Particle Fever

A Teacher Guide for Middle and High School

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Discovery of the Higgs Boson. Courtesy of CERN.Retrieved from http://particlefever.com.

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OVERVIEW

Particle Fever is a feature length documentary film about people who do science. While much science is revealed in the film, its real topic is *doing* science, *enjoying* science, and the kinds of people who devote their careers to science. The film follows seven scientists and engineers for up to six years, leading up to the dramatic discovery in 2012 of a long-sought sub-atomic particle, the Higgs boson, which had been predicted almost 50 years earlier, in 1964.

What makes *Particle Fever* so appealing for classroom use is its focus on the people and the process of doing science, not just on explaining deep and complex ideas. Students in middle and high school may never have met a practicing scientist, but they have certainly seen scientists portrayed in science fiction films, and horror movies, mostly as thoughtless villains or individuals undertaking dangerous experiments with little care for the great damage they may do. Stereotypes of scientists (discussed in this Guide) are common and mostly negative. *Particle Fever* provides a fascinating and exciting antidote to these negative images.

This Teacher guide will examine 8 themes treated in the film. There is no particular order to the themes as described in the Guide; teachers know best which fit into their classroom plan, and in what order. Nearly all of the themes in the Guide are directly related to key components in the *NRC Framework for Science Education, K-12,* the source document for the *Next Generation Science Standards.* These same themes will be found in nearly every 21st Century science standards, world-wide. For most of the themes we identify passages in the film which demonstrate the theme, quotations from the film which illustrate particular ideas, and questions for discussion with students, which could be used as homework assignments, in-class debates or expositions, or even embedded assessment items in a course.

This Teacher Guide can be used in a number of ways. One is simply to read through the guide and make note of questions to ask, to help your students focus on the most important ideas and ways of thinking. Another is to copy some of the themes to share with your students to read the night before they see the film, or to think about the day after. You can do this either with paper copies, or if all of your students have tablets or computers, by providing them with a PDF file of this guide. In some cases it is helpful to refer to one of the illustrations in this guide in class, in which case you could connect your computer to a projector and project the relevant page or illustration as a focal point for class discussion. We recommend that, rather than focusing solely on one theme, students have an exposure to all themes. This needn't occur at one time but can be sprinkled throughout a course in physics as a way to remind students of the film, the nature of science and the culture of science.

Particle Fever and the Next Generation Science Standards

Particle Fever's release coincides with the publication of a new set of science education standards that are just starting to be introduced in many states. Even states that choose not to adopt the Next Generation Science Standards (NGSS) in toto are adopting standards that are similar in many ways. The NGSS is based on a prior document released in 2012 by the National Research Council, called *A Framework for K-12 Science Education: Practices, Core Ideas, and Crosscutting Concepts*. The Framework established the important idea that students need to learn the practices of science, engineering and technology, as well as certain crosscutting concepts that are true of all sciences. These practices and crosscutting concepts thread throughout the NGSS, and teachers and students are expected to learn these essential ideas in the years to come.

The scientific ideas in *Particle Fever*—the Standard Model of matter and the entire field of high energy particle physics, goes well beyond what all students are expected to learn in grades K-12. However, the practices of science and engineering and crosscutting concepts are very well illustrated by the film. So teachers who are interested in presenting these ideas to their students can use the film as a vehicle for doing so, while also presenting science as an ongoing enterprise Following are quotes from the *Framework* (with page references) that highlight the educational ideas that underlie each of the themes.

Theme 1: Big Science

Discussions involving the history of scientific and engineering ideas, of individual practitioners' contributions, and of the applications of these endeavors are important components of a science and engineering curriculum. For many students, these aspects are the pathways that capture their interest in these fields and build their identities as engaged and capable learners of science and engineering (p. 249)

The ability to examine, characterize, and model the transfers and cycles of matter and energy is a tool that students can use across virtually all areas of science and engineering. And studying the *interactions* between matter and energy supports students in developing increasingly sophisticated conceptions of their role in any system. However, for this development to occur, there needs to be a common use of language about energy and matter across the disciplines in science instruction. (p. 95)

Theme 2: Being a Scientist Today

We now know, as discussed in the previous section, that the pursuit of equity in education requires detailed attention to the circumstances of specific demographic groups. When appropriate and relevant to the science issue at hand, standards documents should explicitly represent the cultural particulars of diverse learning populations throughout the text (e.g., in referenced examples, sample vignettes, performance expectations). Similarly, an effort should be made to include significant contributions of women and of people from diverse cultures and ethnicities. (p. 288)

Theme 3: The Experiment

Scientists and engineers investigate and observe the world with essentially two goals: (1) to systematically describe the world and (2) to develop and test theories and explanations of how the world works. In the first, careful observation and description often lead to identification of features that need to be explained or questions that need to be explored. The second goal requires investigations to test explanatory models of the world and their predictions and whether the inferences suggested by these models are supported by data. (p. 59)

Theme 4: Developing and Testing Models

Models can be evaluated and refined through an iterative cycle of comparing their predictions with the real world and then adjusting them, thereby potentially yielding insights into the phenomenon being modeled. (p. 57)

Because science seeks to enhance human understanding of the world, scientific theories are developed to provide explanations aimed at illuminating the nature of particular phenomena, predicting future events, or making inferences about past events. . . . . Although their role is often misunderstood—the informal use of the word "theory," after all, can mean a guess—*scientific* theories are constructs based on significant bodies of knowledge and evidence, are revised in light of new evidence, and must withstand significant scrutiny by the scientific community before they are widely accepted and applied. Theories are not mere guesses, and they are especially valued because they provide explanations for multiple instances. (p. 67)

Theme 5: The Relationship Between Science and Engineering

The fields of science and engineering are mutually supportive, and scientists and engineers often work together in teams, especially in fields at the borders of science and engineering. Advances in science offer new capabilities, new materials, or new understanding of processes that can be applied through engineering to produce advances in technology. Advances in technology, in turn, provide scientists with new capabilities to probe the natural world at larger or smaller scales; to record, manage, and analyze data; and to model ever more complex systems with greater precision. In addition, engineers' efforts to develop or improve technologies often raise new questions for scientists' investigation. (p. 210-211)

Science and engineering complement each other in the cycle known as research and development (R&D). Many R&D projects may involve scientists, engineers, and others with wide ranges of expertise. For example, developing a means for safely and securely disposing of nuclear waste will require the participation of engineers with specialties in nuclear engineering, transportation, construction, and safety; it is likely to require as well the contributions of scientists and other professionals from such diverse fields as physics, geology, economics, psychology, and sociology. (p. 211-212)

Theme 6: The Human Side of Science

Not only do science and engineering affect society, but society's decisions (whether made through market forces or political processes) influence the work of scientists and engineers. (p. 213)

Considerations of the historical, social, cultural, and ethical aspects of science and its applications, as well as of engineering and the technologies it develops, need a place in the natural science curriculum and classroom. The framework is designed to help students develop an understanding not only that the various disciplines of science and engineering are interrelated but also that they are human endeavors. As such, they may raise issues that are not solved by scientific and engineering methods alone. (p. 248)

Theme 7: Science and Art

The creative process of developing a new design to solve a problem is a central element of engineering. (p. 89)

Theme 8: Scale

In thinking scientifically about systems and processes, it is essential to recognize that they vary in size (e.g., cells, whales, galaxies), in time span (e.g., nanoseconds, hours, millennia), in the amount of energy flowing through them (e.g., lightbulbs, power grids, the sun), and in the relationships between the scales of these different quantities. The understanding of relative magnitude is only a starting point.

As noted in *Benchmarks for Science Literacy*, "The large idea is that the way in which things work may change with scale. Different aspects of nature change at different rates with changes in scale, and so the relationships among them change, too" [4]. Appropriate understanding of scale relationships is critical as well to engineering—no structure could be conceived, much less constructed, without the engineer's precise sense of scale.

The DVD

For teachers who wish to show the film in sections that fit into class periods, the DVD provides the option of showing it in four parts, as described below. Although each of the parts has a title that reflects the most important ideas in that section, the film interweaves the themes tightly together, so that we learn about the experiment, the people, and the theory in each part of the film. Although we recommend showing all four parts, if it is essential to reduce the amount of class time on this topic (especially for younger students), it is possible to skip Part 3 and still have the students follow the narrative.

Part 1 The Experiment	(23 minutes) 0:00 to 22:43
Part 2 The People	(23 minutes) 22:44 to 45:14
Part 3 The Theory	(14 minutes) 45:15 to 101:57
Part 4 Success!	(37 minutes) 101:58 to 139:05

Part 1 The Experiment (23 minutes) introduces the key players, the difference between theoretical and experimental physicists, the location at CERN in Europe, and the major components and function of the Large Hadron Collider (LHC). The history of the LHC is briefly summarized, along with an effort to conduct the experiment in the United States, which was canceled by Congress. The Standard Model is introduced in a brief historical context, leading to the prediction of the Higgs boson. The introduction concludes with a frank discussion of the purpose of the experiment.

Part 2 The People (23 minutes) features the key scientists. We learn a little more about the distinction between theoretical physicists and experimental physicists, and gain insight into their personalities, interactions, and passions. We see them at work and at play. We hear about their backgrounds, how they became interested in science, and how they feel about their chosen field. We also gain perspective on how the experiment is viewed in the public media, including the prediction that the LHC will destroy the world when it is turned on. This section includes the catastrophic failure of some of the magnets, which delayed the project for several months. The section ends with musings on why we have curiosity.

Part 3 The Theory (14 minutes) begins with the idea of finding patterns in what initially appears to be disordered chaos, and delves more deeply into the profound questions that have motivated this endeavor, ranging from the immeasurably small to the immensely huge. Key theories described in this section include the expansion of the universe, problems with current theories, and the idea that our universe is just one among many others in a multiverse. This section ends as the damage to the LHC is repaired, and the scientists wonder if they can avoid having the media present when they start up the machine again, to avoid a possibly embarrassing public failure.

Part 4 Success! (37 minutes) The last section of the film summarizes the key theoretical issues, and the implications of finding a Higgs particle of a given mass: if it is near 115 GeV, then it will be good news for the theoretical physicists, confirming their theories and predicting more interesting physics to come. If it is closer to 140 GeV, then it will mean that it is likely our universe is one of many in a multiverse, and further information may be beyond our grasp. The results are revealed by each of the two teams separately (since they were forbidden to discuss their findings earlier). The film concludes with the reactions of the key scientists, including an emotional appearance of Peter Higgs, and plans for the future.

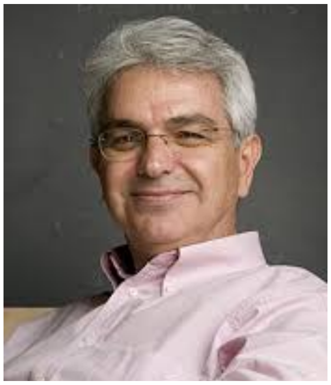
Sequences of Excerpts

Two of the themes have sequences of excerpts on the DVD that you can use to help structure discussion after the students have seen the entire film. You can stop the DVD after each segment for brief discussion, or play through all of the segments and then hold a discussion.

The Experiment illuminates Theme 3. These excerpts concern how the LHC functions and what it is designed to accomplish. Other aspects of the experiment include the immense cost and high stakes of the experiment, and the importance of data. Students are invited to think of experiments that they have done, and the definition of the term “experiment.”

Developing and Testing Models pulls together segments of the film related to Theme 4**.** This sequence of excerpts concerns the standard model of particle physics that gave rise to the search for the Higgs boson, and which is still being tested by additional runs of the LHC. There are opportunities in discussing this theme for students to consider how they use models in their own lives, so they can better understand what the physics stars in this film mean when they refer to “models.”

THE PHYSICISTS IN THE FILM



Savas Dimopoulos

A Greek immigrant who now occupies an endowed chair at Stanford University, Savas has been on an odyssey for 30 years to find the true theory of nature. Many consider him the most likely to have a theory confirmed by the LHC, potentially winning the Nobel Prize. A mentor to many in the field, Savas has recently begun to feel the pangs of age, and worries if he'll be an active participant in the next revolution.

Nima Arkani-Hamed

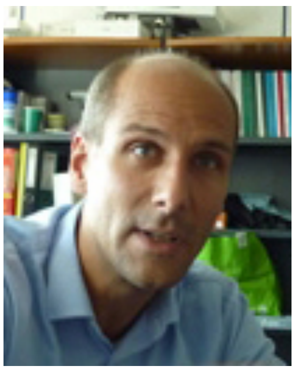
An intense, outspoken young theorist, Nima's father was also a physicist, who spoke openly against the Iranian Revolutionary Guard after the revolution in 1979. In fear for their lives, the family fled into Turkey on horseback. Nima now treats physics with the same life and death imperative. Snatched up by Harvard with a full professorship before he was 30, Nima moved in 2008 to the Institute for Advanced Study in Princeton. With many of his ideas poised to be tested at the LHC, Nima hopes to make the impact his colleagues think he is capable of. He bet several years salary that the elusive Higgs boson would finally reveal itself at the LHC.

Fabiola Gianotti

In 1982, Fabiola received a piano diploma at the Conservatorio Giuseppe Verdi in Milan, Italy. In 1989, she received her Ph.D. in Particle Physics from the University of Milan. She has devoted the last 20 years to the development of the ATLAS detector, the largest detector at the LHC. She became the leader of the experiment just as the LHC began operation, supervising nearly 3,000 physicists and engineers around the world. Like her Italian ancestor, Columbus, Fabiola's fervent dream for the LHC is to discover an entirely unexpected "new world."

Monica Dunford

Awarded a prestigious Enrico Fermi Fellowship from the University of Chicago, Monica's gung ho, adventurous spirit has led her not only to the frontiers of science, but to the boundaries of human endurance. Her "leisure" activities of marathoning, cycling, rowing and mountain climbing have provided useful conditioning for the 16-hour days she regularly spends working on the ATLAS detector. As a young American post-doc, she is excited to be at the center of the physics universe and anxious to make her mark during her stint in Geneva.

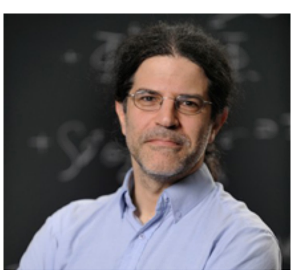


Martin Aleksa

Arriving from Austria over 12 years ago, Martin now has a coveted permanent position at CERN. He was one of the original designers of one of the central components of the ATLAS detector, the Liquid Argon Calorimeter. Elected to the position of ATLAS Run Control Coordinator in 2011, Martin was handed overall responsibility for the collection of data from the ATLAS detector just as the LHC began to produce its first new results.

Mike Lamont

Trained as a physicist in England, Mike migrated to the engineering side of the actual collider machine in Geneva. As Beam Operation Leader, he feels a personal responsibility to "deliver beams" of protons to the experiments. His dry wit has been a welcome relief in the adrenalin-charged, high-pressure environment of the CERN Control Center

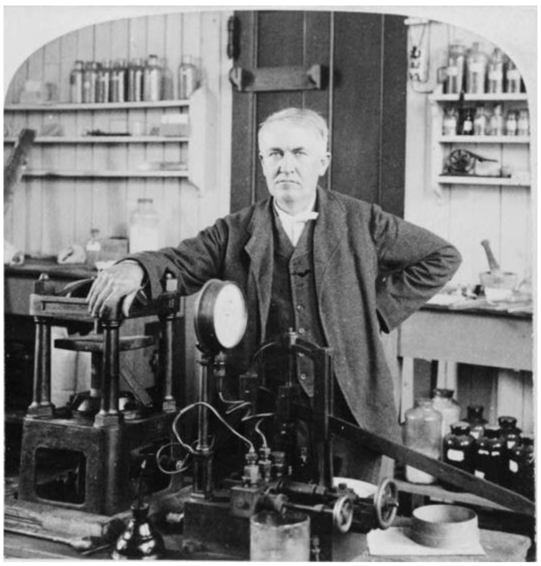


David Kaplan

David Kaplan is a professor of theoretical particle physics at Johns Hopkins University and studies supersymmetry, dark matter, and properties of the Higgs boson. After receiving his Ph.D. from the University of Washington in Seattle, David held research positions at the University of Chicago and Stanford's Linear Accelerator Center. He has been awarded the Outstanding Junior Investigator prize from the Department of Energy and named an Alfred P. Sloan fellow. He has been a featured host and consultant on science programs for the History Channel and National Geographic.

Theme 1: Big Science

What does it look like to do science or engineering today? Some science and engineering looks much like the classic image we have, such as the character Dr. Alan Grant in *Jurrasic Park*: a paleontologist digging up dinosaur fossils, assembling them like puzzle pieces, to describe what the dinosaur looked like, how it lived, and how it fits into the evolutionary web of life on Earth. One person is in charge, assisted by a few students and lab assistants. Rarely, however, do scientists, engineers, or inventors work alone, despite what we may see in movies. Consider, for example, the popular image of Thomas Alva Edison, the person who is widely credited with the invention of the phonograph, light bulb, and many other inventions that helped lay the foundations of the modern world.



Engineer and inventor Thomas Alva Edison in his lab, 1870's. Public Domain. Retrieved from http://commons.wikimedia.org/wiki/File:Edison_in_his_NJ_laboratory_1901.jpg

Although the popular literature depicts Edison as a lone inventor, that image is not entirely accurate. In his early days Edison contributed ideas to the rapidly developing technology of telegraphy, along with many others who were working in that field. In his later days, when he invented the light bulb, he established a laboratory that covered two city blocks and employed dozens of people, all working in teams on various inventions.

The small team model accurately describes much of science today. An excellent example is the team of physicists that originally proposed the Higgs particle as a key element of the Standard Model, as well as the current generation of theoretical physicists shown in the film, who are guiding the work at the LHC today. *Naturally Obsessed* is a recent excellent science documentary that shows another example of real science being conducted by a small team of people [http://www.naturallyobsessed.com/].

An entirely different model is represented by the movie *Gravity*. Although the cast is just a small group of people on a space station, we know that they are backed up by thousands of people back on earth, including scientists who devise experiments to be done in space, and an even larger number of engineers and technicians. (In fact, NASA employs nine engineers for every scientist.) *Particle Fever* is an example of this second model of science. We see a few individuals who are featured in the film; but in the background we see many more, including not only scientists and engineers, but all the other people that it takes to run any big enterprise, from managers and purchasing agents to cooks and plumbers.

Particle Fever depicts "Big Science," which is performed by thousands of scientists and engineers, working in large teams, simultaneously cooperating and competing with each other. "Big Science" began in the 1930's with Ernest Lawrence, who invented the cyclotron, a machine which enabled the first studies of sub-atomic particles, but which took large teams of scientists and engineers to build and operate. Other examples of big science today include the Human Genome Project, the International Space Station, and the International Ocean Discovery Program. One of the biggest scientific research projects is the GLOBE Program, one of many "citizen science" projects, in which ordinary citizens contribute data that scientists could never collect on their own. More than 1.5 million children and youth have contributed GLOBE data to monitor Earth systems, with the help of teachers at 24,000 schools in 112 countries.

The Birth of Big Science

We live in an age of "Big Science," where projects like putting satellites in space, monitoring climate change, and tackling diseases like malaria and cancer require the work of thousands of people, including scientists, engineers, and technicians. Science wasn't always like this. Just a few decades ago such large groups of scientists were unheard of. The Big Science project that is featured in the film *Particle Fever* began when one person had an idea – an idea that would require a huge team of people to realize.

Ernest Orlando Lawrence was born in Canton, South Dakota, in 1901. Farm communities always have lots of wood, tractor parts, and tools, and farmers are always making improvements and useful implements. Young Ernest loved to tinker particularly with that most up-to-date wonder of the age: radio. As late as1922, only one percent of US homes had a radio, but as a teenager Ernest and his boyhood friend Merle Tuve had already built their own shortwave radio transmitter and receiver.

Ernest O. Lawrence. Public domain image. Retrieved from: http://en.wikipedia.org/wiki/File:Ernest_Lawrence.jpg

Going to college was also uncommon in the early 1900's, but thanks to supportive parents, Ernest attended a fine small college (St. Olaf) and then the Universities of South Dakota and Minnesota. After that he worked at the University of Chicago, got his Ph.D. from Yale, and finally arrived at the University of California at Berkeley, where he soon became the youngest full professor ever.

When Lawrence came to Berkeley, physicists around the world were trying to figure out what was inside the tiny, hard nucleus of every atom. To do this, they tried to crack open nuclei and see what flew out. The machines they built to do this used high electric voltages to accelerate straight beams of particles (electrons, protons) into targets of the kinds of atoms they wanted to study. But even with larger versions of these machines, they couldn't get high enough voltages, or produce strong enough beams, to produce much useful information.

Lawrence's ingenious idea was to send the beams of particles around in circles, instead of in straight beams. Each time the particles made a circle they encountered the same high voltage electric force, which kicked up their energies again. After thousands of circles, the particles had spiraled up to high enough energy to smash open the nucleus of an atom. Lawrence's invention, the ***cyclotron***, opened the world inside the atom for investigation.

The very first cyclotron (shown at right) was tiny, just a few inches across. And it was held together with sealing wax. However, it worked well enough to demonstrate the principle.

The first cyclotron. Lawrence Berkeley National Laboratory. Retrieved from http://www.lbl.gov/Publications/75th/files/04-lab-history-pt-1.html

The following diagram illustrates how the Cyclotron functions.

A. Two hollow metal chambers in the shape of a "D" (called *dees*) are connected to a vacuum pump to remove the air that would block the particles from zipping around.

B. Electrically charged particles are introduced into one of the dees near the center using something like a lamp filiament.

C. Magnets on either side of the dees cause the particles to follow a curved path.

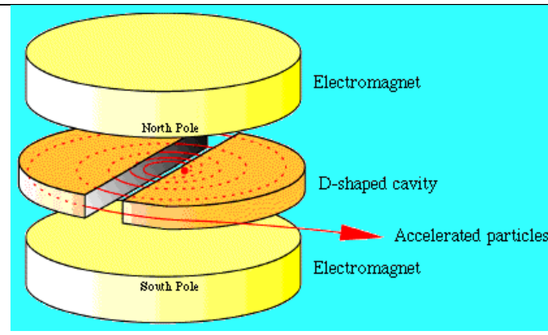


Figure 3. How the cyclotron works (Illustration from the Thomas Jefferson National Accelerator Facility - Office of Science Education http://education.jlab.org/glossary/cyclotron.html)

D. When the particles reach the gap between the two dees an electric field causes the particles to speed up.

F. When the particles enter the next dee they continue to move in a curve due to the magnets. When they reach the gap again the electric field once again they speed up going into the first dee.

G. Each time the particles go between the two dees they speed up faster. This goes on for thousands of cycles until at last a very high energy beam is emitted in a chosen direction.

The Need for Science Teams

But inventing the cyclotron wasn't enough. Atom smashers had to be big, to boost the energy of subatomic particles enough so they could penetrate into the inner core of an atom (its nucleus). Big machines would also need a team of physicists, engineers, technicians, and craftspeople to build, operate, and maintain the big machines. Lawrence recognized that these teams could not work the way science had typically been done, with a couple of professors and a few graduate students, all working on the same thing, at the same time, in adjacent rooms.

1932 Ernest Lawrence and a small team build a larger version of the cyclotron. This one had a magnet 27" in diameter. Lawrence Berkeley National Laboratory. Retrieved from http://www.lbl.gov/Publications/75th/files/04-lab-history-pt-1.html

Lawrence began to build large teams, which could tackle many different challenges at once. His teams occupied many buildings, rather than many rooms. Dozens, soon hundreds of scientists and technicians worked for Lawrence's Radiation Lab ("the Rad Lab," now the Lawrence Berkeley National Laboratory). Lawrence not only guided the research, he also coordinated the team and raised money for their salaries and equipment.

1939 Ernest Lawrence and team, posing on the magnet for the 60" cyclotron. Courtesy of Lawrence Berkeley National Laboratory. Retrieved from http://lbl.webdamdb.com/albums.php?albumId=198646

So Lawrence invented the idea of creating large teams, with many researchers and funders sharing the expense and the routine work of his lab, and in turn gaining access to the giant machines for their own discoveries. This new way of doing science, now known as "Big Science," has become common worldwide today. It turned out to be as important a contribution to science as the invention of the cyclotron itself.

The latest and most powerful instrument for studying subatomic particles is the Large Hadron Collider on the Swiss/French border. A direct descendent of Lawrence's atom smashers and the 184" diameter cyclotron shown here, the LHC is 17 *miles* in diameter.

1940 Ernest Lawrence and team, posing inside the magnet for the 184" cyclotron. Courtesy of Lawrence Berkeley National Laboratory. Retrieved from http://lbl.webdamdb.com/albums.php?albumId=198646

It's difficult to say exactly many people are working on the LHC today. The image below shows just a few of the 1,900 people working on the Atlas team alone. An estimated 4,000 scientists and engineers have been working on the entire project, and as many as 10,000 including all of the technicians and other support personnel.

Collaborators from the Atlas Team. As of 2007, over 1900 scientists from 35 countries took part in the ATLAS experiment alone. Image by Patrice Loïez http://cds.cern.ch/record/42134

1.1 Some people say that Ernest Lawrence was a "visionary," who could envision a future of Big Science. In your opinion, do you think he could see where his work was heading? Explain your thinking.

1.2 What is another enterprise (not necessarily in science) that grew from a single idea, to a vast enterprise that involves thousands of people who must coordinate their work closely?

1.3 The cyclotron works with changing electric and magnetic fields. What other devices that you encounter every day also work with changing electric and magnetic fields?

1.4 The largest cyclotron that Lawrence built had a magnet 184" in diameter. How does that compare with the size of the ring of magnets in the Large Hadron Collider (LHC) at CERN?

1.5 How many students are in your school? If everyone at your school were a scientist or engineer, how many schools of people would it take to run the LHC?

Theme 2: Being a scientist today

Before presenting the remaining themes, show your students the entire film, or at least the first segment, so they have a chance to see and hear some of the scientists involved in the search for the Higgs particle.

Most people have a clear image of a scientist—generally an older white male, with an Einstein mane of white hair, a lab coat, and no interests beyond his science.

Fictional scientist in the film "Back to the Future." Image in public domain retrieved from: http://www.theguardian.com/science/blog/2010/sep/24/scientists-boffin-stereotype

This attitude towards scientists was studied by the famous anthropologist Margaret Mead and her colleague Rhonda Métraux in 1957 (*Science,* Vol. 126, 384-390). Among the teenagers they studied, a representative negative image of a scientist included this:

> *He is a brain; he is so involved in his work that he doesn't know what is going on in the world. He has no other interests and neglects his body for his mind. He can only talk, eat, breathe, and sleep science.*
>
> *"He neglects his family-pays no attention to his wife, never plays with his children. He has no social life, no other intellectual interest, no hobbies or relaxations. He bores his wife, his children and their friends-for he has no friends of his own or knows only other scientists -with incessant talk that no one can understand; or else he pays no attention or has secrets he cannot share. He is never home. He is always reading a book. He brings home work and also bugs and creepy things. He is always running off to his laboratory. He may force his children to become scientists also.*

2.1 In what ways do the characters in *Particle Fever* resemble this image? In what ways are they different?

2.2 What scenes in the film would support or refute that image of a scientist?

2.3 Where do you think the negative images of scientists, reported by Mead and Métraux, might have come from?

In *Particle Fever* we follow 7 individuals, and briefly meet many more. All are highly gifted and extremely hard working, but with few other qualities in common. Some are young and some are old, a few are American but others are Greek, Iranian, Italian, Austrian, and English. They have many deep interests beyond their common interest in physics, including music, art, families, athletics, history, and more. And not all are scientists: some are working as engineers part or all of the time [Mike Lamont is the head engineer for the LHC, and Monica Dunford and Martin Aleska spend part of their time doing engineering]. Others are technicians, security staff, architects, food service providers, janitors, public relations staff, etc.

2.4 How does the variety of characters in *Particle Fever* compare with the stereotype of the scientist?

2.5 Think of another film, fiction or non-fiction, that you have seen and compare the scientists and engineers in that film with those in *Particle Fever* .

2.6 We recognize only a few "minorities" in *Particle Fever* . Why do you think that is?

Consider that a "minority" individual in the US may look very different from minorities in other nations and other cultures. Could there be minorities in ***Particle Fever*** that US audiences may not recognize as such? Savas Dimopoulos' family had to flee from Cyprus and Nima Arkani-Hamed's family had to escape from Iran because they were political or ethnic minorities in their homelands.

2.7 What kind of training, time, and money does it take to become an elite-level scientist or engineer like the ones in *Particle Fever ?*

2.8 If the US wanted to have scientists and engineers who were more representative of the US population as a whole, what would it need to do, and how long would that take?

Although the ideas the scientists have worked on for decades may be proven wrong by the LHC, the scientists generally have an optimistic mood. Savas Dimopoulos says:

> *"Jumping from failure to failure, with undiminished enthusiasm, is the big secret to success." (1:13:50)*

2.9 Who do you know, see on television, or read about in books, with an attitude like that?

Two of the scientists we follow are women: Fabiola Gianotti, and Monica Dunford.

2.10 How do these two women differ from each other? How are they similar?

2.11 How do they compare with women scientist in films or books you have read?

David Kaplan, whom we have followed throughout the film, gives us his final remarks just before the end of the film:

> *"That was exciting. (laugh) If this is true, the Higgs is about 125 GeV, and that means, uhh…yeah actually almost all of my models are ruled out.... anyway, we have something to do."* (1:32)

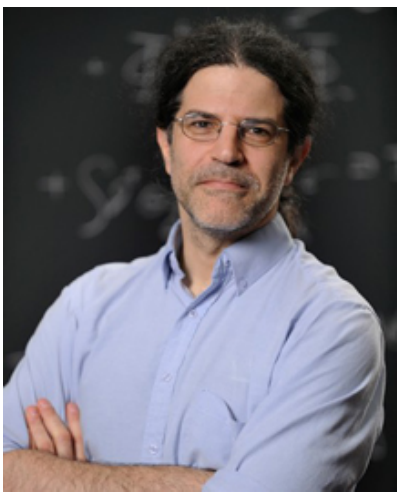
If David is sad that his models have almost all been ruled out, he also seems cheerful that at least "we have something to do."

2.12 If David were a businessman, say a stockbroker, what do you think his employers would think about him after this turn of events?

Theme 3: The Experiment

If you haven't shown the entire film yet, now is a good time to show the remaining segments. This theme and the subsequent themes are best discussed after your students have at least initial impressions of the experiment and model that it was intended to test. When you are ready to have your students reflect on what the film was all about, cue-up "The Experiment," on the DVD, which strings together the clips indicated in the following text. Between each scene the screen fades to black, so you can stop it for discussion.

At the beginning of the film we learn that the stakes are unbelievably high. Not only did it take 19 years, ten *billion* dollars, and the work of 10,000 people, but the outcome of this experiment will be tremendously important for the future of science. Here's how that idea was expressed by David Kaplan, one of the theoretical scientists in the film (play the following clip):



David Kaplan. Courtesy of CERN

02:09 – 02:15…*after many, many years of waiting and theorizing, about how matter got created and about what the deep fundamental theory of nature is – all those theories are finally going to be tested, and we're gonna know something, and we don't know what it's gonna be now but we will know, and it's gonna change everything. And if the LHC sees new particles, we're on the right track. And if it doesn't, not only have we missed something but, we may not ever know how to proceed. We are at a fork in the road, and it's either going to be a golden era, or it's going to be quite stark. And I've never heard of a moment like this in history, where an entire field is hinging on a single event.* — David Kaplan

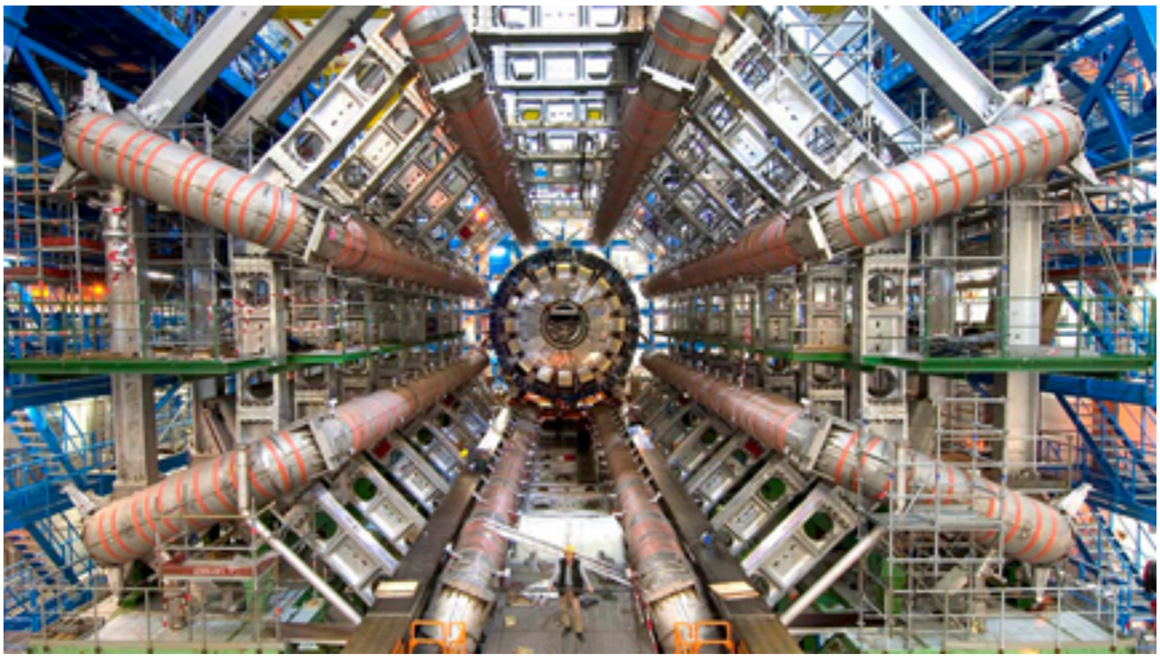
3.1 Now that you've seen the entire film, you know how this high stakes, very expensive experiment came out. In your view did the results "change everything?" Or are the scientists still stuck at the fork in the road? Why do you think that? What do you think might help them make progress?

Perhaps the clearest explanation of how the LHC was used to perform the experiment was given by Monica Dunford, one of the experimental scientists in the film.

> 14:35 – 16:06 …. *So the LHC is basically the most fundamental of experiments. It's like what any child would design as an experiment, you take two things and you smash them together. And you get a lot of stuff that comes out of that collision and you try to understand that stuff. Now in this case what we are smashing together is tiny protons, which are inside the center of every atom. And in order to get them going as fast as*

possible, we have to build this huge 17-mile ring. And we run those protons around the ring multiple times to build up speed, almost to the speed of light. And then we collide two beams going in opposite directions, at 4 points. And at those 4 points are 4 different experiments: ATLAS, LHCb, CMS and ALICE.

Now I work on the Atlas experiment. And Atlas is like a huge 7 story camera that takes a snapshot of every single collision. And that's billions of collisions, and the hope is that we'll see the very famous Higgs particle. But every time we've turned on the new accelerator at a higher energy, we've always been surprised. So the real hope is that we'll see the Higgs but that there's also something amazingly new. —Monica Dunford



The Atlas detector. Notice the person at the bottom of the frame. Courtesy of CERN.Retrieved from http://particlefever.com.

3.2 Remember Ernest Lawrence's cyclotron. How is the LHC different?

Every experiment must have a purpose. Below David Kaplan gives two reasons why this experiment is being undertaken. Play the following clip:

16:10 – 17:00… *You can liken it to when we put a man on the Moon. It's that level of collaborative effort, I'd say, even bigger than that. This is closer to something like human beings building the Pyramids. Why did they do it? Why are we doing it? We actually have 2 answers, one answer is what we tell people and the other answer is the truth.*

I'll tell you both and there is nothing incorrect about the first answer. It's just it doesn't, it's not the thing that drives us, it's not how we think about it, but it's something you can say quickly and the person you're talking to won't, you know, get diverted, or pass out, or pick up the SkyMall catalog if you happen to be next to them on an airplane.

Answer number 1, we are reproducing the physics, the conditions just after the Big Bang. We're doing it in this collider and we're reproducing that so we can see what it was like *when the universe just started. This is what we tell people. — David Kaplan*

Okay, answer 2, we're trying to understand the basic laws of nature, umm it sounds slightly more mild but this is really where we are, and what we're trying to do. We study particles because just after the Big Bang, all there was particles. And they carried the information about how our universe started and how it got to be the way it is and it's future. — David Kaplan

3.3 Think of an experiment that *you've* done. It could be something that you did in school, or maybe something you did on your own. Now ask yourself, what was the purpose of the experiment? What equipment did you use? Was anyone else involved? If so who? How long did it take? And what was the result?

3.4 Now imagine the same experiment but you are not able to buy the equipment, so you have to build everything from scratch. How many people would have been involved in your experiment if you now include the people who built the equipment including things like stopwatches, meter sticks and masses as well as microscopes, beakers and petri dishes?

3.5 Now share the story of your experiment with another student. After you have each told your story, see if you can come up with a definition of an "experiment" that fits both stories. We'll share your definitions and see if we have a similar understanding of what an experiment is.

(Take some time to allow the students to share their ideas, giving examples of what they actually did. Be prepared for some examples that may not fit your definition of a controlled experiment; and encourage the students to discuss what constitutes a real "experiment." The goal is not for them to all agree, but rather to recognize that there are many different definitions of the term, and that the experiment in the film is perhaps one of the most remarkable that has ever been done.)

Continue thinking about the experiment you just described as you watch the following clip:

1:04:00 – 1:07:52 … *First things first. I just have to say: "Data." It's… it's unbelievable how fantastic data is. It's like the world at ATLAS and LHC and CMS and all these places has suddenly changed. I mean, it's like, all of sudden there is data. And after so many years of not having data and new data, new physics, there's just, so much possibility, and even though you're rediscovering the Standard Model, that is more exciting.*

Monica Dunford. Retrieved from http://worldsciencefestival.com/search/tag/physics

> *But the most exciting thing about the data is not, the first collision. Because the first collision, ok great, first collision, everyone loves the first. But the most exciting thing about the data is the, you know, 1 millionth collision, or the 2 millionth collision, or the fact that collisions just keep coming and coming and coming and the more and more collisions we have, the more and more chance we have to look at the interesting physics. Because it just means more and more and more data for us.* — Monica Dunford

3.6 Why was Monica Dunford so excited about data? How do you think you'd feel in her position?

After the experiment was running for a few months, the scientists started getting results. At least one of them was not too happy about it. Why? Watch the following clip and recall the big question this experiment is intended to answer.

> 1:10:08 – 1:10:45 *…. The mass of the Higgs–namely the weight of the Higgs–can actually tell us, or give us a hint about what comes next. If the mass, uhh, is on the lighter side, then that's consistent with some of the standard things we've been looking for: supersymmetry generally favors that the Higgs is as light as possible. About 115 times the mass of the proton. It's 115 GeV: Giga electron volts. If on the other hand, the Higgs is 140 GeV–140 times the mass of the proton–it's a terrible mass, because 140 GeV is associated with theories that rely on the multiverse.*
>
> *And now…bleep! It's 140! It's starting to look like nature has made its choice.* — David Kaplan

However, it's not over until its over, and the preliminary results turned out to be wrong. The two teams heard each others' results for the first time at the meeting that we are about to see. The first team measured 125 GeV. What did the second team measure? Let's see: (Play the following clip:)

> 1:27:38 – 1:28:00*…. Good morning. Atlas is very pleased to present here today, updated results on standard model Higgs searches based on up to 10.7 inverse femptobarn of data recorded in 2011 and 2012, and it's a big honor and a big emotion for me to represent this fantastic collaboration at this occasion. So, let's go to the results for this channel. You can see here the results for the 2011 to 2012 and the combination of the two. The gamma-jet and jet-jet background with one or both jet…requirement that the energy in a cone around the photon is below…a structure which reproduces very well the LHC bunch rate, with a field bunch, small of course we correct…Yeah.*
>
> *We know the linearity between a few GeV and a few hundred GeV at the level of a few per mill…is fit in the nine different categories with an exponential function to model the background so, no theoretical prediction, no Monte Carlo…the background is determined from the side bands of the possible signal...from this spectrum, the background fit you get this plot here. Now the grand combination.*
> —Fabiola Gianotti

Here it goes. —Nima Arkani-Hamed

So this distribution is extremely clean, except one big spike, here, in this region here. Excess with a local significance of 5.0 sigma at a mass of 126.5 GeV. —Fabiola Gianotti

As a layman I would now say: "I think we have it." —Rolf Dieter Huer

And I think all of us, and all of the people outside watching it in the different meeting rooms, everybody who was involved and is involved in the project, can be proud of this day. OK, enjoy it! —Rolf Dieter Huer

We found the Higgs! (laughs) —Nima Arkani-Hamed

Celebrating in the control room. Courtesy of CERN. Courtesy of CERN.Retrieved from http://particlefever.com.

3.7 Keeping in mind the two purposes of the experiment—to reproduce the conditions just after the Big Bang, and to understand the basic laws of nature—would you say the experiment was a success? Why or why not?

How certain were the experimentalists that their results were correct? We heard Fabiola Gianotti say that "*Excess with a local significance of 5.0 sigma at a mass of 126.5 GeV*." Sigma is a greek letter that represents "standard deviation,"—a measure of the spread of a dataset. No individual measurement is perfectly accurate, but with lots and lots of measurements it is possible to get a very accurate answer. A sigma of 5.0 means that the chance of being wrong is one in three-and-a-half million. To get a feeling for how accurate that is, imagine that you are flipping a fair coin. Getting it to land on heads is a 50-50 proposition, or one in two. Getting two heads in a row would be one chance in four. Getting three in a row would happen by chance once in eight flips, and so on.

3.8 How many heads would you need to flip in a row for the chance to be one in three million?

We've been told the scientists' reasons for conducting this colossal experiment. But another message of this film is that there is an even deeper reason. Consider this short clip of one of the scientists at home. What's going on here? (Play the following clip, showing a scientist engaging his children with a demonstration of air pressure):

> 44:24 – 45:24 …. *This is what doing discovery physics means. This is what discovery means.* —Monica Dunford
>
> *Why do people have curiosity? You know… why do we care about how distant parts of the universe, things that happened billion years ago like the big bang, why do we find them that interesting? It doesn't affect what we do day-to-day. Uh… but nevertheless, once you have curiosity you can't control it. It'll ask questions about the universe. It will ask questions about harmonic patterns that create art; music. — Davas Dimopoulos*

3.9 What did Savas Dimopoulos mean by "Once you have curiosity you can't control it?" Can you recall a situation in which curiosity has driven your actions?

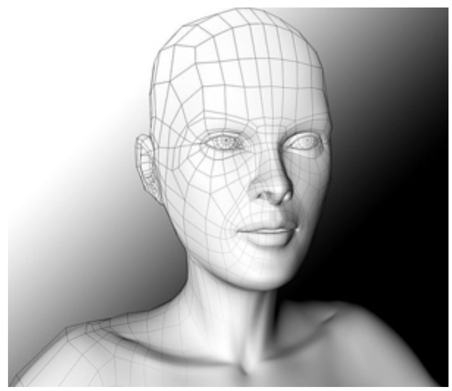
3.10 How has the human quality of curiosity changed life as we know it?

Theme 4: Developing and Testing Models

The following excerpts from the film have been assembled on the disk for you. When you are ready to lead a discussion, cue-up "Developing and Testing Models." Between each scene the screen fades to black, so you can stop it for discussion.

Relationship Between a Theory and a Model. The physicists we see in the film will be testing a theory that they and many others have worked on for decades. In this case their theory is that all matter consists of extremely small particles, which in turn consist of even small particles. Later in the film they use the term "supersymmetry" to describe a variation of the theory in which each particle has a companion particle.

Sometimes the scientists use the word "theory" to describe what they are testing and in other cases they use the word "model." Although they seem to use these terms interchangeably they do not have exactly the same meaning. The term "theory" is a well-developed idea that explains the universe that we see around us; while the term "model" is a representation of reality that derives from the theory, and is used to make predictions—predictions that can be tested by experiments.



Mathematical model of a human face. Wikipedia Commons. Retrieved from https://en.wikipedia.org/wiki/File:Polygon_face.jpg

Models are used for many purposes. For example, the mathematical model of a human face at right is composed of many polygons for the purpose of rendering complex shapes on a computer.

But it is not just physicists and computer scientists who create models. The world is a complex place, and we all create mental models of the world to survive. If we tried to deal with the world in all its complexity all the time, we'd overload our senses. So we invent models to help us function day-to-day.

4.1 To illustrate the idea of a model to your students, ask them to close their eyes and imagine coming home from school. Ask them to picture the front door and the mailbox. Then, to check the mail, and go into the kitchen and pour a glass of milk. What hallway or rooms do you have to go through to get to the kitchen? Where are the glasses? What kind of milk is in the refrigerator? Now share your model with one other student in the class.

If this scenario isn't appropriate for your students then think of something that is—perhaps coming to school, or going to the cafeteria for lunch. The point is that we all have mental models of the world that we used to function. Our models do not include fine details, like the pattern on the wallpaper, or the texture of the rug. But they do include the details that we need to function, such as the location of a light switch.

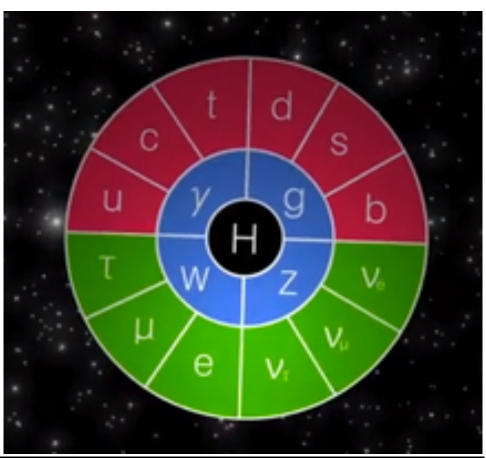
We create these mental models to represent reality. However, they are not real. They are products of our memories, and to some extent of our imaginations.

Physicists do something similar. They create models of the world to represent what they know—or think they know—and then test with experiments to see if their model is a good representation of reality, or if it needs to be changed.

The Standard Model

Throughout the film we hear about "the Standard Model." No one in the film explains the word "standard," but the meaning of the term is not different from its everyday usage. Central to the term is the idea of widespread agreement. We agree to use nuts and bolts with standard threads. We have standard electrical outlets, and we even have educational standards. However, there is an additional reason that physicists agree on the Standard Model—it has stood up to all previous experiments and it makes logical and mathematically consistent sense. Here's how the Standard Model is described in the film (play the following clip):

> 17:42 – 19:00:00 …. *At the beginning of the 1900s it became clear that all known matter, everything that we know about, is made of atoms. And that atoms are made of just 3 particles: the electron, the proton and the neutron. — David Kaplan*
>
> *In the 30s other particles were discovered, and by the 1960s there were hundreds of new particles with a new particle discovered every week. And there was mass confusion. Until a number of theorists realized that there was a simple mathematical structure that explained all of this. That most of these particles were made of the same three little bits, we call quarks. And that there are only a handful of truly fundamental particles, which all fit together in a nice neat pattern. And there was born the Standard Model. — David Kaplan*



Courtesy of Particle Fever. Designed by Walter Murch. The Standard Model. Retrieved from http://www.youtube.com/watch?v=-XDhmyg7Odg

Eventually all the particles in the theory were discovered except one, the Higgs. The Higgs is unlike any other particle. It's the lynch pin of the Standard Model. Its theory was written down in the1960s by Peter Higgs and a number of other theorists. We believe it is the crucial piece responsible for holding matter together. It is connected to a field which fills all of space and which gives particles like the electron mass and allowed them to get caught in atoms. And thus is responsible for the creation of atoms, molecules, planets and people. Without the Higgs, life as we know it, wouldn't exist. But to prove that it's true, we have to smash particles together at high enough energy to disturb the field and create a Higgs particle. If the Higgs exists, the LHC is the machine that will discover it. — David Kaplan

Later in the film we learn a little more about the Standard Model—how it represents a very human quality of seeing patterns. For example, have you ever looked at clouds and seen images of people, animals, or other things? You know they are not really there, but your mind automatically organizes the clouds into recognizable patterns. Sometimes you will notice patterns that indicate something is missing. For example consider the following:

> **4.2 What's odd about February? (missing days)**
>
> **4.3 What's strange about the sequence 1,2,3,4,5,6,7,9,10? (8 is missing)**
>
> **4.4 What's wrong with this sentence? I'm a great speler! (speller is missing an l)**

We find in the film that the Standard Model is driven by this same human tendency to envision patterns; and in this case something important is missing from the pattern (play the following clip):

> 46:30 - 49:42 …. *The way we try to reduce the complexity of the world is by looking for patterns. What we call symmetries. We take all the particles we know today and we attempt to fit them into some kind of underlying structure. Are they the remnants of some more beautiful and complete picture of the laws of nature? It's like, you go to Egypt and you see ruins. If you look at it the right way, I could draw a pyramid and see that these chunks of stone are actually the remains of something very clean and very symmetric. Very beautiful.*
>
> *We know that the Standard Model is incomplete. We know that there's other stuff out there; that there are other particles that we haven't seen yet. Dark matter is a speculated particle, which we think actually dominates the universe, and yet we've never seen it directly and it's not part of the Standard Model. That's one of those rocks. We think, possibly, that that and many other particles are still out there and are all part of a much bigger symmetry, a much bigger theory that includes the Standard Model but much more. The most popular theory is called Supersymmetry, or SUSY for short. Supersymmetry was a theory that sort of started to develop in the late 70s. Savas was one of the first authors of the first theories of supersymmetry.* —David Kaplan.

The connection between the standard model and the experment is explained fairly early in the film by as follows:

10:43-10:50 … *Since the mid 70s we've had an amazingly successful theory of nature that we call the Standard Model of particle physics. But sitting in the heart of the theory is a sickness, very very glaring conceptual problems that infected this fantastic understanding. Why is the universe big? Why is gravity so much weaker than all the other forces?* — Nima Arkani-Hamed

Nima Arkani-Hamed. Image retrieved from:
http://www.youtube.com/watch?v=Rikc7foqvRI

> *The kinds of answers that this theory gives to these questions seem so patently absurd that we think that we're missing something very very big. And on top of all of that there is one prediction of this theory, absolutely crucial for it to even make internal theoretical sense and this is the famous Higgs particle. The Higgs or something like it must show up, if it doesn't show up there is something truly deeply wrong, very very deeply wrong with the way we think about physics. There are strong reasons to think that some of these questions will find answers at the LHC. There has been no shortage of ideas for what they might be um but this is really um… this generation of people's, my generation of people's only shot.* —Nima Arkani-Hamed"

Think about what Nima said: ". . . *there is one prediction of this theory, absolutely crucial for it to even make internal theoretical sense and this is the famous Higgs particle. The Higgs or something like it must show up, if it doesn't show up there is something truly deeply wrong, very very deeply wrong with the way we think about physics."*

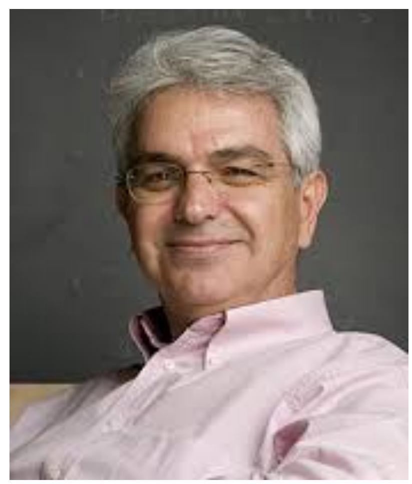
4.5 How did the theoretical physicists feel about finding the Higgs?

4.6 How did they feel about finding that its mass was between the two different predictions of 115 GeV and 140 GeV?

4.7 How would you feel?

Now listen carefully to what the theoretical physicists have to say about next steps:

1:30:00 – 1:34:52 …. *The data is puzzling enough, that it hasn't excluded any of the theories I was involved with, but it hasn't confirmed them either. But, until we look at detailed properties of the Higgs, and until we have the high energy version of the LHC in a couple of years, we will not be able to make a stronger statement.* —Savas Dimopoulos



Savas Dimopoulos

The most important, first lesson, of the discovery of the Higgs, is that physics works. The Higgs on the one hand completes the most successful scientific theory we've ever had. On the other hand opens the door to some very major paradoxes that we now must address. We're at a fork in the road, and the LHC is steadfastly refusing to push us in one direction or the other – the multiverse on the one side and some beautiful symmetry on the other side. It's cranking up the suspense as much as it possibly can. —Nima Arkani-Hamed

> *Before the LHC started, we would always say "new physics is just around the corner." And now we're kind of like, "new physics is still out there." And, for one, I'm not discouraged by this, by any means, because, we know that new physics has to be out there. The next step for two years for improvements and upgrades; and when it returns*

it's going to be twice the energy. And for sure my vote's for supersymmetry. —Monica Dunford

Bleep! That was exciting. (laugh) If this is true, the Higgs is about 125 GeV, and that means, uhh…yeah actually almost all of my models are ruled out. Which…all the supersymmetry models. Which is pretty cool. I mean supersymmetry could still be true, but it would have to be a very strange version of the theory. And if it's the multiverse…well other universe would be amazing, of course. But it could also mean, no other new particles discovered. And then, a Higgs with a mass of 125 is right at a critical point for the fate of our universe. Without any other new particles, that Higgs is unstable – it's temporary. And since the Higgs holds everything together, if the Higgs goes, everything goes. — David Kaplan

It's amazing that the Higgs, the center of the Standard Model, the thing we've all been looking for, could actually also be the thing that destroys everything. The creator and the destroyer. But, we could discover new particles and then none of that would be true. And anyway, we have something to do. — David Kaplan

4.7 What does Monica Dunford mean when she says "*Before the LHC started, we would always say "new physics is just around the corner." And now we're kind of like, "new physics is still out there."*

4.8 What do you think Nima Arkani-Hamed means when he says: "The most important, first lesson, of the discovery of the Higgs, is that physics works."

Monica Dunford riding to work. Image retrieved from: http://www.youtube.com/watch?v=Rikc7foqvRI

Theme 5: the relationship between science and engineering

The film emphasizes the relationship between theoretical and experimental scientists. But there is another equally important distinction in roles—between all of the scientists and the engineers.

Engineers troubleshooting a problem on the Large Hadron Collider (LHC). Image courtesy of CERN. Retrieved from http://www.youtube.com/watch?v=PZEGqXFHgJU

Engineers design all of the technologies around us, from new fabrics for clothing to medical equipment and jet engines. Engineers play an especially important role in the search for the Higgs Boson, since the scientists cannot answer their deep questions about the nature of the universe, unless they work closely with engineers who design, build, test, repair, and maintain the powerful magnets and detectors that make up the LHC.

The search for the Higgs Boson is a modern equivalent of putting a person on the Moon to understand the nature of the Moon—it is a quest requiring deep scientific knowledge, mathematical skills, *and* engineering know-how and invention. It is a common fallacy that the Moon landings depended primarily on scientists, and it's common to hear the phrase "It's not rocket science!" But in fact NASA employs ten engineers for every scientist, since sending rockets into space requires massive engineering know-how to design rockets and put satellites into orbit.

Theoretical physicist Nima Arkani-Hamed. Image retrieved from: http://www.ictp.it/about-ictp/media-centre/news/news-archive/2012/2/questions,-answers,-and-paradoxes-in-fundamental-physics.aspx

5.1 Who are some famous scientists, and who are some famous engineers?

Most people can name some famous scientists, like Einstein, Newton, or Curie. It may be more difficult to come up with the names of engineers, but think about bridge designers, aircraft inventors, or software developers. Perform an internet search for help in finding some names of famous engineers.

5.2 What are the similarities and the differences between the work done by scientists and the work done by engineers?

Both scientists and engineers use mathematics. They also both need to understand the behavior of nature, and apply their understanding of nature to get on with their work. Both require careful attention to detail, working collaboratively, and having flashes of inspiration and insight. And often an individual may be thinking and working like a scientist one day, and like an engineer another day, although in general they spend most time in one camp or the other.

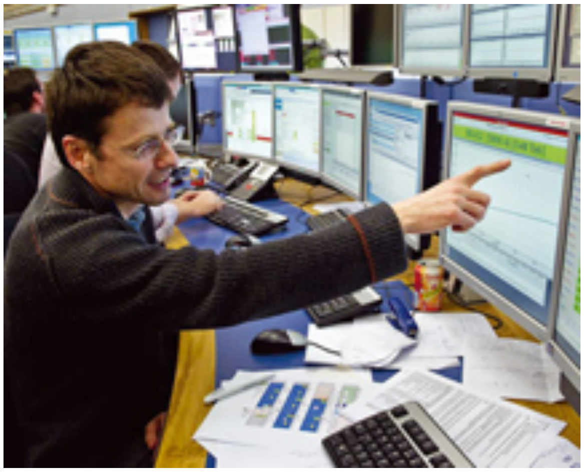
We often think about scientists being driven by curiosity, a desire to extend our understanding of nature. Engineers, in contrast, are usually looking to meet practical needs of society (designing bridges and airplanes for transportation, water-works for clean drinking water, or software to help individuals search the Internet. Albert Einstein is credited with the quote: "Scientists investigate that which already is; Engineers create that which has never been."

In *Particle Fever,* the scientists know that they have a good chance of finding the Higgs boson if they can smash two protons together with a high enough energy and detect the debris from the collision. And they know that this can be done with a large particle collider. But they do not have the training or skills to figure out exactly how big the collider needs to be, how many magnets it needs, or how to design and build each component so they will all work together as planned. Designing the biggest machine in the world, figuring out how much it will cost, and what it will take to keep it running smoothly and repair it if it breaks is the work of the engineers. The LHC would not exist, and the Higgs boson would not be found, if it were not for the work of *both* scientists and engineers.

Who are the engineers in *Particle Fever?*

In many cases the distinction between science and engineering is blurry as scientists often function as engineers and engineers often do science. One example of the crossover is Mike Lamont, who was trained as a physicist in England. He is the chief engineer for the LHC. We first meet him at 28:53 into the film, explaining what the first beam tells us about the operation of his big machine.

As Beam Operation Leader, it is Mike's responsibility to "deliver beams" of colliding protons. He too is excited about finding the Higgs, but his primary responsibility is to keep the machine running.



Mike Lamont in the control room of the LHC. Image courtesy of CERN, retrieved from: http://cerncourier.com/cws/article/cern/42331

We see Mike's role becoming central to the story about 38:12 to 40:00 in the film, when it is up to him and his team to plan for the response to the accident, and balance speed, safety, and cost to figure out the way to get the machine back into operation, 42:00 – 42:30.

Monica Dunford is a physicist, but her work diagnosing, repairing and upgrading the machine (49:30 – 51:00) could certainly be described as engineering.

It's also important to keep in mind that although "scientists" and "engineers" are distinct roles, in many cases experimental scientists must think and behave like engineers to ensure their experiment is successful; and engineers must often think and act like scientists to figure out how their machine will function, or why a problem occurred.

Monica Dunford, an experimental physicist, taking on the role of an engineer. Courtesy of CERN.Retrieved from http://particlefever.com.

Mike is back at 58:00, getting the machine back in operation at high enough energy to potentially produce Higgs bosons. At 1:00:00 he has a typical engineering problem—balancing the desire to make rapid progress and get positive media coverage in the aftermath of the accident, against the engineer's generally conservative approach—keep making adjustments and tests until he is *sure* everything is working optimally.

"The pressure of it being an event of course is there. And of course anything can go wrong, and it has. Last weekend was a complete disaster. We were discussing the possibility that we do collisions during the night, rather than the plan 9 o'clock in the morning. Of course this has caused major, sort of knock-ons for one of the experiments, and two for the media service."

5.3 If you were Mike, would you encourage running the crucial test with the world's media watching, or would you run the test quietly, in the night, and only let the press in when you were sure everything was working?

5.4 What factors would you weigh making that choice?

5 .5 What do you think would have happened if the machine hadn't worked while the world was watching? (1:05 in the video)

Theme 6: The human side of science

The great literature classics tell the stories of a hero who faces an obstacle and then either succeeds or fails at the quest. Does the story of the search for the Higgs boson parallel the great literature storyline? Who are the heroes? What is the obstacle they face? How do the heroes find a way to be heroic?

6.1 As portrayed in the film, the nature of science is not just pure thought, or just expensive machines, but it also involves emotions, like joy, anxiety, fear, and pride. Where in the film do you see scientists or engineers displaying these emotions, or others?

We all want good value for our money. Billions of dollars have been spent on equipment and salaries to discover the Higgs boson. Nobody can give you a practical outcome for this discovery with certainty. Nobody anticipates that the discovery of the existence of the Higgs boson will cure cancer or end world hunger. Some people anticipate that there will be advances in medicine and computer technology as a result. As mentioned in the movie, the worldwide web was one of the byproducts of the search for the Higgs in that physicists needed a way to send data around the world. Was it worth it? As you consider a response to this question, you may want to use the following background materials, questions and quotes to support your views. You may also want to seek out other articles along these same lines.

6.2 The Large Hadron Collider cost six billion dollars to build. Taking all of the costs of maintaining the LHC and the salary of the people involved, some estimates are that it cost almost fifteen billion dollars to discover the Higgs. How many schools could be built with this money? How many people could be fed with this money?

When Michael Faraday invented a way to produce electric currents, it has been rumored that a high official in England asked him about the value of electricity, “so what good will this be?” Faraday is said to have responded, “One day, you will tax it.”

James Clark Maxwell was interested in exploring the mathematical underpinnings of electricity and magnetism. One eventual result of his successful work was to set the stage for the discovery of radio waves (now used for radio and television communications) as well as X-rays (used for medical imaging) and gamma rays (used for eliminating some cancers).

The following is an excerpt from the Congressional testimony of Robert Wilson, director of Fermilab in April, 1969. (Fermilab is another particle accelerator, similar to the Large Hadron Collider, located in Aurora, Illinois.)

SENATOR PASTORE. Is there anything connected in the hopes of this accelerator that in any way involves the security of the country?

DR. WILSON. No, sir; I do not believe so.

SENATOR PASTORE. Nothing at all?

DR. WILSON. Nothing at all.

SENATOR PASTORE. It has no value in that respect?

DR. WILSON. It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with those things. It has nothing to do with the military. I am sorry.

Robert Wilson, breaking ground for Fermilab. Retrieved from: http://www-visualmedia.fnal.gov/VMS_Site/gallery/stillphotos/1969/69-1248.jpg

Fermilab today. Image from Wikipedia Commons. Retrieved from: http://upload.wikimedia.org/wikipedia/commons/4/40/Fermilab_WilsonHall.JPG

SENATOR PASTORE. Don't be sorry for it.

DR. WILSON. I am not, but I cannot in honesty say it has any such application.

SENATOR PASTORE. Is there anything here that projects us in a position of being competitive with the Russians, with regard to this race?

DR. WILSON. Only from a long-range point of view, of a developing technology. Otherwise, it has to do with: Are we good painters, good sculptors, great poets? I mean all the things that we really venerate and honor in our country and are patriotic about. In that sense, this new knowledge has all to do with honor and country but it has nothing to do directly with defending our country except to help make it worth defending.

William Press, the President of the American Association for the Advancement of Sciences, gave an address "What's so special about science (and how much should we spend on it?" The entire address can be read at (http://www.sciencemag.org/content/342/6160/817.full). One quote is, "Indeed, U.S. taxpayers are, to some extent, willing to pay for activities that enrich American social and cultural capital without having a direct economic benefit. Congress, up to now, has appropriated about \$150 million a year for the National Endowment for the Arts (NEA) and about \$170 million a year for the National Endowment for the Humanities (NEH) (*3*). However, by contrast, Congress appropriates about \$40 billion a year for basic research (*4*). If you plot a bar graph with these three numbers, you can barely see that the NEA and NEH numbers are not zero.

Architect of the Capitol. Image retrieved from http://www.aoc.gov/buildings.

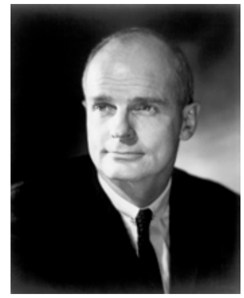
"It is evident that society is willing to pay much more for curiosity-driven research in science than for the analogous thought- and beauty-driven practice of the arts and humanities. It is easy to guess the reason: the link, sometimes subtle but repeatedly established over time, between investment in basic research and macroeconomic growth. Discovery leads to technology and invention, which lead to new products, jobs, and industries.

"Such is the case that we scientists need to reinforce in the austere times that we face. However, mere repetition is not an effective strategy. In today's lean times, we need to articulate our case more powerfully and in a more sophisticated way than in more prosperous times. A skeptical and stressed Congress is entitled to wonder whether scientists are the geese that lay golden eggs or just another group of pigs at the trough."

Nicholas Wade, a reporter for the NY Times, wrote on Nov 8, 2010, "This is why it was such a risk for California to earmark $3 billion specifically for stem cell research over the next 10 years. Stem cells are just one of many promising fields of biomedical research. They could yield great advances, or become an exercise in sustained failure, as gene therapy has so far been. By allocating so much money to a single field, California is placing an enormous bet on a single horse, and the chances are substantial that its taxpayers will lose their collective shirt.

"Stem cell researchers have created an illusion of progress by claiming regular advances in the 12 years since human embryonic stem cells were first developed. But a notable fraction of these claims have turned out to be wrong or fraudulent, and many others have amounted to yet another new way of getting to square one by finding better methods of deriving human embryonic stem cells."

Senator William Proxmire (Democrat, Wisconsin) created the Golden Fleece Award. The Awards were to recognize researchers (amongst others) who had wasted the taxpayers' money. One such award was given to NASA for a "search for extraterrestrial life." Another was given to the National Science Foundation for spending $84,000 on a study on love. Investigate the wide range of over 150 Golden Fleece Awards that were bestowed.



Senator Proxmire and the Golden Fleece Award. Image of the Senator from US Congress Archives. Retrieved from https://en.wikipedia.org/wiki/File:SenatorProxmire.jpg

6.3 The people involved in the search for the Higgs boson come from countries all over the world. The film mentions that the scientists are from countries that are mortal enemies. Are there other examples you can provide where people who would normally not interact choose to work together for a common purpose?

6.4 Why do you think that English is the language with which they choose to communicate?

6.5 The film highlights physicists who worked on discovering the Higgs boson and mentions the engineers. What other support people were involved?   Do you think that the custodians, the food workers and the transportation people should have been included in the film?

6.6 One physicist compares the excitement among the physicists as "a room of six year olds and their birthday is next week." What makes this description so compelling? Can you think of another way to describe the excitement?

6.7 Humans have built the Large Hadron Collider - one of the largest and most complex machines in our history. Do you think that this rates with other classic wonders of the world including the Great Pyramids, the Coliseum, the Great Wall of China, the Taj Mahal and the Empire State Building? How many people were involved in building those wonders? How much time did it take? How much money (in today's dollars)? For what purpose were they built? Were they worth it?

6.8 When the beam makes its first trips around the Collider, there is an enormous celebration. The physicists had not discovered anything at that point. Why were they so excited? Have you ever been so excited? When do humans celebrate?

6.9 Peter Higgs has tears in his eyes when the proof of the existence of the Higgs boson is announced. Thousands of people worked for over 20 years and billions of dollars were spent to find out if Peter Higgs' idea was correct. Can you think of other examples that compare to this?

6.10 Some people believe that the discovery of the Higgs boson can be seen as a symbol of the power of the human mind and a proud moment for humanity. Do you agree? If so why, if not why not?

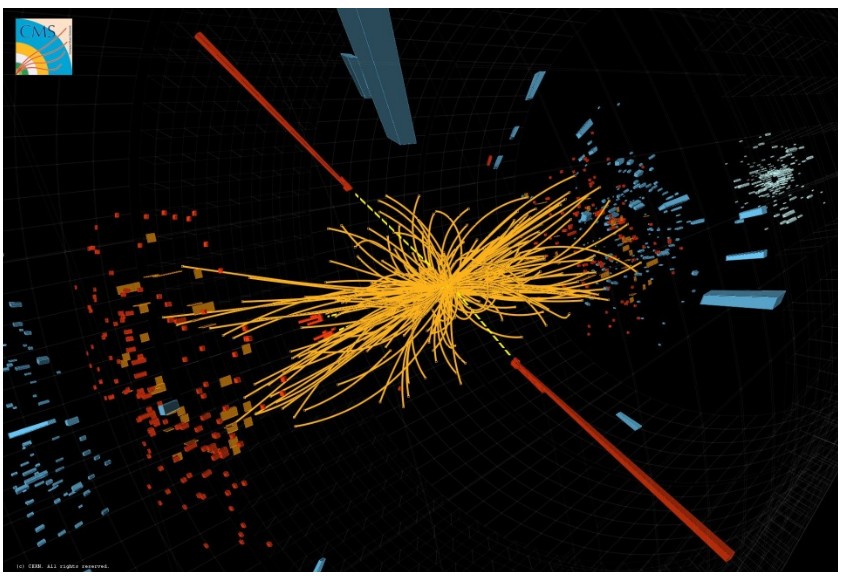
6.11 In the photographic essay entitled, the Family of Man, there is a juxtaposition of two photos. The one on the left is Albert Einstein with his finger to his lips trying to remember something. The one on the right is a six year old boy at the blackboard trying to solve an arithmetic problem 1 +2 = 3. Why do you think the boy's image is placed next to Einstein's?

Theme 7: Science and Art

Hermann Weyl, a mathematician and physicist, once said, "In my work, I have always tried to unite the true with the beautiful; but when I had to choose one or the other, I usually chose the xxx." How do you think Weyl ended this quote – by choosing the true or the beautiful? Surprisingly, Weyl said that he chose beauty over truth. That choice of beauty, by a scientist who appreciates beauty, sometimes overturns the notion of truth to define a new truth. This brings to mind a quote by the great poet, John Keats, "Beauty is truth, and truth beauty—that is all ye know on Earth, and all ye need to know."

Several scientists in the film discuss the connections they see between science and art. This provides us with some opportunities to explore two questions: What is beauty in science? and how do we become better at appreciating it?

In looking at the data from a collision of protons, one can easily imagine that such a "picture" could be found on the wall of a museum.



Possible image revealing Higgs boson. Courtesy of CERN. Image retrieved from http://scienceblogs.com/startswithabang/2013/02/20/the-worst-kind-of-science-hype/

7.1 Does this picture become more or less beautiful when you know that it has something to do with the discovery or Higgs boson? Please explain.

Jackson Pollack employed drip painting and is considered one of the great artists of the 20th century. Here is an image of Pollock painting.

Jackson Pollock working on a painting, 1950 / Rudy Burckhardt, photographer. Jackson Pollock and Lee Krasner papers, Archives of American Art, Smithsonian Institution. Retrieved from: http://www.aaa.si.edu/collections/images/detail/jackson-pollock-working-painting-3910

7.2 How did Jackson Pollack employ the effects of gravity and other physics principles in his painting? How are his paintings different from the selection of tracks from a proton-proton collision?

7.3 The Large Hadron Collider makes thousands of images of proton-proton collisions. Some of those images produce valuable information and discoveries. Other images are seen as exceedingly beautiful. What criteria would you use to in the selection of tracks from a proton-proton collision for aesthetic purposes?

The machine as architecture

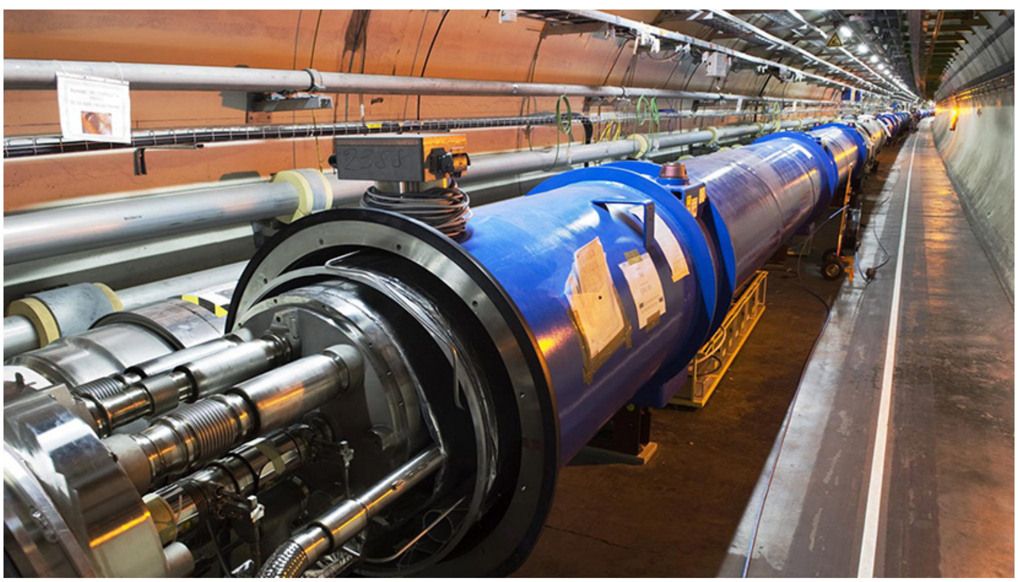
7.4 There are some incredible feats of architecture that have been called the man-made wonders of the world. These include the Taj Mahal and the Great Pyramids. Why are these chosen as wonders of the world?

Taj Mahal. Image by Muhammad Mahdi Karim. Wikipedia Commons. Retrieved from https://en.wikipedia.org/wiki/File:Taj_Mahal_2012.jpg

Ancient Pyramids, Egypt. Wikipedia Commons. Retrieved from https://en.wikipedia.org/wiki/File:All_Gizah_Pyramids.jpg.

As mentioned in the film, "The Large Hadron Collider, the biggest machine ever built by human beings, is finally going to turn on." Another physicist gives more detail, " These big blue things are seven-ton super conducting magnets, which have to be cooled with liquid helium to the coldest….There are a hundred thousand computers connected all over the world to deal with the data. In fact, the worldwide web was invented at CERN so that physicists all over the planet could share the data."

7.5 Do you think that the Large Hadron Collider is another wonder of the world?



Magnets in the tunnel of the LHC. Courtesy of CERN.Retrieved from http://particlefever.com.

There are two repeating images in the film. One is the god Shiva, one of the primary deities of the Hindu religion. The other is the Moon in the sky.

7.6 What is the significance of each of these images to the story of the hunt for the Higgs boson and the Large Hadron Collider?

Statue of Shiva at CERN. Image by Arpad Horvath. Wikipedia Commons. Retrieved from http://commons.wikimedia.org/wiki/File:CERN_shiva.jpg

A full moon captured July 18, 2008. Credit: NASA/Sean Smith. Retrieved from: http://www.nasa.gov/centers/langley/news/researchernews/supermoon.html

7.6 Can you think of other images that the film makers could have chosen? For each of three images you mention, please explain its significance and how it relates to the Higgs or the LHC or the storyline of the movie.

In describing a recent film by Werner Herzog, one of the scientists says, "It was about these incredible caves that they discovered a few years ago in France. Stunningly beautiful. Gorgeously drawn horses; bison; rhinoceros; lions; because 40000 years, this is what was going on there. In exploration, and science is exploration, there needs to be the set of people who have no rules, and they are going into the frontier, and come back with the strange animals and the interesting rocks and the amazing pictures, and to show us what's out there. Discover something. Why do humans do science? Why do they do art? The things that are least important for our survival, are the very things that make us human."

7.7 Can you answer the question that he raises in the movie: Why do they do art?

7.8 Cave paintings were drawn by humans over 15,000 years ago. They show animals and humans. Do you think that there will be any evidence of the Large Hadron Collider in 15,000 years? Are there any other human made structures that have lasted this long?

There is a party shown in the movie where a group of physicists are performing a rap about the physics concepts and physics experiments that they are all involved in. It seems everybody is amused.

7.9 Do the spectators treat this as music or a novelty?

7.10 How does music get the attention of people?

7.11 Do you think that Eminem or Jay Z would ever create a rap about the Large Hadron Collider? Why or why not?

In the film Savas Dimopoulos discusses the power of the human mind and the pride for humanity regarding our understandings that have led to the discovery of the Higgs particle. "It's astonishing that there are any laws of nature at all. That they're describable by mathematics; that mathematics is a tool that humans can understand. That the laws of nature can be written on a page. It's the greatest of all mysteries. There is a strong sense that we are hearing nature talk to us."

Savas Dimopoulos. Image courtesy of CERN. Rerieved from http://www.youtube.com/watch?v=Rikc7foqvRI

Our understanding of the laws of nature have been propelled by our understandings of math.

7.12 How is it that humans can create something as abstract as mathematics?

7.13 Galileo stated that mathematics is the language of nature. How is math different from spoken language? How is it similar?

7.14 Eugene Wigner, a great physicist of the 20th century, once remarked on "the unreasonable effectiveness of mathematics in explaining the physical world." What does Wigner mean by this?

7.15 If math provides insights into our world that we can only learn through math, does that raise math to an art form?

Henri Poincare once wrote:

> *The scientist does not study nature because it is useful to do so. He studies it because it is beautiful. If nature were not beautiful, it would not be worth knowing and life would not be worth living... I mean the intimate beauty which comes from the harmonious order of its parts and which a pure intelligence can grasp...*

The physicist Werner Heisenberg recalled that he once told Einstein:

> *If nature leads us to mathematical forms of great simplicity and beauty... that no one has previously encountered, we cannot help thinking that they are 'true,' that they reveal a genuine feature of nature... You must have felt this too: the almost frightening simplicity and wholeness of the relationships which nature suddenly spreads out before us...*

The mathematician and physicist Paul Dirac held that “A physical law must possess mathematical beauty.”

> Bacon’s dictum that “There is no excellent beauty that hath not some strangeness in the proportion.”

Einstein in describing his General Theory of Relativity, prior to having any experimental evidence of its success, said that “it was too beautiful to be wrong.”

7.16 How do these scientists define beauty?

7.17 Are there definitions of beauty different from yours? What is your definition of beauty?

7.18 We have all seen beautiful people and beautiful landscapes and beautiful art. We have all heard beautiful music. Have you ever learned any beautiful science? Can you think about a science concept that you have studied that could be considered beautiful? What criteria must it have?

7.19 At the state fair, you can see cows that are considered beautiful. If you are not familiar with cows, they all look alike. Does that mean that the people who know about cows are making this all up? Do the judges know something about cow beauty that others don’t? How would one go about learning about cow beauty? Can you extend this learning about cow beauty to learning about physics beauty?

7.20 One of the physicists in the film remarks, “There are many similarities between music and physics. Classical music follows rules of harmony which are really rules of physics and mathematics." What does he mean by comparing the two? How do you think classical music is different from physics?

Monica Dunford shows graph of first beam. Courtesy of CERN. Retrieved from http://www.youtube.com/watch?v=Rikc7foqvRI. Courtesy of Particle Fever.

7.21 In the film, after the proton beam first makes it journey, Monica Dunford is running around showing the graph on her computer to everybody that will look. She asks, "Did you guys see our beautiful plot?" Why does she think her plot is beautiful? Has she created the plot the way she may have painted a picture? Have you ever had this kind of excitement in plotting data during a science lab? What would it take for you to get this excited about data?

The sculpture garden in the film helps Nima Arkani-Hamed better understand the work that he is involved in.

"There's something philosophically about this piece of art that bothers me. It's taking a lot of sort of random things and making some order out of it. Yes. It's trying to make order out of something where there isn't any. Instead of taking things that don't seem ordered and figuring out that there is order. The way we try to reduce the complexity of the world is by looking for patterns. What we call symmetries. We take all the particles we know today and we attempt to fit them into some kind of underlying structure.

Nima Arkani-Hamed and David Kaplan looking at sculpture. Courtesy of Particle Fever. Image retrieved from: http://www.youtube.com/watch?v=dEcWjMX9oCw

"Are they the remnants of some more beautiful and complete picture of the laws of nature? It's like, you go to Egypt and you see ruins. If you look at it the right way, I could draw a pyramid and see that these chunks of stone are actually the remains of something very clean and very symmetric. Very beautiful."

7.22 Can you choose some art, movie, music or dance and explain how that can relate to the themes of *Particle Fever*?

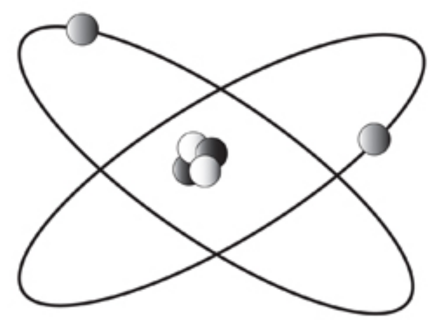
Theme 8: Scale

The scale of distance

There was once a time, just a few hundred years ago, when people could only see with their eyes. A person could see a human hair but not much detail of the hair. A person could look at the moon but would not be aware of the craters on the moon. After Galileo first used a telescope to look upwards, the moon's craters became visible as did the moons of Jupiter and the rings of Saturn. After Van Leeuwenhoek's invention of the microscope, people could look in a drop of water and see an entire world of microorganisms. Now that the LHC has found the Higgs boson, it is possible to look at matter at an even smaller scale than ever before.

Particle Fever highlights the discovery of the Higg's boson and assumes that we can grasp how small this particle really is or how old the universe was when this particle bestowed mass on other particles at the creation of the universe. Getting a sense of the scale of distances and size is both entertaining and awe-inspiring.

The size of the atom and nucleus is virtually impossible for most people to comprehend. We see pictures in books that show the nucleus of an atom as a dot surrounded by electrons in orbits. Occasionally, the drawings show the nucleus to have its internal structure of protons and neutrons in different colors. Such illustrations are not drawn to scale, because if the whole page were the atom, the nucleus would be much too small to see on the page, regardless of how small a dot you could draw. It's disappointing that the texts rarely admit to the inaccurate scales used to depict the components of an atom.



Illustrator's conception of a helium atom.

Students can get a sense of how scientists measured the size of the nucleus in a fun exercise by placing a trashcan beyond the teacher's desk so they can't see it, then crumpling pieces of paper from the recycling bin and lobbing them in the general direction of the trashcan. If the trashcan represents the nucleus and the area behind the teacher's desk represents the atom, it is possible to measure the ratio of the size of the nucleus to the size of the atom by counting the number of papers that went into the trash can versus the number that missed. Imagine, for example that only one in ten pieces of paper went into the trashcan. Then the nucleus in this model must be one tenth the size of the atom. If just one in 100 papers went into the trashcan then our estimate would be that the nucleus is one hundredth the size of the atom.

This experiment can now be compared to Ernest Rutherford's scattering experiment. Rutherford shot alpha particles at a gold foil, in which atoms are tightly packed. He found that only one in every 100,000 bounced back, while almost all the others went right through the foil. His conclusion was that there is a tiny, tiny, tiny location within the atoms of gold that contain all the mass and all the positive charge. He called this location the *nucleus*. More detail on this experiment and related ones on Rutherford scattering can be found in *Active Physics* (Eisenkrft, 1998) and *Active Chemistry* (Eisenkraft, 2003)

We now know, through similar kinds of indirect measurements and our theories of matter that the protons and neutrons in the nucleus are even smaller and the electrons are smaller still. How can we imagine the size of the Higgs boson?

Challenge your students to construct a scale diagram of the atom and the nucleus. They can use the following size approximations.

8.1 The atom is 100,000 times larger than the nucleus. If the students were to imagine the nucleus to be the size of a pea, how large would the atom be?

8.2 At this scale, how large would a model of a tiny salt crystal be? Consider that salt crystals are arrays of sodium and chlorine atoms (NaCl). Assuming that the atoms are all the same size, how big would a three-dimensional model be of a salt crystal be if the nuclei were the size of peas, and a tiny salt crystal contains several million atoms?

8.3 Alternatively, your students can take something large that they know the size of such as the school auditorium. If that is the size of the atom, how large would the nucleus be if it were 1/100,000 the size of the auditorium? How big would the model of the salt crystal be at this scale?

There are other opportunities to get a sense of physical size in *Particle Fever*.

8.4. In the film, you can see the Large Hadron Collider. How large is it? Estimate the size of the LHC by calculating the length of the tunnel that the beam must travel. The diameter of the ring is 17 miles around. How long is the tunnel? (17 x 3.14 = 53 miles)

8.5. How does the length of the tunnel compare with your walk to school? If you could walk the full length of the tunnel how long would it take you?

8.6. How many people would it take, holding hands, to create a human chain all the way around the tunnel of the LHC? (Assume about five feet per person.)

8.7. If the beams were as wide as a nucleus, how is it possible for them to make sure that they collide and not just pass by one another? How wide do you think the beams have to be to make the collision possible? (Creating magnetic fields strong enough to maintain an extremely narrow beam was one of the greatest engineering challenges of the LHC.)

The scale of time

The timescales discussed in the film range from the infinitesimally small to the unimaginably large. In particle physics, collisions of protons produce many exotic particles. Some of these particles exist for less than a millionth of a second. The Big Bang occurred 13.7 billion years ago. How can you help your students grasp this huge scale of time?

You may want to start with the human timescale, which falls between these two great extremes. Here are some suggestions:

8.8. The work leading to the discovery of the Higgs boson took nineteen years. In *Particle Fever*, Monica Dunford explains how much patience is required to work on a project of this length by comparing it to the running of a marathon. What can you think of in your own life that requires patience and persistence over a long period of time?

8.9. Think about what you want to be doing five years from now, or even ten years from now. What long-term efforts will you need to undertake to get there?

8.10. Now imagine a short time frame. You can approximate seconds by counting "1-one-thousand, 2-one-thousand, 3-one-thousand," etc. Practice this for 10 seconds against a clock to see how good you can become at this method. Once you can count seconds, you can use this same technique to measure quarter seconds since each syllable of 1- one-thousand requires ¼ of a second.

8.11. Your reaction time is probably between one tenth and one twentieth of a second. You can measure your reaction time by having someone drop a ruler, which you then catch between your thumb and finger. The distance the ruler falls is a measure of your "reaction distance." Since the ruler falls at a given rate, you can then convert that distance into a time using an equation for falling objects. Reaction time (in seconds) = 0.045 times the square root of the reaction distance (in centimeters). Measure your reaction time and that of your friends. Measure the reaction time while someone is listening to music to see if there is any difference.

8.12. Now imagine a shorter time frame. Calculate how long it takes a proton, traveling at close to the speed of light (300,000,000 meters/second) to make one lap around the LHC ring.

8.13. Investigate even shorter times by doing research on the web:

- **How accurate do clocks have to be to get your GPS to work?**
- **How much time does it take for an electron to go from one orbital to another. How do chemists measure such a short time?**
- **How do scientists measure a billionth of a billionth of a second?**

8.14. Going in the other direction, try to imagine the timescale of the universe in terms of human generations. Assume that on average parents are 25 years older than their children, grand parents are 50 years older than their grandchildren, etc. how many generations have there been since: the invention of agriculture (10,000 years ago)? The end of the dinosaurs (65,000,000 years)? The formation of the Solar System (4,500,000,000 years)? The Big Bang (13,700,000,000 years.)

The scale of speed

In *Particle Fever* we learn that the particles in the LHC travel almost the speed of light. In the 1600s, Galileo was the first person to put an upper value on the speed based on an experiment he conducted. Galileo had a friend stand on a distant hill with a lantern. When Galileo opened his lantern, the light left his hill and traveled to the other hill. As soon as his friend saw the light, he opened that lantern and light traveled back to Galileo. By measuring the time for the light to travel from one hill to the other and back again, Galileo hoped to find the speed of light. Since Galileo could not measure any delay at all he concluded that light must travel at least 10 miles per second.

8.15. Investigate how other physicists improved on Galileo's estimate for the speed of light. Start with how Ole Christensen Rømer used his observations of Jupiter's moons to make the first good approximation of the speed of light.

8.16. Albert Michelson made a very accurate measurement of the speed of light around 1900 and became the first American to win a Nobel Prize in science as a result. What method did he use?

8.17. Michelson measured the speed of light to be approximately 186,000 miles per second. If Galileo's hills were 5 miles apart, how long would it have actually taken for light to travel back and forth?

Portrait of Ole Rømer (Image in public domain)

8.18. An experiment you can do during a lightning storm can help you calculate the distance from the storm to you. Since light can travel the few miles in almost no time, and since sound takes about 5 seconds to travel every mile, you can use the fact that the lightning and sound originate at the same time to find the distance. After seeing the lightning, begin counting seconds: -one-thousand, 2-one-thousand, 3-one-thousand, etc. If you get up to 5 seconds, how far away is the storm? (5 seconds x 1 mile/5 seconds = 1 mile) If you count ten seconds between the lightning flash and sound of thunder, how far way is the storm? (10 seconds x 1 mile/5 seconds = 2 miles)

The scale of money

The Large Hadron Collider cost billions of dollars to build. How much is a billion dollars?

9.16. If you were required to spend $1000 per day, how many days would lapse before you ran out of your billion dollars? What could you buy every day for $1,000?

8.20. If you were required to spend $10,000 per day, how many days would lapse before you ran out of your billion dollars? What could you buy every day for $10,000?

8.21. If you were required to spend $100,000 per day, how many days would lapse before you ran out of your billion dollars? What could you buy every day for $100,000?

8.22. If you were required to spend one million dollars per day, how many days would lapse before you ran out of your billion dollars? What could you buy every day for $1,000,000?

8.23. How much money does it cost to build a house? How many houses could be purchased for one billion dollars?

8.24. How much money does it cost to build a school? How many schools could be purchased for one billion dollars?

8.25. How much money does it cost to build a hospital? How many hospitals could be purchased for one billion dollars?

The vast scales involved in the LHC experiments are challenging to envision. The scales of distance, time, speed, and money are beyond most people's ability to fully grasp. However, the use of analogies, calculations, thought experiments, and other methods suggested here will help your students begin to get a feeling for the magnitudes involved.

GLOSSARY (From particlefever.com)

5 Sigma

Sigma, in a statistical sense, is the deviation from some norm and can represent a probability. When a 5-Sigma excess is announced (like evidence for the Higgs), the chance that the Higgs is not there and the data is due to a random fluctuation is 1 in 3.5 million.

ATLAS

ATLAS (A Toroidal LHC ApparatuS) is one of the seven particle detector experiments (ALICE, ATLAS, CMS, TOTEM, LHCb, LHCf and MoEDAL) at the LHC, and one of two (with CMS) looking for the highest energy particles, such as the Higgs Boson, Supersymmetric partners, and Dark Matter.

Boson

All particles can be divided into two classes based on an internal property called spin. Matter particles, like electrons or quarks, are fermions. Force carrying particles are bosons.

CMS

The Compact Muon Solenoid (CMS) experiment is an LHC detector that lies on its French side and (like ATLAS) its goal is to investigate a wide range of physics, including the Higgs boson, extra dimensions, and particles that could make up dark matter.

Cosmological Constant

A parameter in Einstein's theory of relativity which, when added, amounts to "vacuum energy," or energy stored in space itself. It can cause the universe to expand at an accelerated rate — something which appears to be occurring today. The size of the cosmological constant is one of the biggest mysteries in theoretical physics.

Dark Matter

In astronomy and cosmology, dark matter is a type of matter hypothesized to account for a large part of the total mass in the universe. Evidence strongly suggests it isn't ordinary matter – i.e., it is not made of atoms. A great hope for the LHC is that it will discover a new particle that could explain dark matter.

Hadron

A hadron is a composite particle made of quarks held together by the strong force (in a similar way as atoms and molecules are held together by the electromagnetic force). Protons and neutrons are hadrons.

Higgs Boson

The Higgs boson or Higgs particle is an elementary particle initially theorized in 1964, and confirmed to exist on 14 March 2013. Its discovery completes the Standard Model, represents the first elementary particle seen without spin, and confirms the existence of the Higgs field.

Higgs Field

The Higgs field fills all of space and, according to the Standard Model theory, was 'switched on' moments after the Big Bang, which caused most elementary particles (quarks, the electron, weak force carriers) to acquire mass. The electron mass allows atoms to form and thus the Higgs field is responsible for all normal matter as we know it.

LHC

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. It first started up on 10 September 2008, and is the largest ring (27 km) in CERN's accelerator complex. It consists of superconducting magnets to guide the particles and accelerating structures to boost the energy of the particles along the way. The machine is being upgraded currently and will operate at even higher energies in early 2015.

Multiverse

The multiverse is a theoretical description of spacetime in which our known universe is a small part of something much more vast in which the laws of nature might vary from place to place. The multiverse, while potentially a natural consequence of string theory and cosmic inflation, is not yet well-defined and by some is considered controversial.

Particle

Particles are, by definition, the smallest physical objects. Elementary particles are point-like, but can carry energy, mass, electric charge and other information or attributes. Study of fundamental particles is a key part of the study of the laws of nature.

Proton

Protons are positively charged subatomic particles that, along with neutrons, make up the nucleus of an atom. Protons are the particles that are accelerated and collided at the LHC.

Standard Model

The Standard Model is the current theory of elementary particles. It is literally a list of particles and their interactions, which abide by the laws of quantum mechanics and relativity and describe nearly all known physical phenomena in our Universe at the microscopic level.

Supersymmetry

Supersymmetry is a special type of symmetry in physics, which implies that there is a correspondence, at a fundamental level, between fermions and bosons (roughly particles which make up matter and particles responsible for forces). If supersymmetry were true, each Standard Model particle would have a corresponding 'superpartner, potentially discoverable at the LHC.

In MEMORIAM

As this teacher guide goes to press, we are sad to report that the first author, Alan Friedman, has passed away after a short illness. Dr. Friedman served in many roles during his career, including Director of Astronomy and Physics Education at the Lawrence Hall of Science, in Berkeley, California, Director of the New York Hall of Science, in Queens New York, a member of the National Assessment Governing Board, and more recently, a Consultant to museums, science centers, national agencies, and of course, the film *Particle Fever*. His many contributions to science education have already had a profound impact, and will continue to influence the lives of teachers, students, parents, and children for decades to come.