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The Large Hadron Collider Project

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ABSTRACT

The Large Hadron Collider (LHC) will enable proton-proton collisions at an energy of more than fourteen thousand times the proton mass. This allows the discovery of new elementary particles with very large masses, in particular of the Higgs boson. The Higgs boson is crucial for understanding the mechanism that Nature chose to give mass to particles. The Higgs boson has turned out to be very hard to find but the LHC should allow a decisive step into new territory, unveiling one or even more Higgs bosons. The new energy domain of the LHC also inspires speculations about discoveries relevant for understanding dark matter and about the discovery of new space dimensions, so far hidden to us. In the talk an overview of the physics at LHC and a report on the status of the project, accelerator and experiments, will be presented.

1. INTRODUCTION

The Large Hadron Collider (LHC) is the world's largest particle accelerator presently under construction, to become operational in the Summer of 2007. This is an excellent time, the centenary of Einstein's most famous formula, $E=Mc^2$, and an excellent place, Bern, the place where this formula was born, to remind ourselves of the fact that this formula is not only the basis of high energy physics, it still points the way, together with the uncertainty relations, e.g. in the guise $\lambda = h/Mc$ (the equal sign applying in the quantum limit), telling us that high mass particles can probe short distances.

Indeed, the LHC will provide collisions between proton beams of 7 TeV ($7 \cdot 10^{12}$ electron-volts), leading to a Centre-of-Momentum (CM) energy of 14 TeV, more than 14,000 times the proton mass. In principle this allows for the production of elementary particles with a mass up to 14 TeV. Because the colliding protons are composite particles the effective energy for producing (new) elementary particles is limited to, roughly, 1 TeV. This energy scale is one order of magnitude larger than the scales that have been open to exploration so far, and there are very strong reasons to believe that this order of magnitude is crucial: between

100 GeV and 1000 GeV (1 TeV) the mechanism that leads to large masses for the field particles of the weak interactions (the W and Z bosons), whilst leaving the photon massless should manifest itself. It may manifest itself through the production of one or more Higgs bosons. So the central theme of the scientific program at the LHC is the discovery and study of 'the' Higgs boson, although we hope and expect to find more 'new physics' as will be explained later.

2. THE STANDARD MODEL

Since the discovery of the first elementary particle, the electron (Thomson, 1897) and the first elementary field quantum, the photon (postulated by Einstein, 1905) we have come a long way in understanding elementary particles and fields and their interactions. Our present understanding is summarized in Fig. 1. For the description of 'ordinary' matter, electrons and two types of quarks (up quarks and down quarks) are sufficient. The quarks bind into protons and neutrons, which in turn bind into atomic nuclei. The only force that is relevant at the atomic level is the electromagnetic one, transmitted through photons. (And of course the 'strong' force, holding the nucleus together, but the detailed dynamics of this force is irrelevant for atomic physics.)

Let us come back to Fig. 1: the picture looks astonishingly simple. There are six quarks, coming in three 'families' of two quarks each: one quark with charge fraction $+2/3$ of the elementary charge and one with $-1/3$. There are six leptons, also coming in three 'families' of two members each: one charged lepton (like the electron) and one neutral lepton (a neutrino). Furthermore there are the field particles: the photon, mediating the electromagnetic force; the three heavy vector bosons mediating the weak force, responsible for e.g. radioactive nuclear decays; the gluon mediating the strong force, leading to quarks to bind into hadrons and to protons and neutrons to bind into nuclei. The weak force acts upon all matter particles, the electromagnetic force acts upon all charged matter particles and the strong force acts upon quark matter particles only.

The particles listed in Fig. 1 and their interactions can be cast into a quantitative theory: a relativistic quantum field theory with local gauge invariance. It was proven in the early 1970's that such theories are 'renormalizable': they allow meaningful, converging perturbative calculations.

We will not enter into the technical details of this theory here. It is usually referred to as the Standard Model. In constructing the Standard Model one major difficulty was finding a mechanism that explains the experimental fact that the gauge particles (the W and Z bosons) of the weak interaction are very massive whilst the photon is strictly massless, requiring a mechanism for electroweak symmetry breaking. The real problem was to preserve renormalizability whilst incorporating massive gauge particles into the theory. This can be done by assuming that all of space is pervaded by a field, with a non-zero vacuum expectation value. In this field the W and Z bosons acquire mass whilst the photon remains massless. This mechanism was first proposed by Higgs and by Brout and Englert. The field is usually referred to as the Higgs field and the corresponding quanta, of a well defined (but unknown) mass, are called Higgs particles. The 'Higgs mechanism' provides a solution to the problem of 'electroweak symmetry breaking'

The Higgs field is a scalar field (it has no direction) and the Higgs particles are therefore scalar, i.e. spin 0, bosons. At least one Higgs boson is required by the theory. With the Higgs boson included another crucial property of the theory is realized: it is properly behaved at arbitrarily high energy, it is 'unitary'. It is interesting to note that the unitarity requirement itself leads to an upper limit on the mass of the Higgs boson:

$$M_H \leq \sim 850 GeV$$

This means the LHC is going to cross the threshold of electroweak symmetry breaking, a very exciting perspective indeed!

Even if the 'simple' Higgs mechanism referred to above would not correspond to Nature's choice, it seems unavoidable that the mechanism that preserves unitarity manifests itself at the energy scale indicated, i.e. below $\sim 1 TeV$.

2.1 Beyond the Standard Model - Supersymmetry

There are many theoretical speculations as to what might happen at high energy, in stead of or in addition to the 'simple' Higgs mechanism. We will not attempt a systematic survey here, but will mention two classes of thought. By far the most popular extension of the

Standard Model is so called Supersymmetry. It implies that every known particle has a supersymmetric partner: the partners of fermions are bosons and vice versa. Supersymmetry has many attractive features: it provides a natural way for the strengths of the electromagnetic, weak and strong forces to converge to the same value at very high energy ($\sim 10^{16} GeV$) leading to 'unification' of these forces. It also provides a possible explanation of the enigmatic cosmic 'dark matter', dominating the matter present in the universe.

The weakest of all forces, gravity, is not included in the Standard Model. All forces, including gravity, are expected to 'unify' at the Planck scale: $\sim 10^{19} GeV$. The physical meaning of this scale can be understood by realizing that for masses (energies) this high the gravitational force is equal to the electrical force (for elementary point charges). In such a unified picture the only fundamental energy scale in Nature would be the Planck scale or Planck mass of $\sim 10^{19} GeV$, the lower energy scales would follow from symmetry breaking processes implied in and described by 'the' theory. It is worthwhile to emphasize that we are very, very far from such a 'final' theory: in energy terms we still have more than 16 orders of magnitude to go in order to reach the Planck scale from the presently explored domain.

2.2 Beyond the Standard Model – Large Extra Dimensions

Another possible road leading beyond the Standard Model requires the introduction of 'large extra dimensions'. The basic idea is that the only fundamental scale in Nature is the scale of electroweak symmetry breaking, roughly $\sim 1 TeV$, to be revealed at the LHC. The apparent weakness of gravity is then explained by the fact that, at sufficiently small distances (within the size of the extra dimensions) from the source, gravity spreads in more than the familiar 3 spatial dimensions and therefore increases much more rapidly with decreasing distance than the familiar $1/r^2$ law prescribes. So gravity is not weak at all. In order to bridge the gap from the electroweak symmetry breaking scale to the Planck scale, one can show that for few (say 2) such extra dimensions they should be 'macroscopic', may be measured in microns. If this were true the LHC would, at the same time as entering the electroweak symmetry breaking regime, enter the domain of quantum gravity. Far fetched as this may seem, it is 'theoretically allowed' and incredibly exciting!

3. THE LARGE HADRON COLLIDER: 'THE NEXT STEP'

The crown on CERN's accelerator complex will be the Large Hadron Collider (for the time being...). The LHC allows 'the next step' into the unknown, with many possible new discoveries and leading to certain compelling new insights, as explained above. Its crucial parameters are: 7 TeV beam energy (14 TeV centre-of-mass energy) and a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This represents a step of almost an order of magnitude in energy and two orders of magnitude in luminosity as compared to the highest energy hadron collider operational at the moment, the Tevatron, Fermi National Accelerator Laboratory, Batavia, Illinois.

The LHC accelerator/collider is housed in a 27 km long circular tunnel, limited to this size by environmental, civil engineering, financial and historical constraints. Given this circumference the maximum proton energy is determined by the maximum magnetic induction that can be achieved, along almost 27 km, to keep the particles on orbit through the Lorentz force. The nominal dipole field at 7 TeV is 8.33 T. This large value requires superconducting coils, and in order to achieve the highest current density, these coils are operated at the temperature of super-fluid Helium, 1.9K. Another challenging feature of these magnets is the 'two in one' design: inside a single yoke two coils are embedded, providing opposite fields to accommodate the two counter-rotating proton beams. After an intensive R&D period, followed by an 'industrialization' period, the production of these 15 m long dipoles is now proceeding very well and all 1232 dipoles should be available by the end of 2006. In addition to the 'standard' dipoles several hundreds of additional magnets, including quadrupoles for beam focusing are being produced.

The high 'luminosity' (the collision rate normalized to the total collision cross section) poses its own challenges. Since the pioneering work at the CERN SppS collider (where the W and Z bosons were discovered) we are quite confident that beam-beam instabilities will be under control, i.e. the beams will not 'blow up' due to the electromagnetic interaction of the intense bunches. Another effect, the electron cloud effect, resonant amplification – by the highly charged proton bunches - of electrons liberated from the beam pipe by synchrotron radiation will require further study. It may start limiting the luminosity from $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ onwards, but careful optimization, such as beam pipe conditioning ('scrubbing') should allow the step to 10^{34} . At this luminosity the stored energy per beam will be 366 MJ. This is a factor of 200 above the highest stored energies that have been achieved at previous or present (Tevatron) accelerators: beam collimation at the LHC will be particularly challenging and very important.

The installation of the LHC in the tunnel has started in 2004 and the activities are ramping up with the aim of closing the ring by July 2007, when commissioning with beam will start. LHC installation is an enormous task. The cryogenic infrastructure, including refrigeration plants and 27 km of liquid Helium distribution lines turned out to be unexpectedly challenging and has in fact caused delays, that are now being caught up by planning as many activities in parallel as possible. The installation of the magnets has started, connecting them to the cryogenic line and in particular connecting them to each other ('interconnect', both cryogenically and electrically) is a formidable task requiring craftsmanship (welding) and quality assurance and quality control procedures without compromise.

3.1 The LHC detectors - ATLAS and CMS

The LHC will collide proton bunches every 25 ns. At nominal luminosity this will lead to 10^9 events/s, i.e. to 10^{11} - 10^{12} tracks through the detectors every second. The design of the experimental setups therefore was particularly challenging and innovative ideas and technologies were necessary. This refers in particular to radiation resistance of detection materials and of front-end electronics. These elements should also allow fast generation and processing of signals. Furthermore the detectors should be highly granular, leading to large numbers of channels. The 'dynamic range' of detectors and electronics should be large, because secondary particles have to be detected in the range of below a GeV to above a TeV. In order to cope with the high energy end of this range the detectors need to be big. The trigger and data acquisition systems have to be very powerful, the bunch crossing frequency of 40 MHz has to be reduced to a trigger rate of 100 Hz, still leading to a data rate of 100 Mbytes/s.

Two 'general purpose' detectors are under construction at the LHC, with an ambitious physics program, aimed at revealing electroweak symmetry breaking and more, as explained above. These detectors carry the names ATLAS and CMS and in the future these names will be as familiar and generally known as e.g. the Hubble space telescope. In spite of the 'hostile' conditions ATLAS and CMS will be able to reconstruct detailed features of the events they record, e.g. particle decays occurring only millimetres away from the collision point (from which very many 'primary' tracks emerge). Also the detection of individual photons with excellent energy and angular resolution will be possible. In addition these detectors feature all the characteristics of 'general purpose, 4π acceptance detectors': high resolution charged particle tracking, magnetic

momentum analysis, high resolution calorimetry, muon spectrometry, 'hermeticity' (no holes, no dead regions).

In Fig. 2 we present the 'anatomy of a detector', in fact it is a wedge, orthogonal to the beam direction, taken out of the CMS detector. The functionality is 'generic', the technical realization of these functions is not, in that sense ATLAS has made quite different choices. We will describe the 'generic' part here, for a more detailed (but still quite sketchy) description we refer to [7]. (The detailed design of ATLAS and CMS is documented in Technical Design Reports, containing in total of the order of 10,000 pages).

Starting from the left we see, closest to the interaction point, the 'tracking device' or 'tracker', measuring spatial coordinates of charged particles. The tracker is operated in a magnetic field, leading to 'helical' tracks (propagating along a circle in the bending plane, due to the Lorentz force, and a straight line along the field direction). Charged tracks are 'reconstructed' from the measured coordinates and their curvature is a measure for their momentum. The next layer is the 'electromagnetic' calorimeter to measure energy and position of high energy photons and electrons through total absorption. Hadrons (protons, neutrons, pions, kaons) are more penetrating and they are measured in the next layer, the 'hadronic' calorimeter. Neutral hadrons (and photons) are measured in the calorimeters only, charged particles by both the tracker and the calorimeters. Muons are traversing the calorimeters without being (fully) absorbed. Their electromagnetic energy loss is much smaller than for electrons since they are 200 times as heavy and the process initiating the electromagnetic shower, Bremsstrahlung, is suppressed as the inverse mass squared. Therefore muons are measured in the outer layers of the setup in the muon spectrometer. In the case of CMS the muon spectrometer is magnetized by the return flux from the central solenoid magnet, in the case of ATLAS a dedicated system of air core toroids is used.

The ATLAS and CMS detector designs are illustrated in Figs. 3 and 4, but, more importantly, they are in an advanced stage of construction to be ready for beam in 2007.

3.2 The LHC detectors – LHCb and ALICE

Although the exploration of electroweak symmetry breaking and beyond clearly is the main motivation for the LHC, its new energy domain offers other very interesting possibilities for breaking new ground in high energy physics. LHC will in fact also be a 'B factory'. The production of B-mesons is very prolific, with most B mesons produced at small angles

with respect to the direction of the colliding beams. A study of the decays of these mesons is relevant for improving our understanding of the difference between matter and anti-matter. A 'dedicated' detector, LHCb, is under construction for precision measurements in this area.

The LHC will also offer the possibility of accelerating and colliding heavy nuclei and a dedicated detector for studying collisions between lead ions is also under construction: the ALICE detector. The goal here is to study a new form of matter, a 'deconfined' plasma of quarks and gluons, that should be produced when colliding lead nuclei 'amalgamate' into a very dense and hot system.

3.3 Computing

The Large Hadron Collider and the experimental set-ups around it, represent new and bold steps in technology in the areas of accelerator and detector construction, but not only in these areas. Also the computing requirements are unprecedented and ask for new approaches in this area. To illustrate this we note that the LHC experiments will collect 15 PetaBytes ($15 \cdot 10^{15}$ Bytes) of new data each year. Processing of these data and guaranteeing smooth access to them for the thousands of scientists involved in the experiments requires a radically new approach. This approach has led to the concept of a computing 'grid': the Grid. The LHC Computing Grid (LCG) project aims at bringing together and making available 100,000 of the fastest processors and multi-PB disk and tape storage capacity. The architecture is based on a 'tier structure', with a large central Tier-0 centre receiving, storing and initially processing the data and with of the order of 10 Tier-1 centres spread over the world and with of the order of a hundred Tier-2 centres connected to the Grid through the Tier-1 centres. All 'tiers' have well defined tasks and functionality and guaranteed service levels. The interest of such a 'grid' model obviously goes beyond high energy physics as illustrated by the fact that a large project with very substantial EU support, EGEE (Enabling Grids for E-sciencE), has been launched. Because LCG will be the first worldwide Grid to become operational, driven by the LHC schedule, CERN has been asked to lead EGEE, such that optimal synergy and coherence between both efforts will benefit both.

3.4 Physics

As described above many scenarios are imaginable for 'new physics' at the LHC, but the fact that 'something' needs to happen between 100 GeV and 1 TeV in order to explain electroweak symmetry breaking and/or to

preserve unitarity of the Standard Model is very likely. We illustrate the potential of the LHC in Table 1 where production rates of various known and for the moment unknown particles are given for a luminosity of only 10 percent of the nominal one. W and Z particles (Nobel Prize 1983) will be tools for calibration; top quarks (discovered in 1995) will be produced in quantities allowing precision studies of their properties; beauty quarks will be produced in quantities allowing the exploration of new areas in anti-matter physics; the Standard Model Higgs boson, if it exists, will be produced at rates easily detectable; supersymmetry, large extra dimensions: if this is what Nature chose, the LHC will reveal it to us.

It is interesting to note that the physics results of the LHC will probably also be of high relevance for another scientific discipline: cosmology. The earliest phases of the Big Bang are dominated by creation and interactions of elementary particles: the LHC will teach us everything about the 'electroweak epoch'; the discovery of supersymmetry may solve the dark matter puzzle; new quantitative understanding of anti-matter may be an element in explaining the absence of such matter in the universe; the LHC will allow the study of a quark-gluon plasma that must have existed a microsecond after the Big Bang.

Indeed, we expect the LHC to lead to many new results and to new insights and deeper understanding of the physical world; it will also determine the future course of high energy physics.

5. REFERENCES

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Table 1

Production rates of known and unknown particles at the LHC in the first year, at 10% of its nominal luminosity.

Process	Events/sec	Events for 10 fb ⁻¹ (one year at 10% of nominal luminosity)	Remarks
$W \rightarrow e \nu$	15	10^8	Discovered 1983 (CERN). Studied at LEP (10^4); Tevatron (10^7 end 2007).
$Z \rightarrow ee$	1.5	10^7	Discovered 1983 (CERN). Studied at SLC; LEP (10^7); Tevatron
$t \bar{t}$	1	10^7	Discovered 1995 (FNAL). Initial studies only, so far (10^4 end 2007) – high statistics at LHC
$b \bar{b}$	10^6	$> 10^{12}$	Discovered 1977 (FNAL). Detailed studies at B-factories (10^9 end 2007) (KEK; SLAC) – complementary studies at LHC.
Higgs boson mass 130 GeV	0.02	10^5	Discovery possible at Tevatron, given sufficient luminosity; large discovery potential over large mass range at LHC.
$\tilde{g} \tilde{g}$ mass 1 TeV	0.001	10^4	High mass super-symmetry, the exclusive domain of LHC.
Black holes (theories with extra dimensions) $m_D = 3 \text{ TeV}, n=4$	0.0001	10^3	Wide range of quantitative predictions, depending on number and size of extra dimensions.

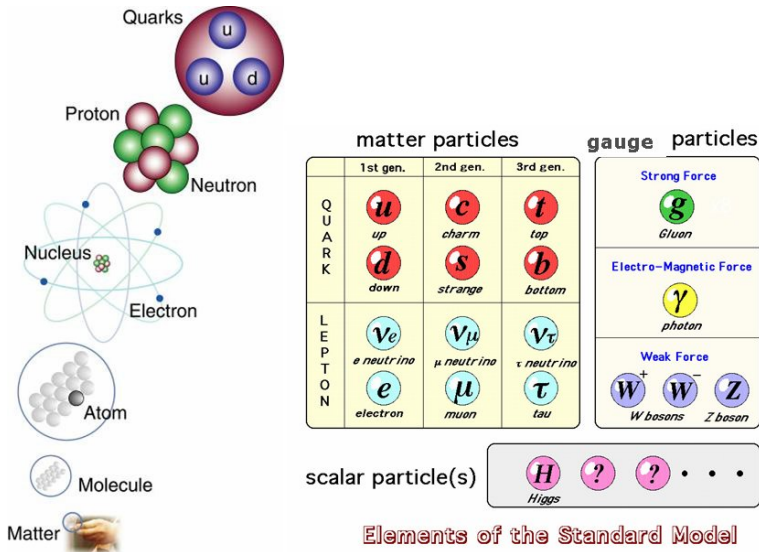


Fig. 1. The structure of matter and the elements of the Standard Model. The scalar particles ('Higgs sector') or more generally speaking the mechanism of electroweak symmetry breaking, remain to be discovered.

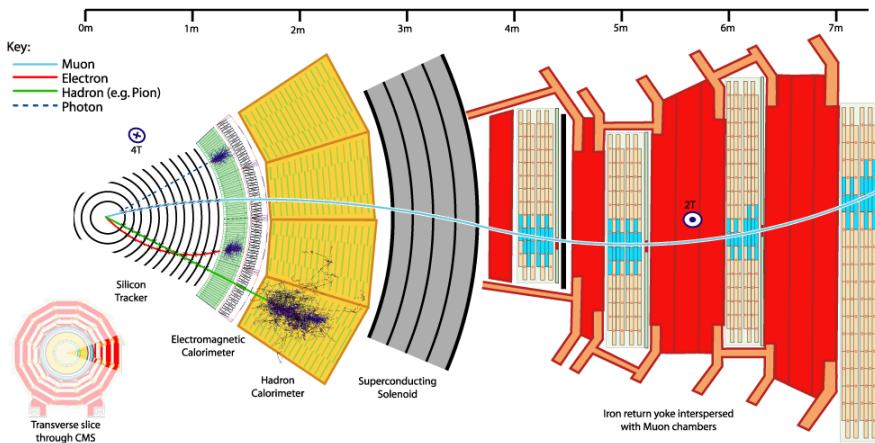


Fig. 2. A 'wedge' taken out of the CMS experimental set-up. The collision point is in the centre of the circle, to the left of the figure. The colliding beams are perpendicular to the plane of the drawing. The 'generic' functionalities of the various detectors are explained in the text.

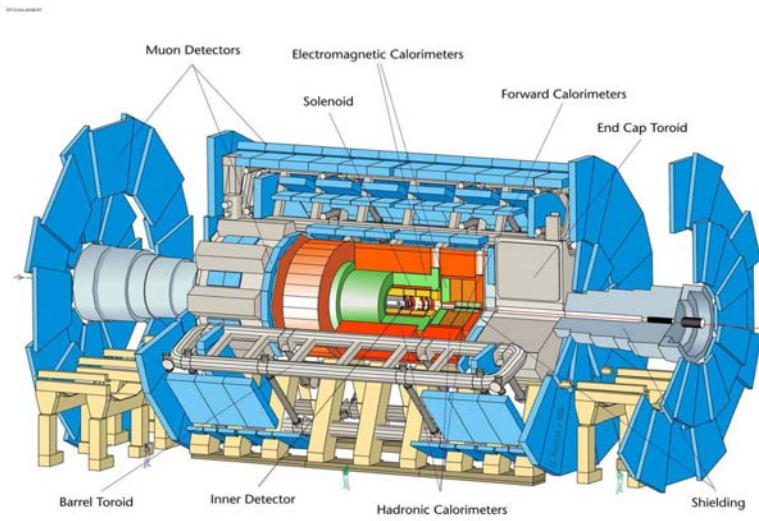


Fig. 3. An impression of the ATLAS set-up.

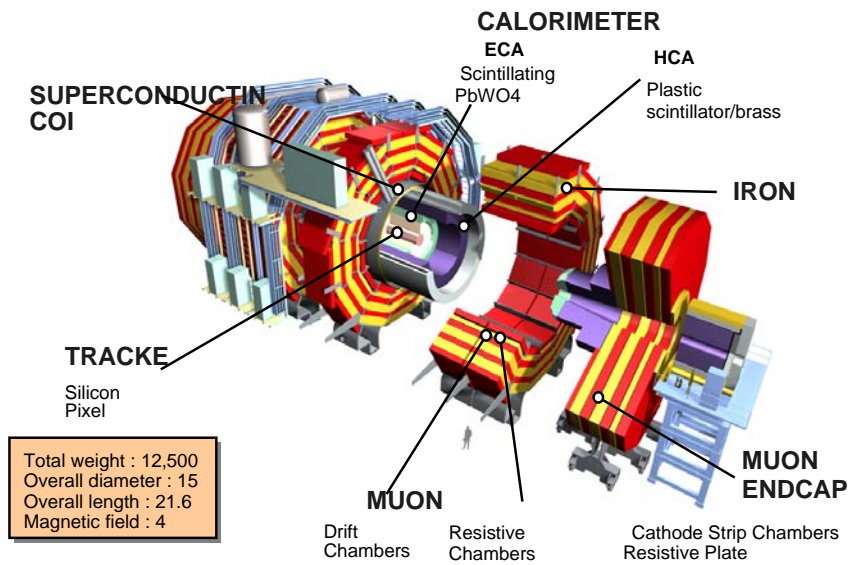


Fig. 4. An impression of the CMS set-up.