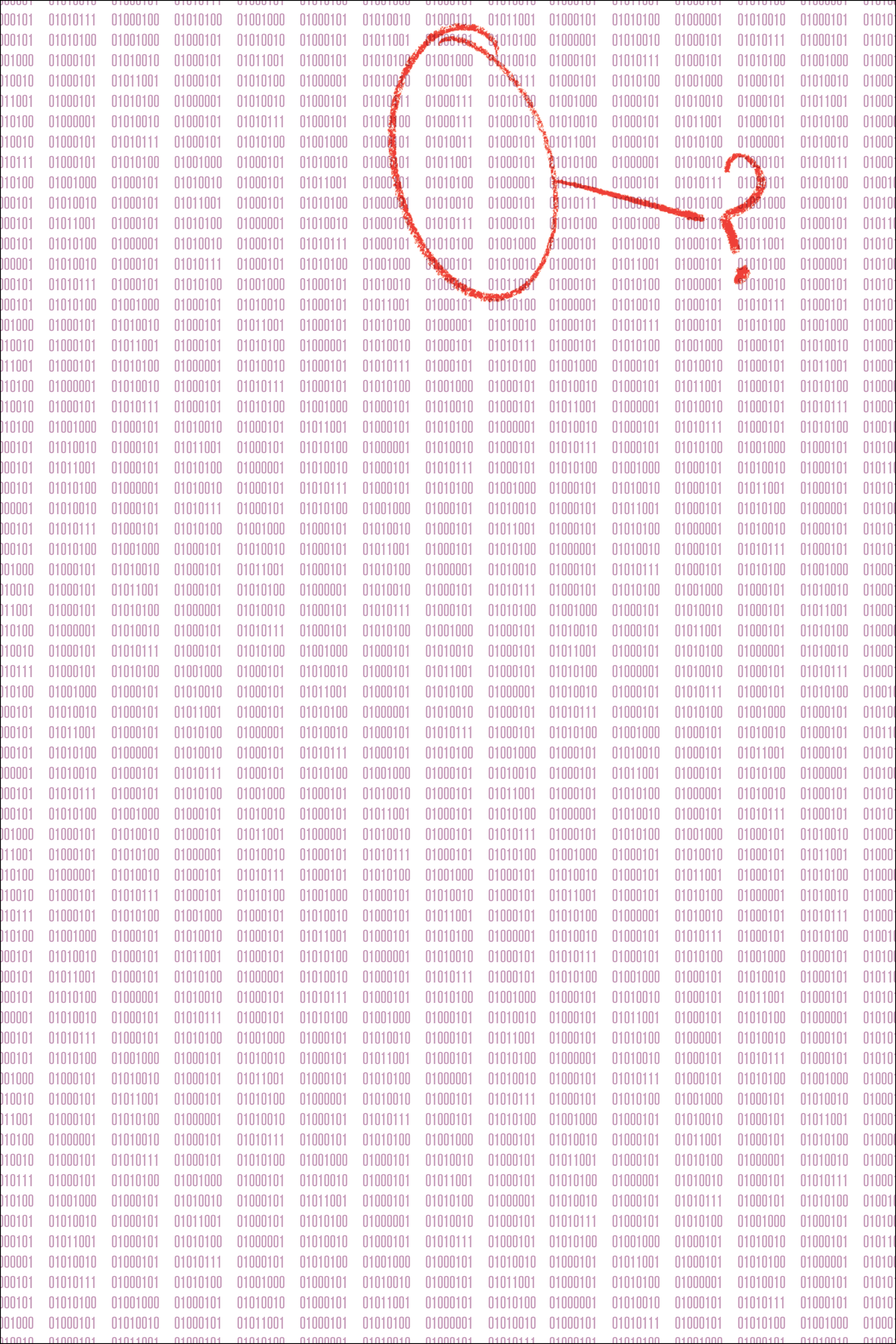
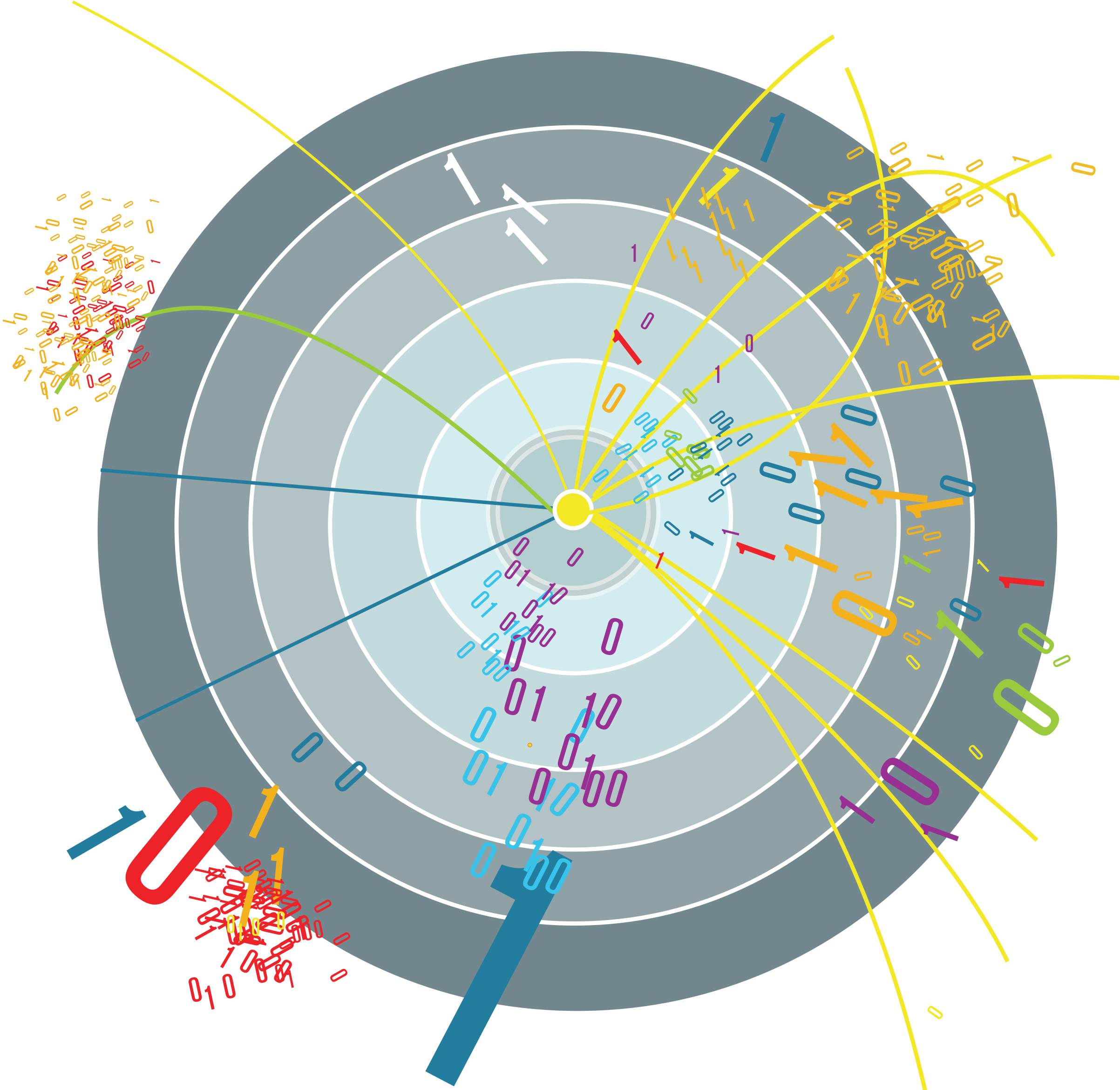


ARE WE THERE YET?

With the Large Hadron Collider up and running, expectations are high: Shouldn't discoveries start pouring in? These things don't happen overnight. We trace the long, careful path from intriguing data to official discovery.

By Daisy Yuhas



Years of effort and roughly 10,000 people have made the Large Hadron Collider the most powerful particle accelerator in the world. This collaborative feat of technology promises to change the way we understand the universe. Now the world is watching, waiting to see what so much effort will yield.

Even at an initial collision energy of 7 trillion electronvolts—half its full capacity—the LHC is in a position to make important discoveries. Deep below the Swiss-French border, protons race around its 27-kilometer ring at nearly the speed of light and collide billions of times per second. Each collision produces a spray of particles, which are so elusive that physicists glimpse them only indirectly by the patterns they leave in the detectors as they decay.

These fleeting patterns can help physicists answer questions such as how matter acquires mass and whether there are extra dimensions of space, revealing the most fundamental components of the natural world. But these discoveries are not single moments of revelation. A discovery in high-energy physics takes months, if not years, becoming official only once it has been published. To understand why, it might be useful to turn to one of the most sought-after particles in physics today, the Higgs boson.

Higgs-spotting: Catch a falling star

One of the joys of a clear night is going outside to look at the stars. Staring up at the sky, you enjoy a view of the moon and stars, spotting planets and constellations.

All of a sudden you see something move. Next thing you know, you're scanning the skies. The movement might have been just a trick of your eye or the light of a passing airplane. But when you see it repeatedly, you become more and more confident that these brief flashes of light are shooting stars, part of a meteor shower.

Hunting for the Higgs boson is a little like spotting a meteor shower. It's a rare phenomenon—only one in a hundred billion collisions in the LHC is expected to produce a Higgs—that's hard to document or predict. But if you see enough of these rare events, you can be pretty confident that they're real.

Unlike stargazing, though, the Higgs search takes far more than one clear night.

Collecting ephemera

Imagine you are one of the more than 2900 physicists who study particle collisions in the LHC's massive ATLAS detector.

The ATLAS scientists are divided into a number of groups that work on specialized tasks. Some are looking for specific collision patterns that a Higgs could leave in the detector. Since theorists predict a number of distinct decay patterns for the Higgs boson, and even multiple types of Higgs, there are a lot of bases to cover. Your five-member group is focusing on just one of these possibilities.

Making things even more difficult, common particles pass through the detector all the time and leave patterns that look like the footprints of a Higgs. The rarity of a Higgs boson amid the confusion of these events, which are collectively known as background, makes looking for the Higgs like trying to spot a meteor shower near a busy airport.

That's why when you think you see an intriguing pattern your reaction is a lot like when you first see a shooting star: "Did I really just see that?"

Not-quite-Eureka

If you spot the pattern you're looking for just once, you will probably attribute it to background. If you see it repeatedly, you begin to suspect that you may have found a Higgs boson.

But you can't claim a discovery yet. First you must demonstrate that your measurements are accurate and that you are finding the same pattern so frequently that the probability this is actually a Higgs is overwhelmingly high.

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A discovery in physics is not so much a "Eureka!" moment as a long process of data collection and analysis. You need a lot of tested evidence to convince the scientific community that you are seeing something never seen before.

Because Higgs-producing collisions are so rare, the collider needs to run for a long time before there's a chance a Higgs might appear somewhere in the data. To flush it out, your working group spends months analyzing the data with specialized computer programs.

Even with tremendous care, analysts can mistake background patterns for a sought-after signal. In 1984, the UA1 experiment at CERN claimed the top-quark discovery on the basis of 12 collisions. In this case, however, an incomplete theory and misunderstood background led to a false conclusion. When UA2, a competing experiment, could not confirm the find, the discovery was retracted.

Write, review, revise

"Before you see this unambiguous signal that everyone agrees is a great discovery, you're going to hear hints and whispers," says ATLAS's Tom LeCompte.

As these whispers build, your working group keeps analyzing and accumulating data until you feel confident enough to share the results with other ATLAS working groups involved in the Higgs search.

Dmitri Denisov, spokesperson of the DZero experiment at Fermilab's Tevatron collider, says verifying a signal sometimes takes years. He recalls one group at DZero that studied what appeared to be an unusual kind of Higgs for more than a year; in the end, their finding failed to pass cross-checks by other groups within the collaboration.

If the evidence does withstand examination, the working groups combine their analyses and compile the notes that explain their methods and results. They present this material to a specially appointed review board that will guide its development into a scientific paper. The review board includes people familiar with the search methods as well as fresh eyes to challenge the work. The board critiques and scrutinizes the notes to help the groups craft a paper that clearly and comprehensively presents the discovery.

All in this together

After months of work, the draft paper is finally ready. Now it goes to the entire collaboration, of which all 2900 or so members will be listed as authors. You must persuade each individual member that the evidence for the discovery is solid.

At this stage you spend weeks reading and responding to questions, suggestions, and criticisms from fellow collaboration members. In the process, you demonstrate just how strong your findings are, and their input ensures that the science involved is really at its best.

Joe Incandela, who is now with the CMS experiment at the LHC, was working with the CDF collaboration at the Tevatron when they found evidence for the top quark. He recalls when the search results were shared with the full collaboration on January 21, 1995:

"There was a very clear signal and the checks were solid. Everyone there was convinced and it was agreed we should publish as soon as possible, but it wasn't until March 3rd that we submitted the paper. Even with a clear consensus and people working extremely hard it took six weeks to get it out.

"We needed to answer questions from the collaboration and update the internal documentation accordingly. I think there were about 450 people on the experiment at that time and in the last few days up to the deadline we got e-mail from almost every one of them with great questions and comments. It made us realize not only how important this result was to everyone, but how important everyone was to this result."

In a few rare instances, a paper's content is so unusual that a significant number of people remove their names from the list of authors. This occurred in 2008 when a CDF paper announced the observation of muon particles with unusual properties that could not be fully explained by familiar physics models. Controversy stemmed in part from an inability to conclusively explain this multi-muon phenomenon. One-third of the 600 collaboration members removed their names from the author list, though the reasons for this varied.

Spokesperson Rob Roser says, "Some people thought the result was wrong. Others felt the paper presented an interesting anomaly but offered no explanation or definitive conclusion, and, finally, still others were just not paying enough attention to weigh in on this."

The competitive and collaborative spirit

While your paper claiming discovery of a Higgs is under rigorous review by the ATLAS collaboration, you should bear in mind that across the LHC ring the CMS experiment, also studying LHC collisions, may be looking at very similar numbers and analyses.

The relationship between experiments can be collaborative, competitive, or both. For example, the Tevatron's DZero and CDF experiments, usually rivals, will need to combine analyses if they want to compete with LHC experiments in the search for a Higgs. Since each experiment approaches the search in a different way, their ability to check each others' work produces a more thorough investigation.

Competition from other experiments pushes collaborations to work harder and faster so they can be first to publish and claim credit for a discovery.

DZero's Denisov describes the decision to push for either quicker publication or more extensive analysis as "a smart balance on this very sharp edge. You could always be more conservative but at the forefront of science, you have to take risks to progress."

One such risk was DZero's publication of a paper in 2006 showing hints of the B_S meson oscillating between matter and antimatter. DZero had found strong suggestions of the oscillations but with low statistical significance. The collaboration was aware that their competitor, CDF, was better equipped to study the phenomenon; yet DZero had amassed evidence faster.

Though the low statistical significance gave the collaboration pause, they decided to publish rather than wait for more data. The risk paid off. The results held up under scrutiny, and DZero's publication of the discovery remains among the most-referenced recent papers in high-energy physics.

Into the unknown

That same balance of eagerness and deliberation will apply to any team that thinks it has snagged a Higgs, including yours. Once you have the collaboration's support and persuade a journal to publish the completed paper, you can relax a little; the discovery of the Higgs boson is finally official. But brace yourself for a new round of questions, comments, and possible challenges as the rest of the high-energy physics community weighs in.

The LHC could usher in a new era of physics discoveries. We cannot predict exactly when the next big discovery will happen, though we know it will take time. Ultimately, no one knows precisely what the universe has in store for us.

But we are eagerly waiting to find out.

Q&A with the Universe

From the quest for the most fundamental particles of matter to the mysteries of dark matter, supersymmetry, and extra dimensions, many of nature's greatest puzzles are being probed at the Large Hadron Collider.

What is the form of the universe?

Physicists created the Standard Model to explain the form of the universe—the fundamental particles, their properties, and the forces that govern them. The predictions of this tried-and-true model have repeatedly proven accurate over the years. However, there are still questions left unanswered. For this reason, physicists have theorized many possible extensions to the Standard Model. Several of these predict that at higher collision energies, like those at the LHC, we will encounter new particles like the Z', pronounced "Z prime." It is a theoretical heavy boson whose discovery could be useful in developing new physics models. Depending on when and how we find a Z' boson, we will be able to draw more conclusions about the models it supports, whether they involve superstrings, extra dimensions, or a grand unified theory that explains everything in the universe. Whatever physicists discover beyond the Standard Model will open new frontiers for exploring the nature of the universe.

What is the universe made of?

Since the 1930s, scientists have been aware that the universe contains more than just regular matter. In fact, only a little over 4 percent of the universe is made of the matter that we can see. Of the remaining 96 percent, about 23 percent is dark matter and everything else is dark energy, a mysterious substance that creates a gravitational repulsion responsible for the universe's accelerating expansion. One theory regarding dark matter is that it is made up of the as-yet-unseen partners of the particles that make up regular matter. In a supersymmetric universe, every ordinary particle has one of these superpartners. Experiments at the LHC may find evidence to support or reject their existence.

Are there extra dimensions?

We experience three dimensions of space. However, the theory of relativity states that space can expand, contract, and bend. It's possible, therefore, that we encounter only three spatial dimensions because they're the only ones our size enables us to see, while other dimensions are so tiny that they are effectively hidden. Extra dimensions are integral to several theoretical models of the universe; string theory, for example, suggests as many as seven extra dimensions of space. The LHC is sensitive enough to detect extra dimensions ten billion times smaller than an atom. Experiments like ATLAS and CMS are hoping to gather information about how many other dimensions exist, what particles are associated with them, and how they are hidden.

What are the most basic building blocks of matter?

Particle physicists hope to explain the makeup of the universe by understanding it from its smallest, most basic parts. Today, the fundamental building blocks of the universe are believed to be quarks and leptons; however, some theorists believe that these particles are not fundamental after all. The theory of compositeness, for example, suggests that quarks are composed of even smaller particles. Efforts to look closely at quarks and leptons have been difficult. Quarks are especially challenging, as they are never found in isolation but instead join with other particles to form hadrons, such as the protons that collide in the LHC. With the LHC's high energy levels, scientists hope to collect enough data about quarks to reveal whether anything smaller is hidden inside.

Why do some particles have mass?

Through the theory of relativity, we know that particles moving at the speed of light have no mass, while particles moving slower than light speed do have mass. Physicists theorize that the omnipresent Higgs field slows some particles to below light speed, and thus imbues them with mass. We can't study the Higgs field directly, but it is possible that an accelerator could excite this field enough to "shake loose" Higgs boson particles, which physicists should be able to detect. After decades of searching, physicists believe that they are close to producing collisions at the energy level needed to detect Higgs bosons.