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THE LHC GENERAL PURPOSE DETECTORS

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Abstract

We present the main characteristics of the two large, general purpose detectors ATLAS and CMS, which will start operation in 2007 at the LHC.

1 Introduction

The prime motivation of the LHC is to discover the nature of electroweak symmetry breaking. The Higgs mechanicsm is the currently favoured mechanism. However, there are alternatives that invoque new symmetries, such as Supersymmetry, or new constituents or forces. The TeV is believed to be the ideal energy scale to study this potential wide range of physics.

The cross sections of the discovery channels are very small, typically less than 1 pb, and the branching ratios into useful decay modes can be as low as

10^{-3}. A very high accelerator luminosity is therefore required. The selection of the rare events among a large background imposes strong requirements on the detector performance. These harsh conditions, together with the requirement to reduce on-line the billion interactions/s to 100 events/s for storage, have created unprecedented challenges in the design and construction of the detectors.

This paper focuses on the two multipurpose detectors ATLAS and CMS which are being assembled at CERN and will start operation in 2007. After a short review of the physics and the experimental requirements, we will present how the two collaborations have addressed these challenges, often in a different but complementary way.

2 Physics requirements

At the LHC, the Standard Model Higgs provides a good benchmark to test the performance of a General Purpose Detector. The current lower limit on the mass of the Higgs boson from LEP is 114.5 GeV. Fully hadronic final states dominate the branching ratios but unfortunately these cannot be used to discover the Higgs boson at the LHC due to the large QCD backgrounds. Hence the search is conducted using final states containing isolated leptons and photons. In the mass interval 114-130 GeV the two-photon decay is the most promissing channel. The natural width of the Higgs boson is small (≈ 10 MeV) and the width of a signal will be entirely dominated by the instrumental two-photon mass resolution. An excellent photon energy and a good angular resolution are therefore needed. In addition, a correct localization of the primary interaction vertex, π^0 rejection and efficient photon isolation are required.

If the Higgs mass is larger than 130 GeV, the Higgs boson should be detectable via its decay into two Z bosons (one of them may be virtual), resulting in 4 isolated leptons in the final state. The detector requirements can be summarized as a good dimuon (or di- electron) mass resolution, implying good momentum resolution for low momenta, and a large geometric acceptance up to pseudorapidity $|\eta| = 3$.

In the region $700 < m_H < 1000$ GeV the reactions likely to provide the clearest signals involve neutrinos and/or jets from W or Z decays. Hence, good missing E_T and di-jet mass resolution will be important. In the case were the Higgs is produced by W fusion, the signal/background ratio can be enhanced by using tagging jets emitted in the high rapidity ($3 < |\eta| < 5$) region, where hadronic calorimetry is therefore required.

Searches for physics beyond the Standard Model put further requirements. The search for new, massive heavy vector bosons imposes a momentum resolution that is sufficient to unambiguously determine the charge of leptons up to 1 TeV in the region $|\eta| < 2$. Many final states contain undetected particles, leading to significant missing E_T, and abundance of b-jet or τ-jet production. Hence, efficient b/τ-jet tagging and triggering on τ's are important.

3 Experimental Challenges

The main LHC parameters in the proton proton mode, at $\sqrt{s} = 14$ TeV, are a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ and a bunch crossing interval of 25 ns, corresponding to an inelastic event rate of 8×10^8 interactions per second and ≈ 20 superimposed events per crossing. Thus, the products of an interaction under study may be confused with those of other interactions in the same bunch crossing (pileup). This effect can be reduced by using highly granular detectors with good and fast time response, giving low occupancy, at the expense of having a very large number (more than 10^7) of detector elements.

The high particle fluxes emanating from the interaction region lead to high radiation levels (fluences up to 10^{17}n/cm^2 and doses up to 10^7 Gy) requiring radiation hard detectors and front-end electronics. In some cases, the radiation levels impose a special environment for long term viability: for example, the Silicon sensors used in the central trackers must be run at low temperature ($-10°$C) to limit the leakage current and avoid reverse annealing. The radiation damage deteriorates often the performance and may induce time-dependent variations. Finally, the induced activity restricts the possibility of access and maintenance, requiring a long term reliability similar to what is asked for satellite experiments.

A major R&D effort was therefore necessary during the last 15 years to select and develop detectors and electronics that could operate reliably at the LHC.

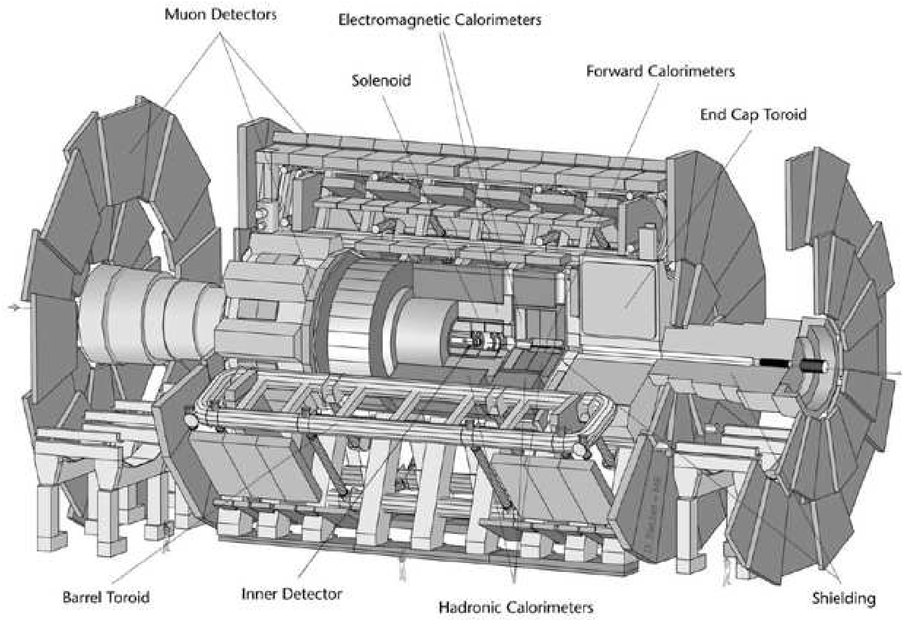

Figure 1: *The ATLAS detector. The total length is 46 m, the diameter 25 m and the weight 7000 t.*

4 The ATLAS [1] and CMS [2] detectors

4.1 General layout and magnetic field configuration

Sketches of the ATLAS and CMS detectors are shown in Figure 1 and 2 respectively. They both exhibit the typical 'onion' structure of a 4π colliding beam detector. From inside to outside, one finds

- the inner tracker, to precisely measure the charged particles produced in the collision. The tracker is embedded in a constant magnetic field parallel to the beam axis, in order to measure the curvature and therefore the momentum of the particles,
- the electromagnetic calorimeter, made of high Z material, which absorbs

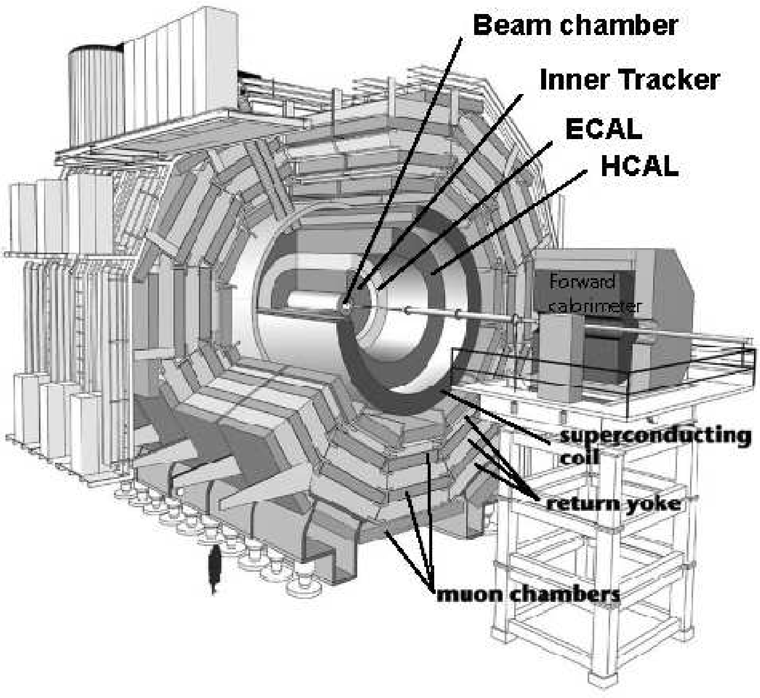

Figure 2: *The CMS detector. The total length is 21.6 m, the diameter 15 m and the weight 12500 t.*

electrons and photons. It allows a precise measurement of their position and energy,

- the hadronic calorimeter, which absorbs and measures the energy of the charged and neutral hadrons. After this detector remain only the weakly interacting particles, i.e. muons and neutrinos,
- finally, the muon system, measuring the curvature of the muons in a magnetic field.

Both detectors comprise a Barrel part, closed by two endcaps. However, ATLAS and CMS differ strongly (in particular in size) because they have chosen a different field configuration for the muon system.

In ATLAS, the magnet configuration uses large superconducting air-core toroids consisting of independent coils arranged with an eight-fold symmetry. Toroids have the property that the transverse momentum resolution is constant over a wide range of pseudo-rapidity. In an air-core toroid, a good stand alone momentum resolution can be reached as long as the product BL^2 (B being the magnetic field and L the tracking length) is large enough. Two drawbacks of the toroidal configuration are:

- the bending does not take place in the transverse plane and hence benefit cannot be drawn from the precise knowledge of the beam-beam crossing point (20 μm at LHC), and
- an additional 2T solenoid is needed to provide field for the inner tracker.

The sagitta, s, for a track of momentum p in a uniform magnetic field is given by $s = \frac{0.3BL^2}{8p}$. In the case of ATLAS, where B = 0.6 T, L= 4.5 m, the sagitta has to be measured with a precision of 50 μm. For a muon system as large as in ATLAS, precision of this nature presents special challenges of spatial and alignment precision.

In CMS, a large BL^2 is obtained using a high field solenoid (4T). The bending, which takes place in the transverse plane, starts at the primary vertex. For tracks that pass through the end of the solenoid, the momentum resolution worsens, but the effect can be attenuated by choosing a favourable length/radius ratio. Centrally produced muons are measured three times: in the inner tracker, after the coil and in the return flux. As shown in Fig. 3, in the stand alone mode (no inner tracking) the momentum resolution is limited by multiple scattering to $\approx 6\%$ below 400 GeV/c and therefore worse than for the ATLAS stand-alone muon sytem. However, in the combined mode (inner tracking + muon system), the CMS momentum resolution is better, in particular because one uses the property that after the yoke the track points back to the interaction point to improve the momentum measurement inside the inner cavity. Note also that the CMS muon system requires a less precise sagitta measurement (≈ 100 μm).

Both magnets are nearing completion: the eight ATLAS coils have been recently installed in the experimental cavern. The cold mass of the CMS coil has been inserted in its cryostat and will be cooled down early 2006.

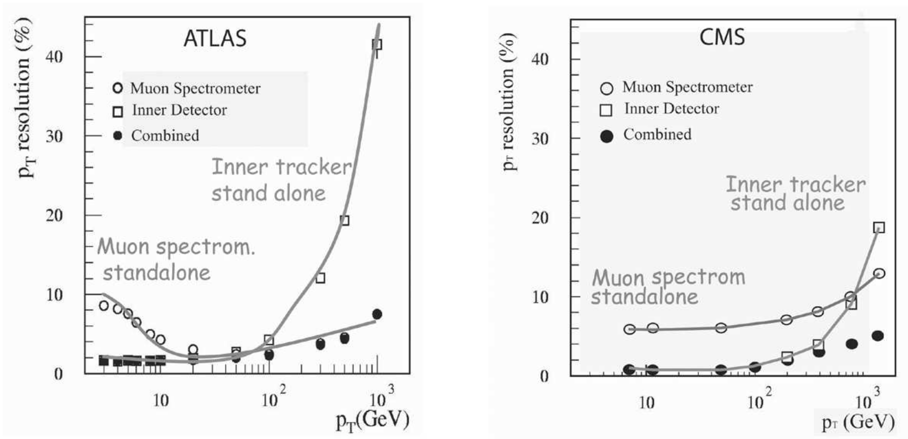

Figure 3: *The muon momentum resolution at* $\eta = 0.1$ *for ATLAS (left) and CMS (right).*

4.2 Inner Tracking

Both ATLAS and CMS detectors contain pixel detectors, placed closest to the interaction vertex where the particle flux is the highest. The typical size of a pixel is 125 μm $\times$ 125 μm. The occupancy of a pixel element is very low, even at high luminosity (10^{-4}). Furthermore, the pixel detectors allow one to reconstruct secondary vertices from B meson decays.

For the larger radii, ATLAS and CMS have adopted a different strategy (Fig 4):

- In ATLAS, the intermediate region at radii between 25 and 50 cm is equipped with silicon microstrip detectors, with a total area of 60 m^2 which provide only 4 precision space points in the barrel region and 9 points in the endcaps on each side. The silicon microstrip detectors are surrounded by straw-tubes, with transition radiation capability for electron identification (TRT), that provide a continuous tracking with many, but less precise, points per track.
- In CMS, the full volume is equipped with Si microstrip detectors providing precision space points. In the barrel region, at radii between 20 and 115 cm, the track is measured with 10 precision points. The forward

region has nine micro-strip layers in each of the two End-Caps. The total area of the silicon detectors is 220 m^2, about two orders of magnitude larger than in previous experiments.

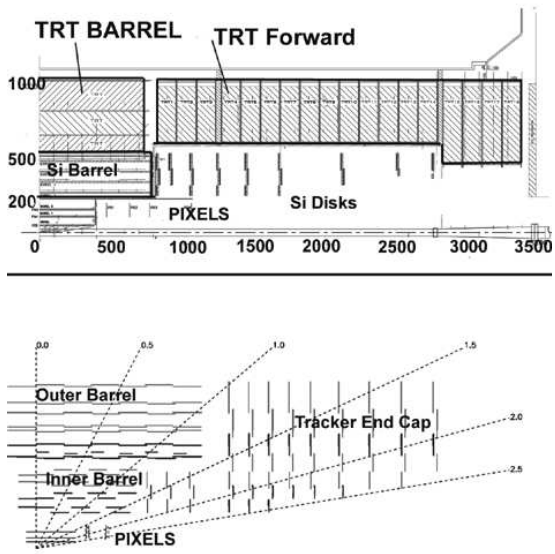

Figure 4: *Layout of the ATLAS (top) and CMS (bottom) inner trackers.*

4.3 Calorimeters

4.3.1 Electromagnetic calorimeters

The best performance in terms of energy resolution is only possible using homogeneous calorimeters such as inorganic scintillating crystals. CMS has chosen lead tungstate (PbWO4) scintillating crystals. These crystals have a short radiation length (0.89 cm), are fast and radiation hard. However, the low light yield requires use of photo-detectors with intrinsic gain that can operate in a magnetic field; silicon avalanche photo-diodes (APDs) have been chosen for the barrel crystals and vacuum phototriodes for the endcap crystals. The calorimeter comprises over 75000 crystals, with a granularity of $\Delta\eta\Delta\phi = 0.016 \times 0.016$ in the Barrel. The sensitivity of both the crystals and the APD response to temperature changes requires a very good temperature stability (a stability of 0.02°C has been achieved in the test beam). An other difficulty is that the radiation damage modifies slightly the crystal transparency, which is monitored with a laser light injection system. In the 2004 test beam running, the energy resolution has been measured to be $\frac{\sigma(E)}{E} = \frac{0.033}{\sqrt{(E)}} \oplus \frac{0.12}{E} \oplus 0.004$ (E in GeV). More than half of the crystals have already been delivered and mechanically assembled.

ATLAS (Fig. 5) is using a lead/liquid argon sampling calorimeter (LAr). The absence of internal amplification of charge results in a stable calibration over long periods of time. The flexibility in the size and the shape of the charge collecting electrodes allows high granularity both longitudinally and laterally. The main longitudinal compartment has a granularity of $\Delta\eta\Delta\phi = 0.025 \times 0.025$. ATLAS introduced a novel absorber-electrode configuration, known as the accordion geometry, in which the particles traverse the chambers at angles around 45°. This avoids azimuthal cracks. The resolution is parametrized as $\frac{\sigma(E)}{E} = \frac{0.10}{\sqrt{(E)}} \oplus \frac{0.3}{E} \oplus 0.007$ (E in GeV). An excellent response uniformity, better than 0.7% has been demonstrated in test beams. To limit the amount of dead material in front of the em. calorimeter, the 2T solenoid and the LAr share the same cryostat.

The Barrel LAr calorimeter is assembled and will be soon installed in the experimental cavern.

4.4 Hadronic Calorimeters

In CMS, the Barrel and Endcap hadronic calorimeters (up to $|\eta| = 3$), located inside the magnetic coil, are brass-scintillator tile sampling calorimeters readout out by wavelength shifting fibres. The tiles are perpendicular to the particles. The measured resolution is $\frac{\sigma(E)}{E} = \frac{1.3}{\sqrt{(E)}} \oplus 0.065$ (E in GeV). The very forward calorimeter $3 < |\eta| < 5$ consists of steel plates with grooves in which quartz fibres are inserted and measures the Cerenkov light emitted by relativistic shower particles.

The ATLAS Barrel hadronic calorimeter is an iron-scintillator tile sampling calorimeter readout out by wavelength shifting fibres. The tiles are placed radially. The measured resolution can be parametrised as $\frac{0.7}{\sqrt{(E)}} \oplus 0.033 \oplus \frac{1.8}{E}$ (E in GeV). The Endcaps and Forward calorimeters use the liquid Argon

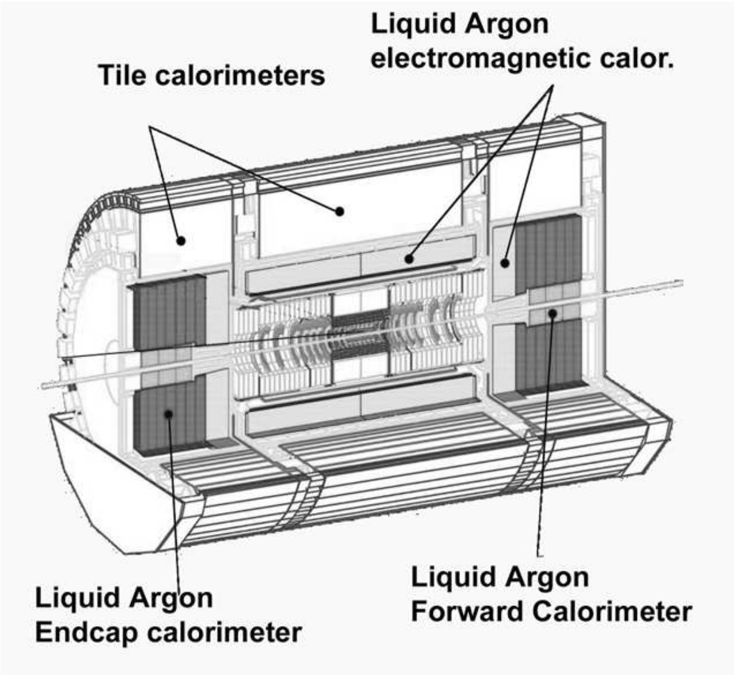

Figure 5: *Calorimetry in ATLAS.*

technology.

Both CMS and ATLAS Hadronic calorimeters are essentially ready.

It should be noted that the jet energy resolution is dominated by the jet reconstruction algorithm and not by the intrinsic performance of the hadronic calorimeter. A significant improvement in resolution is obtained by replacing, for charged tracks, the energy measured in the calorimeter by the momentum measured in the tracker and by adding charged tracks that bend out of the reconstruction cone, as measured in the tracker.

4.5 The muon detectors

Two kinds of muon detectors are used at LHC, serving complementary roles. These are gaseous drift chambers (DT), that provide accurate position measurement for momentum determination, and trigger chambers, such as resistive plate chambers (RPC), that have a short response time (< 25 ns) for precise bunch crossing identification but a less accurate position measurement. In the endcap region, drift chambers are replaced by faster chambers such as cathode strip chambers (CSC). A sketch of the CMS muon system is shown in Fig. 6. To cope with the neutron induced background and provide a local angular measurement, each of the muon stations comprises several layers of detectors.

The main challenge is the construction, assembly and installation of a very large detection area. For example, the ATLAS muon chambers total a surface area of over 12000 m^2.

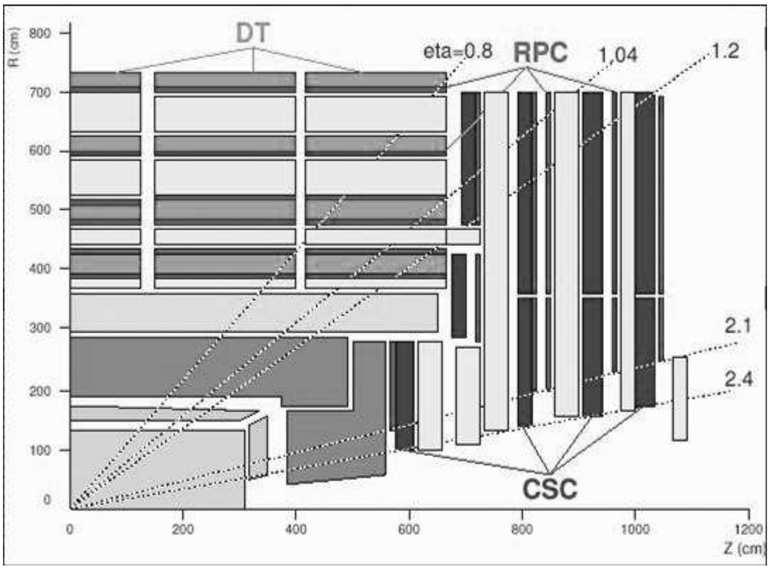

Figure 6: *The CMS Muon system.*

5 Trigger and Data Acquisition

The data acquisition and synchronization of $O(10^7)$ channels is a huge task, requiring large pipelines, very fast control and switching networks and large processing farms containing several thousands PCs. Furthermore, the initial interaction rate of 40 MHz has to be reduced to $\approx$ 100 Hz, corresponding to the storage capacity, while keeping the interesting physics events with high efficiency. A Level-1 trigger, using specialized boards with fast digital electronics

(FPGAs), reduces the initial rate to 100 KHz. The remaining factor 1000 is obtained by reconstructing the events in real time using commercial processors.

6 Conclusion

The construction of the LHC detectors required to meet a set of unprecedented challenges, due to the high rate of interactions, the hostility of the environment, the need for very high resolutions, acceptances and selectivity. More than 15 years were necessary between the initial ideas and the construction of the actual detectors, and many todays achievements seemed pure dreams at the start of this long enterprise. Most of the detectors are now in the phase of installation and commissioning and will probe very effectively the Physics that LHC will deliver starting 2007.

7 Acknowledgements

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