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Challenges of the LHC: the detector challenge

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1 Introduction

The quote I remember must date from the mid 1980's or a little bit later. It says: "we think we know how to build a high energy, high luminosity hadron collider – we do not have the technology to build a detector for it; for a high energy, high luminosity linear electron–positron collider the situation is just the opposite". Clearly the decision was taken to first choose the former of these "impossible" routes towards new discoveries and to, somehow, make the necessary progress in detector technology to allow detection and analysis of complex and rare final states resulting from proton–proton collisions at very high energy.

As is illustrated in the presentation by Lyn Evans at this symposium, the claim that the technology for building a very high energy hadron collider was already available at the time of the statement quoted was a serious simplification of reality; after years of hard work this technology now is available and the Large Hadron Collider is well underway towards first collisions of 2 × 7 TeV proton beams in 2007.

The LHC detectors are radically different from their predecessors at the *$Sp\bar{p}S$* collider, LEP, SLC, HERA, Tevatron, etc.: they are designed for a luminosity of 10^{34} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for *pp* collisions at an energy of 14 TeV in the center of mass reference system, so the detectors need to be fast, radiation hard (also the electronics) and big.

ATLAS and **CMS** took up the challenge to elucidate electroweak symmetry breaking, find "the" Higgs boson and more;

LHCb took up the challenge to exploit the prolific production of *b*-quarks in the forward direction to study *CP* violation and rare decays;

ALICE took up the challenge to explore the properties of QCD matter at extreme energy densities (the quark–gluon plasma) over a large, new region of its phase diagram;

TOTEM took up the challenge to accurately measure the total cross section.

Jos Engelen

2 The ATLAS and CMS detectors

ATLAS and CMS are 4π "general purpose" detectors (Fig. 1 and Fig. 2 respectively). They will see 20 to 40 events per bunch crossing, i.e. every 25 ns, leading to 10^9 events per second and to something like 10^{11} to 10^{12} tracks per second. It is really remarkable and quite a step from what could be anticipated when first discussions on the design of these detectors started, that ATLAS and CMS will, in this environment: – reconstruct secondary vertices from B mesons and τ leptons, only mm's away from the primary vertex; – reconstruct individual photons with sufficient energy and angular resolution for detection of a light Higgs boson decaying in two photons. In addition, these detectors have many more capabilities. As stated above they are "general purpose" 4π detectors featuring tracking, magnetic momentum analysis, calorimetry, muon spectrometry in an, almost, *hermetic* setup. (Incidentally: the importance of hermeticity was emphasized by the pioneering *$Sp\bar{p}S$* experiments, the achievements of which we are celebrating at this symposium.)

We will not extensively review the layouts and design choices of ATLAS and CMS here; we will discuss some of their characteristics, however.

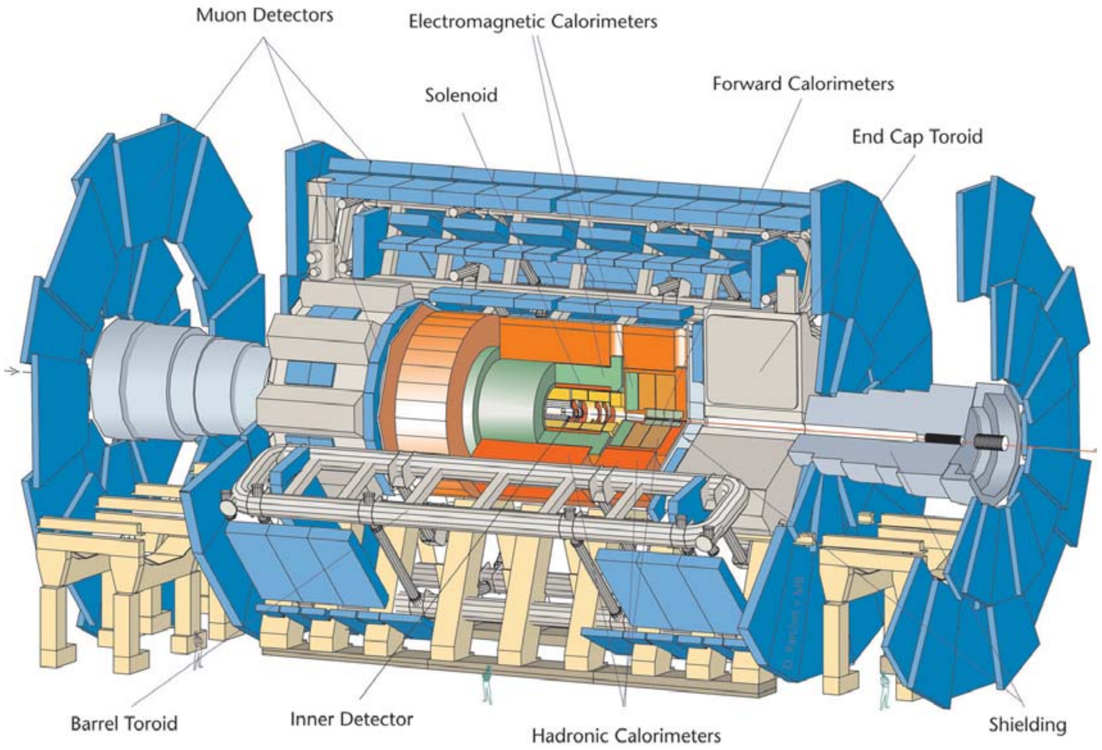

Fig. 1. A schematic view of ATLAS, a low density, general-purpose detector at LHC

A remarkable feature of ATLAS is its huge air core toroid muon spectrometer with stand-alone capabilities for momentum measurement. This will allow accurate reconstruction, in particular of muons with high transverse momentum, e.g. resulting from the decay of a very heavy Higgs boson. This spectrometer makes the ATLAS setup very large with a length of 46 m and a diameter of 25 m. The specific weight, however, is only 300 mg/cm^3.

CMS, the Compact Muon Solenoid, is characterized by a large, 6 m bore, central solenoid with a 4 T magnetic

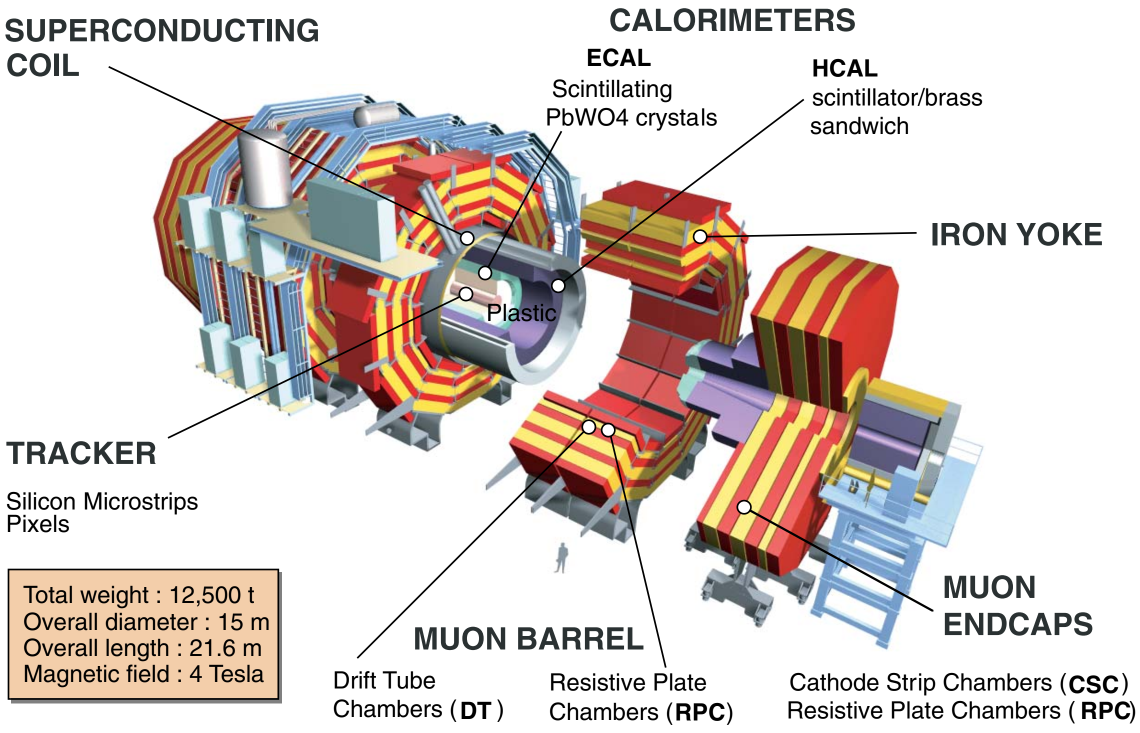

Fig. 2. A schematic view of CMS, a compact, general-purpose detector at LHC

field, containing tracking and calorimetric devices. With a diameter of 15 m and a length of 22 m this setup is relatively "compact", with a specific weight of 3 g/cm^3.

One of the most important developments for the instrumentation of the LHC detectors is in the field of Silicon sensors and the associated electronics. For example: the innermost pixel detector layer will typically be exposed to 10^5 Gy/year due to ionizing radiation and to 1.6 10^{14} n/cm^2/year.

Radiation hardness of sensors has been achieved empirically, there are many parameters that can be varied – crystal cut orientation (<100>, <111>); geometry of implants; pixel dimensions, pitch of microstrips; temperature; improvement of production methods; etc. Increasing depletion voltage can (up to a limit) compensate for signal loss.

Radiation hardness of electronics can be achieved by using special rules and processes, but there was a very pleasant "coincidence": the 0.25 μm technology appears to be intrinsically radiation hard (and will be widely used by LHC experiments, not only for pixel detectors) – even though ATLAS also uses DMILL electronics.

CMS has taken the drastic and, in a sense, revolutionary step of opting for an "all silicon" tracker consisting of barrel and end-cap detectors, providing of the order of 10 high precision points per track. The barrel consists of 3 pixel layers, 4 inner and 6 outer microstrip layers. The availability of large wafers (6") was crucial for the decision to also produce the outer layers of silicon.

The ATLAS tracker consists of pixel and microstrip silicon detectors (3 + 4 layers) completed with a Transition Radiation Tracker (TRT). The TRT provides track coordinates with a lower precision than the semiconductor tracker, but provides a large number of measurements for each track. It is produced from small diameter (4 mm) straw tubes. The layers of straw tubes are interspersed with poly-ethylene foam or foils where electrons generate transition radiation, also detected by the straw tubes, providing electron–pion separation at high energies.

Great care had to be taken to limit the amount of material in the trackers to the absolute minimum in order to limit multiple scattering and photon conversions as much as possible. Among others, this led to the design of advanced light weight support structures of composite material. This typically resulted in an average of 50–60% of X_0 in the central active volume.

As already indicated above, the successful implementation of the pixel and other read-out chips in 0.25 μm technology was a great success, leading to the required radiation hardness and to cost effectiveness.

Both ATLAS and CMS have developed new concepts in electromagnetic calorimetry. The detection of a relatively light Higgs boson (120 GeV) decaying into two photons requires electromagnetic calorimeters of exceptional performance. ATLAS will have an electromagnetic calorimeter with very high granularity and longitudinal sampling – providing directional information for individual photons – and good energy resolution ($\Delta E/E = 9\%/E^{1/2}$) (calorimeter placed outside the central solenoid); CMS will have an electromagnetic calorimeter with very good energy resolution ($\Delta E/E = 3\%/E^{1/2}$) and good granularity (calorimeter placed inside the central solenoid).

ATLAS has developed an electromagnetic calorimeter based on liquid argon technology, with essentially no dead space. The latter is achieved by employing "accordion" electrodes and absorbers, that zigzag along the particle's flight direction. Mechanical and electrical design and construction of absorbers and electrodes was extremely challenging, but all specifications have been achieved.

CMS has invested in a long and intensive R&D program on $PbWO_4$ as a crystal for high resolution electromagnetic calorimetry. The challenge was to produce crystals with the required properties (radiation hardness, reproducibility, light yield, uniformity) at an affordable price, starting from cm^3 samples leading to a m^3's calorimeter. Also here the goals have been achieved and crystals are being produced at a steady rate.

This brief presentation is not the place to give a comprehensive overview of the achievements and the status of these very large, complex, state of the art detector systems. Both experiments are now well into the production phase and although there are still many challenges ahead we may optimistically look forward to first data taken with these detectors in 2007, at the start up of LHC.

For both ATLAS and CMS new, large underground caverns had to be excavated. The ATLAS caverns have been handed over to the collaboration recently. The CMS detector will be largely assembled on the surface, the experimental cavern will be handed over to the collaboration in 2004. As a recent example of the "surprises" one can encounter in large civil engineering projects we mention the water leaks that developed in the two CMS access shafts, as a consequence of the settling of the underground halls. It is clear that unexpected events like these (there are many more and certainly not only in civil engineering) require the utmost resourcefulness and flexibility of the collaborations in order to minimize delays.

Among the remaining challenges ahead, assembly, installation and integration are the most immediate ones. For example: CMS recently successfully tested the insertion of the 220 ton central coil (using a "dummy" of course) inside the vacuum tank shell: a "heavy duty" but very delicate operation. ATLAS is presently integrating its 25 m long barrel toroid coils, a complex operation. In one year's time, i.e. towards the end of 2004, these large and heavy devices (there are eight in total) will have to be installed in the ATLAS cavern, filling it to the roof.

3 The LHCb detector

The LHCb experiment (Fig. 3) will exploit the Large Hadron Collider as a B-factory (including B_s, B_c – not produced at the presently running e^+e^- B-factories – and also b-baryons). Its design is optimized for the detection of B mesons in the "forward" direction. Dynamics (mainly gg fusion) and kinematics (Lorentz boost) lead to a "one arm spectrometer" design, rather unusual at a collider.

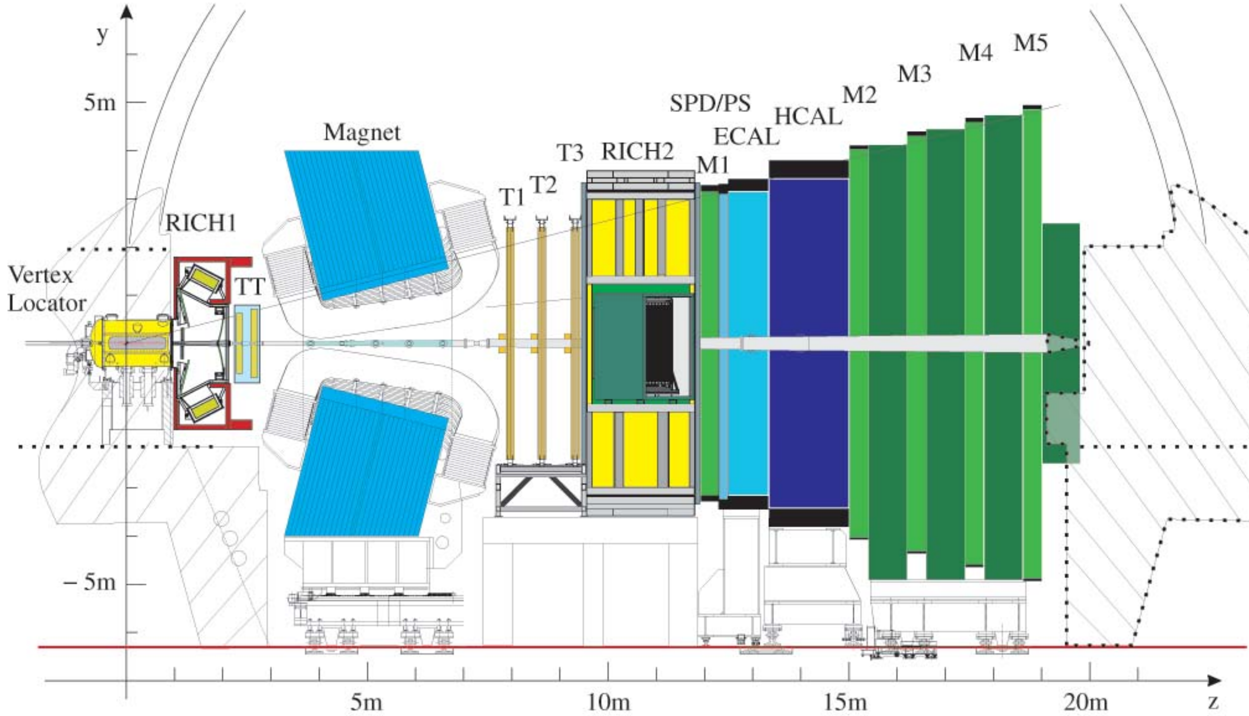

Fig. 3. A schematic view of the LHCb detector at LHC, optimised for B physics in the forward direction

Due to the large *b* production cross section at LHC energy, the luminosity at the LHCb interaction point will be tuned at 2×10^{32} cm^{-2}s^{-1}. The main challenges for this experiment are: trigger, sensitive to multibody hadronic final states; particle identification (K/π separation) over a large momentum range and tracking (vertexing), the latter allowing a proper time resolution of the decaying B mesons of 40 fs.

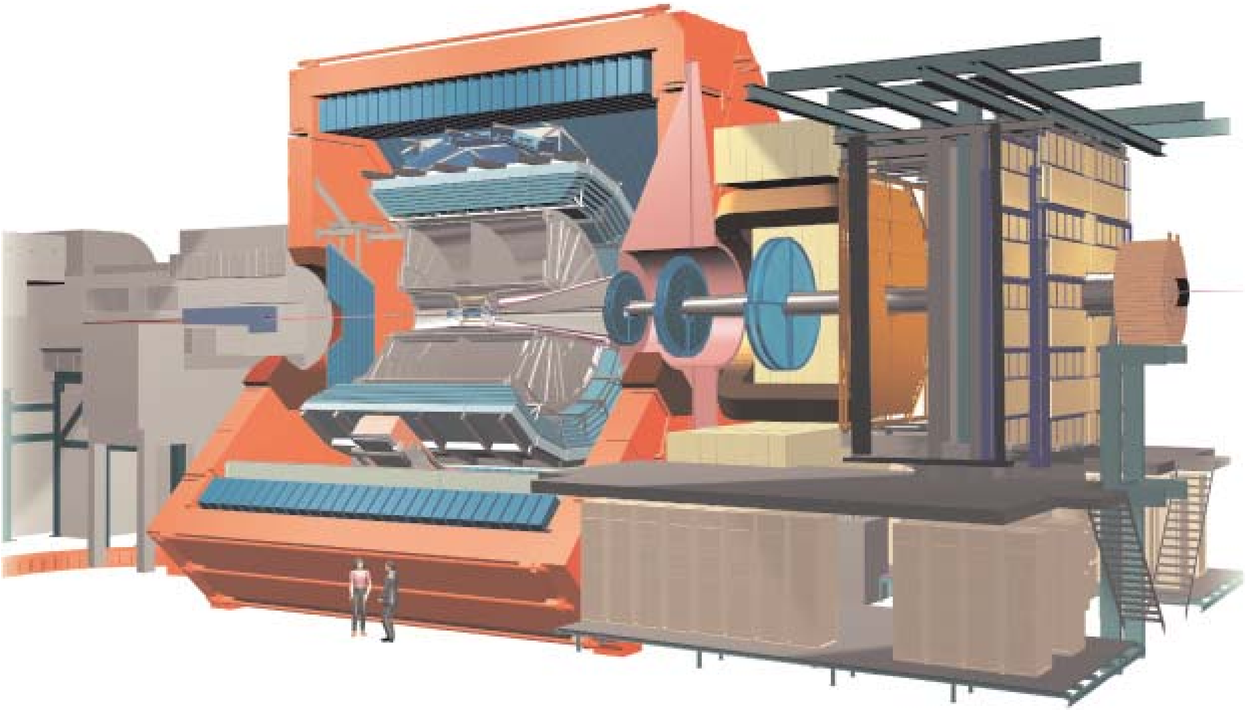

Fig. 4. A schematic view of the ALICE detector at LHC, optimised for the study of heavy ion collisions

4 The ALICE detector

The LHC will collide Pb beams at 2.75 TeV per nucleon: this should, in central collisions create the extreme temperature and density required for producing a plasma of quarks and gluons. In order to investigate the many facets of this unusual state of matter, in a single dedicated experiment at LHC, ALICE (Fig. 4) will have to study a diverse set of observables, needing a great variety of subdetectors, not all of them requiring full angular coverage, but providing unique particle identification. Rather than "rate", the problem for ALICE is "occupancy" and "data volume", as one central Pb–Pb collision will produce one thousand times more particles than a typical *pp* collision.

The greatest instrumental challenge certainly is the central, large Time Projection Chamber (88 m^3) and its associated electronics (570,000 channels). Combined with a six layer, silicon vertex detector, it will provide an excellent momentum resolution over a broad range from 100 MeV/c to above 100 GeV/c. A further remarkable feature of the ALICE detector is the integration of a "muon arm" (for J/ψ and Y detection) in the setup.

In addition to Pb beams, the ALICE detector will study collisions with lighter ions, proton–nucleus interactions as well as a number of topics in *pp* reactions where its unique coverage of soft and semi hard observables combined with particle identification are relevant.

5 Looking forward to ...

We are all eagerly awaiting the startup of the LHC and the data taking of the LHC experiments in the second trimester of 2007. Discovery of "the" Higgs boson, investigation of electroweak symmetry breaking are of course on top of the priority list. Even moderate (!) initial luminosities of $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ will open a promising window on new physics. For example, if (low-energy) super-symmetry is realized in nature, this could be one of the first discoveries at the LHC, perhaps already within the first 6 months.

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