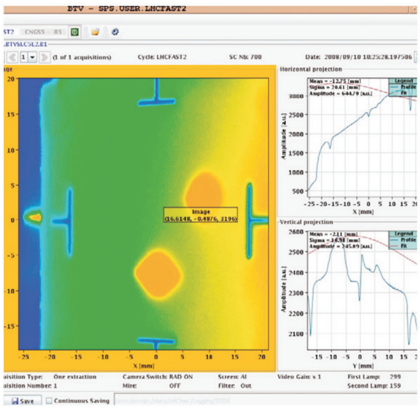
After More than 25 Years of Meticulous Preparatory Work

Large Hadron Collider Activated

10 September 2008 had long been anticipated by particle physicists at CERN and across the globe. The suspense and excitement was tangible as physicists gathered in the control room to follow the protons on their maiden voyage around the 27 km accelerator ring complex. As dots subsequently appeared on the monitor, indicating the successful completion of one full turn, the room burst out in celebration. And for good reason. The event marked not only the culmination of more than 25 years of meticulous preparatory work, but equally the beginning of one of the most exiting research programs in the history of particle physics.

Scientist eagerly following the first beam injection in the CERN Control Center on September 10, 2008. Picture: CERN

CERN's flagship project, the Large Hadron Collider (LHC), is often described as one of the largest, most complicated scientific undertakings in history. And it is not without reason that scientists from across 80 different nations have put hard time and effort into the construction of this mammoth experiment. When ramped up to its design performance, the LHC will collide protons at unparalleled energies, at a staggering rate of a billion collisions per second. Acting as a powerful microscope onto the inner structure of matter, the LHC will allow particle physicists to probe distances and energies never yet explored. More specifically, the LHC opens the gates to an energy domain often



Two dots marking the first complete circuit of the beam about the LHC ring. Picture: CERN Courier

dubbed the terascale where a plethora of new phenomena are expected to unravel. Indeed, many claim the LHC heralds a new "golden age" of physics because the anticipated discoveries are not only expected to shed light on problems that have boggled physicists for decades, but could drastically reshape our ideas of the physical universe we inhabit.

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Why Bother?

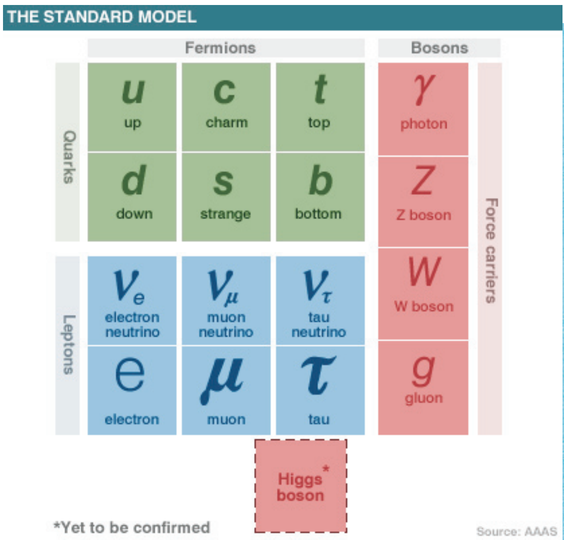
At first glance, it might seem odd to engage in such a gigantic project when the current model of the elementary constituents of matter - poetically named the “Standard Model” (SM) - agrees with nearly all experimental data collected at previously and currently running experiments. Indeed, deviations from the SM in LEP data (the LHC’s older and less energetic brother) is only seen at the per-mille level, arguably making it one of the most successful theories in the history of science. So should particle physicists not be content?

The Missing Piece of the Puzzle.

One problem is that for all its successful predictions, the theoretical calculations of the SM are mathematically consistent only in the presence of an all permeating field, thought to be responsible for bestowing masses to elementary particles. A seminal feat of the SM was the unification of electromagnetism and the weak force into a single electroweak theory and with it the power to explain processes as disparate as the reactions that fuel the Sun to the forces that bind a snowflake together in one mathematical framework. In this symmetric description, the force carriers of electromagnetism (photons) and the weak force (the W and Z bosons) are all massless. But while the SM describes these forces “symmetrically”, they behave very differently in physical reality. The electromagnetic force has an infinite range, whereas the weak force spans only very short distances. These differences are intimately related to the fact that the mediator of the electromagnetic force is massless, whereas the intermediaries of the weak force, the W and Z bosons, have masses comparable to reasonably large atomic nuclei. The electroweak symmetry is therefore clearly broken in Nature. Indeed, if the fundamental particles were as massless as they appear in the equations of the SM, they would fly about at the speed of light, never form composite structures and life would never evolve.

As a remedy, Peter Higgs (1964)[1] proposed a mechanism by which the underlying symmetry between different SM particles is broken so that some acquire masses, while others do not.

Higgs hypothesized a space filled with an all-permeating “quantum syrup”, later dubbed the “Higgs field”. When the fundamental particles interact with this field, their passage is “hampered”, in much the same way a hand meets resistance when it moved through water. It is through the interactions with this Higgs field that particles become massive, and the greater the degree of interaction, the more massive the particle is. Massive particles also have a greater chance of exciting the Higgs field, of creating “ripples” in the quantum syrup as it were, and it is by way of detecting such “ripples” that physicists at the LHC hope to confirm the presence of the Higgs field. The “ripples” are manifested in an elusive particle called the



The well-known standard model. The SM groups the fundamental particles into fermions, the constituents of matter, and bosons, the messengers of interactions. The Higgs boson remains the single undetected particle of the model. Figure AAAS

When the fundamental particles interact with this field, their passage is “hampered”, in much the same way a hand meets resistance when it is moves through water.

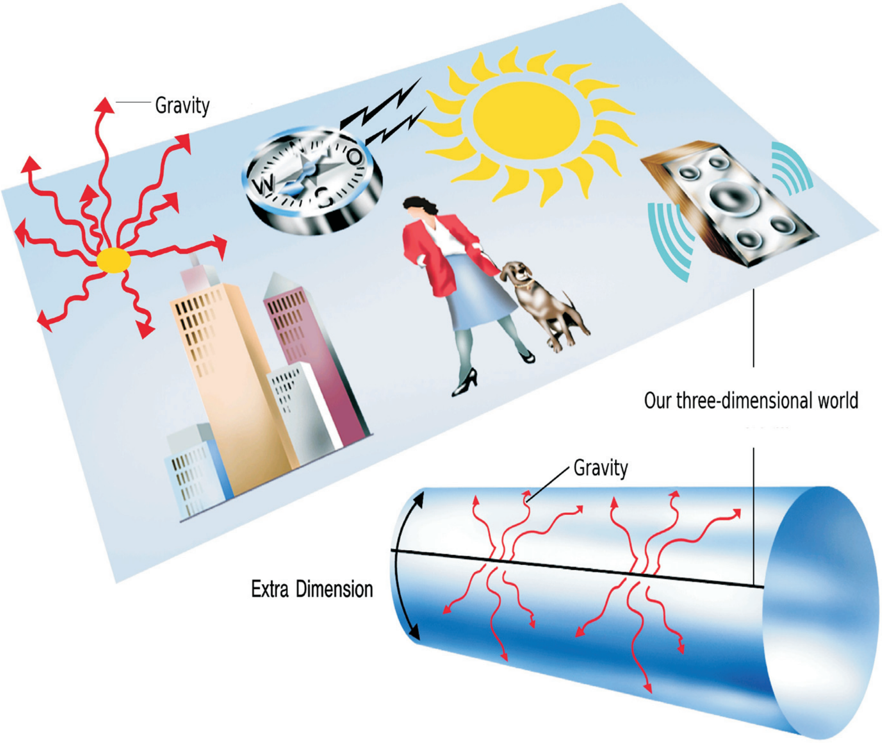
Picture: FNAL (Fermi National Accelerator Laboratory)

Higgs boson. It is predicted to be unstable and decay into other particles, and so the two multi-purpose experiments ATLAS and CMS have made it one of their prime tasks to look for the Higgs boson in several different ways. The incredible agreement of all current data with SM predictions strongly indicate that the Higgs boson (or something equivalent) should exist and indeed lie within the reach of the LHC. Expectations are high that indications of the its existence may even be seen within the very first years of LHC operation.

Leaping Beyond the Standard Model

Finding the Higgs boson and measuring its properties would complete the SM, but it would not put a lid on the LHC experimental programme.

For all its triumphs, physicists are convinced that the terascale heralds the break-down of this long successful model. The reasons are many, but one most profound can be found within the structure of the theory itself: the so called hierarchy problem.



Theorists speculate that our three-dimensional world is embedded on a "membrane" in a higher-dimensional space

Picture: DESY

When calculating quantum corrections to the mass of the Higgs boson owing to exchange of virtual particles, problems arise in the form of infinities. A standard way of curbing this problem is to “cut off” the theory at some high energy at which a more complete theory is believed to kick in, such as e.g. a grand unified theory or a quantum theory of gravity. If the SM is indeed embedded in a more encompassing theory that reveals itself at higher energies, the Higgs mass should be sensitive to the details of this more complete model. Unless there is some uncanny delicate cancellation of the quantum corrections to the Higgs mass, it then becomes difficult to explain why the mass of the Higgs is so much smaller than the mass scale at which this new physics appears.

Most physicist reject such a fine-tuned cancellation as “unnatural” and many espouse a solution offered by a hypothetical view of the world known as supersymmetry - or SUSY for short. SUSY postulates an underlying symmetry between the matter particles of the SM (fermions) and its force carriers (bosons), pairing each SM fermion and boson with a bosonic and fermionic superpartner, respectively. While SUSY doubles the number of fundamental particles, the quantum corrections between virtual fermions and bosons cancel in a systematic fashion to produce a Higgs mass that no longer appears unnaturally fine-tuned. The theory also provides physicists with an elegant framework to facilitate the unification of strong, weak and electromagnetic forces into a Grand Unified Theory. The idea has beguiled theorists for more than three decades, but however attractive, experimental verifications of supersymmetric models remain evasive to this day.

There are, however, strong reasons to hope for a discovery at the terascale: the leftover corrections to the Higgs mass would be small if the masses of SUSY particles should be at the terascale. Moreover, present data indirectly favours a Higgs mass <~150 GeV, precisely the range predicted by terascale SUSY. There is also one more compelling reason why physicists will actively search for signs of SUSY in LHC data:

Astrophysical data indicate that visible matter only accounts for a measly 4% of the total energy density in the Universe. More specifically, the rotational velocities of stars in galaxies are such that the galaxies should be ripped apart in the absence of additional non-visible matter. The nature and existence of so called dark matter, thought to account for as much as 22% of the Universe, remains an open question in physics.

While most SUSY particles are expected to be heavy and quick to decay, many models of supersymmetry postulate that the lightest of the supersymmetric particles (LSP) should be stable and only weakly interacting. As such, it is an ideal candidate for the unknown dark matter, and should SUSY be discovered at the LHC, it would provide unique and groundbreaking insights into the properties of the unknown dark matter.

More to Space than Meets the Eye

A confirmation of SUSY would undoubtedly be a spectacular find, but perhaps more spectacular yet would be signs of extra spatial dimensions. The idea that additional dimensions of space are curled up on scales small enough to make them imperceptible, is at least 80 years old [3]. Such theories have gained new ground in recent years, after it was suggested that these new dimensions might be larger than previously believed and possibly have observable consequences at the LHC. The long list of possible new exotic phenomena include gravitons - the elusive messenger of gravity -, and so-called Kaluza-Klein excitations of SM particles which might even prove to be an alternative dark matter candidate[2]. The most spectacular of all however is one that, perhaps undeservingly, has received the most media attention, namely the prospect of tiny, unstable black holes cropping up in the collisions at the LHC. Should they appear, these black holes are widely expected to rapidly evaporate into a spray of particles, making them relatively easy to identify for the LHC experiments. And such a find would be truly sensational: it would not only alter our current understanding of the structure of space, but would shed invaluable insight into one of the most puzzling unknowns of contemporary physics, into the world of quantum gravity.

Whatever new physics will manifest itself at the terascale, ATLAS and CMS will independently search for all possible experimental signatures. Two more specialized detectors, LHC-b and ALICE, are dedicated to the study of other phenomena thought to have occurred in the immediate wake of the Big Bang.

The Matter-Antimatter Conundrum

One such phenomena relates to a miniscule asymmetry with striking implications. For every particle of the SM, there is a corresponding “antiparticle”, identical to its particle in most ways but for its charge. When particles and antiparticles meet they annihilate into pure energy. In the early Universe, the production and subsequent annihilation of particle-antiparticle pairs is thought to have occurred at an even rate. After a few seconds, the Universe had cooled sufficiently to halt the production of new particle-antiparticle pairs, while the annihilation of existing pairs continued uninterrupted traces of which are seen even today in the guise of the cosmic microwave background. If all remaining matter and antimatter annihilated, as theory suggests, it is hard to explain the observable excess of matter we are all made of. And therein lies the rub. Consequently, physicists believe that some processes in the early Universe must have taken place to secure a tiny excess of matter over antimatter, an excess as small as one part in one billion. Present experimental data agrees well with the matter-antimatter differences permitted in the SM, but these differences cannot account for all matter observed in the Universe. Incidentally, SUSY allows for more differences between anti-matter and matter, and so it is not unlikely that terascale physics will help shed light on the observed asymmetry between matter and antimatter. All the experiments at the LHC will look for clues, but only LHC-b is fully dedicated to the study of B-meson decays, where as yet unobserved symmetry violating processes are hoped to unravel.

The Primordial Soup

ALICE will study the primordial Universe in a different manner. In normal matter, quarks are bound together into hadrons such as protons and neutrons. Indeed quarks appear to be confined inside composite hadrons, to the effect that no quark has been observed in isolation. In the immediate aftermath of the Big Bang however, the soaring energy density is believed to have allowed quarks and gluons to move about freely in a phase of matter known as a “quark-gluon plasma”. As the Universe expanded and cooled, the quarks and gluons condensed into mesons and baryons, ultimately producing protons and neutrons from which all elements are composed. Quark-gluon plasmas have been created in laboratories at previous experiments, but by colliding lead ions at considerably higher energies, the LHC hopes to provide ALICE with a more long-lived quark-gluon plasma, the subsequent study of which will allow physicists to study the properties of this scarcely known phase of matter which is believed to have had such a profound impact on the evolution of the Universe.

What exactly the LHC will churn out is anyone’s guess. The first months, perhaps even years of operations, will see physicists trying to understand and control the enormously complicated piece of machinery the LHC is. The current delay is testimony to that fact. Groundbreaking discoveries will only follow in the wake of patience and hard work, but most physicist are convinced that something new and profound must lurk beyond the terascale horizon and whatever it may be, it is sure to alter our current understanding of the natural world at its most fundamental.

Footnotes:

[1]and independently by R. Brout and F. Englert.

[2] Servant G., Tait. T.M.P “Is the lightest Kaluza-Klein particle a viable dark matter candidate?” Nucl. Phys. B650, 391-419 (2003).

[3] In the 1920s T. Kaluza and O. Klein proposed a model unifying electromagnetism with gravity by introducing a compactified additional spatial dimension.

References:

1. J. Ellis, "Beyond the Standard model with the LHC, Nature, vol 448, 19 July 2007

2. LHC first beam: a day to remember", CERN Courier, 20 Oct 2008. (http://cerncourier.com/cws/article/cern/36296)

3. (http//www.weltmascine.de/)