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The God particle *et al.*

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The territory of the Large Hadron Collider might be populated not just by the Higgs particle but also by all manner of other exotic apparitions.

The birth of particle physics — that is, high-energy physics — can be dated to about 1950, offspring of the marriage of nuclear physics and the study of cosmic rays. It exploited techniques and technology from both disciplines, and its objective was to identify the primordial particles of nature — those from which all matter is made — and codify the laws of physics that oversee their properties and social behaviours.

Progress in high-energy physics has always been mortgaged to the requirements of the ever more powerful particle accelerators required to reveal the inner life of the particle 'zoo'. Around 1950, the world energy record was held by a synchrocyclotron accelerator that accelerated protons to 400 megaelectronvolts (MeV) around a circular path. That was enough to shatter atomic nuclei and produce copious quantities of pions and muons. These particles, first discovered in investigations of cosmic rays, were indicators of a vast complexity to come.

The record-breaking 'atom-smasher' of 1950 was constructed by the physics department of Columbia University on the Nevis estate, about 30 miles north of the university, bordering the Hudson River. At its dedication, by the then University president, Dwight Eisenhower, a series of relays brought the Nevis synchrocyclotron to life, as attested by a Geiger counter emitting an amplified series of clicks. My job, as a new graduate student intent on using the accelerator for my PhD research, was to stand by with a radioactive source in case the machine failed. It did, of course, and, as I had misplaced the source, the dawn of this new era in particle physics was delayed, in the ears of the assembled company, by five very embarrassing minutes.

The Nevis machine soon left this small setback behind. This machine, and others that followed all over the world, ensured that by 1995 the cutting-edge energy domain had climbed by a factor of more than 2,000 over those early days. The probe of choice was protons at an energy of 900 gigaelectronvolts (GeV) in head-on collision with antiprotons of the same energy. These collisions, which occurred at a rate of almost 10^6 per second, took place in the 6.3-km-circumference ring of the Tevatron accelerator, at Fermilab, in Batavia, Illinois. The principle of conservation of momentum tells us that a head-on collision is much more violent than is aiming one beam at a stationary target, as the Nevis machine had done. It is the difference between a large speeding truck colliding with a ping-pong ball and two equally huge trucks involved in a full-on collision. In the first case, nothing much happens to the truck, and the ping-pong ball recoils rapidly, none the worse for wear. In the second case, bumpers, mirrors, radios and steering wheels fly off in all directions. Picking through the debris left by such an impact gives us a good grasp of how the truck's interior was put together.

In 1979, as the new director of Fermilab, I made the decision that protons should smash into antiprotons in the new accelerator. The Tevatron's success was crowned in 1995 with its discovery of the last and heaviest of the expected fundamental matter particles: the top quark. The ultimate product of the increasingly savage collisions at Fermilab and elsewhere in the years between 1950 and 1995 was the seemingly complete, self-contained and self-consistent table of nature's fundamental particles — the 'standard model' (see page 270).

With this table now seemingly replete, why is there still hunger for further discovery? Why is the Tevatron now running 24 hours a day, 7 days a week at huge, historic collision rates for fear of what its soon-to-be rival, the Large Hadron Collider (LHC), might find? There is a palpable sense of expectation in the control rooms of the Tevatron; in the construction activities of the physicists from all over the world participating in the LHC project; in the coming together of the massive detectors that will provide the eyes of the LHC; and, most especially, in the quiet rooms populated by theoretical physicists.

A new frontier

By 2009, it is reasonable to expect that the LHC will have claimed the crown of king of the accelerators. When the LHC is completed, the frontier of particle physics will be at a total collision energy of 14 teraelectronvolts (TeV), far beyond the energies reached by the Tevatron. At this frontier, the past decade of research in high-energy physics and in experimental astrophysics tells us that the known, explored world of the standard model and the summed achievements of the past half-century will be behind us. Defects in our theoretical construct — founded on the twin pillars of quantum field theory and Albert Einstein's general theory of relativity — that have become ever more apparent, but that could until now be ignored, will have to be confronted. We are reaching what the medieval map-maker would have denoted *terra incognita*.

By far the most popular expected denizen of these unknown lands is the Higgs particle, which was postulated to tidy up the glitch in the standard model known as electroweak symmetry breaking. Ever since Einstein published his special theory of relativity in 1905, theorists have had great respect for symmetry. At the heart of special relativity is the idea of Lorentz symmetry: that all laws of physics should be the same for all observers moving with constant relative velocities. The equation $E = mc^2$ is a direct consequence of this symmetry. Today, you cannot visit a high-energy physics laboratory without stumbling over symmetry on your way in. As in art and architecture, symmetry in this sense is an aesthetic concept: we believe that nature is best described in equations that are as simple, beautiful, compact and universal as possible. According to this way of thinking, the W and Z particles, which carry the weak nuclear force, and the photon, carrier of the electromagnetic force, should combine to show electroweak symmetry, and all should have zero mass.

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Unless the aesthetes are fundamentally wrong, therefore, the fact that electroweak symmetry isn't perfect — because the W and Z particles are heavy — means that something is acting to break the symmetry. This something will give mass not only to the W and Z particles but also to all other particles except those few (such as photons) that can escape its clutches. The effect can be compared to running swiftly on hard ground versus knee-high through oil. In oil, your motion is slower, as if your mass had increased. The Higgs particle is that oil, and a Higgs 'field' is spread across the entire Universe.

In 1993, I co-authored a book on the history and status of high-energy physics. Then, as now, this mysterious Higgs field haunted us. As well

as explaining why particles had mass, the Higgs field allowed theorists to calculate reactions that, lacking such a speculative field, yielded nonsensical values. The beauty of the Higgs idea stimulated us to name the book *The God Particle*. "Besides," as my editor explained with an eye on the sales figures, "no one has ever heard of Higgs."

Ever more precise data emerging from the Tevatron indicate that the Higgs particle itself is not very heavy. It should be relatively easy to produce at the huge energy of the LHC. If so, questions abound. Is the Higgs alone, or is there a whole family of Higgs-type particles? Does the Higgs really give mass to everything: not just to the *W* and *Z* particles but to quarks and charged leptons as well? That really would be the key to a unified theory embracing the gamut of particle physics. But even just knowing the role of the Higgs in breaking electroweak symmetry will allow us to gain understanding of that symmetry and add consistency to quantum field theory. For the sake of its own consistency, the standard model needs something like a Higgs.

The Higgs is not, of course, the be-all and end-all of the LHC. There is also the question of supersymmetry (SUSY). SUSY is a theory that maintains that every particle in the fermion enclosure of the particle zoo (the quarks, the leptons and the composite particles with an odd number of half-integer spins) has a heavier twin in the boson enclosure (where photons, gluons, and the *W* and *Z* particles currently reside). Thus, the electron (a fermion) has a supersymmetric boson partner, known as a 'selectron', and so on. Theorists love SUSY for her elegance. The LHC will allow us to establish whether SUSY exists or not: even if 'squarks' and 'gluinos' are as heavy as 2.5 TeV, the LHC will find them.

And then there is the question of the extra space dimensions predicted by string theory — that herculean attempt to unify quantum theory and gravitation. For these new dimensions to exist, yet for us to be unaware of them, they must be 'curled up' incredibly small. Theoretically, some might be just big enough to be detected at the LHC through the escape of (gravitational) energy into them.

A speculative laundry list

To me, these three factors — the Higgs particles, supersymmetric particles and new dimensions — are the discoveries most likely to emerge from the first five or so years of LHC operations. But there is a long, more speculative laundry list of objects that might be illuminated by the powerful beams of the LHC. Most of these are speculative in the extreme.

Dark matter origins

Dark matter is one cosmological discovery that has shaken up particle physics, giving rise to many a joint conference with an 'inner space/outer space' theme. The rotational speed of galaxies requires more gravitational 'stuff' than is accounted for by the shining stars. Measurements during the past decade have yielded the information that about 25% of the Universe's mass must be this dark stuff. Neutrinos, which were the initial prime suspects because huge quantities of them were known to have been left over from the Big Bang, are not massive enough. Over time, other exotic candidates — dead suns, black holes and large planets (known as Jupiters) — have been ruled out.

Theorists have supplied us with a plethora of possible solutions, mostly out of their bag of supersymmetric particles. What is known about dark matter is that, first, there is lots of it; second, it does not shine; and, third, it has gravitational force. It is certainly possible that particles will emerge from the collisions of the LHC that will both gladden the hearts of SUSY theorists and account for dark matter.

Dark energy origins

This is, potentially, the elephant in the control room of the LHC. We haven't a clue as to what it is, but we know what it does: it maintains a continuous outward push on the matter of the Universe, sustaining and increasing the expansion rate, and thereby counteracting the gravitational attraction that should be slowing the expansion. It might not be dark, and it might not be energy. But it accounts for more than 70% of the mass of the Universe, so its identification is an important objective. Illumination by the LHC would be a seminal discovery.

Compositeness

Increasingly precise experiments, in the spirit of Ernest Rutherford's scattering experiments on the substructure of gold atoms, have attempted to detect some sort of substructure to the quintessential electron, using progressively more powerful microscopes, each capable of 'seeing' objects smaller than its predecessor: 10^{-18}, 10^{-19}, 10^{-20} cm. This is the maximum scale for an electron's radius (and therefore any internal structure it might have). By necessity, we are now comfortable with the hypothesis that all standard-model particles have zero radius and so no substructure. But this doesn't preclude a future machine detecting a finite size: the higher its energy, the smaller the domain searched.

It is also possible to imagine a sort of substructure that would escape detection by scattering experiments. If one were ever to detect a quark so structured that it could have a higher energy quantum state, and so might absorb energy from the scattered protons, that would be a just-fancy-that moment!

Technicolour

'Technicolour' refers not to the glowing shades in which the fantasy land appears in *The Wizard of Oz* but rather to the quantum field theory postulated as an alternative to the Higgs hypothesis for explaining the masses of the *W* and *Z* particles. Theories that have not yet been confirmed experimentally are judged by their mathematical 'elegance' and their economy in predicting new particles. Supersymmetry predicts a doubling in the total number of particles and must therefore be considered uneconomical. From the point of view of the ambitious experimental physicist desperate to make discoveries, however, SUSY is a godsend. Technicolour predicts a new strong force and a large number of new particles (although fewer than SUSY), whose 'signatures' could stand out above backgrounds of the complex collisions that the LHC will produce.

Strong scattering

One of the wonders of the Higgs hypothesis for high-energy physics is that it cures a particular 'pathology' present in certain predictions: for example, there are infinities in the cross-sections (a measure of the probability of a process) for the scattering of two *W* bosons. The presence of the Higgs would cure this 'disease'. Thus, experiments such as W–W scattering (I don't know how to do these, but I am sure there are experiments that would include infinite contributions in a Higgs-less theory) should be carried out at the highest energies. If Higgs cannot be discovered, such experiments will be crucial to establish what the missing ingredient that we need to make our theories sensible looks like.

New gauge bosons

Our old force carriers are photons, the *W* and *Z* particles, and gluons. It is strongly assumed that gravitons are 'almost' discovered — although not by suspicious conservatives. Perhaps, a decade into the LHC's operation, our skills in precise analysis of collisions at 14 TeV will have been honed such that we can discover a new force, and so a new boson, predicted by a theorist now in a good high school. At present, our theories don't need such bosons, but that doesn't mean they don't exist.

Right-handed neutrinos

The neutrinos we know and love have less than one millionth the mass of the electron and are left-handed — that is, their spin direction is opposite to their momentum. To be accepted gracefully into current theory, a right-handed neutrino — the spin and momentum of which would be parallel — must be very massive. In addition, we must lose the distinction between the massive neutrino and its antimatter twin. A discovery of such particles at the LHC would be a fantastic step forwards in our quest for a theory of everything. It would, for example, have a bearing on the 'origin of matter' dilemma — that is, why is there a small excess of matter over antimatter, and, by extension, how did we come to be here?

Mini black holes

Black-hole physics deals with the astronomical phenomenon of a massive sun using up its nuclear fuel and eventually collapsing, if it is heavy enough, into a black hole. Of more interest to particle physicists are smaller black holes, left over from the Big Bang, which may well exist in and around our Galaxy. At first pass, even such mini black holes must be much more massive than any imaginable accelerator could reach. But the existence of extra dimensions of finite size, as proposed by string theory, would lower the energy required to produce these hypothetical particles. The idea of the LHC as a mini-black-hole factory is not as worrying as it sounds; they will quickly evaporate through the radiation of energy (Hawking radiation).

What did we leave out?

Theoretical physicists are an imaginative group, and each of these exotic suggestions has its proponents and its naysayers. But the history of the sort of step that the LHC will be making teaches us that, more often than not, a discovery will be made that was not anticipated by theorists. That discovery will change our theories beyond imagination. Fifty years spent investigating the standard model have taught me that, by year ten of the LHC's physics, many an expected and unexpected discovery could well have been celebrated with champagne drunk from styrofoam cups. ■

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