The LHC, shining light on the Dark Side

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Starting in the summer of 2007, the Large Hadron Collider (LHC) will collide proton beams at center-of-mass energies of 14 TeV exceeding by a factor of ten what was previously achieved. It will be located in the 27km long underground tunnel, in which the Large Electron Positron collider (LEP) was working until the year 2000. The Large Hadron Collider is a part of the accelerator complex of the European Laboratory of Particle Physics (CERN), situated on the Franco-Swiss border close to Geneva.

Those who read the Economist do not need to be convinced that physics is the queen of experimental sciences. Physics pertains to the whole 100% of the content of the Universe, while only 5% of it is ordinary matter, and can be the subject of Chemistry. The so-called Cold Dark Matter forms close to 25% of the content, the rest is the even more mysterious Dark Energy.

Dark Matter consists of heavy, elusive particles, interacting with ordinary matter even less than neutrinos do. However it interacts gravitationally, and was most probably responsible for the formation of Large-Scale Structures. VIRGOHI21 is a recently discovered Dark Matter galaxy, where ordinary matter is only 0.1%. In most of the galaxies including ours the density of Dark Matter is about ten times larger than the density of ordinary matter. The stars in our Galaxy would fly apart, if Dark Matter was not gluing them together with gravitational forces. The local density of it is close to 0.3 proton masses/cm³. A cup of coffee contains around five Dark Matter particles. However, the coffee cup contains at the same time around $2 \times 10^{28}$ protons and neutrons (provided it is filled with coffee)! This illustrates the problem of studying Dark Matter particles here on Earth. Yet, as the Big Bang produced apparently so much Dark Matter, perhaps we can produce lots of it too, if we recreate similar conditions.

Recreating energy densities needed for Dark Matter production will be one of the purposes of proton-proton collisions at the Large Hadron Collider. The rest energy of a proton is 0.938 GeV. To attain such an energy an electron has to be accelerated in a potential difference of 938 million volts! A proton in the LHC beam will have the energy of 7000 GeV, thus 7500 times more than its rest energy. Should LHC protons race to the Moon against a beam of light, they would arrive only 2.7 meters behind. Beams will be organized in bunches of around $10^{11}$ protons each, colliding 40 million times per second in several collision points. The energy stored in the beam is close to $10^8$ Joules. If you have to dump all of it in an instant you will evaporate an equivalent of 300 kg of water!

Three detectors are being built to register proton-proton collisions, two general purpose detectors ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Spectrometer), and a more specialized one, LHCb, dedicated to physics involving beauty quarks. The fourth detector, ALICE, will study heavy ion collisions. Beams of heavy nuclei (ions) will occupy around 15% percent of the beam-time starting from the third year of the LHC running. Groups in Norway are active in the ATLAS and ALICE Collaborations. The physics programs of ATLAS and ALICE are quite different. This article is devoted to physics topics pertaining to proton-proton collision.

The construction of detectors is progressing fast. Figure 1 shows the ATLAS detector filling up its grand underground cavern. Parts of the detector are already in place and being tested with muons originating from cosmic rays.

To probe small structures and to produce new particles, high energies in elementary collisions are needed. Protons are not elementary however, and collisions between the constituents of protons: quark and gluons, will occur. These constituents carry on average considerably less energy than the proton, rendering genuine high energetic collisions less probable. That is why lots of collisions are needed. Several proton-proton collisions will occur...
Every 25 nanoseconds. Extremely short time spacing between subsequent beam interactions poses extreme requirements on the detector technology, local data transmission and storage. Every 25ns a stream of particles, produced in beam collision will flash the detector, moving with nearly the speed of light to the outer layers. Before particles from one collision reach the outer layers there will be another flash of particles coming from the next collision. On-detector electronics will have to correctly associate signals from particles to the right collision event. The pixel detector, the most granular subdetector of ATLAS, provides 80 million bits of information which needs to be correctly handled! The data transmission rates involved are gigantic. The ATLAS detector will transmit more data than all of the worlds phone networks integrated.

Only one collision in a million will be interesting enough to deserve permanent storage and further study. The selection system, the so-called trigger, will have to reliably reject one million of “spam” collisions to find the interesting single one to store, all these in an extremely small fraction of a second. Imagine a spam-mail filter performing a similar task! Two hundred megabytes of interesting data will be stored by the ATLAS experiment 100 times per second. This corresponds to 1200 CDs per minute. To reconstruct and analyze this information GRID-based technology linking PCs and PC farms all over the world will be used. CERN-related research in Norway in particular is a forefront runner in GRID technology development.

The search for collisions where Dark Matter is produced (see Fig. 2) is just one of the topics the ATLAS experiment will embark on. One of the enigmas ATLAS and CMS will be trying to solve is why the “ordinary particles”, the known elementary fermions and bosons have masses at all.

The most viable hypothesis of mass generation is that particles acquire masses via interaction with the so-called Higgs field, which permeates the vacuum. The particles sort of glue themselves to the Higgs field. Thus, the heavier the particle, the stronger is the interaction with the Higgs field. The presence of the field in the vacuum causes the so-called Electroweak Symmetry breaking: a difference between electromagnetic and weak interactions, and between, for example, an electron and a neutrino. There is a vast literature on the subjects touched in this short article, which can be tackled starting for example from this reference (5).

The Higgs mechanism was proposed by Peter Higgs of Edinburgh University (see Figure 3). Before going into details of explanations, let me suggest how the Higgs field hypothesis can be verified. Einstein postulated in 1905 that electromagnetic field should have its quantum, the photon (γ). It is now believed that all interactions and fields should manifest themselves as quanta → particles. ATLAS will hunt for the quantum of the Higgs field, the Higgs boson. The Higgs boson must interact strongly with heavy particles, thus it is expected to decay mostly to them.

The Higgs particle is the only missing piece of the so-called Standard Model. This quite
Unfortunately, a name arose before particle physicists realized they were going to be stuck with the Standard Model for decades! The Standard Model describes "ordinary" matter particles, fermions, and interactions between them transmitted by bosons. It has been shown to work in an extremely accurate way up to center-of-mass energies of the order of 100 GeV, explaining an era of the order of a nanosecond after the Big Bang. It allowed to make very accurate calculations, which were confirmed experimentally with matching precisions. However, there is no candidate for the Dark Matter particle in the Standard Model, there is really no good place for the neutrino masses, and even the missing piece of the puzzle, the Higgs boson, does not fit in by itself without invoking beyond-the-Standard Model particles. Thus physics "beyond the Standard Model" must exist.

**The Standard Model**

Known matter is built of fermions, while interactions keeping it together are transmitted by bosons. Fermions can be "Lego blocks" of interesting structures because the Pauli principle forbids that all of them fall to the lowest energy state. Electrons, protons and neutrons are needed to build atoms. Protons and neutrons contain other fermions: up and down quarks. Electrons, the electron neutrino, and up and down quark form the so-called first fermion family needed to build ordinary matter. Surprisingly, two more families exist. The second family consists of the muon neutrino, the muon, charm and strange quarks, while the third one has the tau neutrino, the tau, top and bottom quarks.

When it comes to all known properties (except masses) the second and third families seem to be replicas of the first. The masses of fermions are quite well measured, again except for neutrinos. The masses of the first family fermions are a small fraction of the proton mass. The top quark mass, however, is equal to that of 187 protons, it is the heaviest known elementary particle. It is also, unlike the proton, point-like and has no internal structure down to around 1/100th of the proton size. Thus masses of family members increase with the family number, although this might be different for neutrinos. The reason for mass patterns and mass values of elementary fermions remains a mystery.

Increase a hydrogen atom to the size of a physicist's office in Norway, and the proton will become the size of a small dust particle. If the proton moves, the change of its position is communicated to the electron via electromagnetic interactions. This information propagates with the speed of light, as an electromagnetic wave.

The static electric field surrounding all charged particles becomes electromagnetic waves when the particle accelerates. Einstein's concept of electromagnetic wave particle, the photon, was a revolutionary idea. Nowadays electromagnetic waves can be observed as photons by anybody equipped with a photo-diode or a photomultiplier. Electromagnetic interactions are mediated by photons, electrically neutral bosons with spin=ℏ and zero rest mass. Other known elementary bosons are eight electrically neutral massless gluons transmitting strong interactions, heavy electrically charged $W^+$, $W^-$ and the electrically neutral $Z^0$ transmitting the Weak Interactions. The $Z^0$ weighs as much as about 97 protons.

The experimental observation of the $W$ and $Z$ bosons brought the Nobel Prize to Carlo Rubbia and Simon Van der Meer of CERN, in 1984. In the years 1989-1995 the LEP accelerator at CERN produced a few million $Z$ bosons, allowing for precise studies of the Weak Interactions.
The Electroweak Symmetry and its breaking

All electrically-charged particles feel electromagnetic interactions. All known fermions have Weak Interactions charge. Actually, from the point of view of Weak Interaction there is no difference between an electron and a neutrino. In the so-called natural units ($\hbar = c = 1$) the electron (proton) charge is a magic number $e = -0.303 \text{ (0.303)}$, while the weak charge of every elementary fermion is close to another magic number of $g = 0.631$. If both the electron and the neutrino were massless, and if all bosons were massless as well there would be hardly any observable difference between the electron and the neutrino and between Weak and Electromagnetic interaction. Weak attraction would be as strong as the electromagnetic one, and neutrinos would be captured into bound states in atoms as much as electrons are. This is the world of “unbroken Electroweak Symmetry” in particle physicists’ jargon. However, in our world the Electroweak Symmetry is broken: the neutrino and the electron are perceived as different particles, and Weak Interaction bosons are massive, while the photon is massless. As a result Weak Interactions are much weaker than the electromagnetic ones at atomic scales.

It is tempting to uncover the Electroweak Symmetry and find a common description of electromagnetic and weak $\rightarrow$ Electroweak Interactions. Such a unified Electroweak theory exists due to Sheldon Glashow, Steven Weinberg and Abdus Salam who were awarded the Nobel Prize in 1979. The Electroweak symmetry is extremely useful and actually allows to perform precise calculations in the Electroweak theory. How to deal with the apparent breaking of the symmetry while preserving all its good features? The answer is the Higgs mechanism. A heuristic analogy with a ferromagnet is often used to explain it, see Box 1.

**Figure 4:** An electron can have two magnetic moment states, one parallel, one anti-parallel to a chosen direction in space. The state of a ferromagnet without the magnetic field is symmetric, there is no chosen direction in space, electrons with magnetic moment pointing to the left and right have the same energy. However the lowest energy state of the ferromagnet is with a non-zero value of the magnetization. If minimum on the right is chosen resulting spontaneous magnetic field would point to the right. This is the so-called spontaneous symmetry breaking. The result is that rightels (electrons with magnetic moment to the right) and leftinos (electrons with magnetic moment to the left) behave like different particles and there is a non-zero “expectation” value of magnetic field in the ferromagnet.

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**Box 1. The Higgs mechanism**

The analogy makes use of concepts of magnetic fields, electron magnetic moment and ferromagnets. Electrons are charged and have spin ($\frac{1}{2}\hbar$). An electron can have two magnetic moment states, one parallel, one anti-parallel to a chosen direction in space (see Figure 4). Most electric phenomena are not affected by the direction of the electron’s magnetic moment. The electron mass does not depend on it. Imagine, that the space around us is permeated by a constant magnetic field pointing from left to right on figure 5. In this case all observed electrons would have their magnetic moment pointing to the left, assuming minimal energy in the magnetic field. Let’s call them leftinos. Electrons with magnetic moment to the right (rightels) would have to be produced by providing some energy to leftinos. In other words some energy would be needed to flip the magnetic moment of an electron in the magnetic field, but most probably the “true” picture of the situation would be hard to uncover. Rightels could then decay into a photon and a leftino. Rightels and leftinos would appear as different particles with different masses and different interactions.
Box 1 cont.

The reason behind the magnetic field in the vacuum could be that it has properties of a ferromagnet, and its lowest energy state is with a non-zero magnetic field pointing in some direction, as in Figure 4. The state of a ferromagnet without the magnetic field is symmetric, there is no chosen direction in space, rightels and leftinos have the same mass and interactions, and are simply the same particle, the electron. However the lowest energy state of the vacuum is with a non-zero value of the magnetic field pointing in some direction. This is the so-called spontaneous symmetry breaking. The result of it is that rightels and leftinos are different particles, there is a non-zero “expectation” value of magnetic field in the vacuum. This is an approximate picture of the Higgs mechanism, if one translates magnetic field into Higgs field, rightels and leftinos to electrons and neutrinos.

There is one more analogy here. It is enough to heat the ferromagnet to allow it to go to the higher energy state and destroy the spontaneous magnetization. The symmetry is recovered. We expect this was the situation a fraction of a nanosecond after the Big Bang. When the Universe was cooling down, the vacuum chose its lowest energy state and the Electroweak symmetry broke. In a ferromagnet there can be domains, where the symmetry is broken in a different way and the magnetization points to different directions. Do we have a similar situation in the Universe? Possibly, but this is a subject for another article.

There is lots of proofs of the Electroweak theory with spontaneous symmetry breaking. The most striking one is that it relates the ratio of the weak to the electromagnetic charge to the ratio of the masses of the W and Z bosons. This relation was confirmed experimentally. When (if?) the Higgs particle is found the picture of Electroweak symmetry breaking will be complete.

A lot is known about the Higgs boson, even if it was not found yet. Actually its mass is the only unknown parameter. Even the mass has been “measured” already with a certain accuracy. The Higgs boson has to be heavier than 114 GeV/c² otherwise it would have been observed at LEP. From its “shadow” in the masses of other particles: the top quark and the W boson, one can infer it should be lighter than about 200 GeV/c². How? Atomic physicists are familiar with the Lamb shift. Willis Eugene Lamb received the Nobel Prize in 1955 for his discoveries concerning the fine structure in hydrogen. The Lamb shift, hyperfine energy splitting between S and P orbitals in hydrogen is caused by the creation of virtual electron-positron pairs in the atomic electric field (vacuum polarization) and modification of both the electron mass and the magnetic moment due to interaction with quanta of the atomic electric field (virtual photons). In a similar way the masses of the top quark and the W boson are affected by the existence of the Higgs boson. This method of determining a particle mass without producing it was already tested in the 90’s. The LEP experiments determined the top quark mass with an accuracy of 10%, before it was actually observed at the Tevatron experiments in the Fermi National Laboratory near Chicago, USA.

Beyond the Standard Model

Symmetry is one of the basic concepts of science. Nature and art are full of symmetries. Many of us pondered on the symmetric beauty of snowflakes and wondered about the laws of nature.

Symmetries are often only approximate. Left-right symmetry is an example. External features of our bodies are to a large extent left-right symmetric. Internally however, having the liver on the right hand side and the heart on the left we strongly violate the left-right symmetry. The situation is quite similar in the world of elementary particles. Weak interactions strongly violate the left-right (P) symmetry and matter-antimatter exchange symmetry (C), while all other interactions seem to conserve them. Lewis Caroll’s Alice, walking through a looking glass into a room where left and right were reversed might have found herself in a completely different Universe, in which certain nuclear interaction do not occur. Our Universe is believed to be CPT-symmetric. Exchange at the same instant left with right (P), matter with antimatter (C), and reverse the arrow of time (T), and nothing observable will change, even if each of these operations performed separately produces a Universe different from ours.

Certain symmetries are woven into the structure of space and time. We can change summer to winter time without rewriting physics books. We can also move the zero longitude from Greenwich to Bergen, and formulations of all known physics laws will remain the same. Emmy Noether (see Fig. 5) proved in 1915 that every continuous symmetry of physics (time and space translation and space rotations are examples) results in a conserved physical quantity. For example, space translation symmetry results in the conservation of momentum. Noether’s theorem linking symmetries to conservation laws is one of the basic foundations of physics. Thus, it might be instructive to examine even approximate symmetries.

The so-called supersymmetry (SUSY) might be one of them. SUSY is a boson-fermion symmetry.
Figure 5: Emmy Noether 1882-1935, born in Erlangen, Germany. Noether’s theorem stating that every continuous symmetry in physics results in a conserved physical quantity is a cornerstone of physics. Her most famous work “Die Invariante Variationsprobleme” appeared in 1918. Noether was granted a doctorate in 1907 at the University of Göttingen, and later lectured in Vienna and in Italy. In 1915 Hilbert and Klein invited her to return to Göttingen. Hilbert was advertising her courses under his name, as she was not allowed to give courses under her own. Much of her work appears in papers written by her colleagues and students, rather than under her own name.

The known matter particles are fermions, while interaction particles are bosons. If the world was supersymmetric each fermion would have an identical mirror particle, but a boson, and vice versa. The names for these mirror particles are already there, the bosonic partners of fermions are called sfermions, while fermionic partners of the photon, W, Z, and gluon were named photino, gluino, Wino, Zino. Is there anything more than names? We have not found any supersymmetric particles so far. If sfermions were identical to fermions except for spin, their masses would be the same as well, and we would have seen them already. Thus if supersymmetry is real, it must be, like the left-right symmetry, only approximate. SUSY partners must be heavier than “ordinary” fermions and bosons. Why do we need them at all?

As symmetries go, aesthetics is one of the arguments. SUSY is consistent with the Theory of Relativity and Quantum Mechanics. It also helps to integrate gravity with other interactions. The only known candidates for a quantum theory of gravity, string theories, are supersymmetric, they produce equal numbers of bosonic and fermionic particles, however at a very high energy scale.

There are also more “practical” arguments in favor of SUSY. If supersymmetric partners are lighter than about 1000 GeV/c², Weak, Electromagnetic and Strong forces become equally strong at distances of around 10⁻³² m. The already mentioned “Lamb effect” (vacuum polarization), is responsible for the apparent change of electric, weak and strong charges of particles with the distance. Depending on the distance from a particle we see more or less polarized vacuum on our way toward it. How the vacuum is polarized and what effect this has on the observed charge depends on the strength of the field and on what particle-antiparticle pairs exist in the real world! SUSY brings in the right particles, and all charges become equal if viewed from a distance of 10⁻³² m! Like in the Lamb effect, the existence of virtual particles in the vacuum affects not only the observed charges but also the masses. One can imagine that every particle drags behind itself a cloud of virtual particles it interacts with. This has disastrous effects for the Higgs boson mass. It glues itself so strongly to virtual top quarks, that its mass becomes much larger than experimentally preferred bounds. If SUSY exists, the supersymmetric partner of the top quark, the stop, would have a healing effect on the Higgs boson mass, by partially screening the boson from interactions with virtual top quarks. Another nice feature of SUSY became clear some time after it was conceived. The lightest supersymmetric particle is just an ideal Dark Matter candidate.

If SUSY is in the energy range needed to provide all the nice features above, it will be pretty quickly discovered by the ATLAS and CMS experiments. Our understanding of the content of the Universe will improve from 5% to 30%!

Observable space around us has three dimensions. One speaks often about time as the fourth dimension, with different properties. If there are more space-like dimensions, they must be of a small size, otherwise we would have observed them by now. String theories invoke extra space dimensions of the Planck-size, about 10⁻³⁵ m, far too small to be observed experimentally in the foreseeable future. Two small extra dimensions would be like a small sphere was attached in every point of our space. Recently it was noted that extra spatial dimensions of sub-millimeter size could solve a long standing problem why gravity is so much weaker than other interactions. If we allow gravity (and no other interactions or particles) to propagate into
these extra dimension it simply “leaks out” of our space, and we do not see its full strength. However, if the energies high enough to probe distances comparable with the size of the extra dimensions are attained, the full strength of gravity will be revealed. We might see its consequences in the form of Black Hole nanotechnology: production of nanosized Black Holes at the LHC.

Concluding remarks

What is the use of supersymmetric particles, extra space dimensions, Black Holes and Dark Matter? Before the electron was discovered any questions about its possible “utility” might have been equally difficult to answer. TV, electricity and the World Wide Web are all by-products of basic research. Perhaps old science-fiction authors’ dream of storing energy in Black Holes and tunneling via extra dimensions to other parts of the Universe will become true? One thing is sure. The quest for universal answers is an inherent part of human culture and the technological development is often a by-product. The LHC is pushing the technology frontier in areas of electronics, computing, telecommunication, detectors and accelerators, superconducting magnetic systems and cryogenics. Last, but perhaps not least, after the LHC experience particle physicists will be able to construct the best spam-mail filters in the world!

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