

THE ATLAS AND LHC COLLABORATIONS AT CERN: EXPLORING THE BIG BANG

Research Associate Philippe Margery prepared this case under the supervision of Professor Donald A. Marchand as a basis for class discussion rather than to illustrate either effective or ineffective handling of a business situation.

What happened in the first trillionth of a second after the Big Bang? How was matter – and ultimately everything on Earth – created? Are there parallel worlds?

In late 2008, scientists hoped that the world's largest ever physics experiments would soon provide confirmation of theories that seemed to belong to the realm of science fiction, such as extra dimensions and microscopic black holes on Earth.

The experiments were part of the Large Hadron Collider (LHC) project. Built by CERN – the European nuclear research organization based in Geneva – it consisted of a 27-kilometer ringlike underground tunnel, straddling the border between Switzerland and France. There were four so-called detectors located around the LHC, the largest in size being ATLAS.

The LHC accelerated particles known as protons through its tunnel in opposite directions at close to the speed of light. It then forced head-on collisions inside the detectors and the resulting debris was analyzed. By understanding these collisions, physicists hoped to learn about the basic forces that have shaped our universe since the Big Bang. They might discover entirely new laws of nature, produce mini black holes, prove the existence of extra dimensions and explain how mass is created. An entirely new era of physics was unfolding.

By 2008, about 7,000 scientists – more than half of the world's experimental particle physicists – were involved in the LHC project, with its four large detectors. Over a period of more than 20 years, some 300 universities and research institutes in 50 countries on six continents had contributed.

ATLAS is one of the largest, most complex scientific devices ever built. What journey led to the successful completion of this incredibly complex project? How did 169 institutions and national agencies from 37 countries agree to fund it? How could a group of 2,500 scientists and engineers, spread all over the world, collaborate over such a long time span?

The Physics in a – Very Small – Nutshell

Fundamental physics tries to find out what the universe is made of. To do this, scientists need to study collisions between the smallest constituents of matter – the fundamental particles such as quarks and electrons.¹

Particle physics, sometimes called high-energy physics (HEP), studies these fundamental particles. Zooming down in scale from a person to one of these particles is like shrinking the diameter of the whole earth to the size of a five-cent coin and then shrinking the coin by the same amount again.

Particle physics involves the biggest, most complicated experiments in the history of science, with the fastest computers, the coldest temperatures and the strongest magnets on Earth. In particle colliders, particles traveling at almost the speed of light are made to collide with one another, re-creating the conditions in the universe just after the Big Bang. Scientists then observe the results of the collisions and draw conclusions about how all these particles interact with one another.

The Fundamental Forces

There are four fundamental forces in the universe that govern the way particles interact with one another: gravity, electromagnetism, and the weak and strong nuclear forces. Each of these is produced by fundamental particles that act as carriers of the force. The behavior of these particles and forces can be described with impeccable precision by the so-called standard model, with one notable exception – gravity. The gravitational force – the most familiar in our everyday lives – has proved very difficult to describe. For many years, this has been one of the most difficult problems in theoretical physics.

Thus the standard model falls short of being a complete theory, and to explain it, one more particle remains to be discovered. Scientists have called the “missing” particle the Higgs boson, after the British scientist Peter Higgs, who in 1964 first suggested that it must exist. They believe that the underlying theory which predicts the Higgs provides an explanation for why matter has mass, allowing for the formation of stars, planets and galaxies.

According to some theorists, the Higgs particle could bring to light entirely new types of strong interactions; others believe the LHC experiment will reveal a new fundamental physical symmetry referred to as “supersymmetry”; still other theories predict it might point to the existence of additional dimensions – up to 11 in total.

Brief Background: CERN, LHC and ATLAS

CERN

CERN (*Conseil Européen pour la Recherche Nucléaire*), the European Organization for Nuclear Research, was established in September 1954 by 12 European states. It is situated in the northwest suburbs of Geneva and extends across the Swiss/French border.

¹ Quarks and electrons are, among other particles, the basic constituents of matter.

By 2008 it was the world's largest and most respected center for particle physics. It was run by 20 European member states, each with two delegates to represent the national administration and scientific interests. A further eight organizations or countries had "observer status" – the European Commission, India, Israel, Japan, Russia, Turkey, UNESCO and the United States. Observer status allowed non-members to attend Council meetings and to receive Council documents, but they could not take part in the decision making. (*Refer to **Exhibit 1** for the origin of users.*)

Mission

CERN's mission was to foster fundamental research in particle physics. Its work could not be for military purposes and results from its research had to be openly available. CERN had two main activities: (1) to construct and maintain research facilities (particle accelerators) for the use of the global scientific community; and (2) to foster international collaboration among scientists both inside and outside the laboratory. Five Nobel prizes in physics had been awarded to CERN physicists since it was founded.

Structure and Funding

The CERN Council was the organization's highest authority, controlling all its activities in scientific, technical and administrative matters. The Council was assisted by the Finance Committee and the Scientific Policy Committee – the latter eminent scientists who set the long-term goals (*refer to **Exhibit 2***).

Each member state had a single vote and most decisions required a simple majority, although in practice the Council aimed for unanimity. It appointed the director-general for a term of five years through a two-thirds majority. The director-general managed the CERN Laboratory and ultimately decided on all issues in CERN (*refer to **Exhibit 3***).²

CERN and its projects were financed by the member states, by states with observer status (*refer to **Exhibit 4***) and through voluntary contributions by other, non-member states. Only member states paid a subscription. Subscriptions were proportional to gross national product, but no country paid more than 25% of CERN's total budget. The budget for 2007 was over CHF 1 billion.³ In the words of Sir Chris Llewellyn Smith, director-general between 1994 and 1998:

I saw my job as one of a salesman, in a sense. I had to go out and convince the governments of Europe – and the world – to join projects. But to do that, you've got to have the confidence of the user community, the physicists. Of course, there was a big internal job as well.

² The director-general from 2004 to 2008 was Robert Aymar, a French plasma physicist, with Rolf-Dieter Heuer, a German particle physicist, due to replace him from 2009 to 2013.

³ CHF 1 = €0.62 = \$0.96.

Legal Status

An agreement⁴ between the Swiss Federal Council and CERN stated that CERN would be governed as an international organization, that it would enjoy the immunities and privileges usually granted to such organizations; that no agent of the Swiss public authorities could enter its grounds and building without the express consent of the director-general and that the archives of CERN were equally inviolable. CERN was able to establish its own rules, including labor laws; it could buy goods and services and pay salaries free of tax; and it was subject to international arbitration. In 1965, as CERN's site was extended into France, a similar agreement was signed with the French government.

The Large Hadron Collider (LHC)

The LHC was the fourth generation particle accelerator and collider at CERN, succeeding the Large Electron Positron collider (LEP), in use from 1989 until 2000. When the LHC was commissioned in 2008, it was the most powerful particle accelerator ever made.



The LHC accelerated beams of particles around its 27-kilometer tunnel at depths ranging from 50 to 175 meters underground and operated at temperatures very close to absolute zero.⁵ The beams, traveling in opposite directions, consisted of protons strung like beads on a chain 25 billionths of a second apart. A total of 1,800 superconducting underground magnets – most weighing over 27 tonnes – kept the beams on target. It took just 90 microseconds for an individual particle to travel once around the accelerator. (Refer to *Exhibit 5* for a graphic representation.)

The ATLAS Detector

Along the LHC were four detectors in which scientists engineered head-on collisions between particles. The energies at which quarks and gluons⁶ collide through the LHC are those that prevailed a pico-second⁷ after the universe was born in the Big Bang, when its temperature was a billion times that in the core of the sun. The detectors allowed physicists to analyze the fallout from the collisions.



The ATLAS detector, the largest in size of the four, was assembled in an underground “cavern.” The detector was 46 meters long, 25 meters in diameter – about half the size of Notre Dame cathedral in Paris (pictured) and weighed around 7,000 tonnes – as much as the Eiffel Tower.

⁴ Legal information can be found at: <http://dsu.web.cern.ch/dsu/ls/documentsE.htm>.

⁵ Absolute zero: temperature at which nothing can be colder (-273.15°C, -459.67°F).

⁶ Gluons: elementary particles causing quarks to interact. They bind protons and neutrons in nuclei.

⁷ Pico-second: 10⁻¹² of a second or 0.000000000001 second.

ATLAS was not only big, but it was also extremely complex. The space shuttle, for example, had in the order of 10 million “hand-touched” components. ATLAS had about 20 million, including the cables, connectors and electronics housed outside the underground cavern.

The ATLAS detector had to sort out the debris from particles colliding every billionth of a second and handle data rates roughly equivalent to the transmission of 20 simultaneous telephone conversations by every person on Earth. Although the collisions were occurring at almost the speed of light (more than 1 billion km/h), the error margin of the measurements had to be less than 0.001 centimeters. Of the 800 million collisions occurring per second, only about one in a billion was potentially interesting to physicists. (*Refer to Exhibit 6 for an overview of the ATLAS detector.*)

The ATLAS Collaboration

The ATLAS collaboration evolved as a project within CERN and had no legal existence of its own. However, because of the sheer scale of the project, about 80% of the costs and resources for building ATLAS came from outside CERN.

ATLAS and the other LHC experiments more or less replicated the CERN structure, with a Collaboration Board (CB) of institutional representatives overseeing the scientific and technical work and a Resource Review Board (RRB) for financial supervision by funding agencies. The RRB was chaired by the director of research for the LHC program. Roger Cashmore, chairman of the RRB from 1999 to 2003, explained:

The chairman of the RRB’s first task was to make sure that all of the collaborating countries lived up to the promises they made to their national groups, and indirectly to ATLAS. The second thing was to make sure that the experiments such as ATLAS understood that they had to show they were using the money properly, effectively and within timeframes. The funding agencies expected me to give them clear guidance on the reporting and requirements coming from the scientists but also that CERN could do its part. I was ultimately responsible for the 20% CERN committed to the project.

ATLAS was composed of four major sub-systems. Each was in turn divided into sub-elements and the project leader of each sat on the Executive Board. The chairman of the Executive Board was the spokesperson,⁸ who did not formally report to CERN. He was part of and led the executive team, along with initially one and later two deputy spokespersons;⁹ the technical coordinator,¹⁰ who had overall technical responsibility for the project and was deputy chairman of the Executive Board; and the resources coordinator,¹¹ who had overall financial responsibility for the project. The executive team members were proposed by the spokesperson after consultation in the collaboration at large. They were formally approved by the

⁸ Spokesperson: Peter Jenni, Swiss experimental physicist (1992–2009).

⁹ Deputy spokespersons: Torsten Åkeresson, Swedish (1992–2004) and later Steinar Stapnes, Norwegian and Fabiola Gianotti, Italian (2004–2009), both experimental physicists

¹⁰ Technical coordinator: Hans Hoffmann (1992–1999), Mike Price (1999–2001) and Marzio Nessi (2001–2009).

¹¹ Resources coordinator: Peter Schmid (1992–2001) and Markus Nordberg (2001–2009).

Collaboration Board for a period of two years (*refer to **Exhibit 7***). The technical coordinator and the resources coordinator were CERN employees.

National funding agencies paid for their scientists to participate in building the four sub-systems – the tile calorimeter, the liquid argon cooling system, the muon spectrometer and the inner detector – as well as the trigger data acquisition (TDAQ) and the shared elements of the project, which included software development, on-site infrastructure and cryogenics. Of the money the funding agencies contributed to ATLAS, 44% was allocated to the so-called Common Fund for development of the shared elements (*refer to **Exhibit 8** for cost sharing*).

By October 2008, when it was finally commissioned, ATLAS involved 2,500 physicists at 169 institutions in 37 countries. About 20% of all experimental particle physicists worldwide were involved with ATLAS.

Precursors to ATLAS

Because of the complexity and evolving nature of science, many projects were discussed before being implemented – or jettisoned. Some of them overlapped and developed from one another. The following is a brief outline of the major steps leading to the ATLAS project (*refer to **Exhibit 9** for a more detailed timeline*).

UA1 and UA2 (1981–1993)

Particle physics experiments Underground Area 1 and 2 (UA1 and UA2) started at CERN in 1981. UA1 was driven by Professor Carlo Rubbia.¹² Hans Hoffmann was a young researcher at the time, but one of a few real experts in both colliding beams and high-energy experiments. He later became the ATLAS technical coordinator. He recalled:

When the idea of UA1/UA2 was first proposed in 1977, three-quarters of CERN thought the whole project was madness, not to mention putting such a young person as me in charge of technology! This was the beginning of the collaborative model in particle physics, involving 130 physicists. For CERN it really was a novel way to work, relying more than ever before on external resources which it didn't control.

UA1 became the most successful project at CERN and Rubbia and his colleague Simon van der Meer,¹³ were awarded the Nobel prize in physics in 1984.

At approximately the same time, construction of the LEP collider had begun at CERN. The excavation of the tunnel that was later to house the LHC was the largest civil engineering project in Europe between 1983 and 1988.

Planning for the LHC and the Detectors (1984–1992)

The UA1 and UA2 results showed there was scope for much more research. In March 1984, CERN and ECFA – the European Committee for Future

¹² Carlo Rubbia: experimental physicist born in Italy in 1934.

¹³ Simon van der Meer: accelerator physicist born in The Netherlands in November 1925.

Accelerators – organized an initial workshop in Lausanne around the design of an even more powerful accelerator than the projected LEP, the LHC.

Rubbia became director-general of CERN in 1989, the year that the LEP began operating. But he was interested in greater things. Hoffmann recalled:

Carlo immediately started pushing for the LHC. But he didn't have any money as he had to pay back debts for the LEP in the first three years of his directorate. So he launched the DRDC, the Detector Research and Development Committee, which was financed by external bodies such as CERN member states and the worldwide physics community. It was a masterstroke. Without funds of his own he could consolidate R&D into workable technologies and focus the research of physicists.

Across the Atlantic, the Americans were working on the SSC (Superconducting Super Collider). Cashmore, director of research for the CERN collider program, chairman of the RRB and later deputy director-general, noted:

The LHC was an inferior machine to the SSC in the sense that it would run at just about a third of the energy that the SSC would run at. Carlo Rubbia then had the idea that you could compensate for that energy difference by having very high luminosity.¹⁴ That was the debate raging around the early '90s. Few believed it could be done.

The project was a big political US–Europe fight. When Clinton became president in 1993 he had to cut budgets and cut the SSC, saving \$8 billion. Had the SSC carried on, the decision to build the LHC at CERN would have been very, very difficult.

So, in order to have a physics reach similar to that of the SSC, the LHC needed to achieve higher luminosity. This meant that the number of particles per “particle-bunch” being accelerated around the LHC was greater and so collisions would happen much more often. A vastly increased number of events per second imposed technical requirements on the detectors which were far more challenging than at the SSC – even impossible, many said at the time. Not only would collision frequency increase but so would radiation levels. Some believed these levels inside the detectors would be too strong for any equipment to survive. But the community continued to investigate its potential until consensus was reached within the collaboration.

Developing ATLAS (1989–1992)

Scientists developed ideas to submit to the DRDC as proposals. Only after conclusive reviews would the DRDC recommend the release of funds for further development. Research groups then created communities and developed the idea. Four main groups formed between 1989 and 1992: L3P, CMS, EAGLE and ASCOT. The *modus operandi* was open meetings and all information was made available to anyone. Scientists from around the world would spontaneously look up projects that seemed interesting to them and attend the meetings. Those already inside the collaboration would use their private networks to recruit the right brains. With them came the backing of their institutes. Within two years, EAGLE, for example, had grown to a network of several hundred.

¹⁴ Luminosity: collision intensity. Increased intensity increases the probability of obtaining one of the rare particle events the experiment is looking for.

Llewellyn Smith described the managerial challenges:

The LHC was built because the scientific community in Europe wanted it. So there was no problem in getting people to join in building the detectors. The problems were finding the resources, preventing the community from becoming too ambitious and bankrupting the whole thing, and then the managerial issue of a very multinational environment.

The groups grew and developed their ideas. In March 1992, CERN and ECFA again brought the parties together in Evian, France to present formal expressions of interest. By the summer of 1992 EAGLE and ASCOT had merged to form the ATLAS experiment. Over the following year, L3P and CMS¹⁵ merged to form the CMS experiment. Llewellyn Smith explained why the four groups were not merged into one to further reduce complexity:

It was always thought that there should be two major detectors for three reasons. First, due to differing technical choices, their risks are different. Second, you need scientific competition. There's only one LHC in the world, so the competition's got to be internal. Third, you need double checks; you need a way to check the science. You do that with detectors with different technologies.

Preliminary Development Work on ATLAS

The Collaboration Board, which included one representative from each institution, would ultimately validate the proposals made by the executive team, which consisted of the spokesperson with deputies, the technical coordinator and the resources coordinator.

Matteo Cavalli-Sforza, one of the first chairs of the ATLAS Collaboration Board, explained:

The Collaboration Board mainly dealt with the governance and with a few capital decisions that had to be made, of which by far the most important was the election of a spokesperson. High-energy physics is historically a process driven from the bottom so we say "spokesperson," but in a company you would say CEO. However, the spokesperson could not even decide where the money was spent because the money was brought in by the many participating institutes – and ATLAS had about 90 in 1992. So the spokesperson had this very difficult task of mediation, to get 90 potential prima donnas to agree on what to do.

Peter Jenni, who had been a key member of UA2, became the first spokesperson. CERN was consulted, but the process and decision came from the scientists working on the experiment. Markus Nordberg, ATLAS resources coordinator:

Peter is a very good example of a person who quietly brings everybody together, doesn't rock the boat, wants to make sure that everybody feels that they are part of the process. He knows how to encourage people through gentle guidance.

¹⁵ CMS experiment: compact muon solenoid. With ATLAS, one of the two large general-purpose detectors at CERN. Some 2,600 people from 180 scientific institutes formed this collaboration.

Building Consensus

A major challenge with ATLAS would be capturing the immense amount of information produced in each collision and selecting which pieces of information to store for future analysis. Livio Mapelli, project leader of the data acquisition and trigger sub-system, spoke of the complexity of managing the multitude of ideas:

The data acquisition and trigger sub-system is designed to have around 3,000 computers running in parallel, each with the equivalent of eight processors. There are close to 30,000 software applications running simultaneously. The amount of data produced in the collisions corresponds to roughly 40 million pieces of information per second, which is instantly reduced to about 200 through a special algorithm. This is the information the physicists will later analyze. We were faced with a huge scalability challenge.

In an international collaboration with tens of institutes and powerful laboratories, each comes with strong views of their own. That was when there were conflicts. On a project the scale of ATLAS, our work as leaders was to have others reach the same conclusion themselves rather than proposing and imposing it or asking people to compromise. We gave all ideas a fair chance to prove themselves. When inferior ideas were rejected, it was vital not to alienate the people who had the idea in the first place but rather always keep the brains and funds within the collaboration.

Llewellyn Smith explained how consensus was reached:

People found a way of thrashing through difficulties and finding solutions. Europe tends to talk everybody into exhaustion – just keep the door locked like a papal election or something. In the end everybody comes around. In the US, you get everybody in a room, and they all shout at each other for two days and then there's a vote. Half the people are dead, you get on with the other solution and they have to follow. Europe doesn't like that. I think that "the European style" had gradually evolved at CERN. People somehow learned to reach consensus, but it was time-consuming.

Cashmore added:

Ultimately, decisions had to be taken on consensus; you had to keep everybody, with an enormous diversity of skills, on board because it was technically very difficult. I don't think one could have built ATLAS or any of the other detectors without that camaraderie and commitment. You could not have done it with a top-down management system.

The members of this community were all highly motivated and knew and appreciated one another's professional capabilities. A team's inferior solution did not automatically reflect negatively on the perceived capacity of the team to contribute. The collaboration was increasingly worldwide in an always open and transparent environment. To maintain harmony in the collaboration, and although there were never compromises on the quality of what was being built, there could be technological compromises. The process and cost-efficiency might be sacrificed, not the quality of the output – even if that meant delaying decisions or not building tightly integrated solutions. A less tightly integrated sub-system also built in redundancy, allowing for a sub-system not to function without bringing the entire detector to a stop.

Once individual groups had agreed on a solution, they could test and promote it in public meetings for inclusion in the detector. Cavalli-Sforza explained:

There were typically several competing technologies. Different groups would develop and test prototypes and then report the results to the collaboration at large. There was a reviewing panel which would advise the Collaboration Board on the preferred options.

These were typically delicate meetings lasting a day every two months. The conclusions were reached in consultation with the spokesperson and were always supported by the Collaboration Board, typically by more than two-thirds. But it was not bloodless.

The LHCC

As ideas were maturing, in March 1992 CERN set up the LHCC – the LHC Committee – to advise CERN on what experiments to pursue by peer review. It met four or five times a year, and the ATLAS executive team presented the status of the project.

Its function was to assess whether the science and the technology were good and whether the people were capable of fulfilling expectations. Funding agencies would look to the LHCC's evaluations of the project before deciding on whether more funds should be provided. Cashmore outlined the process:

When we took a vote at the RRB, consensus had already been agreed beforehand. It was always about smoothing it through so that everybody knew why they were doing what they were doing. A lot of work had been done to convince everybody and see where the divisions were. There was a table of what everybody was going to have to pay to complete ATLAS. It became the budget within which ATLAS had to work.

Formal Milestones for LHC and ATLAS

Scientists were given much freedom in shaping the ATLAS experiment. CERN's role was to provide structure and processes to channel and realize the best ideas. When it felt ideas were maturing, it set the requirements for specific documents to be produced, formalizing the evolution of the experiment. These included the letter of intent, the technical proposal, the approval of the LHC project, the memorandum of understanding and the technical design reports. When it felt the time was right, CERN issued a deadline for when the next document should be produced. The scientists then focused their work on agreeing to what should be included, thus defining the realization of the ATLAS detector in a more detailed manner each time.

The Letter of Intent

In October 1992, a letter of intent (LOI) was produced by the ATLAS management team. It was signed by individual physicists representing their institutes. By then, however, 80% of the detector concept and who would provide the funds was known. All initial 90 institutions were still on board. The cost of ATLAS was then estimated at CHF 370 to 475 million for material alone, depending on the remaining technological choices to be made.

The Technical Proposal

The Technical Proposal (TP), approved by LHCC and CERN in November 1995, detailed what would have to be done to realize the LOI. Both were necessary steps to demonstrate the benefits and feasibility of the experiment but were no guarantee that it would come to fruition. Basic principles were understood but there were still many technical ideas related to, for example, computing, fiber optics and superconducting magnets which were not yet mature enough for the final design. The exact direction the project should take was still unclear, and the collaboration could not agree on many technical aspects. However, CERN had specified a timeline for the project. The first Technical Design Report (TDR) was expected in 1996. Much time and money had already been invested, and prestige was at stake. Failing now would be disastrous for CERN as well as the individual ATLAS collaboration members.

A Growing Community

Physicists around the world increasingly realized that the ATLAS collaboration was at the frontier of modern physics and a once-in-a-lifetime opportunity. As members looked out for experts and encouraged them to join, so the collaboration grew. The responsibility for the development of ATLAS became increasingly distributed outside of CERN. Hoffmann described how it worked:

When you walk into a problem you broadcast it around the collaboration and somebody comes up with the right idea. You then perfect it. If you don't openly share, within the collaboration at least, it doesn't work! So the schedule of meetings where you bring people together to discuss and which you repeat over and over again never stops. It's a culture of being completely open, where you don't go for intellectual property or for acknowledgment for yourself; everyone feels the importance of the ultimate goal. In such collaboration, results count. Everything is discussed. If people don't work out, they are soon no longer invited to participate in experiments. There is no hiding!

Getting the LHC Project Approved

By December 1991, the CERN Council had adopted a resolution that recognized the LHC as "the right machine for the advance of the subject and the future of CERN." Director-general Rubbia was asked to submit a complete proposal before the end of 1993. The task fell to Llewellyn Smith, who was due to become director-general at the beginning of 1994.

The outlook was not encouraging: A new costing estimate was significantly higher than previous ones; CERN group leaders estimated that 20% more staff would be required to build the LHC; attitudes to high-energy physics were hardening in several CERN member states; and the CERN Council had just agreed to a temporary reduction in Germany's contribution on the grounds that reunification was proving very costly.¹⁶

Consequently, proposals were developed to delay LHC commissioning until 2003 or 2004, to stage the construction of the detectors and to find further cost savings.

¹⁶ Llewellyn Smith, Chris. *Nature*, vol. 448, July 19, 2007, pp. 281–284.

Still, Germany and the UK were demanding more cost reductions and additional voluntary contributions from the host states, Switzerland and France. Although the host states offered additional contributions late in 2004, construction of the LHC in one step would still not have been possible under the budgetary conditions demanded by Germany and the UK.

CERN therefore proposed building a “missing-magnet machine” in which a third of the dipole magnets would be omitted in a first phase, thereby saving CHF 300 million. The machine would have operated at two-thirds of full energy for some years before the remaining magnets were installed. This was approved on December 16, 1994. This approval was accompanied by a decision to review the two-stage construction idea in 1997, and by a CERN Council declaration that any contributions to the collider from non-member states would be used to speed up and improve the project, not to allow reductions in member states’ contributions.

Having negotiated voluntary contributions from major non-member states, CERN was confident by the middle of 1996 that single-stage construction was possible, and asked the council to bring forward the 1997 review to December 1996. In July 1996, however, the German government announced out of the blue that it intended to reduce all its international science subscriptions to help ease the financial burden of reunification. The UK government saw another opportunity to look for reductions in the CERN budget. Llewellyn Smith observed:

We were facing a joint German and British front for a 10% reduction in everybody’s subscription [representing CHF 1 billion over some ten years].

It was a fierce battle. Realizing we would probably lose, we were still in parallel trying to get the Americans and the Japanese on board and single-stage construction of the LHC approved. It was very difficult indeed. Once I had the US and Japan signed up, I felt it would be very hard for the project to be canceled, because there would be a feeling of mutual commitment.

CERN’s public response to the proposed budget cut was muted for fear of shaking the confidence of the non-member states, which had been assured that their contributions would not be used to allow reductions in member state contributions. The US in particular had asked for reassurances on the viability and sustainability of CERN’s planning and funding.¹⁷ Against this backdrop, the director-general had no option in the end but to accept a reduction for all members of nearly 10% in CERN’s annual budget, starting in 1997. This required spreading out payment for the LHC, while dealing with the cash flow problem by borrowing, and absorbing as much as possible of the “lost” CHF 1 billion over the construction period of the LHC.

Llewellyn Smith commented:

I went to the Council and said, “With this large reduction, we can’t build the LHC unless CERN is allowed to borrow money to deal with cash flow. The members were mainly interested in annual budgets. So the idea of borrowing, which had previously been strongly resisted, especially by Germany, was finally agreed. I stressed that even with borrowed

¹⁷ Llewellyn Smith, Chris. *Nature*, vol. 448, July 19, 2007, pp. 281–284.

money, if a few things went wrong, the debt could get out of control. It was very risky, but the only strategy available. In the end, led by Germany, the members told me that they understood that there was a risk, but that they wanted CERN to take that risk.”

As many CERN Council members privately pointed out to the director-general, the most important thing was to get the LHC project approved. They knew that when it ran into financial difficulties, there would be no option for the funding countries but to find the necessary funds somehow.

Cashmore expanded:

The Council first approved the “missing magnet” machine in December 1994, but it would never have worked – it was political maneuvering. In the meantime, they convinced the US, Japan and Russia to provide resources directly for building the machine. That sort of thing had never happened before. So when single stage construction of the LHC accelerator was approved in December 1996, it was on a very strict budget with outside help.

The Memorandum of Understanding

A first interim memorandum of understanding (IMoU) for ATLAS was created in March 1996. The final version of the MoU was signed in 1998. It was like an internal constitution, defining how the collaboration should work and its structure and funding. It also outlined CERN’s obligations to the collaboration and the responsibilities of each institute in charge of a sub-system. It included detailed project milestones with deliverables and defined costs. The MoU spelled out who was committing to building what. Some 56% of all components were identified as deliverables by participating institutes and 44% remained to be funded in a collective manner, as part of the ATLAS Common Fund. There were now 140 research institutions from 37 countries involved. Jenni noted:

Until then it was an interim process. You were always expecting that the experiment could be cancelled, that the funding agencies would not clearly demonstrate their support.

The physicists in a given country have to map what they want to build, and this goes into the MoU. Then, they have to get as much funding as they can. Their ambition is of course regulated by the funding. It is a tricky problem. The funding agencies may be enthusiastic about what the physicists want to build, but they may be less keen if 44% of everything they contribute goes to the common part of the project.

In the words of Hoffmann, the MoU became a moral obligation to perform:

The memorandum of understanding says, “We promise our best.” In an international environment, it is a surprisingly valid formula. In a state-of-the-art scientific enterprise you don’t want to be the one who fails. And you will bend over backwards not to fail.

As the MoU was a “gentlemen’s agreement” – first between the physicists and second between the funding agencies and the project collaboration – CERN had little power to enforce it.

With the MoU, the actual funding process could start. The RRB was set up to review spending and budgets twice yearly. The MoU was the clearest sign ever that times had changed. CERN no longer “owned” the project. According to Jenni:

The previous generation of experiments at CERN, in terms of money at least, was a factor of five or so smaller. We had really passed the threshold of where CERN could be a safety net solving problems for us. And many things that were traditionally covered by CERN were not foreseen. Having anticipated this might have avoided a lot of managerial grief. On the other hand, maybe it would also have made it impossible to sanction the experiment and it would have had to be abandoned in its present scope. I am not sure...

Technical Design Report

Nine months after the IMoU was signed, the first Technical Design Report (TDR) was completed, on December 15, 1996, after around two years of effort. The TDRs described in detail what the ATLAS detector would look like; they would ensure there was no compromise on quality and open access to the large funds the construction would require. The central ATLAS executive team started organizing itself into a more formal structure. It identified the major building blocks, or sub-systems, which would constitute the detector.

Each sub-system was the ultimate responsibility of the collaboration of institutes that had committed to build it in the MoU, albeit supervised by the ATLAS executive team. These institutes tapped into their worldwide networks to recruit the best brains. They then divided each sub-system into smaller parts. The project leader of each sub-system was also the coordinator of the networks created and a member of the Executive Board (*refer to Exhibit 7*).

Each sub-system had its own major TDR, although sub-elements would often also require TDRs to get intermediary funding. Cashmore noted:

Over those years a cultural shift developed. Work became increasingly project oriented to keep track of how money was spent. You had to make good arguments and have priorities to secure enough money for what was really needed.

The TDR became the blueprint for production, but before reaching the final blueprint there was lots of prototyping and fine-tuning of technology. The TDR specified what should be built, by whom and under what conditions. Cavalli-Sforza commented:

There were at least ten or so important minds in this process from various institutions. Some were electronic or mechanical engineers, others were physicists. From our interactions, our brainstorming over the first three years, the sub-system was born.

The first TDRs were those for the liquid argon (LAr) calorimeter and the tile calorimeter. When the team was ready to start constructing the tile calorimeter, they needed 3,000 tonnes of iron and had identified the US as a source of funds. Their American partners, however, said that in the absence of a formal process, their funding agencies would not release any money. Llewellyn Smith explained this on a more general level:

The US found it difficult to accept that so much money was handled by a self-organized system with no one with whom you could actually say the buck stopped. But I always argued that that was essential. They asked me to take responsibility for the LHC detectors, but I said, no, that if I took responsibility and somebody in, say, San Diego went over budget, I would have to bail them out. If they knew that this would not happen, they would

be much more likely to keep to the budget and shoulder their share of the responsibility. This was the common understanding. Looking at it on paper, you'd never think that sort of management structure would work. But it had worked on a smaller scale with the LEP, and it worked with the LHC.

The deputy spokesperson, Torsten Åkesson, had been working on a project review system for the implementation of TDRs. Because the involvement of the US scientists and agencies was essential, Hoffmann and Marzio Nesi, head of the tile calorimeter sub-system at the time, decided to become early adopters and help shape the project review process. The first TDRs were produced in December 1996. Along with the TDR process, a Readiness Review was established to consider progress when each sub-system was 30%, 50% and 80% complete to ensure that the team could manage the construction complexity. The open reviewing process contributed to the transparency of the collaboration.

Defining Control Processes to Ensure Effective Results

The central ATLAS executive team had to make sure that the partners could deliver what had been agreed upon. Internal referees were introduced so that the culture of openness and trust that had been built was not jeopardized. They were specialists from within the collaboration working on different sub-systems, and would review the progress of another sub-system. Cavalli-Sforza explained.

To start with, ATLAS was a very loose coalition of people often with divergent interests. Once the strategic decisions were made and people got down to building detectors, things became much more cohesive. Everybody knew at that point that it would make no sense to leave ATLAS and join another detector, because the interesting tasks were already taken.



The tile calorimeter was built in 14 different locations worldwide. So in 1999, Nesi decided to use a project progress tracking (PPT) process on which he and Åkesson had been working. It established a building schedule, the flow of material and other dependencies. By the time Nesi became the ATLAS technical coordinator in 2001, the use of PPT extended across all detector sub-systems. The project leader for each sub-system updated the progress report each month, including what had been done and any problems. Nesi expanded:

We went about five levels below the project leaders. Some technical layers were extremely complicated. It was an incredible fight because nobody wanted to be checked. But this controlled the collaboration, somehow. We then put in place a public “top-watch” list with everybody who was diverging from the planned construction path. That group was then checked by the Executive Board every month. No one wanted to be on that list! And everyone had full access to the list. We were not hiding anything.

Building the ATLAS Detector

In 1999 the detailed specifications for what would be built had been agreed and the TDRs were “frozen.” All 12 TDRs were finalized between 1996 and 2003.

In 2000 the LEP was shut down and dismantled from the tunnel to make space for the LHC. Although not directly affected by this event, a project like ATLAS would benefit from the highly qualified engineers and technicians who had been working with the LEP and started to leave the project in the late 1990s.

Testing on the Surface



Once the parts were in the cavern, engineers could do little to fix problems or bring parts up to the surface again. Nessi and his team simulated assembly, engineering and the physics above ground for three years. He pointed out:

Until 2000, management was focused on the “outside,” i.e. making sure the institutes did what they were supposed to do, that the companies were behaving according to the specifications. It was easy to make a trip to Spain and, like a general, look at what everyone was doing and if they were behaving correctly.

From 2000 on, when the material arrived here, everything changed. They were coming here to make sure we were doing the right thing!

And now, we were playing with 44% of the entire collaboration money [the Common Fund]: I could make a contract for CHF 20 million – not CHF 2 million – which could go wrong. I had nobody who would collect 20 million for me if things went wrong.

To manage the risk, Nessi insisted on maintaining the continuity of the collaborative work:

I brought the people who had been constructing the parts over to CERN. They were very good people, highly motivated, who knew the systems very well – and money can’t buy that. I could employ people without making a special contract, without asking for special visas because they were all on diplomatic status – all we needed was a few signatures.

Financial Difficulties

Originally, when he was director-general of CERN, Rubbia had envisaged that the LHC would be operational before 2000. The ATLAS detector was initially scheduled for completion by 2005. However, in 2002 the discount granted to all member states in 1997 came back to haunt them. Nordberg noted:

It was obvious when I took over as resources coordinator in 2001 that we would run out of money; everybody knew. The initial accounting was not very rigorous and CERN had meanwhile cut back a lot of its traditional support. By the time we all understood what was going on, it was 2002 and we were some CHF 70 million short.

Cashmore noted:

My goal was always to convince the collaboration that it was in their interests to show how funds were being used. It was a bit of a novelty. With the financial turmoil I told them, “Systematically work out what it is going to cost you to complete this experiment. You make the case, I will make sure it is addressed properly and try to smooth it through.”

My relationship with the ATLAS executive team was good, but flawed at times. We had monthly meetings which were often long and heated. They wanted to set up ATLAS as an institution independent of CERN. In my view that was never going to work. What they didn't appreciate is that all the funding agencies worldwide who are providing money to the groups wanted the CERN funding process to make sure that the money was being well used. And I always felt that that was something we had to pay attention to.

Nordberg continued:

The reaction to the eventual CHF 1 billion shortfall at CERN was more severe than the missing CHF 70 million for ATLAS; I felt there was more understanding for ATLAS. I think it was because the funding agencies behind ATLAS found that the CHF 70 million was more easily identifiable; whereas in CERN's case some perceived it as CHF 1 billion into a black hole. We spoke to all the major players, visited the Ministries before we went public. I believe CERN did not do that.

Jenni presented the revised budget for ATLAS to the RRB in early 2002. The immediate impacts were two-fold. Firstly, for the first time CERN had to find alternative ways to fund the deficit; it went to banks to borrow money.

Secondly, the entire LHC project, including the detectors, had to be spread out over time. Nordberg explained:

Of the CHF 70 million, we had original pledges of around CHF 47 million from almost the first meeting. We had to stage delay some CHF 20 million worth of work to free up funds.

By 2008, the shortfall in the budget was down to approximately CHF 3 million. The executive team was confident the funding would be secured.

In-kind Contributions

Substantial in-kind contributions were also provided for the creation of ATLAS. These could come in the form of power supplies, cabling and pumps, as well as time from a skilled workforce. Member states, non-member states and CERN all contributed. Nessi outlined how solutions were found:

We were very active in trying to find in-kind contributions. Item A might be worth 100, and the collaboration would donate 50 in cash to assign a contract to this country. The country would find the remaining 50, often from its natural resources. For example, I bought 300 or 400 tonnes of brass from Armenia.

We constructed many things in Russia. They had many difficulties with cash but were able to get some from the US for ATLAS. In the end what we built would have cost three or four times more if we had done it in the West. We saved money and they saved money.

The ATLAS executive team then had to sell the idea of in-kind contributions to the RRB.

Maturing Technology and Industry Partnerships

Leading-edge technology was another reason why the decision to delay the project became inevitable. Around 2002, the ATLAS collaboration members realized that several new technologies such as radiation-hard electronics – electronics able to resist extreme radiation levels – would not mature in time for the expected latest completion date of 2006. Around then, the collaboration hit a major crisis with the companies providing the parts for the superconducting magnets. The majority of the problems throughout the project came from suppliers. Cavalli-Sforza commented:

Twenty years ago a big technological company would have been proud to do something for a collaboration like ours and even if they lost some money they would still keep in it. Nowadays, companies have sometimes changed ownership two or three times over the duration of a contract. I saw many problems caused by this. The remedy was often to bring in our own institutions when companies were not up to it or broke contracts. We were to a large extent saved by our Russian colleagues. They would send very competent people who worked very hard.

In most cases the ATLAS requirements were just too stringent for the companies, so they bailed out and there was nothing the ATLAS team, or CERN, could do about it. The money was gone and the work had to be redone in-house.

So what motivated suppliers? Cavalli-Sforza described a typical situation:

The best of the suppliers of plastic fibers for the tile calorimeter we'd seen was Japanese, but it was also the most expensive. If they had decided to play hardball with us, we would have been in trouble. They didn't because they were capable of taking the long-term view. It was a relatively new product and our order was for a fairly good quantity. Now they have sold tens of thousands of these devices all over the world.

Cashmore commented on technology transfer:

CERN had to put a lot of its own people out with the constructors and manufacturers to make sure the quality control at all stages of the process was absolutely right.

Looking Ahead to Maintenance and Operations

In 2002 the ATLAS executive team felt the need to plan for the long-term maintenance of what was being built. Nessi noted:

It was kind of shocking for the funding agencies, as they didn't realize upfront that they also had to pay to maintain the system. CERN had in the past been rich enough in resources to take over most of the maintenance of the equipment especially technically. Now, however, the contracts for ATLAS became so significant that CERN was not able to guarantee operational maintenance any more and even had to ask us to pay for the electricity we consumed. Once we had listed all operational needs, it became evident we needed another CHF 25 million a year for maintenance.

CERN member states did not want to pay for operational costs as they already paid a membership. The ATLAS executive team and the chairman of the RRB, Cashmore, traveled to national agencies to work out a deal to satisfy all the parties involved. An MoU for the maintenance and operation of the detector was agreed in 2002, several years ahead of the scheduled start of the LHC.

Assembly in the Cavern

The cavern was ready in 2003, after six years of work, and the collaboration started integrating the sub-systems inside. According to Nessi:



By then we had some idea of what we were doing. CERN built and financed the cavern, ATLAS mainly gave the requirements. At 35,000 cubic meters, it is one of the largest caverns ever built, if not the largest. We practically had to excavate the soil with a toothbrush as we approached the accelerator ring! Hans Hoffmann was the architect and CERN the executor. All parts assembled in the cavern had first been assembled and tested on the surface as far as possible. We kept the engineering teams who had built the parts throughout the process. Still, every time we brought something down we encountered problems, whether it was with the magnets or any other part. The full detector was only finally installed in 2008.

Once in place, testing of the ATLAS detector began using cosmic radiation continuously bombarding the Earth.

Operating ATLAS

The dedication ceremony for the LHC and its detectors took place on October 21, 2008. To operate the ATLAS detector over the course of one year, some 600 people would be needed, although only about half of them at CERN. The rest would be organized in teams connected 24/7, ready to fix any problems that might occur by connecting via computers from where they were to the detector itself.

Now, the collaboration that built ATLAS would shift their focus. They could finally dive back into the fundamental physics research they had spent all those years preparing.

Running the LHC accelerator and the detectors would require as much electricity as to power a city the size of Geneva, with 185,000 inhabitants. The total cost of the LHC project (accelerator, detectors and computing), including materials and personnel, was CHF 6 billion.¹⁸

Learning from the ATLAS Collaboration

For the next 15 to 20 years, ATLAS would enable scientists to expand our knowledge of the fundamental laws that govern nature and the universe. A new era was about to unfold.

¹⁸ CERN FAQ – LHC the guide, January 2008, page 17.

Thousands of scientists from hundreds of institutions across dozens of countries collaborated for nearly 20 years to produce this technical wonder. Key to this collaboration was a common goal that went beyond any personal recognition. Superior ideas were recognized by all contributors. Despite some apparent inefficiencies and loose processes, there was never any compromise on the quality of the end product. Authority came out of respect from peers; it was never used to coerce. Leadership belonged to the person who was best able to achieve compromise and keep everyone motivated.

How was such a collaborative project environment achieved? What were the key principles of successful collaborative behavior on such a scale? Are research scientists better equipped than industry or business managers to complete projects such as ATLAS? Was there something inherent in the way the ATLAS collaboration functioned that would rule out any attempt to replicate it in another scientific or business setting?

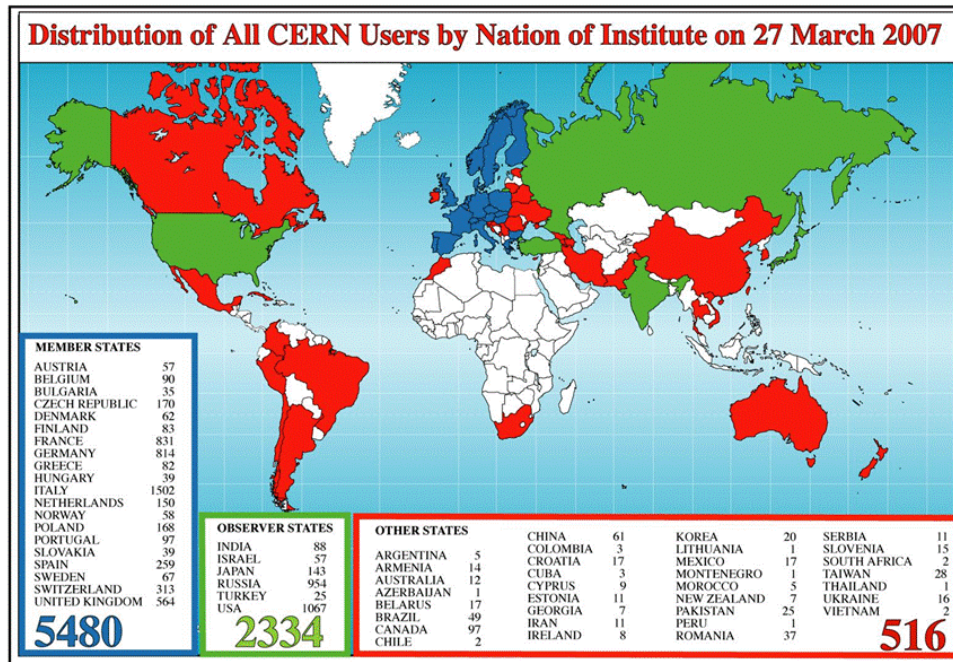
If a prize were to be given for a breakthrough discovery coming out of the LHC project experiment, would it be given to individuals or to a collaboration team?

The ultimate recognition of scientists today is the Nobel prize, but its rules state that in no case may a prize amount be divided among more than three people. So how would the recognition of an achievement obtained through collaborative efforts be rewarded?

For the scientists, it may not be a problem. As Cashmore put it:

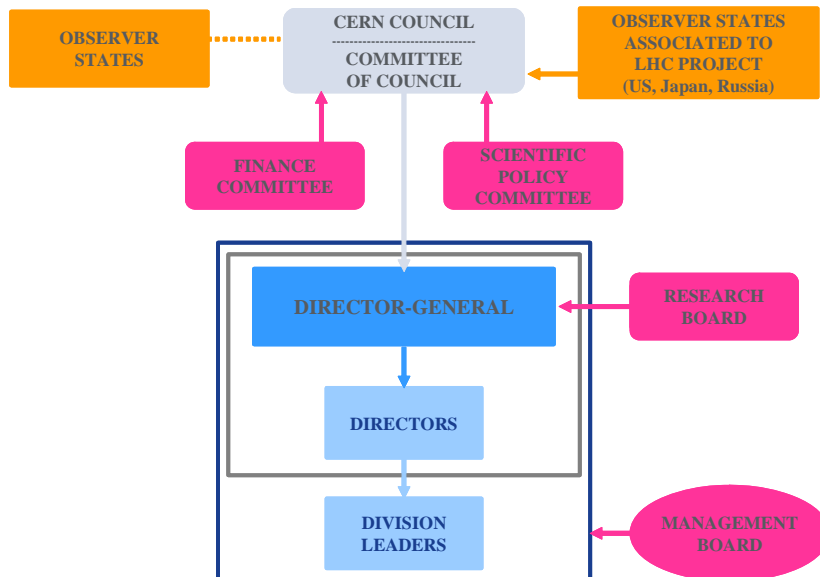
Scientists are not driven by getting Nobel prizes; they are driven by understanding something a bit better or in greater depth than they do currently.

Exhibit 1 Origin of CERN Users



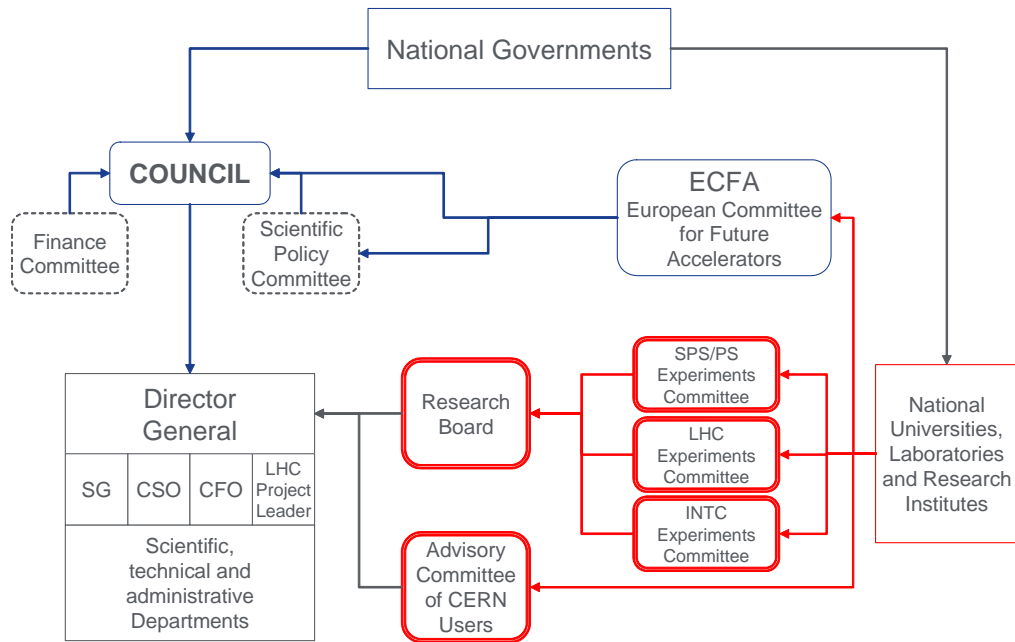
Source: CERN

Exhibit 2 CERN Structure



Source: CERN

Exhibit 3 CERN Decision Making



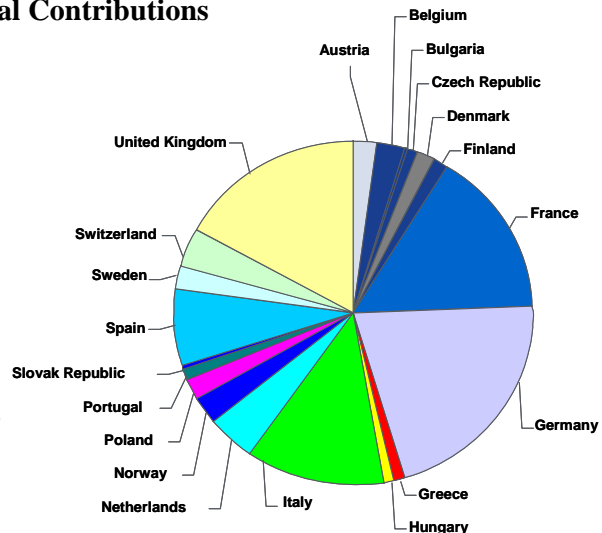
AGC – January 11, 2008

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Source: CERN

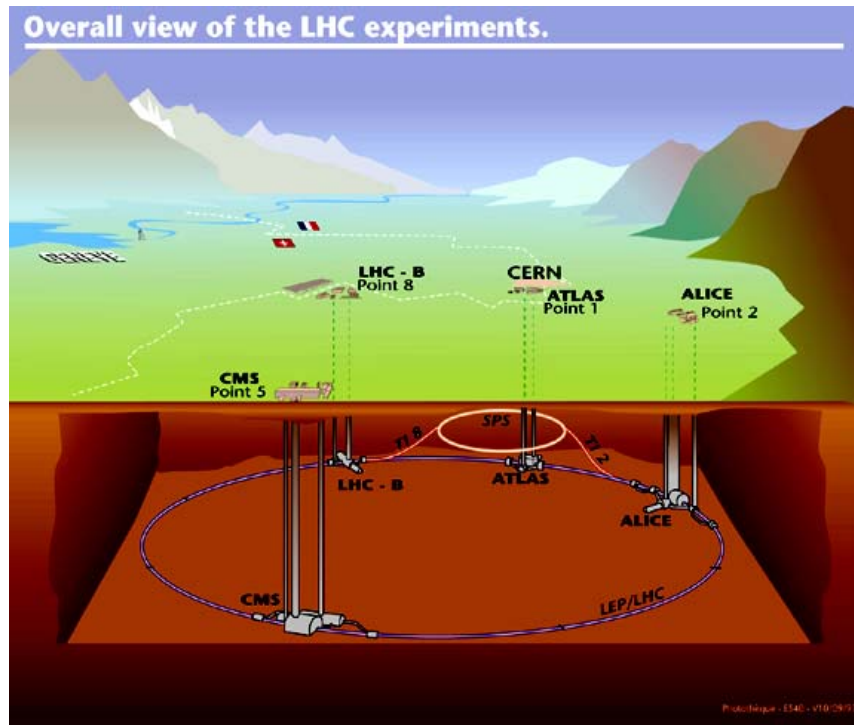
Exhibit 4 CERN Financial Contributions

- Budget financed by member state contributions, shared according to net national income, but it is possible:
 - To fix a maximum contribution for each program of activities
 - To have special conditions decided by a 2/3 majority of member states
- Budget 2007: CHF 1.1 billion
- Experiments financed by funding agencies of collaborating institutes, mostly outside CERN budget (CERN contributes 20% to LHC detectors)



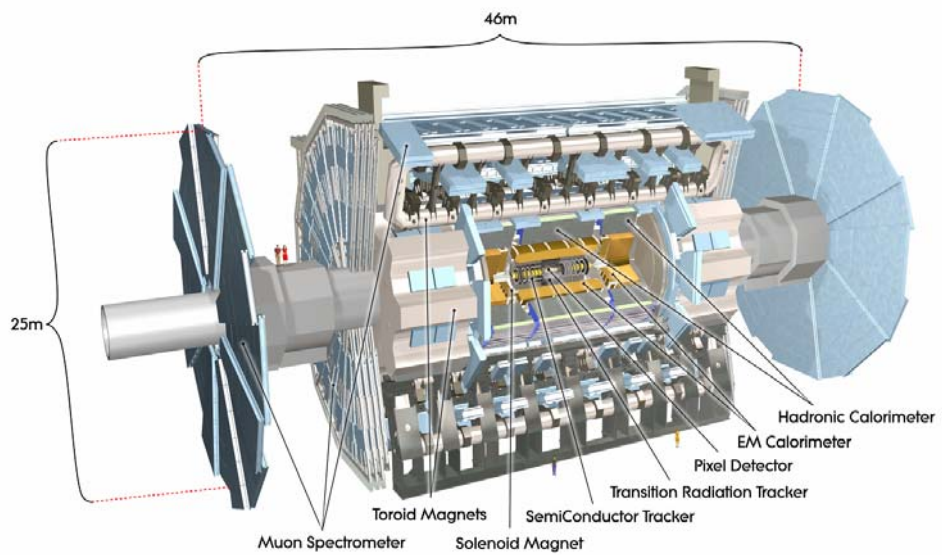
Source: CERN

Exhibit 5 LHC Underground Presentation



Source: CERN

Exhibit 6 ATLAS Detector Overview



Source: CERN

**Exhibit 7
ATLAS Organization**

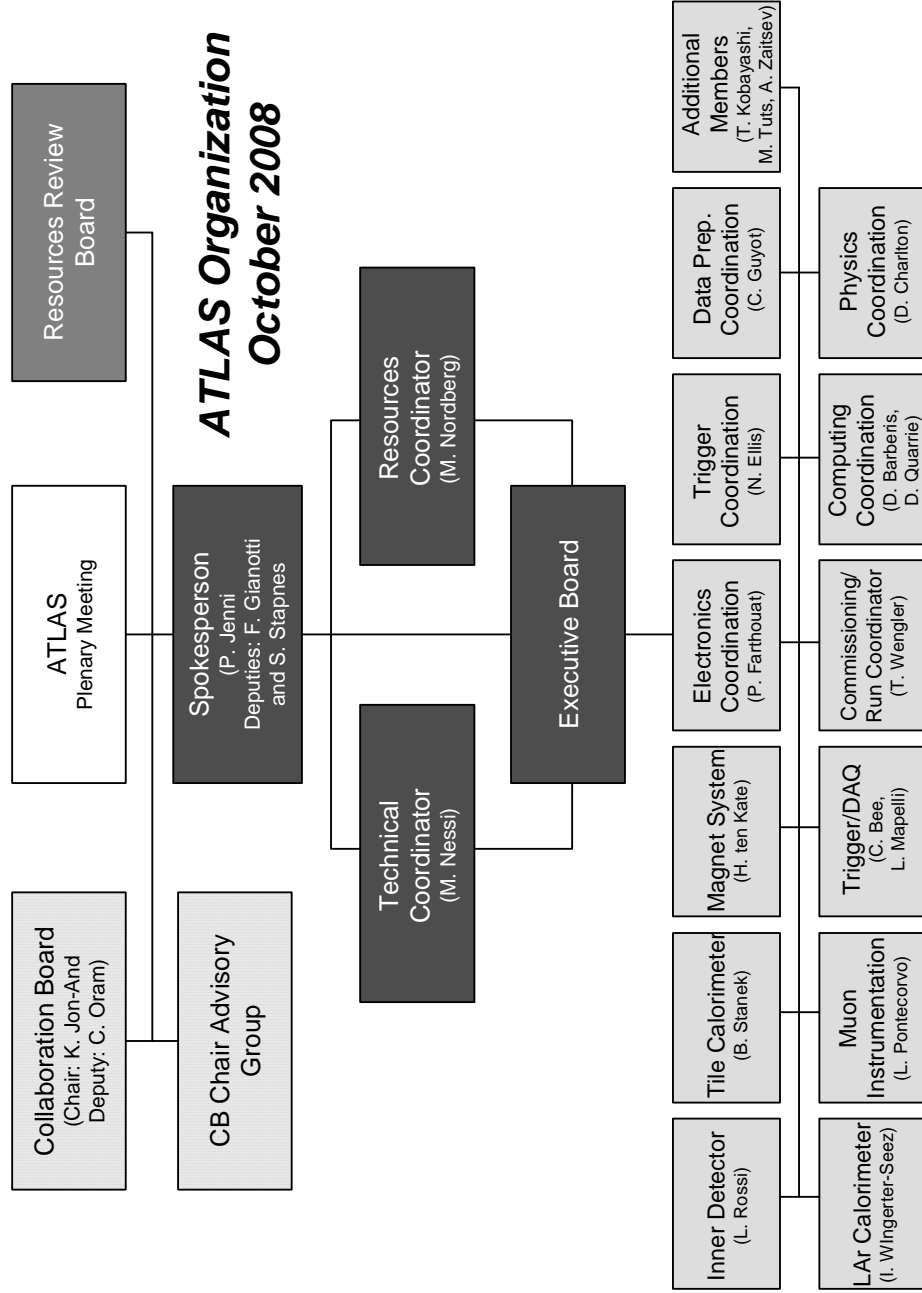
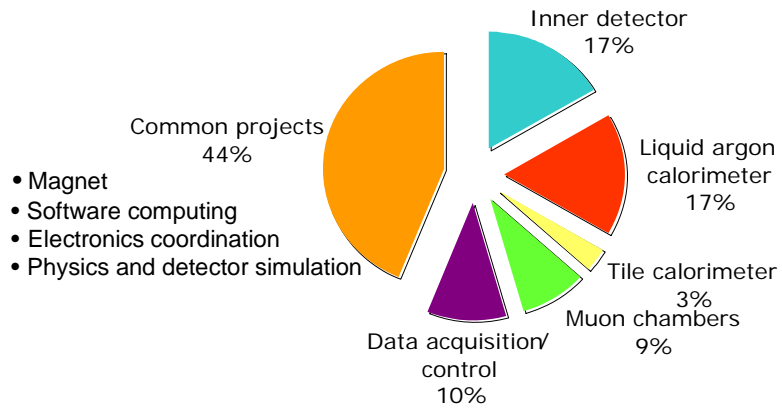


Exhibit 8 ATLAS Cost Sharing



Source: CERN

Exhibit 9 ATLAS Timeline

