

Chasing the Higgs

By Dennis Overbye

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Meyrin, Switzerland — Vivek Sharma missed his daughter.

A professor at the University of California, San Diego, Dr. Sharma had to spend months at a time away from home, coordinating a team of physicists at the Large Hadron Collider, here just outside Geneva. But on April 15, 2011, Meera Sharma's 7th birthday, he flew to California for some much-needed family time. "We had a fine birthday, a beautiful day," he recalled.

Then Dr. Sharma was alerted to a blog post. There it was reported that a rival team of physicists had beaten his team to the discovery of the Higgs boson — the long-sought "God particle."

If his rivals were right, it would mean a cascade of Nobel Prizes flowing in the wrong direction and, even more vexingly, that Dr. Sharma and his colleagues had missed one of nature's clues and thus one of its greatest prizes; that the dream of any physicist — to know something that nobody else has ever known — was happening to someone else.

He flew back to Geneva the next day. "My wife was stunned," he recalled.

He would not see them again for months.

Dr. Sharma and his colleagues had every reason to believe that they were closing in on the Great White Whale of modern science: the Higgs boson, a particle whose existence would explain all the others then known and how they fit together into the jigsaw puzzle of reality.

For almost half a century, physicists had chased its quantum ghost through labyrinths of mathematics and logic, and through tons of electronics at powerful particle colliders, all to no avail.

Now it had come down to the Large Hadron Collider, where two armies of physicists, each 3,000 strong, struggled against each other and against nature, in a friendly but deadly serious competition.

In physics tradition, they were there to check and complement each other in a \$10 billion experiment too valuable to trust to only one group, no matter how brilliant and highly motivated.

The stakes were more than just Nobel Prizes, bragging rights or just another quirkily named addition to the zoo of elementary particles that make up nature at its core. The Higgs boson would be the only visible manifestation of the Harry Potterish notion put forward back in 1964 (most notably by Peter Higgs of the University of Edinburgh) that there is a secret, invisible force field running the universe. (The other theorists were François Englert and Robert Brout, both of Université Libre de Bruxelles; and Tom Kibble of Imperial College, London, Carl R. Hagen of the University of Rochester and Gerald Guralnik of Brown University.)

Elementary particles — the electrons and other subatomic riffraff running around in our DNA and our iPhones — would get their masses from interacting with this field, the way politicians draw succor from cheers and handshakes at the rope line.

Without this mystery field, everything in the universe would be pretty much the same, a bland fizz of particles running around at the speed of light. With it, there could be atoms and stars, and us.

Leon Lederman, the former director of the Fermi National Accelerator Laboratory, or Fermilab, in Illinois, where the boson was being sought, once called it “the God particle,” scandalizing his colleagues but delighting journalists, who kept using the name. Dr. Lederman later said that he wanted to call it the “goddamn particle.”

The “Easter Bump Hunt” of April 2011, as it came to be called, was only one episode in a roller coaster of sleepless nights, bright promises, missed clues, false alarms, euphoria, depression, gritty calculation, cooperation and envy, all the tedium and vertiginous notions of modern science.

On the way to fulfill what they thought was their generation’s rendezvous with scientific destiny, the physicists dangled from harnesses in hard hats to construct detectors bigger than apartment buildings in underground caverns. They strung wires and cranked bolts to coax thousand-ton magnets to less than a thousandth of an inch of where they needed to be. They wrote millions of lines of code to calibrate and run devices that would make NASA engineers stand by the track with their hats in their hands in admiration.

In their down time, they proposed marriage and made rap videos in the tunnels where subatomic particles collided. They ate, slept and partied, threw snowballs and worried that an unguarded smile in the cafeteria or a glance at a friend’s laptop could bias a half-billion-dollar experiment or give away cosmic secrets.

Maria Spiropulu, a professor at the California Institute of Technology, put it this way in an e-mail, “The experiments are very large collaborations and they have the good, the bad, the crooks, the Sopranos, the opportunists — a prototype of the world as we know it.”

August 2010

Promised Fireballs

Everybody agreed that the Large Hadron Collider was the last stand in the hunt for the Higgs boson. Circling for 17 miles underneath the complex of aging postwar buildings outside Geneva (and out into France) that constitute the European Organization for Nuclear Research, or CERN, the collider was designed to accelerate the subatomic particles known as protons to more than 99 percent of the speed of light — an energy of seven trillion electron volts — and crash them together.

The resulting tiny fireballs would recreate temperatures and densities that prevailed when the universe was only a trillionth of a second old. This was unexplored territory, and anything could happen, including — about once in every four billion collisions, according to theoretical calculations — a Higgs boson. To record it all, the two teams erected detectors, mountains of wire and computers, on opposite sides of the underground ring to capture the collisions.

“Either we find the Higgs boson, or some stranger phenomenon must happen,” said Fabiola Gianotti, a CERN scientist who led one of the groups, named Atlas. Their rival was called CMS. Both were named after their gigantic detectors. (Two other detectors, named Alice and LHCb, were built to investigate more specialized physics at the collider.)

The collider, 15 years and \$10 billion in the making, was first turned on in September 2008. Then, just a week later, a section of it blew up when some electrical circuits proved unable to handle the currents needed for the giant superconducting magnets that steered the protons. Repairs took a year and a half; in March 2010, the collider started up again at half power to avoid stressing the circuits.

When I visited in August 2010, Dr. Gianotti’s desk on the fourth floor of a new building a stone’s throw from the main CERN cafeteria was as sleek and uncluttered as an aircraft’s wing, the few papers on it arranged with geometrical precision. A slender woman with dancing eyes, Dr. Gianotti gave the impression of being as graceful and strong as piano wire. She needed all of that.

As the spokeswoman for the Atlas collaboration, Dr. Gianotti, then 46, was the nominal herder of 3,000 putative Einsteins, the orchestrator of a hive mind of brilliance — responsible for getting all the trains to run on time; for all the calibrations and simulations to match; for all the physicists, from the computer analysts who massaged the final data to anyone who ever wielded a screwdriver in the detector cavern, to sign off on the results from those fireball collisions.

That made Dr. Gianotti the most visible woman in high-energy physics, a field notoriously laden with testosterone. Journalists always asked about that, but it was no big deal, she said, adding that a quarter of the Atlas collaborators are women — so many that on occasion she had gone out and recruited men to attend management meetings.

Growing up in Milan, Dr. Gianotti had been fascinated by philosophy. Seduced into physics by reading some of Einstein's early work, she had taken two years off to study piano at the Milan Conservatory before getting a Ph.D. at the University of Milan in subnuclear physics in 1989 and joining CERN.

"Music is always in my mind," she reflected one night, in lightly accented English, as we were driving home from dinner. Asked what kind, she punched a button on the CD player, and the car suddenly filled with Schubert — "the most romantic of the classicists and the most classic of the romantics," she said.

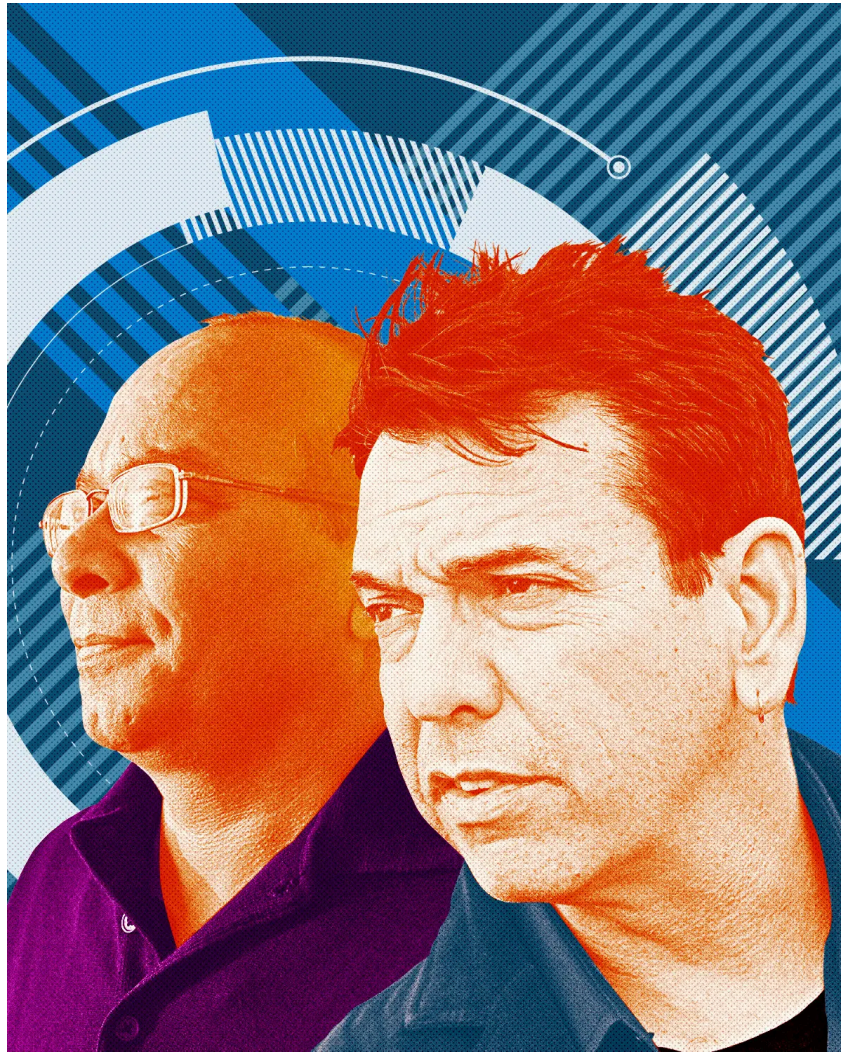
At her desk, Dr. Gianotti was all business. She had made her mark working on liquid argon calorimeters, devices that could measure the energies and tracks of particles. Now she said she sometimes missed the chance to get her own hands dirty.

But then she gestured to the papers awaiting review on her desk.

"There is no typical day," she said, ticking off a list of meetings. "My days are very full, this is for sure. I think they are wonderful."

Asked what made her a good spokeswoman, Dr. Gianotti replied that it was her cheerfulness. Alluding to the explosion and shutdown, she said, "People in a difficult time want to see you are confident and optimistic." Now, she added, "You can see the excitement in their eyes."

Just down the hall was Dr. Gianotti's opposite number and rival of sorts, Guido Tonelli, 63, an ebullient professor from the University of Pisa, newly installed as the spokesman of the CMS collaboration. The Atlas and CMS teams shared the same building, facing each other over an atrium covered with posters of their devices and a coffee bar, using the same printers — and sometimes, the joke went, sleeping with one another.



Vivek Sharma, left, who coordinated for the CMS team, and an Atlas counterpart, Eilam Gross. The two teams were intended to complement and challenge each other. Sean McCabe/Photographs by David Ahnholz and Michal Czerwonka for The New York Times

Dr. Tonelli was the third physicist to head the CMS team and perhaps the one who had traveled the longest road. The son of a farmer and a railroad worker, he had grown up in Pisa and was the first of his family to attend college — a result of effort and sacrifice “that I have tried to reward doing my best in the studies first and in my work later.”

He confessed that he had helped his own cause back then by allowing his professors to believe (incorrectly) that he was related to Leonida Tonelli, a distinguished mathematician whose statue stands near the university’s entrance. Guido Tonelli’s CERN office was dominated by a large poster of his daughter, a ballerina.

Dr. Tonelli had his heart set on discovering the Higgs boson, which he said was crucial to understanding the future as well as the past: measuring it could help determine whether the universe was stable or whether the Higgs field could twitch and dissolve us all back into that bland soup of massless particles.

December 2010

Game of Bumps

Dr. Tonelli described his job as the search for anomalies.

For all their equipment and brainy multitudes, physicists would never be able to hold the Higgs boson in their hands. As soon as it was created, it would disintegrate in a shower of lesser particles — sometimes, for example, in a flash of gamma rays, or into a spray of lightweight particles.

So the signature of a Higgs boson or any other paradigm-shattering new particle would be an unexpected excess of gamma rays or some other particles — an anomalous bump on a graph. Dr. Tonelli said this happened about once a month now that the collider was running, but random flukes would also produce bumps.

If they were flukes, more data would make them fade into the statistical background, just as a flipped coin will eventually revert to an equal number of heads and tails. If not, the bumps would grow in slow motion into a bona fide discovery.

To physicists, the gold standard for a discovery is “5-sigma,” a term meaning that the odds it occurred by chance are less than 1 in 3.5 million.

So “we crosscheck everything” and “try to kill” any anomaly that might be merely random, Dr. Tonelli said. Ninety-nine percent of the time, that is just what happens.

“But you never know when one of them will change everything,” he said, adding, “Those have been the most exciting, intense days of my life.”

In a perfect world, the same 5-sigma answer would emerge from each group independently and simultaneously. But each wanted to be first, if only by a hair: neither wanted to be the team that failed to flag a bump that eventually grew to a major discovery, or the one that jumped too soon on a fluke and wound up looking foolish. On each side, there were hundreds of physicists monitoring the different ways in which the Higgs or something else could show up.

In December 2010, Dr. Tonelli heard a rumor that his team’s rivals in Atlas were chasing an auspicious bump that would be an even bigger deal than the Higgs: an unexpected massive new particle.

“This would be totally new physics,” Dr. Tonelli said.

Dr. Tonelli put together a “quick reaction team” to check out its own data. “After a few days of frantic crosschecks we concluded there was nothing there,” he said.

He said he was later told by an Atlas member whose name he cannot recall that the Atlas investigators had been encouraged by a plot from his own CMS team. It was shown during a workshop in Germany, and there was a small bump on it. Had Dr. Tonelli and his colleagues been chasing their own tail?

An Atlas physicist, Gustaaf Brooijmans of Columbia University, said that he vaguely remembered seeing a CMS plot, but that Atlas had undertaken the study in question of its own accord.

On another occasion the following year, another bump — implying the existence of a massive new force particle — had Dr. Tonelli and his colleagues convinced for a couple of months that they had discovered evidence of extra dimensions of space time. They notified the director general of CERN and drafted a paper — never published — describing the discovery. And then the signal faded like an old tied balloon.

“We’ve made many discoveries,” Dr. Tonelli said, “most of them false.”

Spring 2011

The Easter Egg Hunt

The biggest false alarm, one that went around the world, came from Atlas.

For Sau Lan Wu, of the University of Wisconsin by way of Hong Kong and Vassar, the Higgs boson was unfinished business. She was one of a handful of scientists who thought they were seeing the evidence of the Higgs back in 2000 in data from an earlier CERN collider called LEP. Unconvinced, CERN shut that collider down so the Large Hadron Collider could be built in its place. In the spring of 2011, Dr. Wu thought she had found the Higgs again.

A cheerful and controlling presence, partial to wearing red, Dr. Wu thinks of herself as a mother to the 47 former students and postdoctoral fellows whose portraits line the hallway outside her CERN office. As a young postdoc at M.I.T. in 1974, she had helped Samuel Ting win a Nobel Prize for discovering the J/psi, a particle that was the last big surprise in physics, and later was co-discoverer of the gluon, the particle that holds quarks together in protons.

Dr. Wu’s team in Wisconsin was the first American group to join the Atlas collaboration, back in 1993. When the collider was restarted, they had hit the ground running. By Easter 2011, they had detected a telltale excess of gamma rays, pointing to the same Higgs she and others had thought they were discovering 10 years earlier.

Even more provocatively, Dr. Wu’s gamma-ray signal was much stronger than theory predicted, suggesting that on its way to oblivion the Higgs had temporarily changed into other massive particles yet unknown to science, a discovery that could dwarf that of the boson and shake not just physics but cosmology.

Her group wrote a short paper, an “internal note” to alert their Atlas colleagues, suggesting “that the present result is the first definitive observation of physics beyond the standard model.”

Their note was supposed to be confidential — results are not supposed to be released to the outside world until the entire collaboration has checked and approved them — but within hours the note's abstract was posted in the comments section of a physics blog, Not Even Wrong, run by Peter Woit, a mathematician at Columbia.

Bedlam ensued in the physics world. Dr. Sharma and hundreds of other physicists abandoned their families and canceled vacations to go back to CERN.

The aftermath, when the signal turned out to be another fluke, was brutal. It was suggested that whoever was responsible for leaking the report should leave the Atlas collaboration.

Many physicists, Dr. Wu admits, thought that she herself had leaked the report. A year and a half later, she still found it hard to talk about the Easter event.

"I was so excited I couldn't control my emotions," Dr. Wu recalled. She wrote the note as a way of alerting the Atlas community, she said. "I thought CMS would go on vacation and we could get ahead. I'm sorry I did that."

For Dr. Gianotti, the incident was a lesson in the need for keeping your mouth shut, helping to cement her distrust of bloggers. "Things should be properly understood inside the collaboration before being blogged outside." Still, "things happen in life," she added. "My attitude is always positive."

For CMS, the incident served as what Dr. Sharma called "a good drill."

Dr. Tonelli said: "In retrospect, this fear of being scooped by Atlas was useful. Once you are under attack, you start to focus."

July 2011

Still Missing

Thus tested, both collaborations began drinking from a fire hose of data as the collider kept racking up collisions by the hundreds of trillions. In the early summer of 2011, both Atlas and CMS began recording a surplus of W bosons, particles that carry the so-called weak nuclear force that drives radioactive decay. That was another telltale sign of the Higgs. On the eve of a big conference in Grenoble, France, Dr. Sharma, of CMS, and Bill Murray, of Atlas, held a summit meeting in the CERN cafeteria and opened their laptops.

"I showed mine, and he showed his," Dr. Sharma said. "We had many coffees."

Dr. Murray recalled: "Bang! It's all looking good."



Left, Rolf-Dieter Heuer, director general of CERN, and Bill Murray, deputy physics coordinator for Atlas. The teams encountered several false “bumps” in the data. Illustration by Sean Mccabe/Photograph by Daniel Auf der Mauer for The New York Times

The results were reported at the Grenoble conference with great hoopla.

But by the next big conference a month later, in Mumbai, India, the bump was gone.

Dr. Murray said, “It was bizarre: twice as much data and there was nothing.”

This was beginning to be the story of the Higgs.

Physicists already knew by the time the CERN collider started up that if the Higgs existed, it would be found in a narrow window of possible masses — equivalent to 115 billion to 200 billion electron volts of energy. Their task was to sort through that window, looking for the telltale excess, or bump, like a sports fan scanning the radio dial in his car looking for the Yankees broadcast.

By the fall of 2011, most of that window had been ruled out, and physicists worried that the whole window might be closed by the end of the year, meaning that the Higgs, or at least the simplest version predicted by the theorists, did not exist — and sending theorists back to their blackboards in search of a better understanding of our origins.

Paradoxically, many physicists, including Dr. Sharma, who admitted to an “anarchic tendency,” found that prospect thrilling.

The Higgs boson fit like a key into a lock into the Standard Model, a suite of equations that was a battle-tested explanation of most of the forces of nature. But physics, Dr. Sharma explained, advances on surprises.

“Every measurement I’ve made in my career has been in confirmation of the Standard Model,” he grumbled.

For Dr. Tonelli, however, it was a dark time. He recalled being at a conference in November where a theorist had summarized the situation by showing a “terrible slide” of a grave with the name Higgs on it. “Since Peter was 83,” he said of the physicist from whom the boson takes its name, “that was not a good idea.”

October 2011

Too Big to Ignore

In the fall, there was a changing of the guard in Atlas. Eilam Gross, a former rock musician complete with earring and a Lou Reed haircut, from the Weizmann Institute of Science in Israel, joined Dr. Murray as co-convenor of the Higgs search, filling in for a colleague who was going on maternity leave.

Dr. Gross had followed an unlikely route to this mission. After serving in the Israeli military as an intelligence officer, he was studying sound engineering in New York when he happened to read “The Tao of Physics,” by Fritjof Capra, a popular book melding physics and Eastern thought.

He dropped everything and went back to Israel, studied string theory at the Hebrew University of Jerusalem and then moved on to experimental work, all the while trying to keep up his music career.

He became what he called a “Higgs soldier” while working on the LEP accelerator. “There are 6,000 Higgs soldiers,” he said of the Large Hadron Collider, “and they all deserve the Nobel Prize.”

He had been applying for the Higgs job in Atlas for years, and had given up until he got a call one day.

When it finally happened for him, Dr. Gross recalled expressing some trepidation about his new role. “What will I do?” he asked.

Dr. Murray told him not to worry, he was going to have the time of his life.

It didn’t take long.

While physicists fretted about the death of the Higgs, something was happening out in the wilds of uncertainty. One bump on physicists' charts, from the W bosons, was disappearing. But another was blooming like the shy girl at a dance.

In retrospect, nobody could remember exactly when she had come in. But she was the one who would marry the prince.

The bump may have appeared as early as May. It was then, Dr. Murray said, that the Atlas group had discovered an "excess" in gamma rays corresponding to a mass of about 128 billion electron volts. (By comparison, a proton, the building block of the atomic nucleus, is about a billion electron volts.) The bump corresponded to a single particle, a flake of hypothetical energy, that weighed as much as an atom of iodine.

Nobody paid any attention. "End of story," Dr. Murray said.

The bump persisted, rising and falling as data from more collisions and more channels were added, and kept being dismissed. It continued to grow over the fall until it had reached the 3-sigma level — the chances of being a fluke were less than 1 in 740, enough for physicists to admit it to the realm of "evidence" of something, but not yet a discovery.

Dr. Gianotti recalled being shown the bump during a meeting. Her reaction was characteristically guarded: "Hmm, hmm. That was nice, but let's hope."

Dr. Gross had a markedly different reaction. One evening late in November, he was in Paris at a workshop, staying at a colleague's house. After a wine-soaked meal and some grappa, he fell asleep on the couch.

While he slept, a new data analysis came in from CERN. At 3 a.m. his colleagues Marumi Kado and Alex Read decided to wake up their gently snoring boss. They asked him if he wanted to see the Higgs boson.

Dr. Gross jumped up. "What? Where?" he asked. As he described it later in a blog post, they were all in a state of shock. The bump was too big to ignore anymore.

"We couldn't believe our eyes. We looked at the screen for ages before we started to digest what we were seeing," he said. "I think this was the first time Marumi, me and Alex realized it could be the real thing."

November 2011

Oozing Into View

On the other side of the wall of (mostly) silence between the teams, a signal was also oozing into view.

Dr. Tonelli, of CMS, saw it first on Nov. 8. He was making his rounds, talking to his young recruits. In the morning, one group showed him a pair of events that had resulted in a spray of four light particles, a rare "four-lepton" signal. That was one of the signature

ways that a Higgs boson would dissolve.

That afternoon he met with a second group in the cafeteria. One of them opened a laptop and showed him a bump in the gamma-gamma channel, the other big Higgs decay channel. It was almost 3-sigma and was at the same energy as the morning bump, about 125 billion electron volts.

“At the end of the meeting, there was some light in their eyes,” he said. “It was my birthday. I considered it a sort of gift.”

The following week, at a meeting in Paris, some people were still talking about the death of the Higgs. Dr. Tonelli was one of the few people in the world who knew differently.

“I was laughing internally,” he said.

Dr. Sharma, of CMS, went home for Thanksgiving and a long-awaited reunion with his family.

In his pocket as he ate was a new plot combining the results from both channels, a new bump indicating a Higgs boson at 125 billion electron volts. A neighbor pestered him with questions about the search, but Dr. Sharma wouldn't talk.



Eilam Gross proposed to his girlfriend, Talia Levy Tytium, in the Atlas cavern at CERN in March 2012. Claudia Marcelloni de Oliveira

A year earlier, many of his colleagues had been ready to write off the Higgs boson, and with it the Standard Model. But “on Thanksgiving Day,” he said, “we knew the jig in some sense was up.”

“I would have preferred it the other way,” he said with a sigh, then added: “I knew before the rest of the world. That is all I need.”

Afterward he marveled at how attitudes toward physics had changed from a few years earlier, when some people feared the new collider would destroy Earth. That and the “God particle” talk had gotten the public’s attention, he had to admit: “Once neighbors find out that Sharma is involved in that black hole thing, the dog doesn’t pee in my yard anymore.”

Dec. 13, 2011

The Long Hello

Neither Atlas nor CMS knew what the other had until Nov. 28, when the two team leaders, Dr. Gianotti and Dr. Tonelli, met with CERN’s director general, Rolf-Dieter Heuer, in his office.

It was apparent from the outset that nature had dealt Atlas the stronger hand, at least for the first round. Dr. Murray, of Atlas, felt both reassured and relieved.

“If there really is a Higgs, Atlas got lucky and CMS got unlucky,” he said.

According to Atlas, the new particle had a mass of 126 billion electron volts; according to CMS, it was 124 billion.

Neither experiment was even close to having the statistical goods — a 5-sigma level of significance — to declare a discovery. But the fact that two separate experiments were hinting at roughly the same answer was encouraging, and worth telling the world about. CERN scheduled a special seminar on Dec. 13. Dr. Gianotti, speaking through the pain of a toothache and dental surgery to an overflow crowd at CERN and physics fans everywhere clustered around Webcasts, went first.

“If we are just being lucky, it will take a lot of data to kill it,” she said.

It would also take a lot more data to confirm what was still at best a promising hint, with a 1-in-100 chance of being a fluke.

The results put the focus on the next big meeting, the International Conference on High Energy Physics, scheduled for July 4 in Melbourne, Australia, by which time the amount of data from the collider would have doubled. At the very least it would be an interesting progress report to see if the bumps were still there.

Dr. Tonelli made no bones about his belief that this was the Higgs at long last. He told Dr. Heuer, the director general, to “prepare the troops,” and his old friend Dr. Englert, a founder of the Higgs theory, not to book vacation for the beginning of July.

But the experimentalists had all seen promising bumps (and promising reputations staked on them) come and go. “I don’t see the smoking guns,” said Dr. Spiropulu, the Caltech professor. And Dr. Sharma cautioned: “The game is still on. People have to be prepared for there to be no Higgs.”

January 2012

The Mother of Everything

Characteristically, Dr. Gianotti was playing her cards close to the vest. She was less excited about the nearly overlapping bumps, she said, than about the fact that they had now managed to exclude almost the whole mass range that had existed for the Higgs only a year before. Now there was nowhere left for it to be.

“This was really important,” she said. “For me, it was clear now where we were going to focus in the next months. So no additional distractions in other mass regions.”

From now on, the rules would be different.

To avoid bias, both teams proceeded to “blind” themselves and not look at the relevant data until the Melbourne meeting. Somewhere along that time, Dr. Gianotti admitted, she had stopped playing the piano, unable to give it the focus it deserved.

In January 2012, Dr. Tonelli handed the reins of CMS to Joe Incandela of the University of California, Santa Barbara. Asked if this was a bittersweet moment to step down, Dr. Tonelli said he had been living a dream. He compared himself to the third runner in a four-man relay race, “a runner that did a fantastic time in his fraction.” He said, “I could not have asked more of my life.”

Dr. Incandela, a man with a warm, casual demeanor, was not so sure at all that the Higgs had been discovered on the previous watch.

“Every other day I think we’ve found it, and every other day I think we haven’t,” he said over lunch shortly after taking over. He described collaborations like CMS as “the last bastion of communism,” and his new job as “a crisis a day.” The group had only a month after recording the last data to analyze the results from 2011, he complained. “So much stress,” he said. “We’ll have to do it again this year.”

He firmly rejected one idea that was buzzing around the blogosphere — that by combining their results the two collaborations could take a shortcut to the 5-sigma goal. “There’s no race — this is a 20-year program,” he snapped. “This is a serious business.”

Dr. Incandela had wandered into science from the art world. Growing up in Chicago, he studied at its Art Institute, intending to be a sculptor. He got interested in science while studying the chemistry of ceramics, went on to get a Ph.D. from the University of Chicago, and then worked at CERN and Fermilab, where in 1995 he helped discover the top quark, the last missing matter particle in the Standard Model.

He brought with him a deeply philosophical and historical viewpoint on the quest to understand nature. The Higgs boson reminded him of the ancient Stoic notion of “pneuma,” a sort of force or tension that permeated space and gave substance to things. It was the first example in history of people wondering about the origin of mass.

“The Higgs is sort of like the mother of everything,” he said. “It tells you something very fundamental about the entire universe. So measuring its mass, for instance, could tell us whether the universe is stable or not. This is really unbelievable if you think about it.”

“So that tells you how deeply we’ve touched into this fabric,” he went on, “and this fabric is everywhere. Throughout the universe. So for me that is a really profound thing about the Higgs. It’s not like other particles.”

In March, adding to the sense of momentum that the Higgs was finally being run to earth, physicists from Fermilab said they had measured their own bump in data from the lab’s Tevatron collider, which had been the world’s biggest for 20 years but had shut down for good the previous fall because the government couldn’t afford to run it anymore. As at CERN, there had been two groups and two detectors who were now combining their data for what would amount to a last hurrah and a what-might-have-been for the Tevatron. The Fermilab physicists had found a broad hump in their data, between 115 billion and 135 billion electron volts — the same general area as the CERN results.

Dmitri Denisov, a leader of the Fermilab effort, wrote in an e-mail at the time, “It is clearly not the answer to crossword, but an important piece of the puzzle!”

The data were of scant statistical significance, however, having a chance of about 1 in 100 of being a fluke. Over the following weeks, Fermilab would improve those statistics to a chance of 1 in 550, heartbreakingly short of the 3-sigma criteria required to claim “evidence” of the Higgs. If there really had been a race, one of the contestants was now out.

Back in Switzerland that same month, during a break when the Large Hadron Collider was not running, Dr. Gross took his girlfriend, Talia Levy Tytiun, down into the Atlas cavern. “I decided that I want to propose to Talia in the place which was the symbol of my life at this Higgs hunting period,” he explained.

“But believe me, I checked a thousand times with her before to make sure she will say yes.”

June 2012

Opening the Box

On June 18, the two experiments stopped recording data in order to get ready for Melbourne. By then they had already collected as many collisions — some 400 trillion — as they had the entire previous year.

The Atlas teams had already begun analyzing the first batch of this data a week before. Dr. Gianotti was at a conference at Fermilab when her colleague Dr. Kado sent her a plot of the new data.

The gamma rays were still there, and had grown in significance, putting the boson on the verge of reality. Dr. Gianotti scrawled a note back: "Oh, my God."



On July 4, 2012, CERN erupted in celebrations after both teams announced they had discovered a Higgs-like boson. Over its life, the project involved 6,000 physicists and cost more than \$10 billion. Dr. Natalia Panikashvili

A week later, her team looked at another important decay channel, and her enthusiasm deflated. There was nothing. She spent a few days and nights with her "neurons spinning," she recalled, wondering how they could have been fooled.

In the next two batches of data, however, nine candidates showed up in the "zed" channel, as they called it. "It was just beautiful to see those," Dr. Gianotti said.

At 10 p.m. on June 14, small teams of CMS physicists began "opening the box" on their data. Later that night, Dr. Incandela received a plot from the so-called 4-lepton channel, showing a spike at 124 billion electron volts.

He later told the writer Ian Sample that his life changed at that moment.

That afternoon, almost 300 physicists crowded into the room to hear talks on the first results of the unblinding, and the entire collaboration learned that the Higgs was nigh. People were sitting on the floor and standing, Dr. Tonelli said. Another 307 people had linked in by videoconference.

The room was too hot, all the doors had been opened. Dr. Tonelli said, "Everybody was really feeling we were doing something important."

On June 22, Dr. Heuer announced that there would be a special symposium at CERN on the morning of July 4, the day the Melbourne meeting was to start. Scientists who had already bought tickets to Australia rushed to rebook.

At the time, it seemed like a gamble: neither experiment had yet reached the all-important 5-sigma level.

But as various scientists were pointing out, CERN couldn't go on almost discovering the Higgs boson forever. Some said CERN should just shut up until the discovery was official.

"If you only have 4.9 you are not allowed to call it a discovery," Dr. Heuer said later. "But it was sure that even if being short of 5-sigma, if I see both experiments I can still call it a discovery because we are beyond 5 if we combine the two."

The members of each of the collaborations had to approve anything that was to be presented at Melbourne, which meant that their leaders had a week to mobilize an army and read a thousand pages of papers and reports.

Dr. Incandela, of CMS, said he felt "like a hunted animal."

"I felt tremendous stress, obviously, because things were very tight," he recalled. "Several times per day, I would just say, 'O.K., don't panic, we're going to make this.' But my goal was to make sure we did everything right, and that the collaboration would not regret it, and that the collaboration would all feel part of it, because everyone worked on this in one way or another."

In a conference room near his office, he set up a SWAT team of a dozen of his brightest young analysts, his "kids," as he called them. "Keep your smiles to yourself," he warned them, if they happened to find themselves in the company of their rivals.

On the night of June 24, the graduate students and postdocs in Atlas were tiptoeing toward the 5-sigma finish line. Among them was Sven Kreiss, a New York University graduate student who got a preliminary glimpse of the answer alone in his office late that night when, as part of a crosscheck, he combined the data from two signatures of the Higgs decay and found the result breached 5-sigma. The next day he sent a plot to his adviser Kyle Cranmer, whose birthday it was, saying he had a present for him.

Dr. Cranmer shot back a joyful expletive worthy of the discovery of a sacred particle.

The job of ultimately confirming the boson's discovery had been entrusted to another pair of graduate students, Haoshuang Ji, a Wisconsin student, and Aaron Armbruster of the University of Michigan — who had sent the plot that Dr. Gross had woken up to in

November. They were each working to combine all the Higgs data from all the myriad ways it could fall apart and leave a trace in the detectors. This calculation would make or break the Higgs, because the boson had to behave properly in all its guises.

On the afternoon of June 25, Mr. Ji announced he had gotten a result of 5.08 sigma, causing cheers to go ringing down the corridor outside Dr. Wu's office; everybody ran to sign the printout. The next day, Mr. Armbruster arrived at the same result.

Atlas was at 5-sigma.

The scorecard, as later enumerated by Dr. Wu:

1,000 trillion proton-proton collisions

240,000 Higgs bosons

350 pairs of gamma rays

8 sets of lightweight particles from the lepton channel.

From this trickle of a trickle of atomic pitter-pat, 6,000 physicists had finally started to put a face on the ghost of the vacuum, the secret controller of cosmic destiny.

Filling in that face could take years. Not knowing yet how closely the new particle matched the predictions of the Standard Model, the physicists took to calling it a "Higgs-like boson." Or as Dr. Cranmer put it, "Not a God particle but a God-like particle."

"We don't know what nature has prepared for us," Dr. Gianotti said.

She added, "Clearly if we had not discovered the Higgs boson it would have been much more intriguing from a physics point of view. But it is so nice to find a new particle."

On the eve of the scheduled announcement, Dr. Incandela rehearsed his talk and found that his team was still nervous. Were they ready to go public? It was too late, he told them. They were at 5-sigma. The train had left the station. "We have to stand by our data," he said.

Later, he said it was what they needed to hear.

July 4, 2012

Champagne and Pandemonium

CERN officials locked their auditorium three days before the special symposium to prevent people from camping out in it. Still, the night before, students and scientists began sleeping on the steps. Dr. Higgs and the other founders of the Higgs theory, Dr. Englert, Dr. Hagen and Dr. Guralnik walked into the auditorium on the morning of July 4 to a standing ovation.

Dr. Incandela finished writing his talk at 8:42 that morning. The seminar started at 9. When he walked in, he recalled, "I was just so happy that everything came together — I really enjoyed giving the talk."

At one point, he noticed that the hand holding a laser pointer was shaking. "It was just the adrenaline," he said. "My heart was pounding."

At the end, he flashed a plot of CMS's final data analysis, showing the big new bump. The room exploded in applause.

He thanked CERN and the world. "These results are global," he said, "and now shared with all of mankind."

Dr. Gianotti, of Atlas, now had to follow Dr. Incandela, having gone first in December. After the news from CMS, she wondered if anyone would even be interested in what she had to say. "I'm saying to myself, 'Well, even if our results were essential, in some sense they will be nothing new compared to what they've seen already.' "

If nothing else, she thought, her talk would be a valentine to the passion and competence of the 3,000 Atlas scientists.

"Every slide was a reward to the work of many, many people," she said. "So I was feeling so proud."

"And I think I got the energy from the eyes of some of my Atlas colleagues who were sitting here in the auditorium," she added. "The fact that they were looking at me with such intensity and attention was giving me really the strength to go on."

When she showed the Atlas 5-sigma result, the audience exploded again. The applause seemed to go on forever. It had been left to Dr. Heuer to declare officially that a new particle had been discovered.

"I think we have it," he said. The cheers began again. Dr. Higgs was seen wiping away tears.

The morning dissolved into pandemonium and Champagne, in the CERN auditorium and in labs, classrooms, conference rooms and living rooms in every time zone in which humans wondered about their universe. Dr. Wu waded through the crowd. She hugged Dr. Higgs.

"I've been looking for you my whole life," she said.

"Well," he replied, "now you have found me."

A correction was made on March 5, 2013: Because of an editing error, an earlier version of a photo caption with this article misstated the temperature of the cooling system around the accelerator ring at CERN. It is -456 degrees Fahrenheit, not -520 degrees.

A correction was made on March 8, 2013: An article on Tuesday about the search for the Higgs boson misidentified, at one point, the group for which a physicist, Vivek Sharma, works. As the article correctly noted elsewhere, Dr. Sharma works for CMS, not for Atlas.

When we learn of a mistake, we acknowledge it with a correction. If you spot an error, please let us know at corrections@nytimes.com. [Learn more](#)

A version of this article appears in print on , Section D, Page 1 of the New York edition with the headline: Chasing the Higgs