All smiles. "I think we've got it," quipped CERN Director General Rolf-Dieter Heuer (*center*) after ATLAS's Fabiola Gianotti (*left*) and CMS's Joseph Incandela presented the data.

PARTICLE PHYSICS

Higgs Boson Makes Its Debut After Decades-Long Search

MEYRIN, SWITZERLAND—When physicists here at the European particle physics laboratory, CERN, reported last week that they had discovered the famed Higgs boson, or something much like it, they captivated the world. A hundred journalists descended upon the lab to hear scientists working with the world's largest atom smasher, CERN's Large Hadron Collider (LHC), present evidence of the Higgs, the key to physicists' explanation of how all fundamental particles get their mass. Photographers swarmed Peter Higgs, the 83-year-old theorist from the University of Edinburgh in the United Kingdom, who dreamed up the most-coveted particle 48 years ago.

"I'd like to add my congratulations to everyone involved in this tremendous achievement," Higgs said immediately after the special seminar. "For me, it's really an incredible thing that it's happened in my lifetime." Otherwise, like a seawall resisting the surf, the demure Higgs refused to take questions. Greta Garbo would have admired his resolve.

The discovery of the Higgs marks a triumph for particle physicists. For the first time since 1995, they have unearthed a new fundamental particle. They have apparently confirmed a decades-old prediction of how the universe works and found the last piece in their standard model of fundamental particles and forces, perhaps the most elaborate and precise theory in science. And they've reenergized their field, as attested by the hundreds of physicists who lined up all night for a chance to get into the auditorium for the talks.

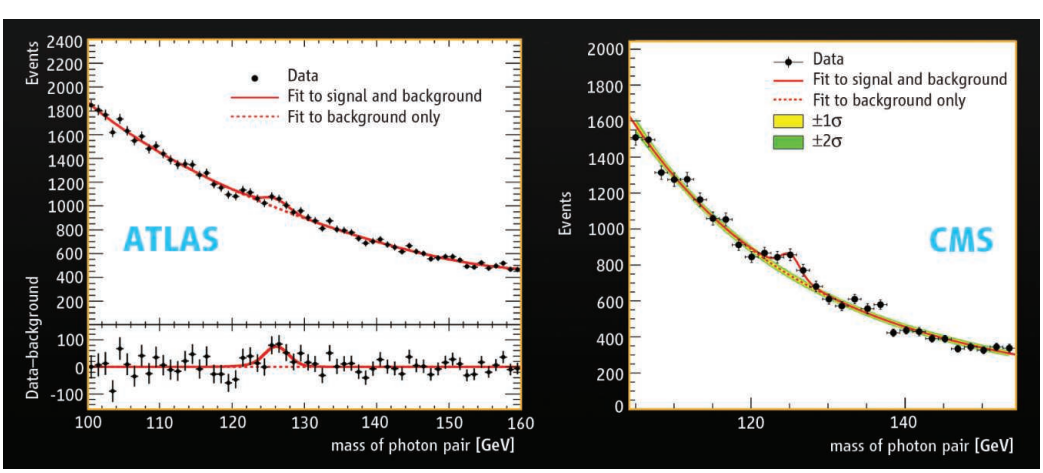
But the advance also leaves particle physics at a curious crossroads. Physicists aren't sure whether new particles or phenomena lie within the reach of the LHC or any conceivable atom smasher. If nothing else shows up, the discovery of the Higgs could mark the end of the road (*Science*, 23 March 2007, p. 1657). "My nightmare—and it's not just me, but a lot of us—is that the LHC discovers the Higgs and nothing else," says Steven Weinberg, theorist and Nobel laureate at the University of Texas, Austin. "That would be like closing a door."

Still, physicists say they're optimistic that even bigger finds will follow. "We've reached deeper into nature than ever before and we didn't come up empty," says Joseph Incandela, an experimenter at the University of California, Santa Barbara, and spokesperson for the 3000 researchers working with a massive particle detector called CMS. "There aren't any guarantees [of more discoveries], but there's a strong likelihood."

What's a Higgs boson anyway?

The Higgs boson was born as the answer to a seemingly abstruse question: Why does the range of the electromagnetic force, which creates light and binds the atom, stretch infinitely far, whereas the range of the weak nuclear force, which causes a kind of radioactive decay, reaches across only the atomic nucleus?

In the early 1960s, theorists realized that they could both roll the electromagnetic and weak forces together and explain the differences in their ranges. To do that, they assumed that just as the electromagnetic force is conveyed by quantum particles called photons, the weak force is conveyed by particles called the W boson and the Z boson. But whereas the photon has no mass, the W and Z would be weighty, and their masses would shorten the range over which they act.



Twin peaks. The coincident bumps in these plots reveal Higgs-like particles decaying into pairs of photons.

CREDITS: (TOP) DENIS BALIBOUSE/STRINGER; (BOTTOM LEFT TO RIGHT) ATLAS COLLABORATION; CMS COLLABORATION

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Published by AAAS

There was just one hitch: If theorists simply assigned masses to the W and the Z, the theory would go mathematically haywire. So instead, the masses of the W and Z had to come from interactions among the otherwise massless particles themselves. That's where the Higgs boson came in.

In 1964, Higgs and others independently realized that they could make a massless particle put on weight if they assumed that empty space was filled with a field a bit like an electric field. That "Higgs field" would then interact with and drag on other particles to produce the effects of inertia or mass. So in the late 1960s, other theorists adopted Higgs's scheme to give mass to the W and Z bosons, which were observed with precisely the predicted properties in experiments at CERN in 1983.

Physicists then simply assumed that the Higgs field gives rise to the masses of all the other fundamental particles. For example, the electrons that whiz around in atoms and the quarks that make up protons and neutrons in atomic nuclei get their mass by moving through the Higgs field.

Quantum theory assumes that any field consists of quantum particles. So just as an electric field consists of photons, the Higgs field consists of Higgs bosons. That does *not* mean that space is filled with scads of Higgses floating about. Rather, the massive particles lurk "virtually" in the vacuum, exerting their influence without stepping into the spotlight of bona fide existence.

The Higgs is much more than a bandage on the theory, says Stuart Raby, a theorist at Ohio State University, Columbus. "The standard model is framed on having a Higgs boson," he says. "If the Higgs weren't there, the whole theory would have to be rethought."

Loose lips and long lines

To spot Higgs bosons, physicists must literally rip them out of the vacuum in violent particle collisions, as experimenters working with the LHC have done. The 27-kilometer-long circular collider smashes protons together at energies four times as high as any previous machine could reach—even though, because of technical flaws, the LHC is running at just over half its design energy. Collisions take place within two gargantuan particle detectors, called ATLAS and CMS, that have been hunting the Higgs since the LHC started taking data 27 months ago. Any Higgs bosons created in the collisions should decay into telltale combinations of familiar particles.

For example, the Higgs boson ought to sometimes decay into two photons. From the photons' energies, experimenters can infer the mass of their parent particle. So in a plot of the masses of the inferred particles, the Higgs should appear as a peak atop a background produced by random photon pairs. Both ATLAS and CMS see peaks at a mass of about 125 giga-electron volts (GeV), 133 times the mass of a proton (see figure, p. 141). The coincident peaks by themselves make a strong case for the Higgs. And ATLAS and CMS see other signs of the Higgs decaying into two Z bosons, as well as other combinations of particles.

Hard pressed. The eponymous Peter Higgs (*right*) faced an onslaught of media attention.

The data from either experiment alone would clinch the case for the new particle. Physicists measure the strength of a signal in multiples of the uncertainty in it, denoted sigma. A higher multiple implies a stronger signal, and the CMS data yield a signal just shy of particle physicists' 5-sigma standard for declaring discovery, CMS's Incandela reported. The chances that random background could produce a spurious signal as large are one in 3.5 million.

ATLAS's signal reaches the 5-sigma standard, reported Fabiola Gianotti, an experimenter at CERN and spokesperson for the 3000-member ATLAS team. As soon as she showed a slide stating that fact, the audience erupted into cheers. "I'm not done yet!" Gianotti responded. "There's more to come."

The presentations capped off 2 weeks of growing anticipation, fueled by rumors and anonymous leaks. Hours before the CERN auditorium opened at 7:30 a.m., people began lining up, creating a queue that snaked through CERN's main building. Even 20 minutes before the seminar, dozens remained in line hoping against hope to get a spot inside the packed hall. "I want to stay close to this event for now," said Serena Persichelli, a graduate student from the Sapienza University of Rome. "Maybe at 9:00 I'll go somewhere else and watch the video feed."

Is it really the Higgs?

Physicists still have to see how closely the particle they've discovered resembles the Higgs boson as described in the standard model. "This is *the* piece that was missing from the standard model jigsaw puzzle," says John Ellis, a theorist at King's College London. "Of course, when you find a piece from a jigsaw puzzle, you have to check that it's the one you want and not a piece from another puzzle."

First off, researchers will check the rates at which the supposed Higgs decays into various combinations of particles against the rates predicted by the standard model. In fact, physicists say, the rate for Higgses decaying into photon pairs already appears a bit high. To support such studies, CERN will postpone the end of the LHC's current run from November to February, says Stephen Myers, CERN's director of accelerators and technology. After that, the collider will undergo 20 months of repairs that should enable it to run at full design energy.

Ironically, most physicists seem to hope the new particle won't quite match the mug shot of the standard model Higgs boson. That's because strict agreement with standard model predictions would leave them with a theory that is complete, internally consistent, and devoid of any promise of new discoveries to come. Physicists would prefer a new puzzle to mull over.

In fact, they say the mere existence of the Higgs already gives them a conceptual one. In the standard model, interactions between the Higgs and the other particles ought to force the mass of the Higgs to skyrocket to a value a trillion times larger. Yet that doesn't happen. So new particles out there must somehow counteract the ballooning of the Higgs's mass, physicists suspect. A concept called supersymmetry, or SUSY, posits a heavy new partner for every known particle for exactly this reason. "In the context of SUSY, a Higgs with

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a mass of 125 GeV is just what we're looking for," Raby says, "so it gives us hope that SUSY [particles] will be found at the LHC."

Still, the new particle was spotted decaying in the ways a standard model Higgs is supposed to. And that suggests that it cannot be too radically different from that plain-vanilla version, Ellis acknowledges.

The discovery was reported on 4 July, Independence Day in the United States, and for U.S. physicists it dredges up thoughts of what might have been. The Higgs could have been spotted years ago, they say, by an even bigger atom smasher called the Superconducting Super Collider (SSC), which physicists started building in Waxahachie, Texas, in 1991. But Congress killed the uncompleted SSC in 1993, after its cost ballooned to $10 billion. "Go ahead, twist the knife," Weinberg says, when asked about the SSC. "As a theorist, I don't really care where the data comes from, but as an American I'm sad that America seems to have bowed out of this kind of science."

Even without the SSC, U.S. physicists may have gotten close to finding the Higgs. On 2 July, researchers working on data from the Tevatron at Fermi National Accelerator Laboratory in Batavia, Illinois, a collider that shut down in September 2011, reported the final data from their Higgs search. They see a 2.9-sigma signal of the Higgs decaying mainly into particles called bottom quarks.

But the glory belongs to Europe. "It's a historic day," CERN Director General Rolf-Dieter Heuer told *Science* at the seminar. "We've been waiting for 50 years for this. That's the lifetime of a physicist." Physicists hope that the next, even bigger discovery will come within a few months or years. The survival of their field may depend on it.

–ADRIAN CHO

FUKUSHIMA MELTDOWN

Commission Spreads Blame for 'Manmade' Disaster

TOKYO—A powerful commission set up by Japan's parliament last week blamed Tokyo Electric Power Co. (TEPCO) and government regulators for what it called the "manmade" disaster at the Fukushima Daiichi Nuclear Power Plant. As the conclusions of the hard-hitting report sank in, Japan's scientific community pondered its responsibility in failing to provide sound advice to the government and the public during the crisis. "The scientific community at large lost some trust," commission chair Kiyoshi Kurokawa, a medical doctor and former president of the Science Council of Japan, told *Science*.

The powerful earthquake and tsunami on 11 March 2011 left the plant's reactors without power to cool their nuclear fuel, leading to multiple meltdowns and massive radiation releases that forced the evacuation of 150,000 people. Fukushima was an accident waiting to happen, the commission found. "There were many opportunities for taking preventive measures prior to March 11. The accident occurred because TEPCO did not take these measures," its report states, noting that upgrades needed to fix identified deficiencies in the plant's seismic and tsunami resistance were never carried out. In a strongly worded preface, Kurokawa blamed Japanese culture for "our reflexive obedience; our reluctance to question authority; our devotion to sticking with the program; our groupism; and our insularity."

According to the commission, the saga shows the dangers of "regulatory capture," in which an agency acts on behalf of the industry it oversees instead of representing the public interest. The Nuclear and Industrial Safety Agency, a part of the economy ministry that promotes nuclear energy, allowed TEPCO to delay upgrades and ignore problems, the report found. Vulnerabilities identified at Fukushima raise questions about the rest of Japan's nuclear facilities, commission member Katsuhiko Ishibashi, a professor emeritus of seismology at Kobe University in Japan, said at a press briefing last week. "The seismic resistance of every nuclear power plant in Japan needs to be investigated," he said.

"The scientific community at large lost some trust."

—KIYOSHI KUROKAWA, COMMISSION CHAIR

The industry was also overconfident in its own expertise. The commission claims in its report that because of a "not invented here" attitude, neither the power companies nor regulators learned any lessons from the Three Mile Island nuclear power plant accident in the United States or from the Chernobyl disaster in Ukraine. The commission called this attitude an example of the closed nature of the entire nuclear industry, including its academic experts.

That analysis exposed what some see as another shortcoming of the scientific community. "There was always a very strong separation between nuclear and other scientists," says Hiroyuki Yoshikawa, an engineer and former president of the University of Tokyo. The split, which goes back to the 1960s when the government was pushing to jump-start nuclear power through imported technology, means that scientists have had little input into the nation's nuclear energy policies, and its nuclear engineers were cut off from advances in related fields that might have improved reliability and safety, Yoshikawa says. It is an example, he says, of how "there is not very good communication between scientists and the government."

The commission calls for the creation of an independent and professional nuclear regulatory body. Kurokawa thinks that the proposed agency's independence could be bolstered if the Science Council of Japan nominates candidates to head it. That, he says, would be an opportunity for scientists to engage with society.

Yoshikawa would like to go further. He is urging the government to establish the post of science adviser to the prime minister. He would also like to see the advisory Council for Science and Technology Policy revamped to take on the added responsibility of providing scientific input to health, energy, and industrial policies. With tens of thousands of Japanese still unable to return to their homes and the damaged reactors in a fragile state, the need for sound scientific advice is more urgent than ever.

–DENNIS NORMILE

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Higgs Boson Makes Its Debut After Decades-Long Search
Adrian Cho (July 12, 2012)
Science **337** (6091), 141-143. [doi: 10.1126/science.337.6091.141]

Editor's Summary

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