
An abstract graphic featuring a green grid pattern that tapers towards the top. Overlaid on this grid are several thick, orange, curved lines that radiate from a central point at the top, resembling a stylized tree or a network of connections. The overall color palette is muted greens and oranges on a light background.

MIT at the Large Hadron Collider— Illuminating the High-Energy Frontier



Gunther Roland and Markus Klute



Over the last few decades, teams of physicists and engineers all over the globe have worked on the components for one of the most complex machines ever built: the Large Hadron Collider (LHC) at the CERN laboratory in Geneva, Switzerland. Collaborations of thousands of scientists have assembled the giant particle detectors used to examine collisions of protons and nuclei at energies never before achieved in a laboratory. After initial tests proved successful in late 2009, the LHC physics program was launched in March 2010. Now the race is on to fulfill the LHC's paradoxical mission: to complete the Standard Model of particle physics by detecting its last missing piece, the Higgs boson, and to discover the building blocks of a more complete theory of nature to finally replace the Standard Model. The MIT team working on the Compact Muon Solenoid (CMS) experiment at the LHC stands at the forefront of this new era of particle and nuclear physics.

The High Energy Frontier

Our current understanding of the fundamental interactions of nature is encapsulated in the Standard Model of particle physics. In this theory, the multitude of subatomic particles is explained in terms of just two kinds of basic building blocks: *QUARKS*, which form protons and neutrons, and *LEPTONS*, including the electron and its heavier cousins. From the three basic interactions described by the Standard Model—the strong, electroweak and gravitational forces—arise much of our understanding of the world around us, from the formation of matter in the early universe, to the energy production in the Sun, and the stability of atoms and

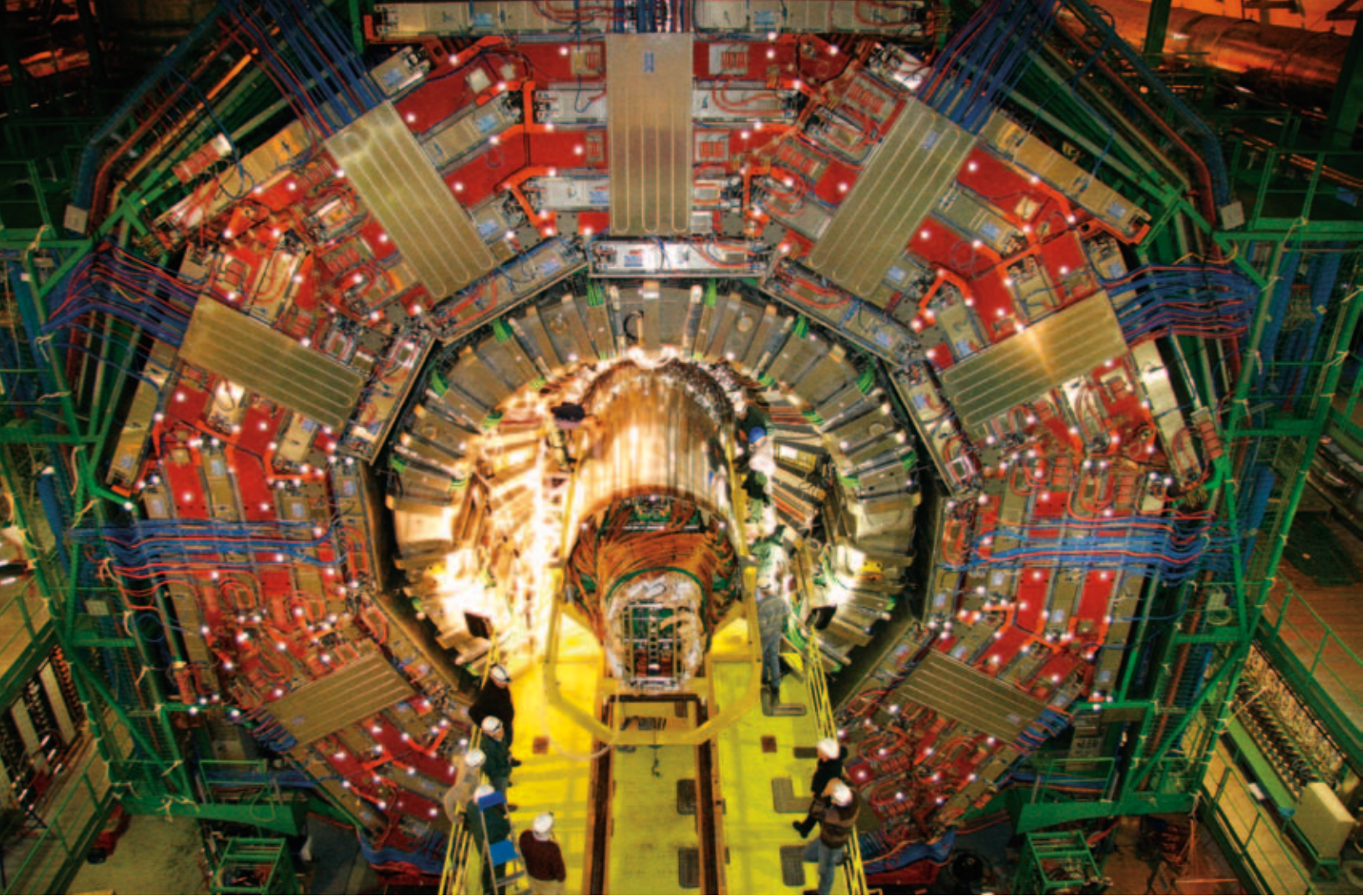


FIGURE 1

A photograph of the interior, central part of the CMS detector, before the experiment was closed for taking data. Shown are the inner tracking detector, the calorimeters, the superconducting magnet and several layers of muon detectors.

molecules. Even the emergence of the mass of elementary particles is explained in the Standard Model, where particles like quarks or electrons gain their mass from interactions with the so-called Higgs field. For several decades, the quantitative predictions of the Standard Model have withstood rigorous tests at particle accelerators and all particles predicted by the Standard Model have been discovered—with the exception of the Higgs boson, which has eluded detection for half a century after its existence was first predicted.

Previous accelerator measurements and indirect methods have allowed us to constrain the properties of the Higgs boson. Its mass is known to be between 120 and 200 times that of a proton. To finally detect the Higgs boson, the LHC will collide protons with greater energy than any machine has before: 7 trillion electron volt (TeV). This is equivalent to the kinetic energy of a speeding fruit fly, packed into a single elementary particle.

The LHC will also collide lead nuclei at a higher energy than any previous accelerator. Using the same detectors and analysis techniques developed for the proton collisions, the heavy-ion program will seek answers to a very different question. In collisions of two lead nuclei, a small region of extremely hot matter, called the Quark-Gluon Plasma (QGP), is created. Understanding the QGP may

teach us about the universal properties of strongly coupled matter, a topic that is of intense interest in many areas of physics, from condensed matter and atomic physics to string theory.

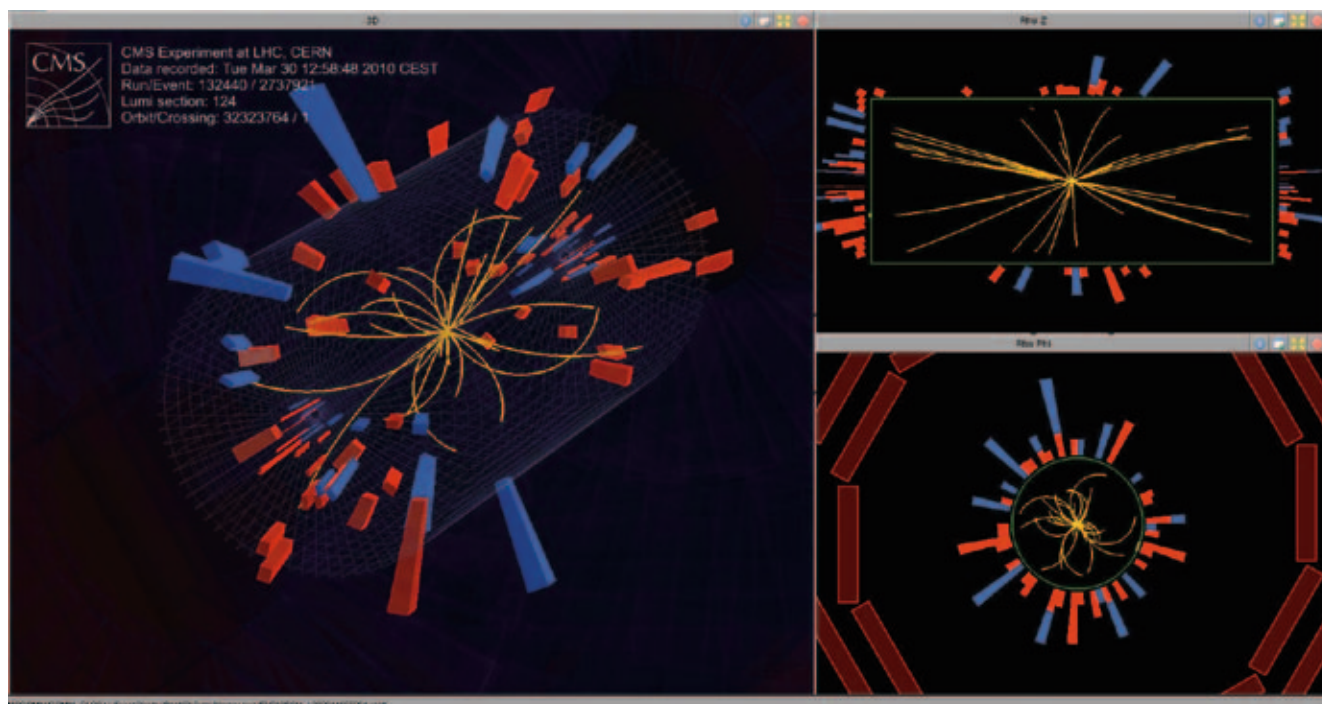
The Largest Experiment Ever Built

The LHC is located about 300 feet underground in a tunnel with a 17-mile circumference, straddling the French–Swiss border outside Geneva. The LHC tunnel is instrumented with more than a thousand 15-meter long superconducting magnets that guide counter-circulating beams of protons or heavy ions inside vacuum pipes. The LHC magnet system is operated at 1.9K, requiring liquid helium cooling and making it the largest cryogenic facility in the world. The superconducting bending magnets are one of the many technological marvels of the LHC. The maximum field they can achieve is 8 Tesla, corresponding to an energy of 10 billion Joule stored in the magnets—the equivalent of 2.4 tons of TNT! The LHC design foresees a proton beam current of 0.53 Ampere, giving the circulating beam a kinetic energy of 700 million Joule, the same as that of a Boeing 767 jet at takeoff. Utmost care is necessary to maintain precise control of the beam to prevent damage to magnets and detectors. The detectors used to examine collisions are precisely positioned at the four different interaction regions around the ring where the two beams collide, recording collisions every 25ns, or 40 million times per second.

The MIT team is part of the collaboration operating the CMS detector at LHC at one of the interaction regions. Upon collision, the constituents of the two protons involved interact with each other, producing new particles out of the

FIGURE 2

This event display shows the detector signals recorded for a collision of protons at 7 TeV. The blue and red bars indicate the energy detected in the calorimeters, while the yellow lines show the trajectories of charged particles reconstructed using the silicon tracking detector.



protons' kinetic energy. Some of the produced particles are stable enough, or at least sufficiently long-lived, to traverse the detector before decaying. Others, however, including many of the most sought-after particles, decay nearly instantaneously, and only the stable particles at the end of their decay chain can be identified through their interaction with detector material. The general strategy, then, is to measure the position, energy and momentum of all the stable particles and identify their type. From this information we work backwards to reconstruct the nature of the underlying collision.

The detection of stable particles in CMS is based on two techniques. For particles carrying electric charge, their trajectory in a strong magnetic field is determined by tracking detectors, allowing a determination of their momentum and charge sign. Secondly, the energy of all particles is determined by a calorimeter, a device in which particles come to rest through interactions with the detector material. In CMS, a 3.8 Tesla superconducting magnet provides the magnetic field (it's the largest superconducting solenoid in the world), and layers of instrumented silicon sensors measure the positions and trajectories of charged particles. The MIT team, led by Prof. Steven Nahn, contributed to the commissioning and operation of this, the world's largest silicon detector.

One of the biggest challenges faced by Nahn's team is the enormous rate of collisions at the LHC. Out of the 40 million events occurring every second, only a few hundred can be stored permanently. A dedicated trigger system is charged with deciding which 0.001% of all collisions are most likely to contain "interesting physics," such as a potential candidate for a Higgs boson decay. The trigger decision is split between a "Level-1" trigger, installed underground next to the detector, and a huge computer farm of more than 10,000 processors installed above ground, called the High Level Trigger. The MIT groups led by Professors Boleslaw Wyslouch and Christoph Paus have been involved in the development, integration and commissioning of the so-called "data to surface system," which is responsible for the data traffic from the CMS detector to the high level trigger computing farm. Professors Gunther Roland and Boleslaw Wyslouch have led the effort to expand the computing farm for heavy ion collisions and Prof. Markus Klute designed the mass storage system. The full system is capable of recording data at speeds of up to 2 GB/s while simultaneously transferring almost 1 GB/s for offline processing. At this rate, it would take the system just one-fifth of a second to transfer the text of the *Encyclopedia Britannica*.

At CERN, the data undergoes a first pass of reconstruction in the Tier-0 computing system and is then transmitted to seven globally distributed Tier-1 computing centers for long-term storage. From there the reconstructed data is further disseminated to almost 50 Tier-2 centers worldwide, where more than 2,000 CMS physicists can perform their analyses to reveal the few events containing signatures of new phenomena. All in all, CMS will produce about 10 Peta-bytes of data each year—the equivalent of two million DVDs! The MIT group led by Klute is responsible for the handling and processing of all CMS data. Under

the leadership of Wyslouch, MIT operates a Tier-2 computing center at MIT's Bates Linear Accelerator Center in Middleton, MA. The new High Performance Computing Center is fully operational and is designed to host all of MIT's CMS computing resources in the coming years.

Hunting for Higgs

In one out of ten billion proton-proton collisions at the LHC, scientists hope to find traces of Higgs bosons, which could lead to a discovery of the particle. Before explaining how a Higgs boson signature might manifest itself within the CMS detector, let's step back and discuss why the quest for the Higgs boson is of such importance.

Since the time of the ancient Greeks, man has sought to understand nature's fundamental building blocks. Our long journey has finally brought us to a point where we understand to a large degree what those fundamental blocks are. Yet many important details are still lacking.

A fundamental particle is an entity that in and of itself is not composed of anything more basic. Scientists discovered the first fundamental particle, the electron, during the 19th century; since that time we have discovered many more particles, most of which are composed of other, even smaller constituents. The Standard Model of particle physics, a theory in which the collective knowledge of particle physics research in recent decades is combined, was developed in the 1960s. It describes our understanding of those fundamental building blocks of nature and of the interactions between them. It distinguishes between matter particles—the so-called **FERMIONS**— and force carrier particles called **BOSONS**, which mediate forces between the fermions. Observations show that the fermions are grouped into three families which differ in only one property, their particle masses.

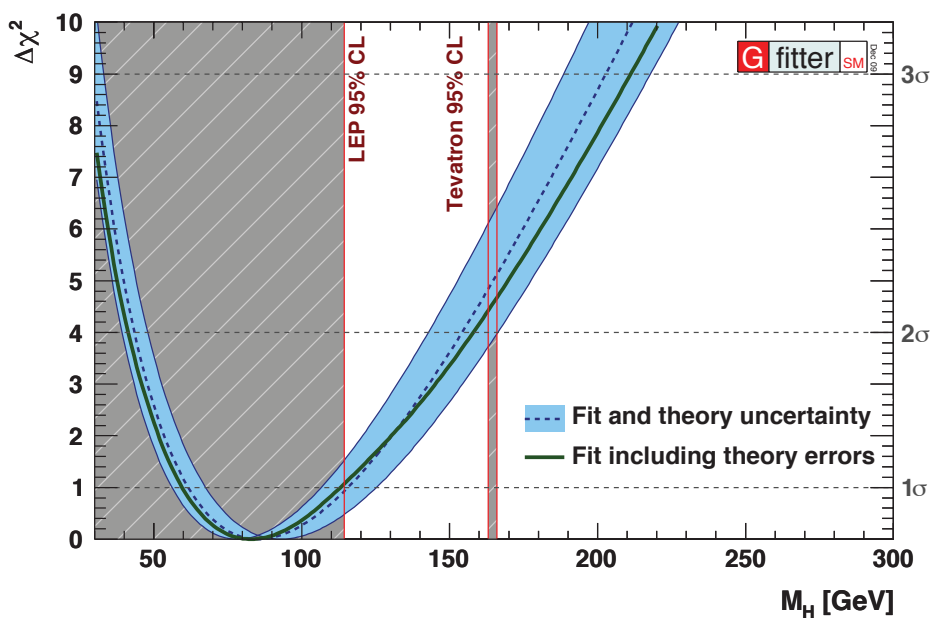


FIGURE 3

This graph summarizes our present knowledge of the mass of the Higgs boson. The blue band shows that indirect methods favor a Higgs mass of 85 GeV and disfavor a heavy Higgs boson above 200 GeV. Higgs masses in the grey regions below 114 GeV and between 162 and 166 GeV have been ruled out by previous experiments, making the region between 114 and 162 and from 166 to 200 GeV the most promising hunting ground for the Higgs boson at the LHC.

The underlying equations of the Standard Model do not include the observed masses for elementary particles directly. In fact, naively adding particle masses destroys the fundamental symmetry principles upon which the theory is based. Instead, the Standard Model proposes a particular mechanism to give rise to the particle masses, the Higgs mechanism, which generates masses for bosons and fermions and also leads to a new particle, the Higgs boson.

Theoretical calculations made using the Standard Model closely match the known experimental data, but are only valid in the presence of the Higgs field. Without this missing ingredient the calculations yield infinite results, yet despite decades of experimental searches, the Higgs boson has not been observed. However, the consistency of the Standard Model calculations and data allows indirect constraints on the mass of the Higgs particle and a precise calculation of the rate with which it should be produced for a given value of its mass. These constraints suggest that the Higgs boson should finally be within physicists' reach at the LHC experiments.

How can we understand the concept of elementary particle masses? Since only particles without mass move at the speed of light in a vacuum, one could define a particle with mass as a particle that moves slower than the speed of light in a vacuum. When we observe the massless photons passing through a medium like water, they do, in fact, travel at lower speeds and appear massive. Their progress is slowed down by interaction with the medium.

Using this analogy, the Higgs mechanism proposes that the vacuum itself is filled with a "medium"—the Higgs field—which interacts with particles passing through anywhere in the universe. The stronger the interaction, the slower the particles move. Mass in this model is no longer a property of the particle, but a result of its interaction with the Higgs field. As the interaction of a particle with the Higgs field increases, so does its apparent mass.

The Higgs boson itself can be understood as an excitation of this ubiquitous Higgs field. The excitation can be caused by a massive particle traveling through the field. The larger the mass of the particle, or equivalently, its coupling to the Higgs field, the greater the likelihood of creating and observing the Higgs boson.

Yet, creating the experimental conditions in which the Higgs boson can be produced and observed is extremely difficult. It requires very powerful particle collisions and sensitive detectors to record the results of the collisions. The collisions must provide sufficient energy to produce very massive particles, which then have a small likelihood of creating a Higgs boson. Once the Higgs boson is produced, it will decay almost immediately. Its lifetime of only 10^{-22} seconds is barely enough for the Higgs boson to travel the length of an atomic nucleus at the speed of light. True to its nature, the Higgs boson preferentially decays into the most massive fundamental particles lighter than itself.

The experimental challenge is to identify the signature of the Higgs boson decay products within the particle detector. We aim to reconstruct the Higgs boson using both the nature of the decay products and their kinematical information. As the Higgs boson is produced very rarely, the efficiency of the trigger mentioned before is of great importance. This task is further complicated by the presence of other

processes yielding similar signatures that do not stem from Higgs boson decays. The challenge can be compared to finding not the proverbial needle in a haystack, but rather one distinct piece of hay.

Previous experiments such as those at LEP (Large Electron-Positron collider), which operated in the same tunnel used today by the LHC, and ongoing experiments at the Tevatron at the Fermi National Accelerator Laboratory in the U.S., have conducted searches for the Higgs boson without success. The LHC experiments are more promising because they produce larger collision rates at energies up to four times greater than the largest collision energies previously achieved. Thus the LHC will produce more massive particles to excite the Higgs field and produce Higgs bosons.

The MIT team is certain to find the Higgs boson if the predictions of the Standard Model are truly realized in nature. It will be even more exciting if the LHC experiments fail to discover the Higgs boson and thus reveal the first cracks in the Standard Model. The data will be scrutinized for evidence of supersymmetry, the nature of dark matter observed in galaxies, extra dimensions proposed by string theory, and even more exotic models. In fact, we have already found clues as to why matter dominates over anti-matter in the universe we live in.

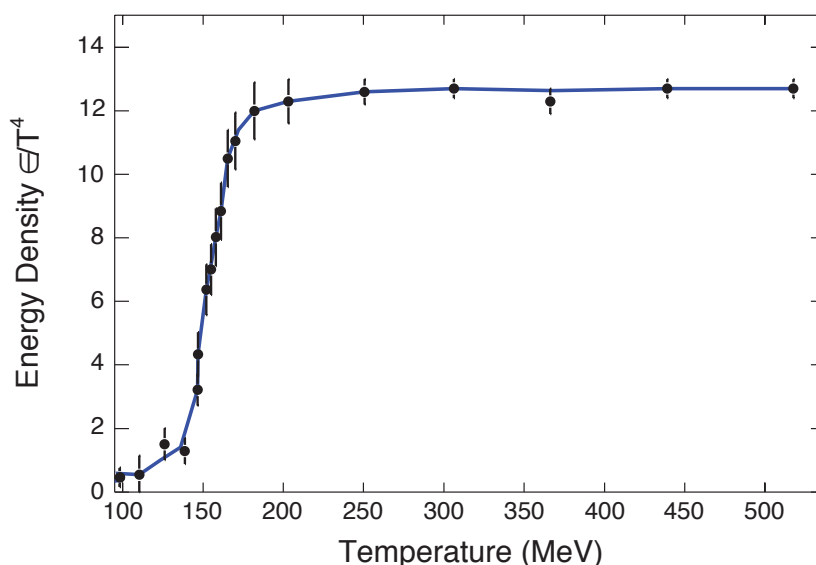
The Hottest Matter in the Universe

For one month each year, the LHC will interrupt the search for the Higgs boson to provide the detectors with collisions of lead nuclei. The collision rates for the lead program will be only 1/100000th of those for protons, so the potential for discovery of rare new particles or interactions is much smaller. What do we hope to find in these collisions? The motivation can be found in a quote by Nobel Laureate and MIT Herman Feshbach Professor of Physics Frank Wilczek, “Our equations know more than we do,” which illustrates one of the beautiful properties of physical laws. Even if the fundamental equations describing the basic interactions in nature are known, much work remains to uncover the complex phenomena hidden in the mathematical description of these interactions. This is particularly true for our theory of the strong interaction, Quantum Chromodynamics (QCD). Following the discovery of point-like constituents in the proton (for which Professors Jerome Friedman and Henry Kendall from MIT and Richard Taylor from the Stanford Linear Accelerator were awarded the Nobel Prize), QCD was formulated in the early 1970s. It describes the forces between point-like particles called quarks, which interact through the exchange of force carriers called gluons. Combinations of three quarks form the familiar protons and neutrons, the building blocks (with electrons) of the visible matter in the universe. Predictions of QCD have been tested with high precision at particle accelerators.

Among the theories describing the fundamental forces of nature, QCD has the unique property that the basic entities in its equations, the quarks and gluons, have never been observed as free particles in nature. Under normal conditions, quarks and gluons appear to be forever confined inside composite particles like protons and

FIGURE 4

This graph shows the result of a Lattice QCD calculation by Frithjof Karsch and collaborators, plotting the energy density of matter versus its temperature. At a temperature of 150 MeV, corresponding to several trillion degrees Kelvin, the energy density jumps rapidly. This is a sign of the predicted phase transition to the Quark-Gluon Plasma, where hadrons melt into quarks and gluons.



neutrons. The equations of QCD are notoriously difficult to solve. However, using powerful computers, like the “Blue Gene” supercomputer operated at MIT, it has been predicted that at extremely high temperatures, protons and neutrons should dissolve to form a new state called the Quark-Gluon Plasma (QGP). This transition from normal matter to the Quark-Gluon Plasma is expected for temperatures of about 10^{13} degrees K, or about a million times hotter than the center of the sun. Such temperatures prevailed in the first fraction of a second in the universe after the Big Bang, but cannot be found anywhere in the present-day universe.

Experimentally, the only possible approach to creating the temperatures necessary for the formation of the QGP in the laboratory are collisions of heavy ions, such as gold or lead, at speeds approaching the speed of light. In such collisions, most of the kinetic energy of the nuclei is released and transformed into a tiny region of very hot matter. This could elucidate the state of the universe after the Big Bang, and help unravel some of the secrets hidden in the equations of QCD. Heavy-ion collisions have been studied for the past 20 years at less powerful accelerators. A major step forward was achieved in 2000 at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven Laboratory. One of the four experiments at RHIC was PHOBOS, initiated and led by Prof. Wit Busza. These experiments and their interpretation are very challenging: the QGP, after it is produced in the collision, rapidly cools down and decays back into a normal state of matter, thus the experiments have to infer its transient existence from its decay products. Complex analyses are necessary to extract the underlying properties of the QGP from the observed number, mass and momentum distribution and emission direction of these particles. The LHC will provide higher collision energies than previous accelerators; this will allow higher temperatures and lifetimes for the QGP than have been achieved thus far.

One of the most surprising effects discovered in lower energy heavy-ion collisions is “elliptic flow.” It was observed that the decay particles produced in the

collisions are not emitted randomly in all directions, but follow a distinct pattern, where their density is enhanced along some axis and reduced along a perpendicular axis. The emission pattern was found to closely reflect the initial overlap geometry of the two colliding nuclei. This is only possible if the initial state, the QGP, evolves in a nearly frictionless manner. More precisely, it requires a very low shear-viscosity to entropy-density ratio, η/s , such that the geometrical information about the flow is not washed out.

Using hydrodynamic calculations to describe the observed effect, it was possible to determine an upper limit on the viscosity of the QGP of $\eta/s < 0.4$. This was much lower than expected from calculations treating the QGP as a gas of quarks and gluons, suggesting that the QGP behaves instead like a near-perfect liquid. In relative terms, the QGP is a much “better” liquid than water or even super-fluid helium. In fact, the shear viscosity of the QGP approaches a universal lower bound of $\eta/s > 1/4\pi$, that was postulated for strongly coupled systems using methods from string theory. The matter produced in heavy-ion collisions may therefore be part of a universal family of strongly coupled systems, such as those studied using ultracold atoms (another surprising application area for string theory). It is fascinating to note that both the hottest and coldest matter produced in the laboratory may become the first testing grounds for the ideas of string theory.

Lead-Lead Collisions at the LHC

In string theory calculations, the properties of the strongly coupled system can be varied by changing the coupling constant governing its interaction. This is much harder to achieve in the heavy-ion collision experiments, where the effective coupling constant is set by nature. The only feasible approach is to vary the collision energy. This is part of the promise of the LHC. Compared to RHIC, the LHC collision energy for heavy nuclei is 20 to 28 times higher. The larger collision energy will produce a hotter initial QGP state, allowing for a longer-lived QGP. It is worth noting that RHIC provided a 10 times higher collision energy than earlier machines, and that this step gave rise to a multitude of new phenomena not observed at lower energies.

RHIC provided another important lesson. Many theoretical approaches to understanding the QGP properties in QCD rely on the interaction of a high momentum “probe” particle with the hot QGP medium of quarks and gluons. At RHIC energies, very few “probe” particles exist with momenta sufficiently

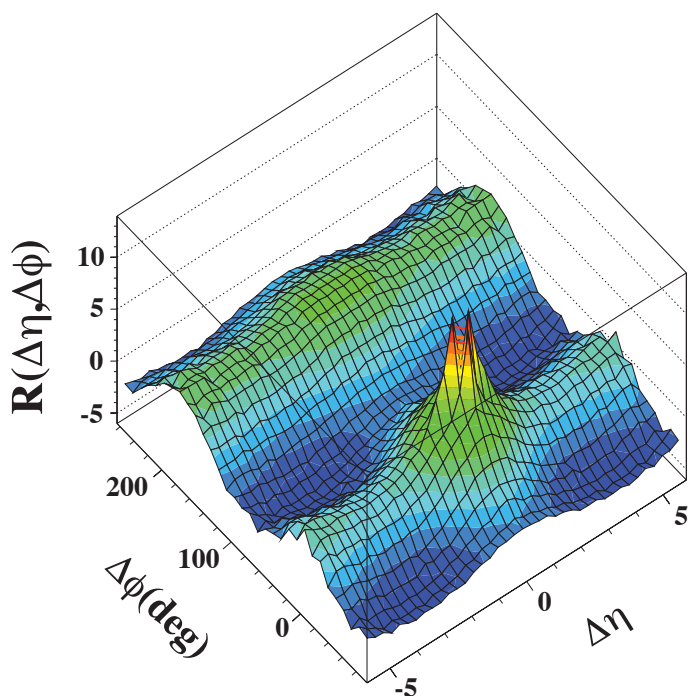


FIGURE 5

This figure shows two particle correlations along the beam axis ($\Delta\eta$) and the azimuthal angle around the beam axis ($\Delta\phi$), measured for collisions of gold nuclei by the PHOBOS experiment. The sinusoidal modulation along the ($\Delta\phi$) direction is a direct sign of the hydrodynamic expansion of the hot and dense matter produced in these collisions.

higher than those of the typical particles in the QGP, making a precise theoretical treatment exceedingly difficult. However, the rate of high momentum probe particles grows very quickly with increasing collision energy. At the LHC, particles with momenta of 150-200 GeV/c become accessible, corresponding to about 200 times the expected thermal energy of an average particle in the QGP medium. This clearer separation between the plasma and its probe will allow a much more precise theoretical treatment of their interactions, and therefore provide a more direct connection between experimental results and the fundamental properties of QCD systems.

This emphasis on high momentum probes has a very important consequence: the techniques for detecting high momentum probes in heavy-ion and proton-proton collisions are basically identical, turning a general purpose proton-proton detector like CMS into an ideal device to study the most important aspects of QGP physics. This was realized by Professors Busza, Wyslouch and Roland shortly after the first RHIC results appeared. Since then, the MIT group has led the preparations for CMS heavy-ion studies over the last decade. The challenges for these analyses are daunting. At the LHC, in a single collision of two lead ions, more than 20,000 particles, such as pions, protons and kaons, will be produced. Yet in simulation studies, CMS has shown to be well-suited to these very high particle densities. The MIT group and their collaborators are busily preparing for the first collisions of lead ions at the LHC in the fall of 2010. Although the collision rate for these heavy-ions will be low initially, the first data will allow us to determine the properties of the QGP liquid at higher temperatures and to explore the exciting universality of strongly coupled systems and their connections to string theory.

Answers Arriving Soon

In the months since the LHC physics operations began, the accelerator team has worked systematically to increase the rate of proton-proton collisions on the long road to the machine's performance goals, which are expected to take several years to reach. Yet, already CMS and the other experiments are publishing the results of first measurements and calibrating models and predictions for the new conditions in the LHC energy range. In fact, the very first CMS paper published in January 2010 showed the fruitful collaboration between the proton-proton and heavy-ion analysis teams in CMS: using techniques developed for the analysis of lead-lead collisions, MIT physicists were co-leaders for the first CMS paper on proton-proton collision data, which measured the increase in the number of produced particles with collision energy. Many other analyses are now underway in CMS to precisely characterize the known parts of the Standard Model. These analyses will systematically establish the finely tuned knowledge of detector, accelerator and theory necessary to finally either detect the Higgs Boson, or rule out its existence in the expected form, and thereby force our hands in reaching for the next level in

understanding the fundamental interactions of nature. The answers found at the LHC will set the agenda for future generations of particle physics experiments. The MIT team stands at the very forefront of exploration. Our discoveries there will open doors to the new era of high energy physics.

GUNTHER ROLAND joined the Heavy Ion Group in the MIT Department of Physics as an Assistant Professor of Physics in January 2000 from CERN, where he was a Scientific Associate. In July 2004, he was promoted to Associate Professor of Physics and in 2007 to Associate Professor of Physics with tenure. He received his Ph.D. from the Institut für Kernphysik, Frankfurt, Germany, in 1993.

MARKUS KLUTE joined the MIT Physics Department in July 2009 as an Assistant Professor. He received his Diploma and Ph.D. in 2004 from Rheinische Friedrich-Wilhelms University, Bonn, Germany, with research on the OPAL, ATLAS and DZero experiments. After earning his Ph.D., Klute joined MIT as a postdoctoral associate and later as a research scientist, working on the CDF and CMS experiments. In 2007, he accepted a position as an Associate Professor with tenure at Goerg-August University in Goettingen, Germany, where he started a research group on the ATLAS experiment before returning to MIT.