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research article

A Summer with the Large Hadron Collider: the Search for Fundamental Physics

—**Austin Purves** (Edited by Aniela Pietrasz and Matthew Kingston)

For centuries people have pushed the boundaries of observational science on multiple fronts. Our ability to peer ever more deeply into the world around us has helped us to understand it: telescopes and accurate measurement of planetary motion helped us to break free from the earth–centered model of the solar system; increasingly powerful microscopes allowed us to see how our bodies work as a collection of tiny cells; particle colliders allowed us to better understand the structure of atoms and the interactions of subatomic particles.

The author backed by the Jet d'Eau, a 459 foot vertical fountain of water in Lake Geneva.

Construction of the latest and most powerful particle collider, the Large Hadron Collider (LHC), was completed in fall 2008 at Conseil Européen pour la Recherche Nucléaire (CERN), the world's largest particle physics research center, located near Geneva, Switzerland. CERN began in the 1950s as a collaboration between twelve European states and has grown into a highly international effort involving states outside the European Union, including the United States. It currently runs under the direction of Rolf–Dieter Heuer. The construction of the LHC has been subject to delay over the years. The most recent delay is due to an electrical failure on September 19th, 2008, and the current schedule foresees the LHC going online at the end of September 2009. The LHC promises to bring us closer to the smallest constituents of our universe, potentially revealing things about its origins.

I was fortunate enough to work on the LHC during the summer of 2008. I returned with not only a better understanding of how particle colliders work and the great challenges of building a collider of such unprecedented size, but also a greater appreciation for what this collider means to humanity and our understanding of the universe. By elaborating on the scientific implications of the LHC and dispelling some myths, I aim to spread understanding of the LHC's significance from an undergraduate scientist's perspective.

The Collider

The LHC is one of the largest scientific instruments ever built. The gigantic circular accelerator is 27 kilometers in circumference and buried hundreds of meters under the ground, straddling the border between Switzerland and France. (See Figure 1) It will smash protons, which belong to a certain class of particles called hadrons, into each other at higher velocities than have ever before been achieved. This happens by sending two beams of protons around the circular racetrack in opposite directions. (See Figure 2) At specific "interaction points," the two beams will cross each other and collisions will occur. (See Figure 3) This is where all the exciting physics happens.

When two of these protons collide at high velocity, an array of subatomic particles will be created in order to dissipate all the energy from their velocity; the more energy in the collision, the greater the number of particles that will be created. Also, heavier particles require more energy to be created, so with higher collision energy (higher velocity of the colliding hadrons) than any previous particle collider, scientists should be able to see heavy particles that they've never seen before. Specifically, the LHC will be able to collide protons with an energy of seven terra–electron–volts (or 7 TeV, or 7,000,000,000,000 eV) so that each collision between two hadrons will have up to 14 TeV. An electron–volt (eV) is a unit of energy (like the calorie and the joule) equal to the amount of energy gained by an electron when it passes through a one–volt electric potential. For example, in a flashlight powered by two 1.5 volt AA batteries, an electron which passes through the batteries will gain 3 electron–volts of energy, which are then transferred to the light bulb and released as light. With 7 TeV in each hadron, the collective energy of the LHC's circulating hadrons is roughly equal to the amount of kinetic energy in the USS Ronald Reagan, a nuclearpowered aircraft carrier, when it is traveling at 5.6 knots. (1)

Figure 1. Arial photo of the LHC. In the background the Geneva airport is visible, as well as Lac Léman (Lake Geneva) and the Swiss Alps. Geneva is located at the right–hand end of the lake. Image courtesy of LHC Machine Outreach, http://lhc–machine–outreach.web.cern.ch.

There are four interaction points around the collider, and surrounding each of these points is one of the LHC's four main detectors: LHCb, which will study a specific particle called the "beauty quark"; ALICE, which will study the collisions of lead ions; ATLAS and CMS, both of which are general purpose detectors. When two protons collide at an interaction point, many particles come streaming out with a considerable amount of energy; these "free" particles (particles not bound in an atom) then interact with a particle detector.

Figure 2. The LHC tunnel is large enough for a person to stand up inside. Two hadron beams will circulate in opposite directions inside the blue tube in the center of the tunnel. Image courtesy of LHC Machine Outreach, http://lhc-machine-outreach.web.cern.ch.

Particle detection can happen in a variety of ways. In general, the free particle will interact with electrons, and a small electrical current will be created. This current can then be measured, telling us that a free particle has just hit a detector. Particles that are electrically charged, such as the electron (negatively charged) and the proton (positively charged), are open to another kind of observation. Electrically charged particles traveling in a magnetic field will follow a curved path, and by analyzing the curve of this path we can gather information about the electric charge, velocity, and mass of a particle. Measuring a particle's mass and electric charge is an important part of identifying what kind of particle it is. Incidentally, this is also how the positively charged protons are made to travel in the large circular path around the collider: by placing them in a strong magnetic field. The four main LHC detectors incorporate a combination of different types of detectors to deal with the variety of particles that must be detected. One particular sub–detector of the ATLAS detector was the focus of my work. (Figure 4)

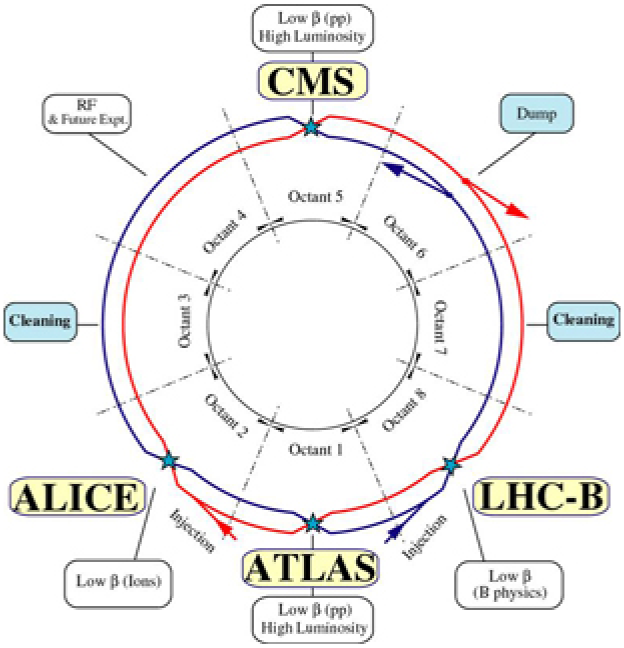

Figure 3. Schematic of the LHC. The red line represents the clockwise moving beam, and the blue represents the counterclockwise moving beam. The blue stars mark interaction points where the beams intersect and collisions occur, and also the locations of the four main detectors. Also marked is the site of the beam dump, where the beam can be safely diverted out of the collider ring into large blocks of graphite. Image courtesy of LHC Machine Outreach, http://lhc–machine–outreach.web.cern.ch.

My Work

I first became interested in working on the LHC in summer 2007 as a junior physics major at the University of New Hampshire. Going to CERN would allow me to learn more about how particle colliders work, and also to be part of this extremely high profile and historically important physics experiment. Fortunately, University of New Hampshire Professor Per Beglund, with whom I began working on theoretical research in fall 2007, once worked at CERN and was able to put me in touch with his colleague there, Dr. Hans Danielsson, who in turn connected me with Dr. Daniel Dobos, a physicist working on the LHC.

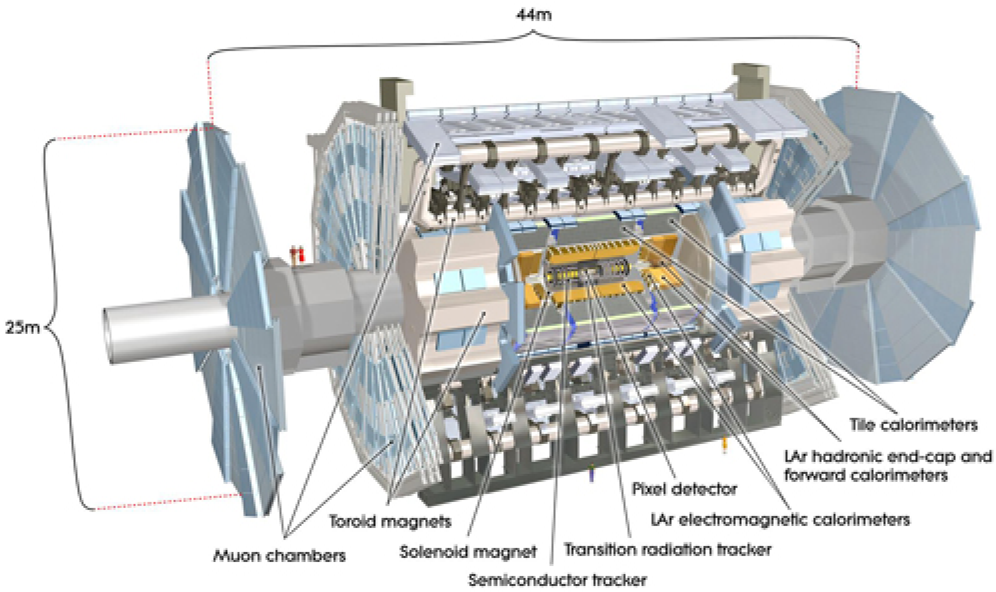

Figure 4. Computer generated diagram of the ATLAS detector showing sizes and labeling many of the various sub–detectors. People

included for scale. Particle beams will come in from the right and left sides and intersect at the center of the cylindrical detector. Image courtesy of the ATLAS Experiment at CERN, http://atlas.ch.

Dr. Dobos works on a specific sub–detector of the ATLAS detector called the Beam Conditions Monitor (BCM). The BCM's task is to monitor the focusing of the particle beams traveling in opposite directions through the ATLAS detector. If the beam becomes unfocused, sensitive parts of the ATLAS detector could be showered with high–energy hadrons, causing damage. With a monitoring system in place, if the beam starts to become dangerously unfocused, the BCM will detect this and trigger a beam dump. A beam dump will quickly redirect the beam of high energy hadrons into large blocks of graphite, which will absorb the energy from the beam. (2)

After arriving at CERN in summer 2008, I was free to choose what I would work on during the summer. Of my several options, I decided to work on two tasks for the BCM. One was the Detector Control System (DCS), with Dr. Ewa Stanecka mentoring me. The second project was offline data monitoring for the BCM, with Dr. Dobos mentoring me. I chose these projects because they were more directly related to the operation of the collider than the others, and because I enjoyed interacting with the people already connected with these projects.

Working on DCS involved designing a Graphical User Interface (GUI) that would run on a Windows desktop computer and facilitate control and monitoring of the BCM. I was working within a software package called PVSS (Prozessvisualisierungssoftware), which is meant for exactly this kind of task: creating graphical interface between a desktop computer and hardware. Since I was not the one who would ultimately be using these GUIs, and at times didn't even understand the inner workings of the hardware to be interfaced by them, I worked with frequent guidance from other scientists who understood the hardware and would be using these GUIs.

My work with offline data monitoring involved writing software that would take data from the BCM and create histograms (similar to a bar graph) that present the data in a readable format. Offline monitoring software reads data that has already been collected and stored; this is distinct from online data monitoring which reads data in real time as it comes from the detector. The detector produces data at a very high rate, so online monitoring software must run very quickly to keep up; offline monitoring software does not have this requirement.

I worked more independently writing this software than I did designing the GUI. My advisor explained to me what histograms were needed and told me the essential facts I needed to begin writing the software. Beyond that and some occasional advice when I had a question, I worked mostly on my own. In order to keep the format of the output from offline monitoring consistent with that from online monitoring software, I often referred to the online monitoring code being written by Lucie Gauthier, another summer student at CERN.

The Higgs Boson, Supersymmetry, and String Theory

No one is certain what the LHC will find when it goes online (hopefully in September 2009). Among the four main detectors there are sure to be many new discoveries, and at this point there has been much speculation about what we will see. One of the most anticipated discoveries is that of the Higgs boson. A boson is another type of subatomic particle, different from a hadron. The Higgs boson is a specific boson named after the physicist Peter Higgs, who, along with some colleagues, theorized its existence. (3) A Higgs boson has never been observed, but many physicists are anticipating its discovery when the LHC becomes fully active.

If the Higgs boson does exist, then mass is not something intrinsic to matter (or subatomic particles, which make up matter). Instead, it would be a particle's interaction with the Higgs boson that makes the particle behave as though it has mass. In this scenario, what is intrinsic to each particle is its propensity to interact with the Higgs boson. Heavier particles would interact more strongly with the Higgs boson, while mass–less particles like the photon would not interact with the Higgs boson at all. Following this theory, if Higgs bosons were to disappear, then mass as we know it would disappear also.

The Higgs boson is the particle sometimes called the “God particle.” I personally think this is a misnomer. The Higgs boson, if discovered, would explain the origin of mass throughout our universe. This would be a very important discovery, indeed, but does not represent some ultimate answer or provide an explanation of our universe and its origin. I feel that associating the particle with God probably overstates its significance.

Another highly anticipated discovery at the LHC is that of supersymmetry. In order to understand supersymmetry we must first understand the Pauli exclusion principle. The Pauli exclusion principle states that two identical particles (for example, two electrons, two protons, or two neutrons) cannot be in the same place at the same time. However, because not all particles obey the Pauli exclusion principle, we separate particles into two classes: fermions, which obey the Pauli exclusion principle, and bosons, which do not. Examples of fermions are the electron, proton, and neutron. Examples of bosons are the photon and the Higgs boson, if it exists. If supersymmetry exists, it means that all the different particles actually come in pairs of one fermion and one boson. The members of these pairs are called “superpartners.” For example, the electron, which is a fermion, would have a boson superpartner with some of the same properties, such as the same electric charge. As of yet, no one has observed any superpartners, so there is no empirical evidence for supersymmetry. However, there are theoretical reasons, many of them rooted in an idea called string theory, for believing that supersymmetry exists. If the LHC discovers a superpartner pair, it will have tremendous implications for physics.

One reason for the interest in supersymmetry is string theory, which hypothesizes that all particles are not particles at all, but tiny, vibrating strings. The different types of particles can all be understood as strings vibrating in different patterns; and the interactions of particles can be understood in terms of vibrating strings interacting with each other. The appeal of string theory is that it may, for the first time, provide a description of particles (or strings) and their interactions that is fully compatible with Einstein’s theory of general relativity. (The current theory of particles and their interactions is mathematically incompatible with general relativity.) (4) According to recent string theory research, the existence of supersymmetry would make it much easier to describe the universe using string theory. For this reason, physicists are anxious to see what the LHC can tell us about supersymmetry.

What It Means for Us

There are countless discoveries anticipated at the LHC aside from the ones I’ve mentioned, and no shortage of speculation about what we will find. I think the only thing we can be sure of is that the LHC results will be full of surprises. Activation of the LHC will be a major stepping stone in the next century of experimental physics, one that promises to bring us a deeper understanding of the universe at the most fundamental level.

Some physicists have expressed concern that the LHC could create a black hole that will swallow up the Earth. But we know that any harmful process that could be instigated by the LHC should already have been caused by cosmic particles. Cosmic particles are constantly hitting and passing through the Earth from outer space. Some of the particles are colliding with particles in the Earth at even higher energies than the LHC will achieve. So the LHC shouldn’t be able to do anything that cosmic particles haven’t already done.

I like to say that my work is a very small piece of a very large puzzle. Though a small piece, it is a necessary piece for the completion of the puzzle, and I am honored to have made a contribution to such a significant and historical project as the LHC.

I would like to thank my research mentor Per Berglund and CERN scientist Hans Danielsson, both of whom were instrumental in helping me secure this work. Thank you to Daniel Dobos for offering me the opportunity to work on the BCM, and Ewa Stanecka for mentoring me. I would also like to thank all the CERN scientists, staff, and students who helped me during the summer, and my friends and family for supporting me throughout the entire process.

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Author Bio

A native of Silver Spring, Maryland, ***Austin Purves*** *came to New Hampshire for the state’s natural beauty, the skiing, and the renown of the University’s Physics Department. A senior majoring in physics with a minor in mathematics, Austin is predisposed to the theoretical aspects of physics. With his mentor Per Berglund, he explores the nature of string theory by applying certain aspects of string theory to cosmological inflation, the brief, incredibly rapid expansion of the universe after the Big Bang. “People are often surprised to hear that my research can be conducted with only pen and paper,” he said, explaining how one goes about research that is purely theoretical. “Much research in theoretical physics is done with only a piece of chalk in one’s hand.” In addition to his involvement in the Physics Department, Austin also serves as the clarinet section leader in the University of New Hampshire’s Wildcat Marching Band. After graduating in May 2009, Austin plans to attend graduate school and earn his doctorate in physics. “I would love to be a physics professor concentrating on theoretical physics,” he says. “That would be my ideal.”*

Mentor Bio

Per Berglund *is an associate professor in the Physics Department at the University of New Hampshire. His research, supported by a CAREER award from the National Science Foundation, specializes in theoretical particle physics with a focus on string theory. At UNH since 2003, Dr.Berglund has taught numerous classes including an Honors course dedicated to the Big Bang Theory and graduate coursework in string theory. He first met Austin Purves in his 2005 Honors course, and they started working together in 2007 on an ongoing research project that uses the concept of the very early universe to assess ideas in string theory. Dr. Berglund also served as a mentor for Austin’s work at the Conseil Européen pour la Recherche Nucléaire (CERN). “Austin has done very well, both on the project we are working on and while at CERN, actively contributing to the success of the projects,” he said. Having assisted and collaborated with several undergraduates before Austin, Dr. Berglund considers the interaction with his students stimulating: “Working with the students has always been a very positive experience for me and, I believe, for the students as well.”*