Into a New World of Physics and Symmetry

by John Ellis

The worldwide particle physics community is about to sail on a voyage into a New World of discovery. The Large Hadron Collider, a multi-billion-dollar particle collider that will begin operations in Europe in 2007, will take us into new realms of energy, space, time, and symmetry.

Entering new territory like Christopher Columbus, we have good reasons to think that these new realms contain "new physics"—a world beyond the Old World of fundamental particles and forces. Like Columbus, we have expectations about where our journey may lead us. And like Columbus, we do not know how far away the New World may lie, and our preconceptions may well be completely wrong.

For the first time, experiments at the LHC will explore physics at the TeV—or tera-electronvolt—energy scale. The machine will have the capacity to create new forms of matter, producing particles weighing thousands of times more than the protons that it smashes into each other.

The LHC, under construction at the European laboratory CERN, in Geneva, Switzerland, will also be the world's most powerful microscope, with a resolution thousands of times smaller than the diameter of a proton. The high energies and small distances accessible with the LHC will be similar to the conditions of the very early universe, shortly after the big bang, turning the collider into a telescope and a time machine that will reveal the physics that underlies the world around us.

What is mass?

Physicists already have voiced many speculations about the nature of the new physics that we may find. But only the LHC voyage, one of the greatest scientific undertakings of our times, will tell us which ideas are wrong and which ones—if any—have a grain of truth.

A leading topic for these speculations is the origin of mass: Why do the quarks inside the proton weigh much more than an electron, and why do some particles have no mass at all? We theorists believe that the universe is permeated by a soon-to-be-discovered, mass-generating field that in some ways is similar to the familiar electromagnetic and gravitational fields. Just as particles with different electric charges "feel" an electric field in differing ways, different particles feel the mass-generating field in different ways, thereby acquiring different masses.

But how can we prove the existence of this new field? In analogy to other fields, such as the electric field

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Discovering symmetries

Symmetries limit what laws of physics the universe can follow. As an analogy, if humans exhibited perfect bilateral symmetry, then one side of the face would have to be an exact mirror image of the other side. Similarly, if the universe had perfect matter-antimatter symmetry, then whatever laws apply to matter would transfer to antimatter exactly. In reality, neither of these symmetries is perfect, but they still provide a good guide to how the parts are related, and they simplify our descriptions of nature.

New symmetries would allow us to simply transfer the laws of physics from one arena to another. Not only does this make it easier to describe nature, but every new symmetry also leads to profound insights about how the universe works. This is why physicists put so much effort into experiments that look for the symmetries that lie behind the laws of nature.

by David Harris

and the gravitational field, the mass-generating field should have its own force-transmitting particle. Just as the photon is the force carrier of the electric field, the mass-generating field should have its own quantum particle, called the Higgs boson. Its discovery is on the mind of all scientists working on the LHC.

The mass-generating field and its Higgs boson are the only way we know how to provide elementary particles with mass. Without the Higgs, our equations would describe a symmetrical world in which all particles had no mass. The Higgs boson breaks this symmetry without wreaking havoc on the rest of the mathematical framework. The result, known as the Standard Model of particle physics, has been confirmed again and again by numerous collider experiments, suggesting that we may be on the right track.

But the Higgs boson, the first outpost of the New World of physics, has eluded detection so far.

The CDF and DZero experiments at the Fermilab Tevatron collider, for now the world's most powerful particle collider, have the best chance of casting light on the existence of the Higgs boson before data from the LHC are available. Then the LHC, producing collisions at seven times the energy of the Tevatron, will have the power to explore the energy territory in which the Higgs is expected to exist, all but guaranteeing its discovery.

Exploring the New World

Columbus' first view of the New World was the island of Guanahani in the Bahamas, where he made his first landfall. Just as Columbus expected to discover more than just one small island, and just as the New World turned out to be something completely different from what he had anticipated, particle physicists expect the New World of physics to contain more particles than just the Higgs.

There is no agreement what this new physics beyond the Standard Model may be, but many theoretical models predict an archipelago of new particles for the LHC to discover. A common expectation is that the LHC will reveal some new symmetry that was present in the early high-energy era of the universe, but which no longer exists on the cold planet Earth. The nature of this symmetry is very much up for grabs, and many physicists—from Albert Einstein onwards—have speculated on its nature.

The existence of such a new symmetry is motivated in attempts to understand the origin of similarities and dissimilarities among the known particles and forces. Why are there so many kinds of particles? Do all forces become one? What happened to the antimatter? Are there undiscovered principles of nature? The LHC will help to unravel these and other mysteries.

Something is missing

Theorists agree that the Standard Model is not complete; its framework allows for too many unruly quantum effects that need to be tamed. Incorporating new symmetries might be the solution.

The most prominent attempt at fixing the flaws of the current model is the introduction of supersymmetry, a novel type of symmetry that relates force-carrying particles, such as the photon and Higgs boson, with matter particles, such as quarks and the electron. Supersymmetry might also play a role in combining the fundamental forces of the Standard Model in a "grand unified theory"—at last fulfilling Einstein's dream.

Most interestingly, the concept of supersymmetry "stabilizes" the Higgs boson mass, liberating it from mathematical infinities and setting an energy scale of about one TeV for the mass and interactions of other particles, which the LHC could readily explore.

Signs of supersymmetry

Supersymmetry is, perhaps, the "most expected of the surprise discoveries" that we may hope to find at the LHC. But how do we expect the New World of superymmetry to appear?

Theory predicts that all Standard Model particles—quarks, leptons, and bosons—should be accompanied by an archipelago of partner particles with identical electric charges but with different spins, an intrinsic property of every particle. Quarks (spin 1/2) should have supersymmetric partners with spin 0, named squarks. The gluon (spin 1), a particle that transmits the strong nuclear force, should have as a partner the gluino, a spin-1/2 particle. In many models, the lightest supersymmetric particle (perhaps the photino, the partner of the photon) is stable and exists as a neutral, invisible particle that permeates the universe. Even though it sounds like science fiction, history may repeat itself. In 1930, theorist Wolfgang Pauli predicted the neutrino, a particle with no electric charge, tiny mass, and almost no interaction with matter. It took experimenters a quarter century to discover the particle, which we now recognize as one of the most abundant particles in the universe.

Could the lightest supersymmetric particle play a similar role? Could it be the dark matter?

Astrophysicists and cosmologists tell us the universe contains five times more dark matter than conventional, visible matter. The photino or some other stable, supersymmetric particle could be the building block of this dark, invisible matter—in contrast to quarks and electrons, which seem to be the building blocks of all visible matter in the universe.

A world with new dimensions

Many of my colleagues expect the LHC to discover quite a different type of symmetry—one that connects our three-dimensional world with extra dimensions. Just as Einstein showed us that the three dimensions of space are related to time via a hidden symmetry, new theories propose that there may exist extra, hidden dimensions of space that "become visible" only at high energies.

The New World of extra dimensions could appear in several different ways. Collisions at the LHC may produce new partners of the Standard Model particles, this time with the same spins as well as the same interactions as the particle we already know. There is also the possibility that some of the energy released in LHC collisions might "leak away," invisibly transferred into the extra dimensions. Careful analysis of the LHC data would reveal this leak.

More possibilities

The big bang almost certainly produced equal amounts of matter and antimatter, yet our universe seems to contain no antimatter. How did the asymmetry arise? The LHC may provide the answer.

Asymmetries between matter and antimatter were first discovered in the decays of neutral kaons, composite particles made of a quark and an antiquark. Differences in the decay of particles and antiparticles also appear in other quark-antiquark composites such as *B* mesons. Experiments at the Japanese laboratory KEK, the Stanford Linear Accelerator Center in California, and Fermilab in Illinois have yielded results on the matter-antimatter asymmetry that so far are in excellent agreement with predictions derived from Standard Model calculations. But the Standard Model asymmetry is not strong enough to explain the disappearance of antimatter after the big bang. What else is going on?

If indeed the LHC discovers a New World of physics at the TeV scale, will this new physics also discriminate between matter and antimatter? Will sparticles and antisparticles behave differently? Will the new physics explain the absence of antimatter in our universe today?

Using their fertile imaginations, physicists have dreamed up many more possibilities, and the LHC will test many of them. Without the input of high-energy experiments such as those at the LHC, we will not find out what the New World of physics has to offer.

Next year, the collider will embark on a true voyage of discovery, together with experimenters from around the world. Very likely, the LHC and its crew will discover something exciting; something we have not foreseen; something that will completely shatter our view of the world.

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