The Compact Muon Solenoid Experiment at the Large Hadron Collider

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ABSTRACT

The Compact Muon Solenoid experiment at the CERN Large Hadron Collider will study proton proton collisions at unprecedented energies and luminosities. In this article we provide first a brief general introduction to particle physics. We then explain what CERN is. Then we describe the Large Hadron Collider at CERN, the most powerful particle accelerator ever built. Finally we describe the Compact Muon Solenoid experiment, its physics goals, construction details, and current status.

RESUMEN

El experimento *Compact Muon Solenoid* en el *Large Hadron Collider* del CERN estudiará colisiones protón protón a energías y luminosidades sin precedente. En este artículo presentamos primero una breve introducción general a la física de partículas. Después explicamos lo que es el CERN. Luego describimos el Large Hadron Collider, el más potente acelerador de partículas construido por el hombre, en el CERN. Finalmente describimos el experimento Compact Muon Solenoid, sus objetivos en física, los detalles de su construcción, y su situación presente.

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INTRODUCTION

As a result of continued experimental and theoretical efforts to understand the elementary constituents of matter, during the decades of the 60s and 70s physicists ultimately elaborated the theory known as the Standard Model of Elementary Particles (SM). The theory — the construction is really far more than a *model* — provides a consistent description of the most elementary constituents of matter and their interactions. The SM permits to explain a vast amount of experimental observations performed during the past decades at many different experimental facilities, including particle accelerators.

The SM is a theory that has passed many experimental tests. But we know that the SM is not complete. The SM does not account for instance for the Dark Matter, that *something* that we suspect pervades our universe and that seems to play an important role on the dynamics of galaxies. The number of free parameters in the SM is above twenty. The number is perhaps just too large for a theory thought to be fundamental. The SM does not completely explain why particles have mass, or why the scales of masses for different particles are so disparately different: why the big difference in mass scales between, say, the electron and the proton? The Higgs particle was proposed in the 60s by Peter Higgs and others to complete the SM by providing a mechanism to account for the mass of particles through the mechanism known as Electroweak Symmetry Breaking (ESB). However the particle has not yet been observed, and several theoretical questions regarding the particle remain to be answered. The SM does not properly include the force of gravity. Furthermore, at very high energies several theoretical predictions of the SM result in probabilities that physically make no sense.

The Large Hadron Collider (LHC) at CERN is the most powerful particle accelerator in the world. It is the most powerful tool ever built to pursue the investigation of the subatomic world. The experiment Compact Muon Solenoid (CMS) at the LHC, is one of the two general-purpose experiments at the LHC (the other one is ATLAS).

Keywords:
LHC; CMS; Particle accelerators; Particle detectors; Higgs boson.

Palabras clave:
LHC; CMS; Aceleradores de partículas; Detectores de partículas; Bosón de Higgs.

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CERN

CERN (http://www.cern.ch) is one of the most important centers for scientific research in the world. CERN, the European Organization for Nuclear Research (originally: Conseil Européen pour la Recherche Nucléaire), is the largest particle physics (PP) laboratory in the world.

CERN, located along the French-Swiss border close to Geneva (figure 1), was established in 1954. The most important mission of CERN is fundamental research. Physicists at CERN use the most complex scientific instruments to study the most fundamental constituents of matter: they study the extremely small but rich world of fundamental particles.

The laboratory is not only a work place for the scientists, engineers and technicians who design the accelerators and detectors, CERN is also home for the many theoreticians who come to the lab to generate new ideas.

CERN is a conspicuous example of international collaboration: more than 85 different nationalities come together at CERN facilities. CERN fosters the dissemination of knowledge and the training of scientists from everywhere in the world. The lab also promotes technology transfer and exchanges with other laboratories worldwide, and with industry.

Though CERN is mainly dedicated to fundamental physics, fundamental research at CERN has as a byproduct numerous innovations. For instance technologies developed for particle accelerators and detectors find important applications in medicine. CERN experiments have also fostered developments in electronics, cryogenics, detector technology, magnet technology, and computing. CERN also promotes information technology developments. CERN's most famous invention is the World-Wide-Web, initially conceived as a tool to promote communication among scientists.

CERN's main project at this time is the LHC, the largest and most powerful particle accelerator in the world. CERN scientists and engineers have built, along five decades, several state-of-the-art accelerator facilities. Today they constitute a complex of interconnected accelerators connected one after the other. The largest and most powerful of these accelerators, just recently completed, is the LHC.

THE LARGE HADRON COLLIDER

Located between the Jura mountains in France and the Geneva Lake—part of the LHC is in France and part of it in the Swiss territory—, the Large Hadron Collider is the largest and most complex scientific project ever attempted.

The LHC is built in a circular tunnel 27 km in circumference (figure 1). The tunnel (constructed in the 80s to house the former CERN accelerator: the LEP) is buried some 50 m to 175 m underground.

Figure 1. Aerial view of the CERN site. The schematic shows the location of the underground tunnel and the location of the CMS experiment.

The LHC project involves thousands of researchers, engineers, and students. More than ten thousand scientists from about 500 institutes, laboratories and companies all around the world participate in the project.

Energy at the LHC will be seven times larger than at the former most powerful accelerator in the world, the Fermilab Tevatron, and 70 times larger than in the former CERN most powerful accelerator, the LEP.

The detectors that will record the interactions of particles created in the LHC collisions are huge. They measure up to 46 m long and their weight must be measured in thousands of tons. The precision that will be reached in the measurements, the produced-data rates, and the storage needs, are all completely unprecedented in these experiments.

The LHC is at the edge of the accelerator energy frontier. The effective energy at the LHC will be about eleven orders of magnitude higher than what was accomplished in the first man-made accelerators.

An early cyclotron of the 50s was able to accelerate protons up to energies of one GeV. (Energy in accelerator experiments is commonly measured in multiples of electron-volts (eV). An electron subject to a potential difference of one volt acquires an energy of one electron-volt. One GeV is 10^9 eV. One TeV is 10^{12} eV.) This energy corresponds to a speed of about 212,000 km/s. In the 60s the PS (Proton Synchrotron) CERN accelerator, 200 m in diameter, was able to accelerate protons at almost 30 GeV (a speed of about 295,000 km/s). Constructed in the 80s the LEP (Large Electron Positron Collider), the most powerful accelerator at CERN before the LHC, accelerated protons up to energies of about 100 GeV (a speed of more than 299,999 km/s). The LHC in turn will accelerate protons up to 7 TeV.

The LHC will produce collisions at the highest energies ever achieved in the world among beams of identical particles, protons or lead ions. The beams will be created in the chain of CERN accelerators. Protons bunches will be pre-accelerated up to 450 GeV and then injected into the LHC, where they will be accelerated up to 7 TeV per proton. The LHC will thus produce 14 TeV proton-proton collisions.

The two beams, travelling in opposite directions, will be guided through the more than 26 km (26, 659 meters) of the accelerator ring by superconducting magnets, working at very low temperatures, in a vacuum comparable to the intersidereal vacuum. Particles of the beam will collide at specific experimental sites. Scientists will observe the collisions by using four gigantic detectors: ALICE, ATLAS, CMS and LHC-b, each located at a collision point along the ring.

ATLAS and CMS are the two general-purpose experiments of the LHC.

ALICE will be dedicated to study heavy-ion collisions and the quark-gluon plasma. LHC-b will be mostly dedicated to study the B sector and CP violation asymmetry.

Two smaller experiments, LHCf and TOTEM will provide complementary information for the other experiments.

In the LHC more than 9,600 magnets will contribute to define the trajectories of the beams. 1,232 superconducting dipoles, operating at a temperature of 1.9 K, will be dedicated to the bending of the two proton beams around the 27 km circumference tunnel (figure 2). These dipoles constituted a major technological challenge for the LHC project. The use of superconducting magnets permits to obtain much higher fields than with ordinary magnets. The LHC magnets will operate at about 8.3 Tesla (a field five orders of magnitude higher than the Earth's magnetic field). Ordinary magnets are able to produce only about two Tesla. If the LHC should use conventional (not superconducting) magnets, the ring would have to measure 120 km circumference in order to achieve the same collision energies! Such a device would need about forty times more electrical power to operate than the actual design.

The 14.3 meter long magnets have two side-by-side apertures, one for each of the counter-rotating proton beams. The niobium–titanium (NbTi) coils create the magnetic fields to guide in separate magnetic channels the two proton beams circulating in inverse directions.

Figure 2. Installation of a superconducting dipole in the LHC tunnel.

At 7 TeV the magnets drive a current of around 11,700 A. This large current results in a force of about 400 ton per meter of dipole!

The LHC dipoles comprise 7,600 km superconducting cable with a weight of 1,200 ton. The cables are ultimately made of filaments of NbTi. The total length of the filaments is more than 10 AU (an astronomical unit, AU, is equal to the mean distance between the Earth and the Sun)!

We are proud to say that the LHC tunnel will actually constitute the coldest place in the universe, even colder that intersidereal vacuum. Several weeks are needed in order for the superfluid-Helium-based cryogenics systems, to reach operating temperatures. In order to keep the low temperatures, the isolation walls are quite thick: about one meter in diameter. The proton beampipes, by contrast, are only 5 cm in diameter. The pressure in some parts of the beampipe will be very low, ten times lower than in the Moon.

The LHC is a colossal scientific instrument, in many senses. The overall size of an LHC detector, such as ATLAS, is that of a big apartment block. However LHC experiments have the precision of a delicate mechanism. For instance the thousands of magnets positioned around the LHC ring are each aligned with better than millimeter precision.

The whole project costs several billions of US dollars. The LHC is an international project, and also CERN non-member states (such as Mexico) contribute to the funding of the project. Scientists consider the investment worth because the LHC is expected to point the way to answer fundamental questions about our world. Many scientists say that Physics will not be the same *after* the LHC than *before* the LHC.

COLLISIONS AT THE LHC

The collision rate at the LHC is about 10^9 Hz, a billion per second. The LHC will operate at a bunch crossing rate of 40 MHz (25 ns bunch spacing). The instantaneous luminosity at the LHC, a measure of the number of interactions per unit time, is L = 10^{34} cm^{-2} s^{-1}. The integrated luminosity over a year at the LHC will be more than 30 times the total integrated luminosity at the Fermilab Tevatron after more than ten years of running. The LHC luminosity is very high because we want the detectors of the experiments to have better chances to get data corresponding to very rare interesting physics processes.

The commissioning of the LHC began in June 2007. The LHC began operation on the middle (10^{th}) of September 2008. But because of technical incidents within a few days of operation, the LHC halted normal operation during several months.

THE CMS EXPERIMENT

The Compact Muon Solenoid (CMS) experiment (Adolphi R. *et al*.,), one of the four big LHC experiments, is located at the Point 5 of the LHC, close to the Cessy French village (figure 1). Over 2,800 scientists (12 from Mexico) from some 180 institutes (6 from Mexico) in 39 countries are involved in CMS. CMS is *per se*, and as part of the LHC project, one of the most complex scientific instruments ever built.

The LHC has two general-purpose detectors, CMS and ATLAS. CMS (Bayatian, 2007) has basically the same scientific goals than ATLAS. However CMS has chosen a different technical approach, in particular, a different design of the magnet system. While CMS weighs the double than ATLAS, it occupies only one eight of the ATLAS volume. The fact is reflected in the word "Compact". The detector is located in an underground cavern 53 m long, 26.5 m wide and 24 m high. CMS weighs 12,500 ton (it contains much more iron than the Eiffel Tower!).

CMS is expected to operate during more than a decade. In addition to proton proton collisions, the experiment will also study heavy ion collisions.

The CMS detector (figure 3 and 4) is 21 m long and 15 m in diameter. But the huge size of CMS should not hide its extreme complexity and detail: CMS comprises about 100 million individual detecting elements. The Inner Tracker for instance employs wires with a thickness of 5µm.

Unlike the other big LHC detectors which were built underground, CMS was first assembled at surface level. 15 assembled sections (each with a weight of up to 2,000 ton) were then lowered into the cavern and there fitted together. This construction method presented important advantages, but it also posed enormous technological challenges.

A CMS prime design requirement was related to the following. A golden decay channel for the Higgs boson is its decay to two Z bosons and then to 4 muons. According to this, the CMS detector was from the beginning designed to have the capability to measure momentum of up to 1 TeV muons with at least 10% precision. This requirement resulted in the use of a very large magnetic field and compact volume (in CMS muons can travel a distance of 3 m in the 4 T bending field).

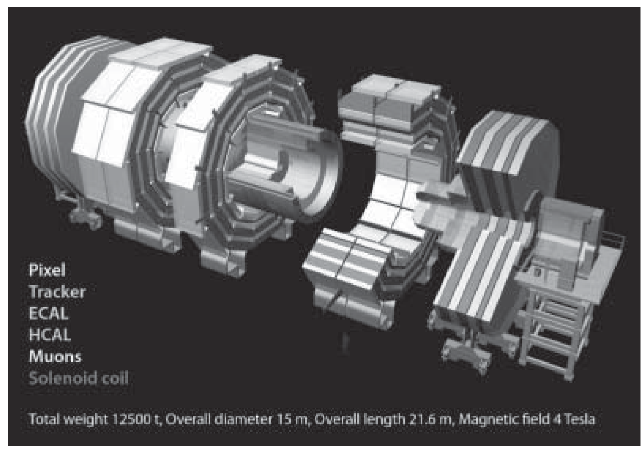

Figure 3. The CMS detector (layout).

Figure 4. One of the authors (E. Casimiro) in the CMS detector cavern.

The CMS detector comprises many stages, each of them carefully designed to accomplish a specific task. By combining the information from the different parts CMS scientists can characterize (identify the nature of, determine the trajectories followed by, measure precisely the energy and the momentum of) the particles produced at the collision point. Each detector subcomponent reveals a different and complementary view of what happens during and just after the collision.

The CMS detectors will measure the momentum of charged particles by the determination of the curvature of their tracks in the magnetic field. They will determine the spatial origin of the particles. The detectors will identify their decays. They will further determine other properties of the particles, such as their polarization.

The detectors of the LHC experiments have the following common characteristics. They must have very fast response (of the order of 20-25 ns). The segmentation of the detectors should be very fine (this requirement implies a very large number of channels and consequently a high cost). The detectors must be resistant to high radiation doses.

We describe next the most important components of the CMS detector (figure 3).

A central element in the CMS detector is a huge Superconducting Solenoid. It is the largest magnet of the kind ever built. It is a cylindrical superconducting coil capable to generate a magnetic field of 4 T. The magnet is intended to bend the trajectories of charged particles to enable momentum measurement. The solenoid has a diameter of 6 m and a length of 13 m. It drives up to 20,000 A. It is cooled down to -270º C. Many of the CMS subdetectors are located inside the magnet.

The Silicon Tracker, made up of finely segmented Si sensors (strip and pixels), located very close to the collision point, is used to determine the tracks of charged particles and to help measuring their momentum. The Tracker can also indicate the points in space where long lived unstable particles decay. The Tracker contains 65 million pixels and about 10 million Si strips. Its function can be said to be similar to that of a high-resolution digital camera: it “photographs” particle tracks with extreme precision.

The Electromagnetic Calorimeter (Lustermann, 2009) will measure precisely the energy of the photons, electrons and positrons. It is made up of 80,000 crystals of lead tungstate (PbWO4). Each single crystal weighs about 1.5 kg but has a very small volume. The transparent crystals produce light as the electrons and photons pass through them. The amount of light produced is proportional to the energy of the incident particles. The calorimeter was designed to fit in the available space and still manage to capture the electromagnetic showers with the necessary resolution. The calorimeter is entirely active, hermetic and homogeneous. The barrel uses avalanche photodiodes, as they can operate in the presence of the high magnetic field.

A Preshower detector, based on Si sensors, provides CMS with good particle identification capabilities in the endcaps.

The Hadron Calorimeter measures the energy of particles such as pions, kaons, protons and neutrons (particles containing quarks). They are made of layers of dense material, steel or brass plates, alternating with layers of scintillator material or quartz fibers.

CMS uses three different types of Muon Detectors, Drift Tubes (DTs), Cathode Strip Chambers (CSCs) and Resistive Plate Chambers (RPCs) to identify muons and measure their momentum. These are the outermost detectors, since muons are the only particles (together with neutrinos, which are not directly detected) that can traverse the several meters of intervening material. Some muon detectors are made of aluminum tubes filled with gas. When a muon traverses the tube, it ionizes the gas producing electrons that can be detected by the electronics associated to the tubes. The location of these tubes is determined almost up to a few μm precision in order to achieve extraordinary resolutions in the determination of the trajectories. The bending of each trajectory is, for each particle type, a function of its momentum. This information, together with independent energy measurement, provides a complete characterization of several of the particles resulting from a collision event. The functions of the CMS muon detectors are: muon identification, momentum measurement, and triggering.

A huge Iron Yoke outside the magnet returns the magnetic field so that the muon chambers are within the field. The eleven 12-sided sections of the yoke also provide mechanical support for the overall detector.

The huge amounts of events per second (particle bunches in the LHC collide up to 40 million times a second), necessary to have a better chance to create rare particles such as the Higgs, will be filtered by an electronic Trigger system that will select only the most interesting events, those most likely to be associated with new physics, thus reducing the number of events. Only about one hundred events per second, carefully selected, will be recorded for analysis. This requires an extremely well designed and implemented trigger system. The selected events will be stored for subsequent detailed analysis. But even this amount of data is roughly the size of 10,000 digital copies of the Encyclopedia Britannica every second! The total amount of data recorded per event will be of the order of 1.5 Mbytes, at a rate of 100 to 200 Hz.

DATA ANALYSIS

CMS physicists from all around the world will use state-of-the-art techniques to analyze millions and millions of events to obtain physics results such as the observation of new particles or new phenomena. CMS Data Analysis will be a worldwide effort possible only through innovations in computing technology such as the GRID. Each year the LHC experiments will generate amounts of data enough to make a tower of CD-ROMS twenty km high, something like 10 petabytes of data per year! Clearly no single supercomputer in the world has the capacity to analyze these gigantic amounts of data. Instead the GRID makes use of the combined computing power of several tens of millions of computers located around the world. The GRID requires transmission of up to 10 gigabytes per second (this can be compared to the 20 megabytes or less, of present ADSL internet lines). It takes a lot of careful work to prepare the strategies needed to understand high energy physics data, and the CMS Collaboration is actively taking care of that. In order to ensure correct performance of the detector CMS scientists can align and calibrate the detectors of the experiment by using cosmic rays. CMS has been collecting cosmic ray data since 2006 (figure 7) to perform the studies needed.

PHYSICS GOALS OF CMS

CMS has the same scientific goals (Bayatian, 2007) as ATLAS. Running two experiments with similar goals permits some redundancy and possibility for cross-checks. Among the physics goals of the experiments we can mention the following:

The search for the Higgs boson. The Higgs particle has not yet been observed experimentally. The Higgs is expected to have a mass at most 200 times larger than the proton, but the theory does not predict exactly its mass. The LHC could provide information on the Higgs particle and could help to understand the ESB process. LHC experiments have the potential to discover the Higgs if its mass is not too high (figure 5 and 6).

In addition to the Higgs boson, CMS will also look for other New Particles such as, Supersymmetric Particles and Gravitons. According to Supersymmetry (SUSY) theories, for each known particle there exists a more massive (heavier) superpartner. SUSY could solve several of the problems present in the SM. For instance it could provide a mechanism for the Unification of the four fundamental forces of nature. The SM only includes three of them: the electromagnetic force, the weak interaction, and the strong interaction, and leaves aside gravity. In a SUSY framework, all the forces present the same level of strength at very high energies (of the order of the Planck scale). The weak force, the strong force, and the electromagnetic force

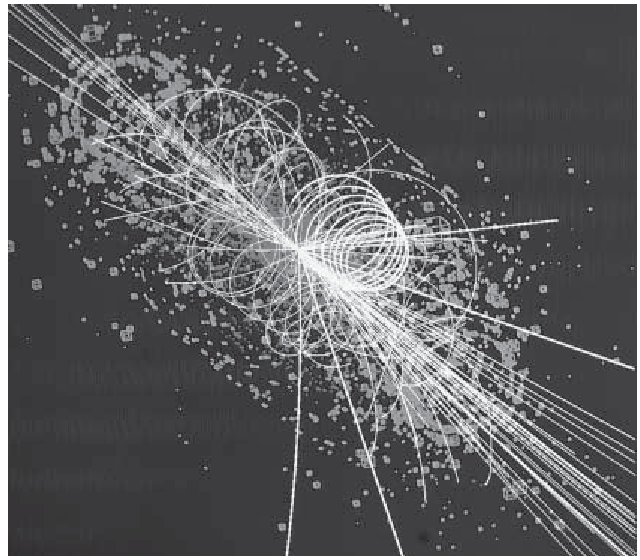

Figure 5. Simulated Higgs boson event in the CMS detector.

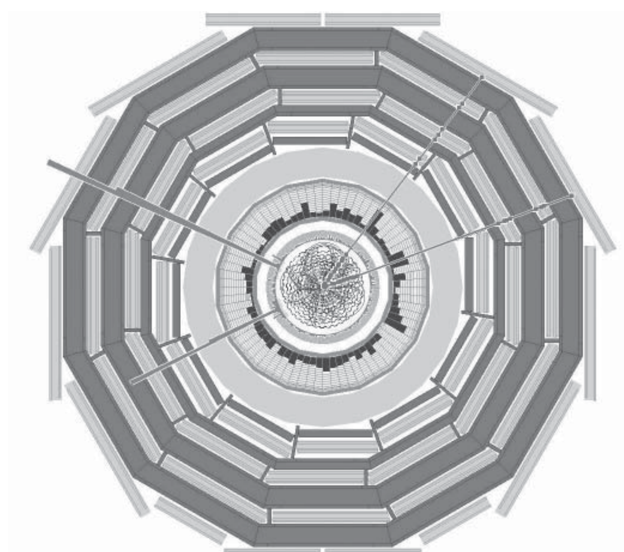

Figure 6. Higgs boson simulated event in the CMS detector (cross section).

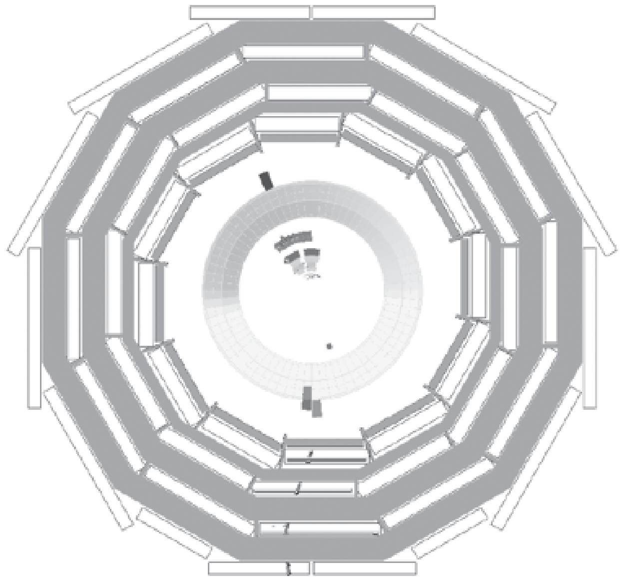

Figure 7. CMS cosmic data event.

all could be unified with the gravity force, in the framework of a Grand Unification theory. Furthermore, SUSY could provide an explanation to the Dark matter of the universe.

In CMS, conditions similar to those that were present a fraction of a billionth of a second after the Big Bang will be created in laboratory conditions.

CMS will search new phenomena such as Micro Black Holes and new states (Byungsik, 2009) of very Dense and Hot Matter.

CMS will explore possible Extra Dimensions of the universe. New space (extra) dimensions whose effects would only be sensible at very high energies. The extra dimensions could provide an explanation of why the gravity force is much weaker than all the others.

CMS will perform Dark Matter (DM) searches. Only about a quarter of the universe is matter. About a fifth of the matter is made of quarks and leptons. The rest of the matter cannot be made of quarks and leptons. DM is not detectable by usual means, but has effects on the dynamics of galaxies. DM could be made up of a stable particle, electrically neutral, and with very feeble interaction with ordinary matter.

The LHC can let us understand why the universe is made of matter and not of equal amounts of matter and antimatter. The universe is made almost entirely of matter and not of antimatter, even though it began with equals amounts of matter and antimatter. We do not know why this is so. While some insight into the problem can be gained from Cosmology, the LHC is a tool that has the potential to provide the elements needed to construct a more complete theory to elucidate the question.

The LHC is a tool that will help to come to a better formulation and test of String Theory.

The LHC could also provide evidence for Strange Phenomena. It may find new constituents of particles nowadays considered elementary.

Generally, the LHC and its experiments will allow a deeper connection between PP and Cosmology.

LHC discoveries are not an easy thing to be made. However the possible discoveries have such a revolutionary potential that the LHC constitutes a most important opportunity for the scientific community. The announcement of revolutionary physics results will take several years, as they will be the result of very careful analyses.

MEXICAN PARTICIPATION IN CMS

Several Mexican institutions participate in the experiment: the Centro de Investigación y Estudios Avanzados del Instituo Politécnico Nacional (CINVESTAV-IPN), the Benemérita Universidad Nacional Autónoma de Puebla (BUAP), the Universidad de Guanajuato, the Universidad Iberoamericana, the Universidad Michoacana de San Nicolás de Hidalgo (UMSNH), and the Universidad Autónoma de San Luis Potosí. Twelve researchers from these institutions participate in CMS. One researcher from the U. Guanajuato has already collaborated with the CIEMAT-Madrid CMS group in the test of the readout electronics and optic-fiber communication system for the Drift Chambers (figure 8 and 9), a crucial CMS system used for muon tracking and momentum measurement. The participants from the U. Guanajuato, as well as the other Mexican collaborators are preparing to participate in the running of the experiment during the coming years, and in the data processing and analysis tasks. The participation of scientists from Mexican institutions in CMS opens the doors for students from Mexican institutions, from graduate and undergraduate programs from scientific and engineering careers to participate in this unique XXI century enterprise. Students from the University of Guanajuato and from other institutions in the country are welcome to join the experiment. The Consejo Nacional de Ciencia y Tecnología (CONACYT)

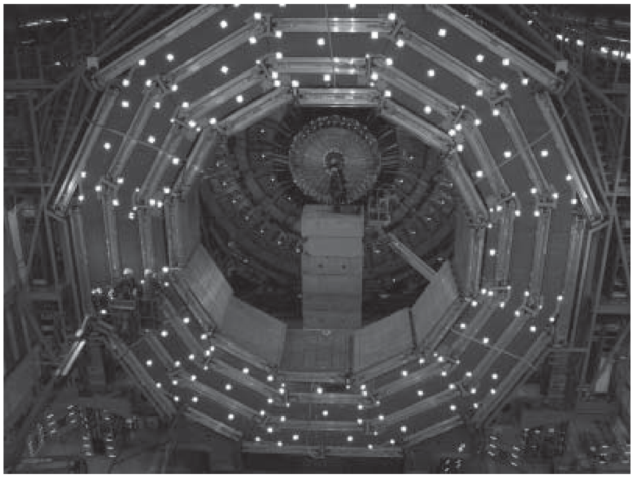

Figure 8. The CMS DT muon chambers and the iron yoke (red).

Figure 9. FPGA-based card for the readout of the DT chambers.

México has recently signed agreements with CERN (figure 10) and is sponsoring the Mexican participation in the CMS experiment.

Figure 10. Professor Jose Antonio de la Peña Mena (right), CONACYT Deputy Director, and Mr. Robert Aymar (left), former General Director of CERN.

ACKNOWLEDGEMENTS

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