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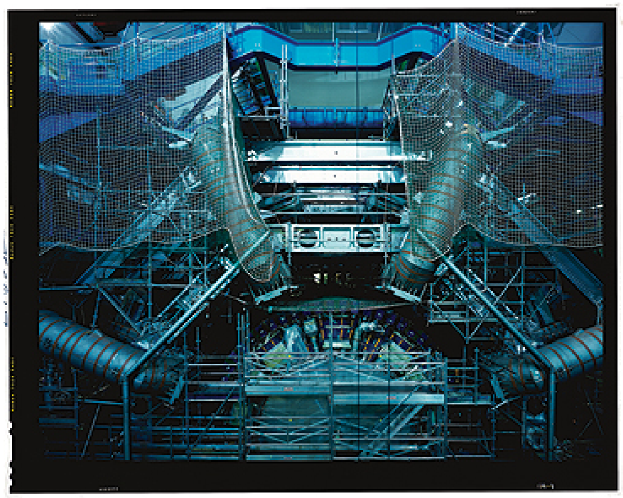
Physics & Math

Why a Large Hadron Collider?

Seed asks some of the greatest physicists alive what we hope to learn from the LHC.

by ***Edit Staff*** • Posted July 6, 2006 12:32 AM



View of the ATLAS detector in the experiment hall, roughly 100 meters underground. ATLAS is one of the five particle physics experiments at the Large Hadron Collider. *Credit: Guido Mocafico*

The Large Hadron Collider (LHC) currently under construction at CERN is the greatest basic science endeavor in history. Roughly half of the world's particle physicists, 7,000 individuals, make the Collider their workplace. This single-minded group of men and women hails from more than 80 countries. They represent almost every religion and ethnicity on Earth—embodying curiosity, cooperation, brilliance and ingenuity on the grandest scale.

The LHC is a circular tunnel 27 km around, bisected by the Franco-Swiss border. Over 100-billion protons will traverse its pathways at near-light speed, guided by some 9,300 superconducting magnets, each weighing several tons and chilled to temperatures colder than deep space. At four points in the tunnels, the counter-revolving protons are to smash into one another at a rate of nearly one *billion per second.*

At the crossing points, huge detectors are in place to register the tiny wisps of debris that emerge from each of the collisions. One of these instruments has enough iron to re-construct the Eiffel Tower; another is two-and-a-half times larger than the Parthenon and taller than the Colossus of Rhodes. Information from these subatomic traffic accidents will be sped around the globe on the largest computer grid in existence—the nervous system for all the brains that will struggle to make sense of the myriad data. All these superlatives exist for one reason: To understand the universe.

Seed *asked those with the greatest stake in discerning nature's wonders to share their hopes, questions and wildest fantasies for the LHC.*

Are There Other Dimensions?

The smashingly successful Standard Model of particle physics describes matter's most basic elements and the forces through which they interact. Physicists have tested its predictions to better than 1% precision. Yet despite its many successes, we know the Standard Model is not the whole story. If we apply the known principles of quantum mechanics and special relativity to compute what we expect masses to be, we find the result is 16 orders of magnitude bigger than measured values—so big that gravitational effects would be comparable to the strength of other particle forces. But, for the known particle masses, gravity is negligible when compared to other forces. To avoid this problem, the Standard Model relies on an enormous fudge—what we physicists call a "fine-tuning."

Since the 1970's particle physicists have been searching for a natural explanation for known particle masses and the weakness of gravity. But they have not succeeded in finding an elegant solution with only three dimensions of space. A universe with extra dimensions might provide an answer. Gravity could be extremely weak in our region of a higher-dimensional universe, but strong somewhere else.

The magnificent thing is that we know there should be an answer to the question of the weakness of gravity, and that it should be revealed at the LHC, whatever the explanation turns out to be. If it is warped extra dimensions, to cite just one possibility, the experimental evidence would be particles that travel in extra-dimensional space but reveal themselves in our three-dimensional experiments. And the signal will be spectacular. Experimenters think it could be one of the easiest new phenomena to produce and discover. But no matter what the explanation for the weakness of gravity turns out to be, the LHC is prepared. And we're eagerly waiting the answer.

—***Lisa Randall***, *Harvard University, author of* Warped Passages: Unveiling the Mysteries of the Universe's Hidden Dimensions

Why does the Universe Expand?

It will be more than 30 years since last we explored really new high-energy territory in physics. With our previous record-holding accelerator, we moved from fixed targets to head-on particle collisions, and had a four-fold increase in energy. The LHC will give us another near 10-fold boost, bringing us to energies where all theoretical fantasies are possible. This large step is effectively enhanced by a huge increase (about 100-fold!) in luminosity—the number of head-on collisions per second of protons with protons. In effect, the reach of the LHC is the largest incremental increase in observational power in history.

The intensely luminous LHC will surely help us to understand what has become one of the most profound puzzles in modern memory—the accelerated expansion of the universe. LHC is a shimmering example of humankind's age-old need to explore new frontiers. The long-simmering concern over the weakness of Einstein's gravity may well be confronted. However, what is for sure is that the LHC, with its awesome reach, will answer all of our current astro-particle problems and—if history is any guide—expose new truths undreamed of in our philosophies.

—***Leon Lederman***, *Nobel Prize winner, Fermi National Accelerator Laboratory*

How Many Universes?

Are the laws of physics the same everywhere in the universe? Or do we live in a diverse multiverse, with low-energy physics varying drastically from one place to another? Until recently, physicists believed that supersymmetry was responsible for the apparent fine-tunings in particle physics. If this is true, then signatures of supersymmetry are very likely to show up at LHC. However, there is now another popular alternative: the vast "landscape" of "environments" predicted by string theory. In this picture, the fine-tuning is explained by anthropic selection—the truism that we inhabit the kind of universe that is hospitable to life—and supersymmetry may be broken at a much higher scale, well beyond the reach of the LHC. If no trace of supersymmetry is found, this would be—necessarily indirect—evidence for the existence of the multiverse.

*—**Alexander Vilenkin**, director, Tufts Institute of Cosmolgy, Tufts University and author of* Many Worlds in One: The Search for Other Universes

What Is Dark Matter?

For over 50 years, CERN has been a wonderful example of European collaboration. It is now a true "world laboratory," destined to be the focal point of interesting particle physics for at least the next decade. I'm hoping that it will clarify the nature of the particles that constitute the "dark matter" in the universe.

*—**Sir Martin Rees**, Cambridge University, president of the Royal Society and Astronomer Royal*

How Is Symmetry Broken?

One of the big mysteries of physics is why the electromagnetic and weak interactions, which are two of the main elementary particle forces, are so different. We literally see electromagnetic effects with our eyes in the form of light. On the other hand, it takes sensitive modern equipment to detect and study the weak interactions. Yet the modern Standard Model says that at a fundamental level, these two forces are on an equal footing, described by very similar equations (Maxwell's equations for electromagnetism, the Yang-Mills equations for the weak interactions). The difference between these two forces only arises from a process of "symmetry breaking," whereby nature spontaneously picks one force over another—even though fundamentally they are equivalent. The LHC will tell us whether this notion is correct, and if so, how it works.

Understanding how the symmetry is broken is the key to understanding how the weak and electromagnetic interactions are unified in nature. This is believed to be an important step toward understanding a broader unification of the laws of nature.

*—**Edward Witten**, Fields Medal winner, Institute for Advanced Study, Princeton University*

Why 26?

Our theory of particle physics has 26 pure numbers in it. Why do they have these particular values? How did the universe begin? Or did it?

—***Max Tegmark****, MIT, scientific director, Foun-dational Questions Institute*

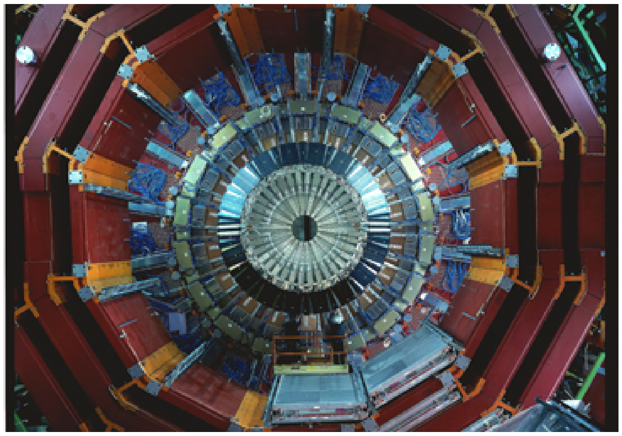
Is The Universe Anthropic?

I see only two possible outcomes of the LHC project—either there will be low energy supersymmetry, or there won't. If there isn't, I would expect that the minimal Standard Model will prevail. In either case, the Higgs particle—a still-hypothetical particle postulated in the 1960's—will be shown to exist, thus explaining the fundamental particles' masses.

The main conceptual issue is the one having to do with fine-tuning. Conventional wisdom that has prevailed since the early 80's is that the pure Standard Model requires ultra-fine-tuning to keep the masses of elementary particles, such as quarks and electrons, from being sucked up to the higher energy unification or Planck scales. (It's called the "gauge hierarchy" problem.) There have been several solutions proposed including technicolor and extra dimensions (really the same thing), but they don't look viable. Supersymmetry can prevent the gauge hierarchy disaster, which is indeed a disaster: Were it to have existed, it would certainly have precluded life as we know it.

Similar logic says that the cosmological constant should also be sucked up to some large scale, which would also have proved disastrous to life. At the present time, the only explanation for the size of the cosmological constant is the anthropic principle—the dreaded "A word" that means if the universe weren't as it is, we wouldn't be here to observe it. So for me, the big question is whether the gauge hierarchy fine-tuning is similar to the cosmological constant fine-tuning, or if it has a more conventional supersymmetric explanation. Either will be incredibly interesting.

—***Leonard Susskind****, Stanford University,*
author, The Cosmic Landscape: String Theory and the Illusion of Intelligent Design



CMS detector. Steered proton beams will collide in the middle of the CMS and the three other detectors. *Credit: Guido Mocafico*

What If We're All Wrong?

What terrifies theorists is that the LHC may discover nothing beyond the single neutral "Higgs" particle that is required by the standard electroweak theory. With no sign of supersymmetry or technicolor or anything unexpected, we would then have no clue to what happens at the much higher energies where gravitation becomes a strong force. We fervently hope for some complicated discoveries.

*—**Steven Weinberg**, Nobel Prize winner, University of Texas at Austin*

Why Do We Look?

There are many speculative ideas for possible discoveries at the LHC. These include indications of extra dimensions, black holes, strings, magnetic monopoles, etc.

I believe that all of these exist, and I would be thrilled to have experimental confirmation—but I am pessimistic about the prospects for finding them in the LHC's energy range. I suspect that the required energies for these effects would need to be at least a trillion times higher. I could be wrong. That's why it is important that these experiments be carried out.

*—**John Schwarz**, Dirac Medal winner, California Institute of Technology*

How Do Forces Unite?

Physicists today are struggling with enormous questions: How can we reconcile quantum mechanics and gravity? Are the forces of nature unified? The time scale over which experiments are designed and carried out has become daunting, yet sensitive experiments are already looking for gravitational waves, dark matter and dark energy, as well as probing neutrinos and the stability of matter.

But the LHC is the best of all, pushing the high-energy frontier into a realm that has puzzled physicists since the time of Fermi. The beauty of science is that we don't know what surprises may await us in these domains. The enormity of the questions and the power of the experiments promise dramatic changes to our understanding of the architecture of reality.

*—**Sean Carroll**, University of Chicago*

How Many More Whys?

Cosmology and astronomy have told us the universe is composed of matter and not antimatter, but they cannot tell us why; they tell us a quarter of the universe is dark matter, but they cannot tell us what dark matter is; they imply that three spatial dimensions inflated very rapidly, ending in the Big Bang, but cannot tell us what physical effect caused that inflation. The Standard Model includes the Higgs field, which allows quarks and electrons to have mass. But it does not tell us the origin of the Higgs field or how it works.

If the universe is supersymmetric, which implies that every fundamental particle has a superpartner, we'll have answers to all these questions, and also learn the why of many of the most basic issues.

The LHC could discover the superpartners in a supersymmetric world. In addition to strong theoretical evidence for Higgs physics, there is strong indirect experimental evidence that Higgs particles do exist with a mass implied by supersymmetry. If so, LHC can detect them. What we learn by studying the superpartners and the Higgs bosons can provide the answers to both the matter asymmetry and dark matter, as well as helping to identify what caused the universe's rampant primordial expansion.

Probably the main thing we have learned in the past two decades is that any understanding of nature at the most fundamental level (beyond a description) will require extending our thinking to embed our world in additional dimensions. String theory requires that we live in extra spatial dimensions, probably wrapped up in a tiny volume at each of our space-time points. Supersymmetry extends all the space dimensions to make them quantum mechanical, of zero size. In a supersymmetric world, we can test string theory's predictions at the LHC and ask about the implications of LHC data for string theory. An optimist (like me) can make a defendable argument that the LHC data could test supersymmetry, establish string theory and move on to the remaining "why" questions.

—***Gordon Kane****, director, Michigan Center for Theoretical Physics, University of Michigan*

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