the background properly. An example is the decay into two photons. Within the multi-particle final state after the proton collisions it is very difficult to identify photons amongst all particle species. Also the resolution on the energy of the photon is much worse compared to muons. Therefore the resonant behaviour of the mass of this two-photon system will be diluted by detector and reconstruction effects, and this signal will be swapped into an overwhelming background. It would take much more collision data to convince ourselves that an excess of two-photon events is significant and effectively due to the presence of the Brout-Englert-Higgs boson in Nature. The mass of the scalar particle defines the production rate and decay rate into a specific final state. Because Nature itself will decide on the value of the mass, physicists cannot predict which analyses will finally discover the puzzling particle. The scientific collaborations preparing the LHC experiments are developing all analyses needed to cover the full possible mass range of the Brout-Englert-Higgs particle to make sure detection will not escape when the boson is present in Nature. Via studies based on simulated collisions, it has been shown that with the current accelerator settings and the detector design and performance, the boson should be discovered when it is indeed responsible for the mass of the elementary particles. Of course next to the Brout-Englert-Higgs mechanism there are many more new phenomena to be explored at the LHC. The collision data allows for a vast range of unique studies to reveal Nature, most of this work is being prepared by the hundreds of universities involved.

Is living at CERN dangerous?

Recently concerns have been raised about the possible creation of phenomena with disastrous consequences for our planet. These phenomena are predicted by some models beyond the Standard Model which incorporate extra spatial dimensions. The creation of micro black holes would make life at CERN dangerous only if they are stable. Hawking radiation theory however teaches us that these black holes would decay rapidly before they attract via the gravitational force the rest of their surroundings. Another argument mentions that within the high energetic collisions between cosmic particles and our atmosphere via a similar mechanism black holes could be created at a rate of a few hundreds per year and apparently without any spectacular effect. It is in general challenging to construct a unified theory incorporating both general relativity and quantum field theory. The invent of the theory of everything including all Nature's forces and valid at all energies is considered to be the Holy Grail for particle physicists. Over the last two decennia string theory has evolved to a solid candidate theory of everything. Some of the concepts of string theory could become accessible with the proton collisions at the LHC, for example the presence of extra spatial dimensions.

The question which is never to be asked

And what if we do not discover the predicted new phenomena? What if Nature was fooling us? What if all our brilliant ideas, be it either with a problem solving or a fundamental attitude, were wrong? If no Brout-Englert-Higgs boson would be found within the range of the LHC laboratory, it would mean that physicists have to develop new theories to explain the origin of mass. This fact would on its own be revolutionary news for the physics community and redirect most theoretical effort in particle physics. Efforts have been made to create alternative models without the Brout-Englert-Higgs mechanism, although none of them is empirically confirmed. All of these models have the Standard Model features as a low energy limit of the true theory living at higher energies densities closer to the Big Bang where more symmetry is present in Nature. The LHC experiments provide an excellent platform to study the properties of these hypothetical extensions of the Standard Model. The link between the cosmological observations and the future findings in the proton collisions of the LHC will become an important research domain. The presence of dark matter in the macroscopic Universe can be understood by performing research on the microscopic level of elementary particles in our laboratories.

Exciting times for scientists

After years of preparation both on the experimental side for the instruments and the analyses and on the theoretical side to model new possible phenomena in proton collisions at 14 TeV, the Large Hadron Collider will start its exploration later this year. It will shed light into most of the unanswered puzzles in our quest to describe and understand the fundaments of the micro- and macroscopic world. With the search for the yet undiscovered Brout-Englert-Higgs boson in front, the consistency of many other phenomena and their theoretical models describing them will be verified with empirical data. Particle physicists have prepared for many exotic scenarios to become reality and most of them will change our way of thinking about the Universe around us. The experimental outcome of the Large Hadron Collider experiments will determine the path to follow in future particle physics research.