Nuclear Instruments and Methods in Physics Research A 666 (2012) 1–9

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Review

Multipurpose detectors for high energy physics, an introduction

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ARTICLE INFO

Available online 15 November 2011

Keywords:
LHC
ILC
Tracking detector
Calorimeter muon detector
High energy physics
Multipurpose detector
Particle identification
Magnet

ABSTRACT

Multipurpose detectors are used widely in high energy physics experiments. They work on the same set of fundamental operating principles although specialized in their design goals and detection features. The Large Hadron Collider (LHC) has four major experiments exploiting these techniques, and in the future the International Linear Collider (ILC) will employ the detectors that are being designed presently and will utilize the particle-flow algorithms in order to obtain the desired dijet mass resolution. A complete understanding of the above mentioned detectors, their designs and the particle detection mechanisms can enable the prediction of the most desirable attributes of an ideal particle-detector design. In this introductory paper, we highlight the techniques used for radiation detection particularly at LHC, and the articles that follow in this volume.

Contents

1. Introduction

With the Tevatron decommissioned [1], the LHC represents a unique opportunity for discovery physics. Here four detectors [2–14] specialized each to its purpose have been installed to harvest major physics discoveries and results at this high energy frontier. All high energy physics detectors have a similar underlying principle, independent of colliding particles in different machines like $e\bar{e}$, $p\bar{p}$, pp, ep or even $\mu\bar{\mu}$ in the future; most of the surrounding detectors do not directly detect the fast decaying particle produced e.g. the top quark or W boson, but their decay products. It is of prime concern to demonstrate the nature of electroweak symmetry breaking for which the Higgs mechanism is responsible. Any consistency checks of the standard model beyond energy scale of 1 TeV require a full reconstruction of all

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0168-9002/$ - see front matter © 2011 Published by Elsevier B.V.
doi:10.1016/j.nima.2011.11.023

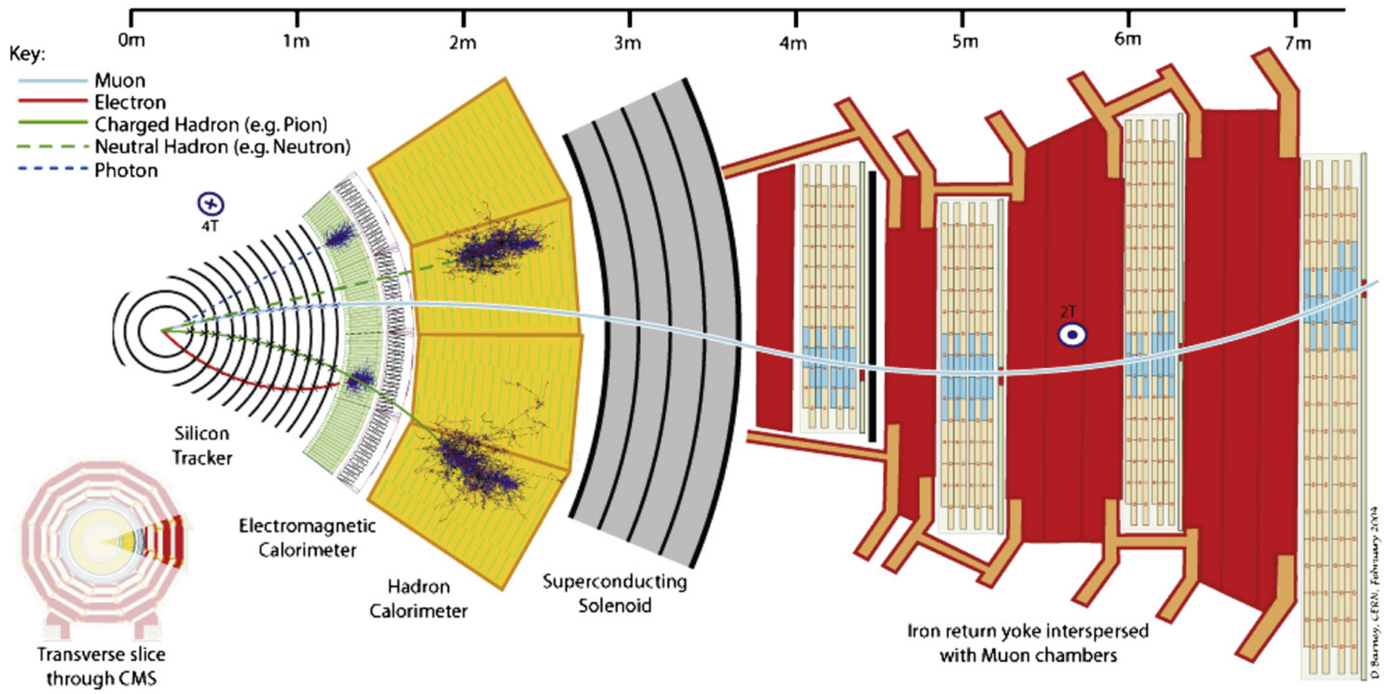

Fig. 1. A slice through the CMS detector. CMS consists of a central silicon Tracker (Pixel and Strips), an Electromagnetic Calorimeter, a Hadron Calorimeter, a Superconduction Solenoid Magnet, a massive iron return yoke instrumented with Muon Chambers. The depicted interactions present an ideal detector behavior for the different particles μ, e, charged and neutral hadrons, and γ. [Courtesy of CERN, CMS].

corresponding decay products including their properties: comprising momentum, energy, spin, mass, charge, lifetime and identity. The limited kinds of basic particles produced are photons, electrons, muons, hadrons, neutrinos, and the detectors need to be hermetic so that each and every particle of interest is tagged and identified. Particle detection comprises the interaction of all above mentioned particles with specially designed and dedicated sensitive detector material and thereby measuring their properties. We need to assemble an excellent combination of individual detectors to achieve all the above mentioned goals. A standard set would exploit a Tracker [15,16], in combination with a strong magnetic field [17] to measure the track, momentum, charge and energy; a calorimeter to measure energy [18,19]; and a tracking detector called muon detector that is further out in this "cylindrical onion mode" [20] and detect muons that traverse all through the material in the inner detectors. Often a Particle Identification Detector (PID) [21] completes the experiment.

1.1. Particles and their observables

In principle the following set of interactions are used to detect a basic set of particles. Photons react via Photo-Effect, Compton-Scattering and Pair-Production; charged particles (e.g. e^+, μ^-, p, π^-, etc.) interact mainly by scattering (unwanted), ionization, excitation, but also by Bremsstrahlung, Transition Radiation and Cherenkov radiation; hadrons (charged and neutral) in addition, interact strongly through inelastic interaction (e.g. induced fission, neutron capture, etc.); neutrinos only interact weakly, meaning they statistically do not interact in the 'light mass' HEP detectors and their signature is 'non-interaction', manifesting itself as 'Missing Energy'. A particle detector obstructs the particle path with suitable materials, generates signals which will then be converted into electronic signals with the aid of electronics,[1] and later into computer bits by Analog-to-Digital conversion. One has to take note that the detector material and electronics have to be tuned for different particle energy ranges and collider timing structure, e.g. a high p_T particle together with a low magnetic field would produce a curved track, where the curvature would be below the measuring sensitivity of the tracker or the calorimeter might not be massive enough to stop the particle and not all the energy would be recorded. Hence a magnet and associated magnetic field dictate the design of a high energy physics detector.

Interaction of different particles with different subcomponents. Fig. 1 gives a scheme of how the different particles react with the different subcomponents of CMS [3] and thereby identifying themselves.

A muon (charged) interacts via ionization and excitation with all subcomponents, fully penetrating the calorimeter. Its track is curved due to the magnetic field. An electron presents itself via ionization in a curved track due to the magnetic field in the Tracker, and deposits its full energy in the Electromagnetic Calorimeter via an Electromagnetic Cascade (Bremsstrahlung and Pair-Production starting with Bremsstrahlung).

The photon leaves no track in the tracker and deposits its full energy in the Electromagnetic Calorimeter via an Electromagnetic Cascade (Pair-Production and Bremsstrahlung starting with Pair-Production). The neutral hadron interacts mainly in the Hadron Calorimeter, depositing its full energy via a hadronic cascade. The charged hadron, like any charged particle, evokes a curved track in the tracker ionization and deposits its full energy in the Hadron Calorimeter. ATLAS and CMS came without a dedicated PID [21] component, like Time of Flight (TOF), Ring Imaging Cherenkov Counter, but the energy deposition dE/dx (Bethe–Bloch) in the tracker serves as one instead [21]. Other detectors like ALICE [14] and LHCb [9] have dedicated PID systems.

Exploiting the properties of the individual particles. To obtain the full properties and the identity of the produced original particle one has to sum up all the momenta, spins and energies of the decay particles, and reconstruct the full decay chain down to identify even the flavor of the initial quarks, e.g. *b*-quarks. Various

[1] Historically, for much slower detectors than today, photos were used to analyze the interactions.

components are designed to add most of the information to the puzzle. The inner tracking components [15] and outer muon detectors [20], together with the magnetic field [17] determine, via—the track curvature (Lorentz force)—the charge, the momentum and energy of charged particles.

The calorimeters [18,19] stop the particles, fully absorbing all their energy, and by measuring the deposited amount of energy proportional to stimulated light and the penetration depth, they determine their intrinsic energy.

The spin of the original particle can be determined by a full angular momentum analysis.

The mass (identity) can be derived from the combination of momentum and energy measured by the Tracker, Muon Chamber and Calorimeter.

The lifetime (identity) can be determined by measuring the path length from production to decay. With the very short lifetimes of the interesting particles, these distances range from some hundred micrometers to some millimeters, residing completely outside the detecting location. Still, it can be measured by interpolation of precisely measured tracks (see Ref. [15]). The path length defines the lifetime of the particle, but vice versa with a known lifetime, the path length identifies the particle; this is used to tag the flavor of the *b* and *c* quarks, adding crucial information of the decay products and thus of the original particle (*b*-tagging).

The mass (identity) of a particle can also be derived by a combination of velocity and momentum. The velocity can be measured either by a Time of Flight system, a dE/dx measurement, or a measurement of the Cherenkov light cone [21].

All the properties of the decay products have to be summed up and the full decay chain has to be reconstructed, taking all detector inefficiencies into account, and finally the event has to be compared with the theory. The full description of interaction with theory and experimental measurements with all the upstream computing and statistical treatments is beyond the scope of this brief introduction but it should be mentioned that a full detector simulation contains all details of the detector, e.g. material budget, and ineffective regions to enable comparison of experimental result and theory.

In this volume the essential components and subdetector techniques mentioned above are discussed at length in dedicated reviews as follows:

1. A magnet system for HEP experiments
2. Vertex tracking detectors
3. Electromagnetic Calorimeters
4. Hadron Calorimetry
5. Muon detectors
6. Transition Radiation detectors
7. Particle identification
8. Alignment systems in large experiments
9. Electronics and data handling

2. Brief description of the major LHC experiments

2.1. A Toroidal LHC Apparatus (ATLAS)

The ATLAS [2,6,7,11,22] detector is the largest detector in operation at LHC. Its design philosophy was to create an ability to detect an entire range of masses allowed for the Higgs while retaining the ability to detect the known particles such as heavy quarks and gauge bosons. In addition to measurements that further an understanding of electroweak symmetry breaking, ATLAS aims to test new theories based on the existence of composite quarks and new gauge bosons, and also the CP violation in B decays. ATLAS has excellent Electromagnetic Calorimetry to detect electrons, photons and provides a full coverage of *H*-calorimetry to detect jets and $E_{\mathrm{T}}^{\mathrm{miss}}$(missing transverse energy). It has a high precision system for accurately measuring muon momentum at high luminosity and an efficient tracking for lepton momentum measurement and the identification of electrons, photons, leptons and heavy-flavor quarks. It provides a full Azimuthal angle coverage and a high η acceptance. The geometry of the detector can be seen from Fig. 6. The Inner Detector, composed of a three layer, three endcap disk pixel detector, a four layer, nine disk silicon strip and a large TRT detector ($\sim$36 hits), resides inside a cylindrical structure 7 m long and with a radius 1.15 m. Solenoid creates a magnetic field of 2 T. Main functionality of ID is pattern-recognition and momenta measurement.
The Electromagnetic Calorimeter is based on a highly granular liquid-argon (LAr) and provides a coverage of $|\eta| < 3.2$. LAr is also used in the Hadron Calorimeter. Both the components share the cryostat at the end-cap which also accommodates a special LAr forward calorimeter with $|\eta| < 4.9$. The total weight of calorimeter system is 4000 ton. The Muon Spectrometer constitutes the major volume of ATLAS with an inner radius of 4.25 m, outer radius of 11 m and a half length of the barrel toroid of 12.5 m. Its function is to identify muons and their momenta by bending the track under the influence of magnetic field (Fig. 2).

2.2. Large Hadron Collider beauty (LHCb)

LHCb [4,9,13] is a single-arm spectrometer with a forward angular coverage from approximately 10 mrad to 300 (250) mrad in the bending (non-bending) plane. The LHCb experiment aims to study the CP violation and the physics of decay in the B-meson system. The geometry as seen in Fig. 3 is influenced by the fact that both *b* and $\overline{b}$-hadrons are created in the same cone. LHCb has excellent particle identification [21] and vertex resolution necessary for the study of rapidly oscillating B mesons. Most parts of the LHCb system can be assembled in two halves and this is advantageous for assembly, maintenance and access. The vertex detector system consists of the silicon vertex detector and a pileup veto counter called VErtex LOcator (VELO). It has 17 stations and extends from $z = -18$ cm to $+80$ cm. Each station has two silicon disks which have circular and radial strips and are perpendicular to the beam. The pileup veto counter is located upstream and creates level-0 trigger. The tracking system which consists of inner and outer trackers has an efficient track reconstruction and a precise momentum measurement. The track direction will be used for RICH system and as information for the level-1 trigger. The RICH system is designed for charged particle identification for the momentum range 1–150 GeV. RICH1 is placed upstream and uses silicon aerogel and C_4F_{10} gas radiator. RICH2 is placed downstream and uses CF_4 for particle detection. Calorimeter identifies the electrons and charged hadrons for trigger and measures their position and energy. The pre-shower detector has 14 mm thick lead plates followed by 10 mm thick square scintillators. Fine lateral segmentation is implemented in ECAL to differentiate the electrons from charged hadrons. HCAL has an iron frame which holds scintillator tiles which are positioned parallel to the beam and the muon detector is the final stage which consists of five stations M1–M5 as shown in Fig. 3. M1 is placed before the calorimeter pre-shower detector (12.1 m from interaction point) and measures the transverse momentum for the level-0 muon trigger. M2–M5 are placed consecutively at 15.2 m, 16.2 m, 17.1 m and 18.8 m from the interaction point. They are interleaved with shields of ECAL, HCAL and iron filters.

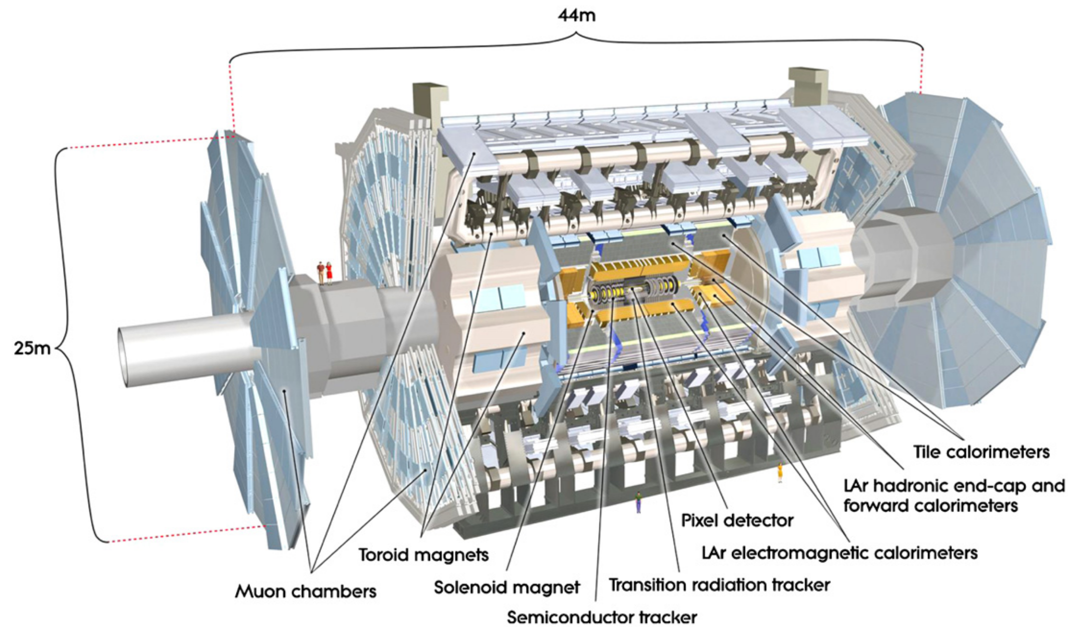

Fig. 2. The ATLAS detector and its components [2].

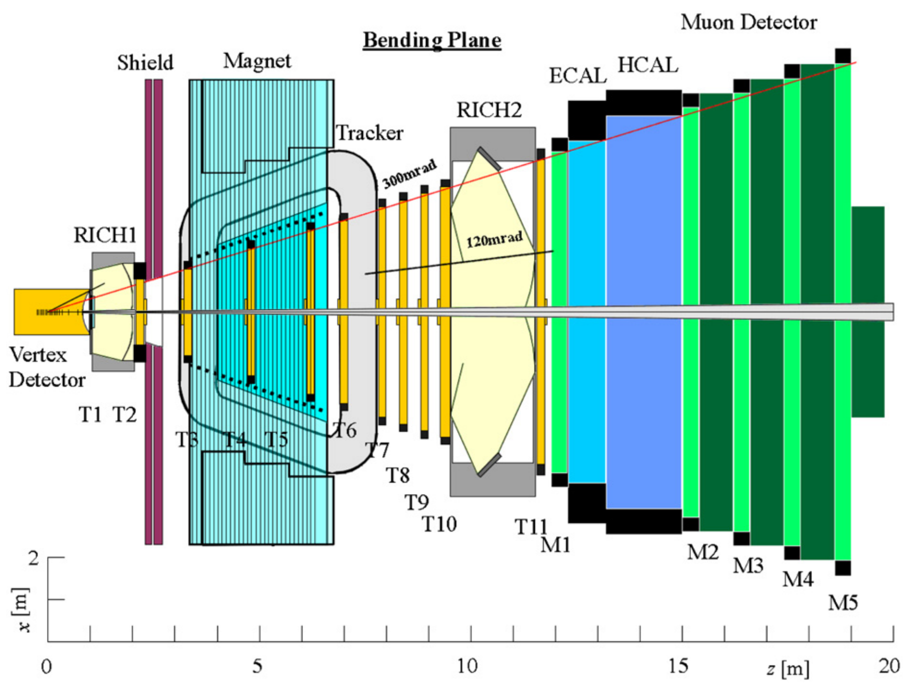

Fig. 3. The LHCb detector and its components.

2.3. Compact Muon Solenoid (CMS)

The overall dimensions of CMS [3,8,12] are 25 m length, 15 m diameter and $\sim 14,000$ ton weight. It was originally constructed to study pp (and lead–lead) collisions at a center-of-mass energy of 14 TeV (5.5 TeV nucleon–nucleon) and at luminosities up to $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ ($10^{27}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$). The prime motivation of the LHC is to elucidate the nature of electroweak symmetry breaking for which the Higgs mechanism is presumed to be responsible. Furthermore, there are high hopes for discoveries that could pave the way toward a unified theory. These discoveries could take the form of supersymmetry or extra dimensions, the latter often requiring modification of gravity at the TeV scale. CMS has a very compact design, high hermeticity and emphasizes good muon identification, good charge particle momentum resolution including efficient b and τ tagging capability as well as a good electromagnetic energy resolution and a good missing transverse energy and dijet-mass resolution. The general layout can be seen in Fig. 4 and a sectional view of the detector is displayed in Fig. 5. The subdetectors are, as usual, situated in an onion-shell arrangement. All barrel systems have a forward equivalent to guarantee a 4π solid angle coverage; studying the layout in Fig. 4 more closely one can observe additional very forward structures (muon detectors and a forward sampling calorimeter) to cover a high $|\eta|$ range. The central system, a three barrel layer two forward disk pixel detector, is mainly responsible for b- and τ-tagging as well as track seeding and primary vertex

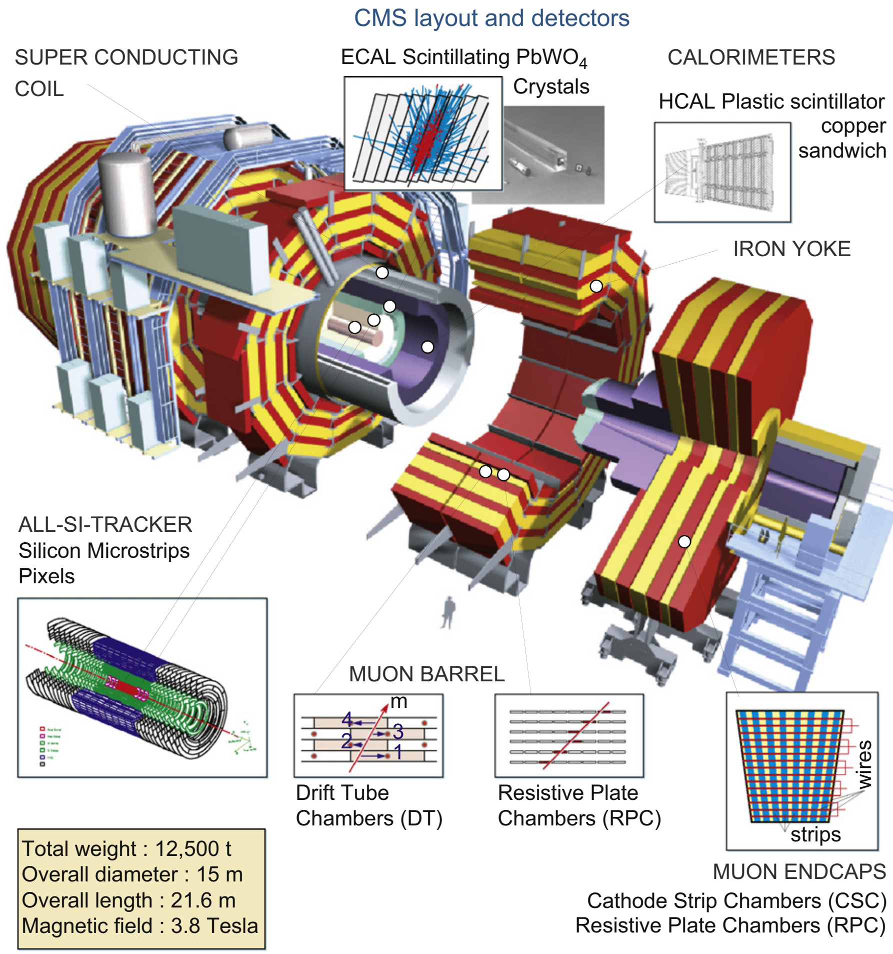

Fig. 4. The CMS detector and its components. [Courtesy of CERN, CMS] [3].

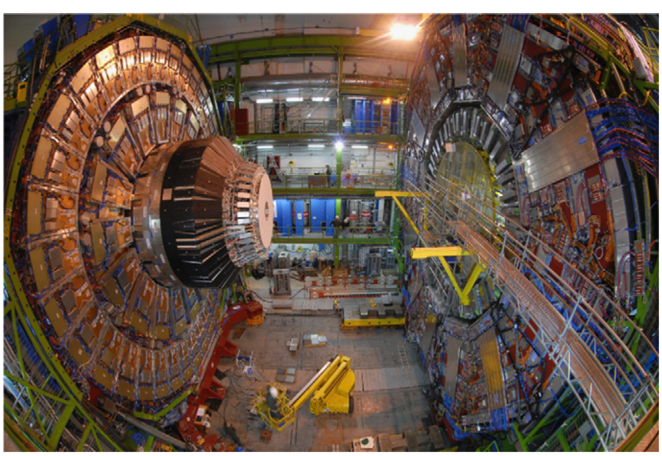

Fig. 5. CMS during assembly, a photo. The left part of the photo illustrates nicely the radial conception of wedge structured muon detector elements—the forward part. The 'nose' on the left consists of a Hadron Calorimeter and an Electromagnetic Calorimeter finished by a silicon pre-shower detector. The barrel part on the right depicts the interleaving of the muon detector elements with the iron return yoke. The yellow structure, a working platform for the final instrumentation, is surrounded by the huge solenoid. Situated inside the solenoid, are the barrel Hadron Calorimeter and Electromagnetic Calorimeter plus the silicon tracker. In the operation configuration, the forward part will be moved to the barrel part and the 'nose' will be inserted into the solenoid to close the system. [Courtesy of CERN, CMS].

identification. It is followed by a 10 layer 12 forward disk silicon strip system, the main tracking device to determine momentum and energy and also to deal with the high track multiplicity.

The tracker [15] is followed by an Electromagnetic Calorimeter (ECAL), which uses lead tungstate ($PbWO_4$) crystals with coverage in pseudo-rapidity up to $|\eta| < 3$ including a pre-shower system in the forward region. The ECAL is surrounded by a brass/scintillator sampling Hadron Calorimeter (HCAL) with coverage up to $|\eta| < 3$. Forward sampling calorimeters extend the pseudo-rapidity coverage to high values ($|\eta| < 5$). The tracking devices and both calorimeters (barrel and forward; not very forward) are situated in a 13 m long, 6 m inner diameter 3.8 T superconducting solenoid. The massive iron return yoke is interleaved with Muon Chambers to identify muons and measure their momentum [20]. CMS does not deploy dedicated PID detectors and relies more on the concept of the different interactions of the different particles in the subdetectors (see also Fig. 1) plus dE/dx information determined with the tracker.

The beauty of CMS lies in its compactness and 'simplicity' of the Tracker, Calorimeter, Solenoid, Muon Chambers inside return yoke.

2.4. A Large Ion Collider Experiment (ALICE)

ALICE [5,10,14] was designed with the intention of studying the quark gluon plasma (QGP) that results from the intense temperatures generated during the heavy ion collisions. The gluon distribution functions will be analyzed with the initial gluon density and the very high temperature of the order $1000\ \mathrm{GeV/fm^3}$ and 1 GeV respectively. It is important from a physics perspective to understand the QGP, its evolution over time and how the hadronic structures are eventually formed out of the plasma. Design considerations of ALICE have been made

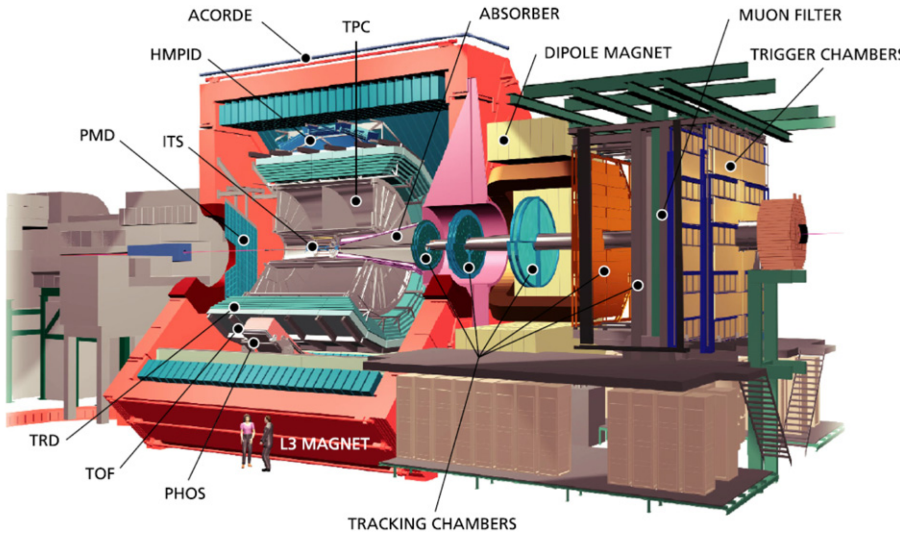

Fig. 6. The ALICE detector and its components [23].

Table 1
Main design parameters of the ATLAS and CMS detectors.

Parameter	ATLAS	CMS
Total weight (ton)	7000	12,500
Overall diameter (m)	22	15
Overall length (m)	46	20
Magnetic field for tracking (T)	2	3.8
Solid angle for precision measurement ($\Delta\phi\Delta\eta$)	$2\pi \times 5.0$	$2\pi \times 5.0$
Solid angle for energy measurements ($\Delta\phi\Delta\eta$)	$2\pi \times 9.6$	$2\pi \times 9.6$
Total cost (million Swiss francs)	550	550

Table 2
Main design parameters of the ATLAS and CMS magnet systems.

Parameter	ATLAS			CMS solenoid
	Solenoid	Barrel toroid	End-cap toroids	
Inner diameter (m)	2.4	9.4	1.7	5.9
Outer diameter (m)	2.6	20.1	10.7	6.5
Axial length (m)	5.3	25.3	5	12.9
Number of coils	1	8	8	1
Number of turns per coil	1173	120	116	2168
Conductor size (mm^2)	30×4.25	57×12	41×12	64×22
Bending power	2 T m	3 T m	6 T m	3.8 T m
Current	7.7 kA	20.5 kA	20.0 kA	19.5 kA
Stored energy (MJ)	38	1080	206	270

Table 3
Main design parameters of the ATLAS and CMS tracking systems.

Parameter (tracking systems)	ATLAS	CMS
Dimensions (cm)		
-Radius of outermost measurement	101–107	107–110
-Radius of innermost measurement	5	4.4
-Total active length	560	540
Magnetic field B (T)	2 T m	4 T m
BR^2 ($T\ m^2$)	2.0–2.3	4.6–4.8
Total power on detector (kW)	70	60
Total weight in tracker volume (kg)	≈ 4500	≈ 3700
Total material ($X/X\ 0$)		
-At $\eta = 0$ (minimum material)	0.3	0.4
-At $\eta = 1.7$ (maximum material)	1.2	1.5
-At $\eta = 2.5$ (edge of acceptance)	0.5	0.8
Total material (λ/λ_0 at max)	0.35	0.42
Silicon microstrip detectors		
-Number of hits per track	8	14
-Radius of innermost meas(cm)	30	20
-Total active area of silicon(m^2)	60	200
-Wafer thickness (microns)	280	320/500
-Total number of channels	6.2×10^6	9.6×10^6
-Cell size (μm in $R\phi$ × cm in z/R)	80×12	$80/120 \times 10$
-Cell size (μm in $R\phi$ × cm in z/R)		and $120/180 \times 25$
Straw drift tubes (ATLAS only)		
-Number of hits per track ($\lvert\eta\rvert < 1.8$)	35	
-Total number of channels	350,000	
-Cell size (mm in $R\phi$ × cm in z)	4×70 (barrel) 4×40 (end caps)	

with the ability to cover a large phase space and to detect hardons, leptons and photons (Fig. 6).

Innermost components are the silicon tracking detectors which measure the properties of the emerging particles and also tracing their origin up to the decay point. There are six layers of tracking detectors. The next detector is the Time Projection Chamber (TPC) with a momentum range capability of up to 600 MeV. It consists of a large drift space parallel to beam axis where charged particles create ionizations in the gas. Ionized particles drift to the endcap Multi Wire Proportional Chambers where the detection occurs. There are a total of over half a million readout pads. The Transition Radiation Detector (TRD) is positioned between TPC and TOF detector [21]. It has a total of 540 modules. TRD detects X-ray radiations emitted by particles crossing the boundaries of different materials. TOF detector identifies the heavier particles by accurately measuring their times with a resolution of around 100 ps achieved by the Multigap Resistive Plate Chambers. TOF has a momentum range of 1.2–1.4 GeV. An array of lead tungstate crystals form the Photon Spectrometer (PHOS) which detect photons through the scintillations they cause in the crystal. The High Momentum Particle Identification Detector (HMPID) detects the higher momenta of particles, as the name suggests, in the range of 3–5 GeV. It is a Ring Imaging Cherenkov Detector with an area of 11 m^2. The Muon Spectrometer reconstructs the trajectories of the muon pairs created from the decay of J/ψ and υ particles.

3. Detector concepts

Both ATLAS and CMS have similar design approach with trackers, electromagnetic and hadronic calorimeters immersed

Table 4
Main design parameters of the ATLAS and CMS Electromagnetic Calorimeters.

	ATLAS		CMS	
Technology	Lead/LAr		$PbWO_4$ crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \phi$		$\Delta\eta \times \phi$	
Presampler	0.025×0.1	0.025×0.1		
Strips/Si-preshower	0.003×0.1 0.003×0.1 to 0.006×0.1	32×32 Si-strips per four crystals		

Table 5
Main design parameters of the ATLAS and CMS Hadron Calorimeters.

	ATLAS	CMS
Technology		
Barrel/ext. barrel	14 mm iron/ 3 mm scint.	50 mm brass/ 3.7 mm scint.
End caps	25–50 mm copper/ 8.5 mm LAr	78 mm brass/ 3.7 mm scint.
Forward	Copper (front)–tungsten (back)/ 0.25–0.50 mm LAr	Steel/0.6 mm quartz
Total channels	19,008	6912

in a magnetic field. Outside the magnet is the muon detector detecting the direction and momentum of the high energy muon. In Table 1 [24] the design parameters of the two detectors are shown. CMS, despite been the smaller detector is almost twice as heavy as ATLAS due to the choice of an iron core solenoid. The cost of the two detectors incidentally is identical.

3.1. Magnet system

In Table 2 [24,6,7,12] the magnet system of CMS and ATLAS is compared, the large bending power required to measure high momenta muon with high precision dedicated the choice of superconducting technology for the very high field required. Both detectors hence achieve excellent momentum resolution over the required η coverage. The review paper [17] elucidates the Magnet systems at LHC and future experiments.

3.2. Tracking system

The central system for both experiments consists of pixel and silicon strip detectors mainly responsible for b and τ tagging as well as track seeding and primary vertex identification. It is followed by several barrel layers and forward disks of the silicon strip system: the main tracking device to determine momentum and energy and also to deal with the high track multiplicity. Table 3 [24] shows the comparison between ATLAS and CMS for the major parameters used.

In general the tracking system provides a redundant and robust pattern recognition with high accuracy and precision tracking measurement for high momentum charged particles. In addition it acts as a high level trigger and affords precision measurement of impact parameters. Electron and hadronic decay identification are also the design goals of tracking system. The review paper [15] describes the start-of-the-art of tracking system.

3.3. Calorimetry

In Tables 4 and 5 a comparison of the technology choice and other details of the calorimeters of ATLAS and CMS are given [6,7,12,24]. The excellent coverage in η and ϕ is guaranteed with ATLAS Lead/Ar sampling calorimeter with accordion shaped

Table 6
Main design parameters of the ATLAS and CMS Muon Chambers.

Muon Chamber	ATLAS	CMS
Drift tubes	MDTs	DTs
-Coverage	$\|\eta\| < 2.0$	$\|\eta\| < 1.2$
-Number of chambers	1170	250
-Number of channels	354,000	172,000
-Function	Precision measurement	Precision measurement
Cathode strip chambers		
-Coverage	$2.0 < \|\eta\| < 2.7$	$1.2 < \|\eta\| < 2.4$
-Number of chambers	32	468
-Number of channels	31,000	500,000
-Function	Precision measurement	Precision measurement, triggering
Resistive plate chambers		
-Coverage	$\|\eta\| < 1.05$	$\|\eta\| < 2.1$
-Number of chambers	1112	912
-Number of channels	374,000	160,000
-Function	Triggering, second coordinate	Triggering
Thin gap chambers (ATLAS only)		
-Coverage	$1.05 < \|\eta\| < 2.4$	
-Number of chambers	1578	
-Number of channels	322,000	
-Function	Triggering, second coordinate	

electrode and absorber and is obtained by careful rotation (by approximately 3° in ϕ and η) of the CMS $PbWO_2$ crystal away from a purely projective arrangement. The reader is referred to Ref. [18] for an in depth review.

For the hadronic calorimeter several constraints were imposed in CMS due to solenoid and hence a special tail catcher was added around the coils. The review paper [19] provides an excellent summary and future projection of the developments during the last two decades.

Particle identification is described at length in review article [21].

3.4. Muon system

The gold plated decay of the standard model Higgs boson into 4 muons is the main thrust of muon systems. The excellent momentum resolution for TeV scale muon is imperative for detectors at LHC. In Table 6 a comparison for ATLAS and CMS detectors systems is given [24]. The ATLAS choice of a toroidal magnetic field provides a pseudo-rapidity independent momentum resolution while bending of the muon tracks in the transverse plane of the CMS solenoid field provides high accuracy reconstruction.

Several technologies have been used in both detectors and have been listed in the review paper [20]; a detailed discussion of these choice and performance is given. Alignment plays a crucial

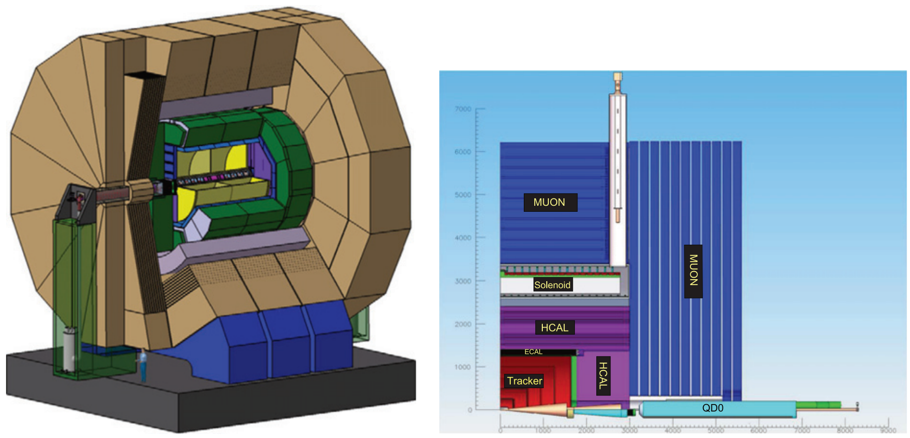

Fig. 7. The layout of the ILD [26] and the SiD [27] detector.

rule in all measurements described above which is discussed in detail in review [25].

3.5. Electronics and services

The electronics, trigger and data acquisition system of any experiment at LHC or future collider play a vital role to collect a large amount of data at collisions every 25 ns. Progress in electronics is reported in review [16].

Integration, services, installation and commissioning. Large projects like those at LHC require a minimum of R&D followed by several years of construction, installation and commissioning for each subdetector. This is important to understand since such sophisticated complex projects are almost impossible to plan and manage within projected initial time scale especially with concurrent technological advances.

Integration issues often have conflicting requirements with hermeticity. Large pieces of detector components need to be designed, planned and coordinated in such a way that they can fit with each other after several years of conception often on different parts of the planet far away from each other. This poses a big challenge for the physicists, engineers and the community in general. Careful project management is required to establish, scrutinize and evaluate milestones step by step.

The services pose an extreme challenge, cables for electronics, power controls, gas systems, safety and so on. A strong technical coordination is required to foresee any conflicts. The installation of large experiments like those at LHC can last several years; this again requires meticulous planning and foresight. Commissioning follows installation to ensure readiness of the experiment to take data. In itself this too is a task multifaceted, requiring interplay of physicists, engineers and technicians.

4. Designs of a future linear collider detector

There is a consensus in the HEP community that the next large machine designed as a global effort after the LHC should be a high energy (1 TeV and above) machine—a linear collider. The main scientific goal is to complement the anticipated discoveries at the LHC by precision measurements at the TeV scale. In this chapter the designs of the International Large Detector (ILD) and the Silicon Detector (SID) will be briefly described as the fifth and sixth example of HEP detectors. More in depth descriptions can be found in Refs. [26–29]. The schematics of both detectors can be seen in Fig. 7.

Both detector concepts will be modern multipurpose detectors combining excellent vertexing and tracking with advanced calorimeter concepts. The general onion-shell concept is untouched:

Vertex detector (Pixel), Tracker, Electromagnetic Calorimeter, Hadron Calorimeter, Solenoid (3.5 T for ILD and 6 T for SiD), Muon Detectors.

The ILD detector concept follows a similar design to the LEP (TPC plus silicon layers, the DELPHI), while the SiD detector concepts shows more similarities to the LHC type detectors (full silicon tracker, the CMS).

Both detectors provide hermetic coverage both for neutral and charged particles. The particle momentum partially energy is measured with precise track curvature measurement in a strong magnetic field, the energy in the calorimeters. The precise pixel detectors are situated in the center allow the tagging of *b*- and *c*-quarks.

With an emphasis on final hadronic states the dijet mass resolution is crucial and the ILC detectors will utilize the Particle Flow algorithm. The information of all detector components will be summed up in optimal way to take all fractions correctly into account.

The basic concept of the ILC detectors is very similar to the LHC ones but the high precision physics requirements and the Particle Flow algorithm ask for several dedicated solutions; a detailed discussion is beyond the scope of this introduction.

5. Conclusions: the Utopian perfect detector

The basic principles have been discussed in the former sections assuming a perfect detector. This section lists the ingredients of a perfect but Utopian detector and names the inevitable problems. A perfect detector should:

- reconstruct ALL interactions with 100% efficiency without changing any particle property
- have no limit on resolution for all ranges of energy and momentum and for all particle types
- cover the full 4π solid angle without any defective area
- identify all particles
- provide easy access for maintenance
- be radiation hard; no degradation or changes during the years of operation

Only then we would be able to directly compare all interactions with the theoretical prediction.

Unfortunately our detectors are not 100% efficient due to

- holes and cracks allowing particles to go undetected
- noisy channels which statistically fake signals

Unavoidable materials (cables, electronics, support structures, cooling pipes) are not massless and induce multiple scattering. HEP detectors are heavy and very compact and they will be radioactive after some time of use, thus maintenance is very difficult and complex, and according to Murphy's Law some components will fail with time decreasing the sensitive volume.

In this volume an attempt is made to review the current status of detector technologies being exploited at LHC and future colliders. All experiments at LHC are successfully taking data and crucial lessons are being learned for detector technologies employed respectively for future upgrade.

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