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# Physics requirements for the design of the ATLAS and CMS experiments at the Large Hadron Collider

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The ATLAS and CMS experiments at the CERN Large Hadron Collider are discovery experiments. Thus, the aim was to make them sensitive to the widest possible range of new physics. New physics is likely to reveal itself in addressing questions such as: how do particles acquire mass; what is the particle responsible for dark matter; what is the path towards unification; do we live in a world with more space–time dimensions than the familiar four? The detection of the Higgs boson, conjectured to give mass to particles, was chosen as a benchmark to test the performance of the proposed experiment designs. Higgs production is one of the most demanding hypothesized processes in terms of required detector resolution and background discrimination. ATLAS and CMS feature full coverage, $4\pi$-detectors to measure precisely the energies, directions and identity of all the particles produced in proton–proton collisions. Realizing this goal has required the collaborative efforts of enormous teams of people from around the world.

**Keywords: Large Hadron Collider; ATLAS; CMS; detector design**

## 1. Introduction

The conceptual design of ATLAS [1] and CMS [2] general-purpose detectors (GPDs) was carried out almost two decades ago. The Standard Model (SM) of particle physics [3] comprises the fundamental particles and a description of how they interact. This theory presents an elegant synthesis of much of twentieth century particle physics, containing the quantum theories of three out of the four fundamental interactions: the weak, the electromagnetic and the strong interactions, with only gravity absent. The fundamental particles of the SM are the following: half-integral-spin matter particles (quarks, electrons, muons and neutrinos; the latter three collectively known as leptons) and integral-spin force particles (W/Z bosons, photons and gluons; forces are 'felt' through the exchange of these bosons). In the early 1990s, the SM was being tested to greater and greater precision.

However, the limitations of the SM were also well known at the time—without the appearance of new physics, in some form or another, the SM breaks down at the Large Hadron Collider (LHC) energies. The conjectures that drove the design

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of ATLAS and CMS detectors have not really changed much since then. Hence, it is no surprise that we still talk about the same potential discoveries. It is hoped that the current data-taking period of the LHC, which has been extended into 2012, will reveal some of the physics that was used as benchmarks for the design of the GPDs.

The LHC has been built to address profound questions in particle physics [4]. In popular terms, these questions are: what is the origin of mass, i.e. how do particles acquire mass, and indeed why do they have the masses that they have; what constitutes dark matter; what is the path towards unification; do we live in a world with more space–time dimensions than the familiar four?

The question of the origin of mass translates to discovering the nature of electroweak symmetry breaking; how do the W and Z bosons acquire a mass approximately 100 times that of a proton while the photon remains massless in the unification of electromagnetic and weak interactions? The Higgs mechanism is the currently favoured explanation. However, there are alternatives that invoke more symmetry, invoke new forces or constituents such as strong electroweak symmetry breaking, technicolour, etc. Even if the Higgs boson exists, all is not completely well with the SM alone: the next question is, why is the mass of the Higgs boson so low? If a new symmetry (supersymmetry) is the answer, then it must manifest itself at the 1 TeV energy scale. Supersymmetry predicts a doubling of the known particle spectrum, each known particle having a superpartner. The lowest mass superpartner is considered to be a prime candidate for dark matter. An as yet unknown mechanism for electroweak symmetry breaking is also possible.

Hence, the LHC and its experiments have been designed to find new particles, new forces and new symmetries, among which could be the Higgs boson(s), supersymmetric particles, Z′ bosons and extra space–time dimensions. An experiment that can cover the detection of all these ‘known’ but yet undiscovered particles should also allow the discovery of whatever Nature has in store at the LHC energies. There could easily be surprises or ‘unknown’ particles. The question for the experimentalists was—how does one go about designing an experiment not only for the ‘known unknowns’ but also for the ‘unknown unknowns’?

The LHC will also allow in-depth studies of CP violation (where C and P refer to charge and parity) in the B sector and of the quark–gluon plasma and will not be dealt with in this article.

## 2. The Large Hadron Collider

The parameters of the LHC [5–8] were chosen to explore the TeV energy scale. The wide range of physics potentially accessible requires an accelerator that allows exploration over a wide range of energies and phenomena. A hadron (proton–proton) collider is such a machine as long as the proton energy is high enough and the luminosity (giving the number of proton–proton collisions per second) is sufficiently large. The most interesting and easily detectable final states at hadron colliders involve charged leptons and photons from processes that usually have a low cross section times branching ratio ($\sigma \times \mathrm{BR}$). The hadron colliders can provide these conditions, but do not achieve the ‘clean’ experimental conditions usually encountered in $e^+e^-$ colliders.

Hadron colliders are broadband exploratory machines. The energy and luminosity requirements can be ascertained by considering the reaction in which a Higgs boson is produced with a mass ($m_{\mathrm{H}}$) of 1 TeV. This happens via the WW fusion production mechanism. A quark from each of the protons radiates a W boson with an energy of about 0.5 TeV implying that the radiating quark should carry an energy of approximately 1 TeV. Hence, the proton should carry about $6 \times 1$ TeV. The LHC accelerates protons to 7 TeV. The required luminosity can be estimated using the same reaction $\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 4$ charged leptons. In order to register 10 such events per year, at $m_{\mathrm{H}}$ approximately 1 TeV, the luminosity has to be $L = 10/(\sigma \times \mathrm{BR} \times \Delta t) = 10/(10^{-37} \times 10^{-3} \times 10^{7}) \sim 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, leading to about one billion proton–proton interactions per second.

## 3. Schematic structure of general-purpose detectors at colliders

In order to discover the phenomena mentioned above, protons have to collide head-on, in fact the partons inside the protons (quarks and gluons) have to collide head-on, in what is termed a 'hard interaction', as opposed to a glancing collision where less energy is involved in the physics of the interaction. Any new particles produced as a result of these collisions will manifest themselves through the well-studied and known particles of the SM mentioned above. The photons, electrons and muons can emerge into the detectors directly from the hard interaction, whereas quarks and gluons, never visible as free particles, appear in the detectors as collimated bunches of stable or quasi-stable particles labelled 'jets'.

In hadron colliders, the initial momentum of the colliding partons (quarks or gluons) along the beam axis is an unknown fraction of the proton's momentum. However, the momentum transverse to the beam direction is zero in the initial state. Hence in the final state, any large net momentum transverse to the beam would be indicative of the presence of escaping particles such as neutrinos or lightest supersymmetric particles (dark-matter candidate particles) that rarely deposit any energy in the detector. Thus, the presence of neutrinos is deduced from the imbalance in the visible momenta of the detected particles in the plane transverse to the beam direction. This is usually labelled missing transverse momentum ($p_{\mathrm{T}}$) or energy ($E_{\mathrm{T}}$). Such an imbalance can also arise from a mismeasurement of the energy of the detected particles or those going through cracks/dead areas inside the detector. It is important to minimize the possibility of such instrumental effects in the design of the experiments at the hadron colliders.

The typical form of a collider detector is a 'cylindrical onion' containing several layers. A particle emerging from the collision and travelling outwards will first encounter the inner-tracking system (figure 1), a collection of pixels and microstrip detectors. These measure precisely the position of the passing charged particles allowing reconstruction of their tracks. Charged particles follow spiralling paths in a uniform magnetic field, and the curvatures of their paths reveal their momenta. The energies of particles will be measured in the next two layers of the detector: the electromagnetic and hadronic calorimeters. Electrons and photons will be stopped by the electromagnetic calorimeter, and particle jets by the electromagnetic and hadronic calorimeters, allowing their energy to be measured. The only particles to penetrate beyond the hadron calorimeter

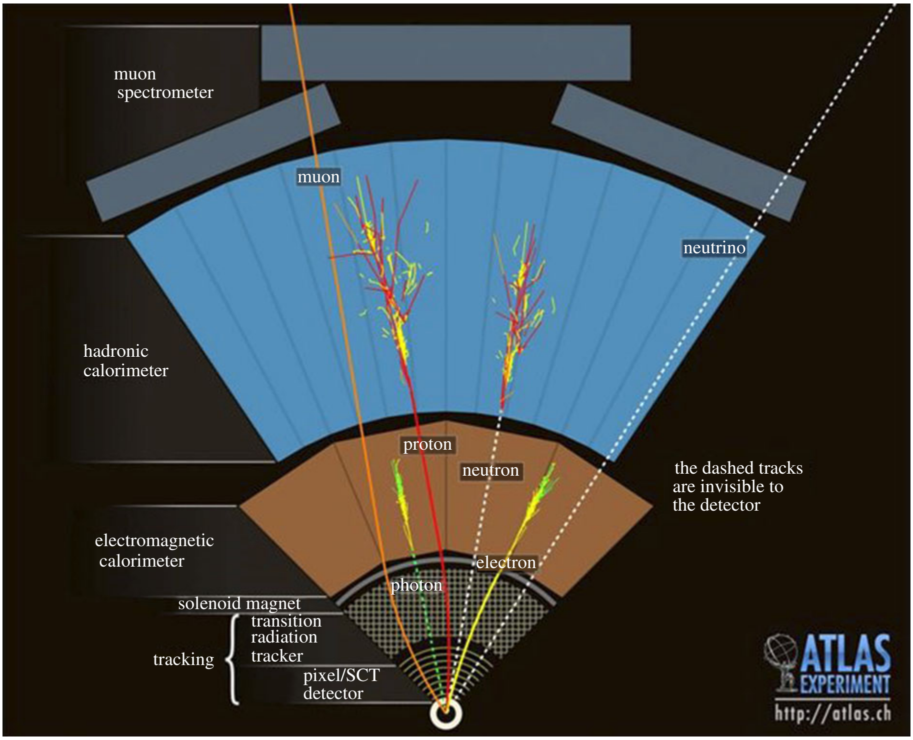


Figure 1. Schematic of a transverse slice of the ATLAS experiment showing the patterns of energy deposits that allow the identification of different types of particles produced in collisions. (Online version in colour.)

are muons and neutrinos. Muons, being charged particles, are tracked further in dedicated muon chambers. Their momenta are also measured from the bending of their paths in a magnetic field. The presence of neutrinos is deduced as mentioned above. ATLAS and CMS comprise technologically advanced detectors covering the full solid angle ($4\pi$) and arranged in these four principal layers, each designed to perform a specific task. Together, these four layers allow us to identify and measure precisely the energies and directions of all the particles produced in collisions.

## 4. Some experimental issues

The production of the Higgs boson, and a few other processes, was used to test the conceptual designs of the GPDs in the early 1990s [9]. But before going into the discussion of requirements, we shall consider some experimental issues.

### (*a*) *Resolutions and backgrounds*

In many cases, the ability of a detector unambiguously to observe new particles, decaying into the known particles, relies on a good resolution for the measurement of the effective mass. Wherever possible, use is made of processes where the backgrounds are expected to be manageable.

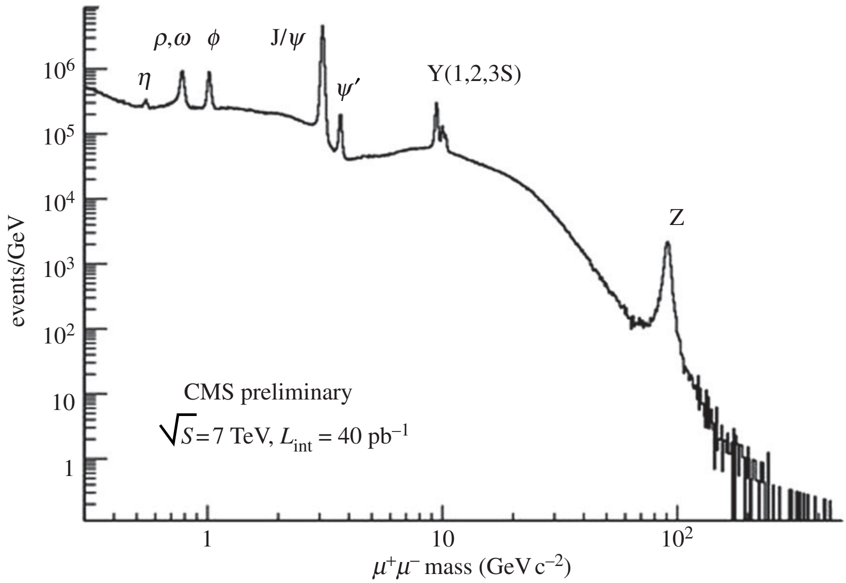


Figure 2. The distribution of di-muon effective masses showing the various resonant states. The mass resolutions in the central region are: 28 MeV c$^{-2}$ (0.9%) for J/$\psi$, 69 MeV c$^{-2}$ (0.7%) for Y(1S), both dominated by instrumental resolution, and $\Gamma = 2.5$ GeV c$^{-2}$ for the Z, dominated by its natural width.

The effective mass ($M$) of a final state, assuming the decay yields two particles (a and b) is given by $M^2 = (p_\text{a} + p_\text{b})^2$, where $p$ is the 4-vector ($E$, $p$) of each particle. This simplifies to

$$M^2 = 2E_\text{a}E_\text{b}(1 - \cos\theta), \tag{4.1}$$

where $\theta$ is the angle between the particles a and b. The resolutions (mass, energy and angular) are given by

$$\frac{\delta M}{M} = \frac{1}{2}\sqrt{\left(\frac{\delta E_\text{a}}{E_\text{a}}\right)^2 + \left(\frac{\delta E_\text{b}}{E_\text{b}}\right)^2 + \left(\frac{\delta\theta}{\tan(\theta/2)}\right)^2}. \tag{4.2}$$

Figure 2 shows the distribution of effective masses, calculated using equation (4.1), of all di-muon pairs detected in CMS upon examination of some three trillion proton–proton interactions. The sharpness of the peaks, corresponding to the labelled particle states, depends on the natural width of the state under study, defined as $\Gamma = h/2\pi\tau$, where $\tau$ is the lifetime of the particle, and/or on the experimentally achievable mass resolution. For example, as can be seen in figure 2, the observed width of particles such as J/$\psi$ or Y is dominated by the instrumental resolution while that of the Z by its natural width. The background can also be seen and the clarity (high signal over background) of the signals is evident. It is remarkable that the ATLAS and CMS experiments, arguably the most technologically challenging scientific instruments ever built, have achieved their design mass resolutions after the first few months of data taking.

### (*b*) *Isolation*

Particles emerging directly from fundamental parton–parton interactions such as electrons, muons or photons, labelled *prompt* electrons, muons or photons, from, for example the production of Higgs boson, tend to be 'isolated', i.e. they are produced with no other accompanying particles in their immediate vicinity. The isolation criterion can be established by requiring that there is no other particle with transverse momentum ($p_{\mathrm{T}}$) above some threshold value (approx. 1–3 $\mathrm{GeV\,c^{-1}}$), where $p_{\mathrm{T}}$ is the momentum ($p$) projected onto the plane transverse to the beam direction, or by requiring that the sum of transverse energy ($E_{\mathrm{T}}$) be below some threshold value (a few GeV), in a cone of $\Delta R = \surd(\Delta\eta^2 + \Delta\phi^2)$ approximately 0.2–0.4 surrounding the particle of interest, where $\phi$ is the azimuthal angle, measured in the plane normal to the beam axis. The pseudorapidity ($\eta$) is defined as $-\ln[\tan(\theta/2)]$, where $\theta$ is the polar angle measured from the nominal centre of the experiment with respect to the direction of the proton beam. In hadron collider physics, the rapidity (or pseudorapidity) is preferred over the polar angle $\theta$ because, loosely speaking, particle production is constant as a function of rapidity. One speaks of the 'forward' direction in a hadron collider experiment, which refers to regions of the detector that are close to the beam axis, at high $|\eta|$. For prompt photons, by applying the isolation criterion, a rejection factor of ten can be obtained against photons in jets (for a few percent loss in the efficiency of reconstruction of these prompt photons).

## 5. The physics benchmarks

### (*a*) *The Standard Model Higgs boson production as a benchmark for general-purpose detector design*

We now come to the question: how well does one need to measure the momenta and energies of particles emerging from the collisions?

The detection of the SM Higgs boson is a particularly appropriate benchmark to test the performance of the experiment designs. The Higgs boson is the only particle in the SM that has not yet been seen by experiments. However, its mass is not predicted by theory. Its production cross section and natural width vary widely over the possible mass range (from 114 $\mathrm{GeV\,c^{-2}}$ to 1 $\mathrm{TeV\,c^{-2}}$). The production, the decay modes and the natural width of the Higgs bosons as a function of mass are illustrated in figure 3*a*–*c* [10]. A search has to be made over this wide mass range, leading to diverse final states: two photons; two tau leptons; two W bosons; two Z bosons. The W is observed through its decay to an electron plus a neutrino, or a muon plus a neutrino. The Z is observed through its decay to a pair of electrons, or a pair of muons, or a pair of jets of hadronic particles. Analysing all these channels ensures that the search is sensitive to observing the Higgs irrespective of its mass.

The decay modes generally accepted to be promising for the detection of the SM Higgs boson at the LHC are listed in table 1. The current lower limit on the mass of the Higgs boson, from the large electron positron (LEP) experiments, is 114.4 $\mathrm{GeV\,c^{-2}}$. In the vicinity of this limit, the decays of the Higgs boson are dominated by hadronic decays, into $b\bar{b}$ quarks, which cannot be used

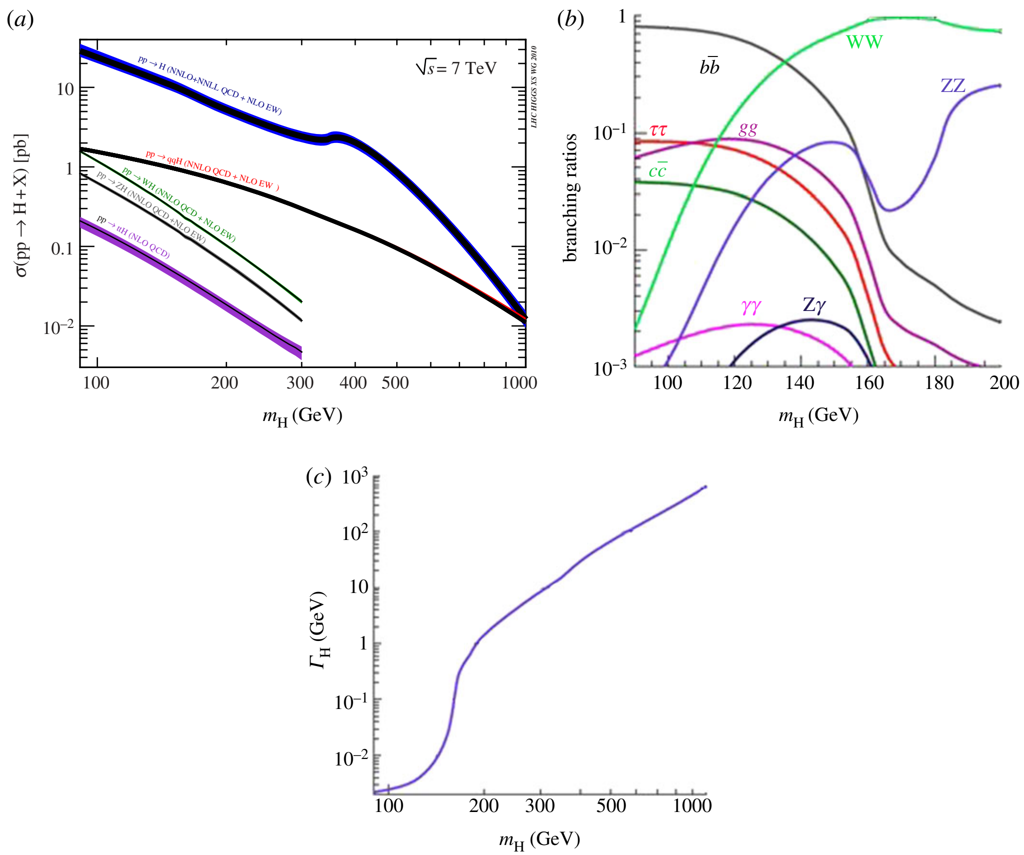


Figure 3. ($a$) The SM Higgs production cross section at $\sqrt{s} = 7$ TeV. ($b$) The SM Higgs branching ratios as a function of the Higgs boson mass for $m_H < 200\,\mathrm{GeV\,c^{-2}}$. ($c$) The natural width of the SM Higgs boson as a function of its mass. (Online version in colour.)

Table 1. The promising Higgs boson decay modes.

region 1: intermediate mass region (LEP limit $114.5\,\mathrm{GeV\,c^{-2}} < m_H < 2m_Z$)
- $m_H < 120\,\mathrm{GeV\,c^{-2}}$: $pp \rightarrow WH \rightarrow \ell\nu b\bar{b}$ or $t\bar{t}\ H \rightarrow \ell\nu X b\bar{b}$
- $m_H < 150\,\mathrm{GeV\,c^{-2}}$: $H \rightarrow \gamma\gamma$, $Z\gamma$
- $130\,\mathrm{GeV\,c^{-2}} < m_H < 2m_Z$: $qq \rightarrow qqH$ with $H \rightarrow \tau\tau$, $H \rightarrow WW$, etc.
- $130\,\mathrm{GeV\,c^{-2}} < m_H < 2m_Z$: $H \rightarrow WW^* \rightarrow \ell\nu\,\ell\nu$
- $130\,\mathrm{GeV\,c^{-2}} < m_H < 2m_Z$: $H \rightarrow ZZ^* \rightarrow \ell\ell\,\ell\ell$

region 2: high mass region ($2m_Z < m_H < 700\,\mathrm{GeV\,c^{-2}}$)
- $H \rightarrow ZZ \rightarrow \ell\ell\,\ell\ell$

region 3: very high mass region ($700 < m_H < 1\,\mathrm{TeV\,c^{-2}}$)
- $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$, $H \rightarrow ZZ^* \rightarrow \ell\ell$ jet–jet
- $H \rightarrow WW \rightarrow \ell\nu$ jet–jet

to discover the Higgs boson at the LHC because of the very large $b\bar{b}$ production from standard strong interaction (quantum chromodynamics) processes and the relatively poor mass resolution that is obtainable with jets. Hence, the search is conducted using final states that contain isolated leptons and photons despite the smaller branching ratios.

In the mass interval $114 < m_{\mathrm{H}} < 150\,\mathrm{GeV\,c^{-2}}$, the two-photon decay is the main channel likely to give a significant signal. The Higgs boson should be detectable via its decay into two W bosons in the mass range $130 < m_{\mathrm{H}} < 180\,\mathrm{GeV\,c^{-2}}$; into two Z bosons if its mass is in the range $130 < m_{\mathrm{H}} < 180\,\mathrm{GeV\,c^{-2}}$, where one or both of the Z's may be virtual; and in the range $2m_{\mathrm{Z}} < m_{\mathrm{H}} < 600\,\mathrm{GeV\,c^{-2}}$ where both Z bosons are real. In this region, the leptonic decays of the W and Z can be used. In the region $700 < m_{\mathrm{H}} < 1000\,\mathrm{GeV\,c^{-2}}$, the cross section decreases so that higher branching fraction modes of the W or Z, involving jets or $E_{\mathrm{T}}$, have to be employed.

The dominant Higgs boson production mechanism, for masses up to $\approx 700\,\mathrm{GeV\,c^{-2}}$, is gluon–gluon fusion. The W–W or Z–Z fusion mechanism becomes important for the production of higher-mass Higgs bosons. Here, the quarks that emit the W/Z bosons end up with transverse momenta of the order of W and Z masses in the final states. The detection of the resulting high-energy jets in the forward regions, $2 < |\eta| < 5$, can be used to tag the reaction, improving the signal-to-noise ratio and extending the mass range over which the Higgs can be discovered. These jets are highly boosted and their transverse size is similar to that of a high-energy hadron shower.

Channels that are demanding of detector performance are now considered to extract the detector performance requirements.

(i) *Search for the Higgs boson decaying into two photons*

The natural width of the Higgs boson in the *intermediate-mass* region ($m_{\mathrm{Z}} < m_{\mathrm{H}} < 2m_{\mathrm{Z}}$) is small, and the observed width of a $\mathrm{H} \rightarrow \gamma\gamma$ signal will be entirely dominated by the instrumental two-photon mass resolution. For the best mass resolution, a good photon energy and angular resolution are needed (equation (4.2)).

A good mass resolution would not be essential were it not for a substantial background ($\mathrm{S/B} \sim 0.1$). There are two major sources of background, an irreducible one from events containing two real photons and a reducible one in which one or both of the photons is 'fake', arising from two-photon decays of energetic $\pi^0$ found in parton jets. Backgrounds from fake photons can be much reduced by requiring that the candidate photons be isolated. This calls for an electromagnetic calorimeter with fine lateral granularity.

The process $\mathrm{H} \rightarrow \gamma\gamma$ can be 'selected' in the trigger (see §6) with high efficiency by requiring two isolated high-$p_{\mathrm{T}}$ photons with a threshold $p_{\mathrm{T}} \gtrsim 20\,\mathrm{GeV\,c^{-1}}$.

The detector requirements can be summarized as: good electromagnetic energy resolution, correct localization of the primary interaction vertex, $\pi^0$ rejection and efficient photon isolation.

(ii) *Search for the Standard Model Higgs boson decaying into two Z bosons*

If the mass of the Higgs boson is less than $2m_{\mathrm{Z}}$, it can decay by emitting one real and one virtual Z, each subsequently decaying into pairs of charged leptons.

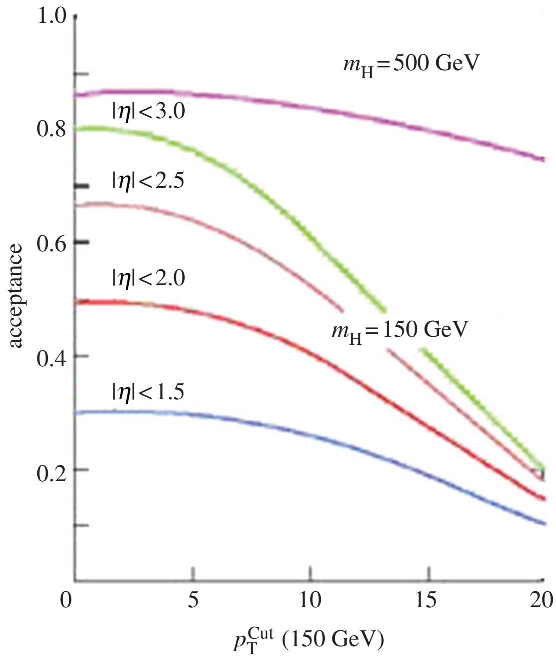


Figure 4. The acceptance of four charged leptons from the $H \rightarrow ZZ^{(*)}$ decay as a function of $p_T$ threshold for different pseudorapidity cuts. (Online version in colour.)

Some of these leptons have low-to-moderate $p_T$, in the range of 5–50 GeV c$^{-1}$. All the four leptons should be isolated. In this region, the natural width of such a Higgs boson is small and the observed width of the $4\ell^{\pm}$ effective mass distribution will be entirely dominated by the instrumental resolution.

The major source of background arises from $t\bar{t}$ quark pair production, with charged leptons from the top quark decay (isolated) and second-generation b-quark decays (non-isolated). This source of background can be reduced by requiring that one lepton pair be consistent with arising from a Z boson. It is therefore desirable to have a di-lepton mass resolution that is better than $\Gamma_Z$. Another source of background is from events with a $Zb\bar{b}$ final state. Isolation criteria are efficient against both of the above backgrounds by rejecting leptons from decays of b-quarks (usually not isolated) produced in the decays of top quarks.

The expected number of signal events is small, so a large geometrical and kinematic acceptance for the detection of leptons is essential (figure 4).

Typical trigger thresholds are $p_T > 40$ GeV c$^{-1}$ for the single-electron trigger, $p_T > 20$ GeV c$^{-1}$ for the single-muon trigger and $p_T > 20$ GeV c$^{-1}$ for each lepton in di-lepton triggers.

The detector requirements can be summarized as: good di-muon and di-electron mass resolution implying good momentum (energy) resolution for low momenta muons (electrons), a large geometric acceptance and efficient lepton isolation at high luminosities.

(iii) *Search for the Standard Model Higgs boson in the high mass region* ($700 < m_{\mathrm{H}} < 1\ TeV\ c^{-2}$)

In this region, the rate of Higgs production decreases so that higher branching fraction modes involving neutrinos and/or jets from W or Z decays need to be used. Hence, good $E_{\mathrm{T}}$ and di-jet mass resolution will be important. The jets from W and Z will be boosted and the jets may be close to each other in the $\eta$–$\phi$ space.

In addition to the energy resolution, the mass resolution depends on the jet–jet angular resolution, $\mathrm{d}\theta$, and is given by $\delta M/M = (p_{\mathrm{T}}/M)\delta\theta$. The width of the measured effective mass distribution from boosted di-jets (e.g. from boosted Zs from $\mathrm{H} \rightarrow \mathrm{ZZ}$) has a significant contribution from the angular error. Hence, fine lateral granularity in the hadron calorimeter is required to resolve the two boosted jets from W/Z decays and attain a good mass resolution. A lateral granularity of $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$ would be sufficient.

The detector requirements can be summarized as: good $E_{\mathrm{T}}$ and di-jet mass resolution. This requires hadron calorimeters with a large geometric coverage, down to small angles with respect to the beam (approx. $1^{\circ}$ or $|\eta| < 5$), and fine lateral segmentation.

(iv) *Search for the Standard Model Higgs boson in the high mass region using vector boson fusion*

There is a sizeable production cross section (approx. 10%) for Higgs bosons via the vector boson fusion process $\mathrm{qq} \rightarrow \mathrm{qqH}$. The vector bosons are radiated from the initial state quarks which get a typical $p_{\mathrm{T}}$ kick of $m_{\mathrm{W/Z}}/2$. As these quarks carry a high energy, they appear as narrow jets in the forward region (i.e. at high rapidities). Therefore, a large calorimetric rapidity coverage is required to detect these forward jets to 'tag' this vector boson fusion process. The rapidity of such jets, usually labelled 'tagging' jets, lies typically between $2.5 < |\eta| < 5$, with $p_{\mathrm{T}}(\mathrm{jet}) \geq 40\,\mathrm{GeV\,c^{-1}}$ and $E_{\mathrm{jet}} \geq 0.8\,\mathrm{TeV}$ for $m_{\mathrm{H}} = 1\,\mathrm{TeV\,c^{-2}}$. Most of these jets are detected by the very forward calorimeters.

Tagging of jets is also needed for the study of strong $\mathrm{W^{\pm}W^{\pm}}$, $\mathrm{W^{+}W^{-}}$, WZ and ZZ scattering at a parton–parton centre of mass energy of 1 TeV and beyond. Typical cuts at LHC would be: high $p_{\mathrm{T}}$ isolated charged leptons ($p_{\mathrm{T}} \geq 40$ or $100\,\mathrm{GeV\,c^{-1}}$), no central jets (with $E_{\mathrm{T}} \geq 30$ or 60 GeV in $|\eta| \leq 3$) and a single tagging jet (with $E \geq 0.8$–$1.5$ TeV in $3 \leq |\eta| \leq 5$).

The detector requirements can be summarized as: hadron calorimeter geometric coverage up to $|\eta| < 5$ with sufficiently fine lateral granularity to reconstruct narrow jets above large background from general proton–proton collision (labelled minimum bias) events in the forward region ($3 < |\eta| < 5$).

### (*b*) *New massive vector bosons*

The detector requirements for the measurement of high momenta can be ascertained by considering decays of postulated high mass objects such as $\mathrm{Z}' \rightarrow \mathrm{e^{+}e^{-}}$ or $\mu^{+}\mu^{-}$. For $\mathrm{Z}'$ masses above $1\,\mathrm{TeV\,c^{-2}}$, the main background comes from the production of lepton–anti-lepton pairs through the Drell–Yan process. The discovery of objects such as $\mathrm{Z}'$ will be rate-limited and hence a good mass resolution for both the electron and muon channels is desirable. Good momentum

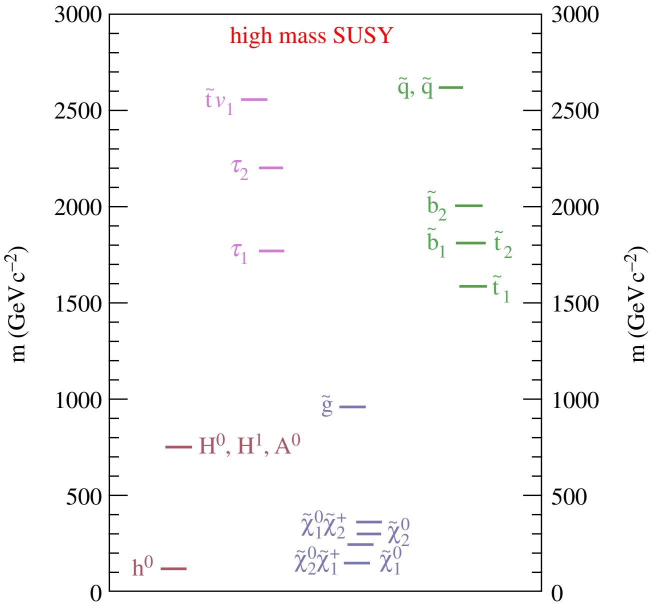


Figure 5. The mass spectrum of supersymmetry with a particular set of parameters in the CMSSM: $M_0 = 2.55\,\mathrm{TeV\,c^{-2}}$, $M_{1/2} = 360\,\mathrm{GeV\,c^{-2}}$, $\tan\beta = 51$, $\mathrm{sign}(\mu) = -1$ and $A_0 = 1.73\,\mathrm{TeV\,c^{-2}}$. (Online version in colour.)

resolution is required only in the central region ($|\eta| \leq 2$). Ways of distinguishing between different models of new physics involve the measurement of the natural width and the forward–backward asymmetry of charged leptons from the decays of Z′. Both of these require sufficiently good high $p_\mathrm{T}$ momentum resolution ($\Delta p_\mathrm{T}/p_\mathrm{T} \approx 0.1$ for $p_\mathrm{T} \approx 1\,\mathrm{TeV\ c^{-1}}$) to determine the sign of the leptons.

The detector requirements can be summarized as: good momentum resolution that is sufficient to unambiguously determine the charge of high $p_\mathrm{T}$ leptons in the region $|\eta| < 2$.

### (*c*) *Supersymmetric Higgs bosons*

Supersymmetry predicts a doubling of the particle spectrum: every particle would have a superpartner with its mass determined by the chosen parameters of the model. Figure 5 shows the predicted spectrum of the superparticles for a particular set of these parameters in the constrained supersymmetric standard model (CMSSM) [4,11]. The decays of supersymmetric particles, such as squarks (quark superpartners) and gluinos (gluon superpartners), involve cascades that always contain the lightest supersymmetric particle (LSP) if $R$-parity is conserved. $R$-parity is a new quantum number which, if conserved, would lead to the production of supersymmetric particles in pairs and with a stable LSP. $R$-parity is defined as $P_\mathrm{R} = (-1)^{S+3B+L}$, where $S$ is the spin, $B$ the baryon number and $L$ the lepton number. The LSP is expected to escape detection, leading to significant $\not{E}_\mathrm{T}$ in the final state. The rest of the cascade can result in an abundance of leptons, b jets and/or $\tau$ jets.

A search has also to be made for supersymmetric Higgs bosons and some of the relevant final states are listed below.

h, H, A $\to \tau^+\tau^- \to (\mathrm{e}/\mu)^+ + \mathrm{h}^- + E_\mathrm{T}$ or $\to \mathrm{e}^+ + \mu^- + E_\mathrm{T}$ or $\to h^+ + \mathrm{h}^- + E_\mathrm{T}$
$\mathrm{H}^+ \to \tau^+ + \nu$ from $t$ quarks and the conjugate,
$\mathrm{H}^+ \to \tau^+\nu$ and $\mathrm{H}^+ \to t\bar{b}$ for $m_\mathrm{H} > m_\mathrm{top}$
$\mathrm{A} \to \mathrm{Zh}$ with $\mathrm{h} \to b\bar{b}$
H, A $\to \tilde{\chi}^0_2\tilde{\chi}^0_2,\ \tilde{\chi}^+_i\tilde{\chi}^-_i$, etc.

The neutralino states are labelled $\tilde{\chi}$ (1 for the LSP and 2 for the Z-like state). It can be seen that even here the decay chains contain the LSP and an abundance of b-jet or $\tau$-jet production.

Hence in addition to the requirements mentioned above, including good $E_\mathrm{T}$ resolution, the additional important requirements are efficient tagging of b or hadronic decays of $\tau$ leptons, and triggering on $\tau$ leptons.

## 6. The experimental and technological challenge

At the design luminosity of $L = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, there are a billion proton–proton interactions per second, by large glancing ones and hence of little interest. The protons in the counter-rotating beams are organized in bunches, each comprising some 100 billion protons, and spaced by 25 ns. At the design luminosity, there are some 20 interactions per bunch crossing. These parameters lead to formidable experiment challenges [9].

It is physically impossible to record the data from all the one billion interactions with each one corresponding to approximately 1 Mb. Hence, a selection has to be made; this process is labelled as ‘trigger’, comprising two distinct levels: the first one using custom hardware and the second using commodity computing processors. The trigger must reduce the billion interactions per second to approximately $10^2$ events per second for storage using kinematics information from the interactions as mentioned in §4. The short bunch-crossing interval has implications for the design of the readout and trigger systems. At design luminosity, around 1000 charged tracks emerge from the interaction region every 25 ns. Thus, the products of an interaction under study may be confused with those from other interactions in the same, earlier or later bunch crossings. This problem clearly becomes more severe for detectors with a response time longer than 25 ns. This effect can be reduced by using highly granular detectors with good time resolution, leading to a low *occupancy* (fraction of detector elements that contain information in a given event or crossing) at the expense of having large numbers of detector channels. The resulting millions of detector electronic channels require very good time-synchronization.

The particles coming from the interaction region lead to high radiation levels requiring radiation-hard detectors and front-end electronics. Access for maintenance is very difficult, time-consuming and highly restricted. Hence, a high degree of long-term operational reliability, similar to that associated with space satellite systems, had to be attained.

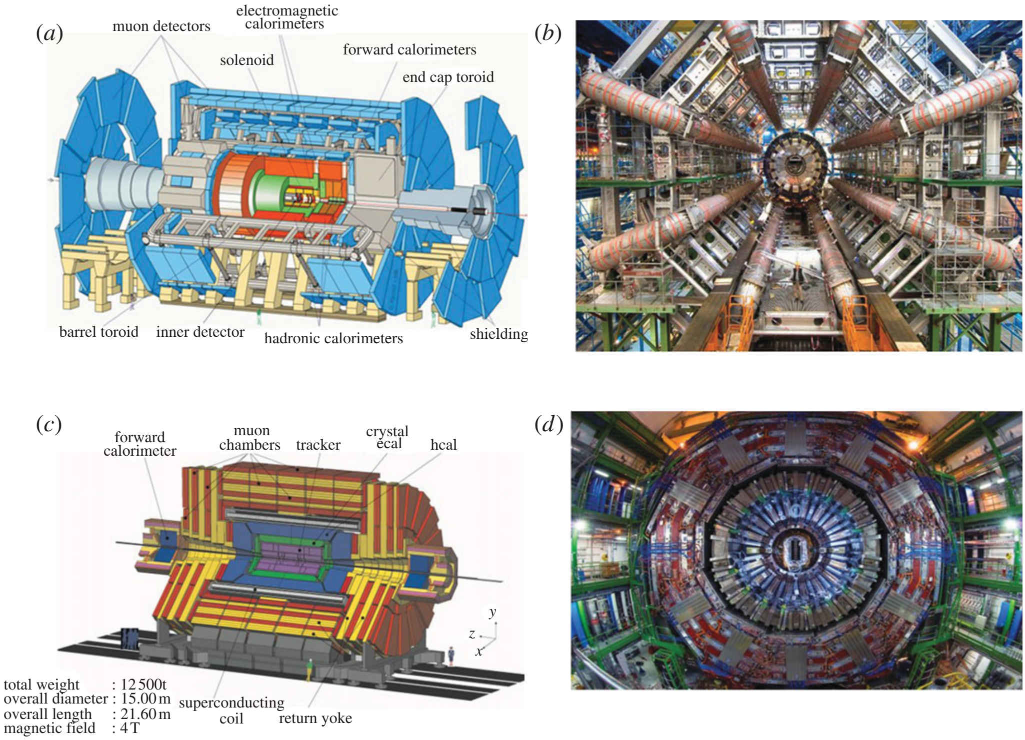


Figure 6. ($a$) A schematic of the ATLAS detector. ($b$) A view of the ATLAS experiment during construction. ($c$) A schematic of the CMS detector. ($d$) A transverse view of the CMS experiment during construction. (Online version in colour.)

The online trigger system has to analyse information that is continuously generated at a rate of 40 000 $\mathrm{Gb\,s^{-1}}$ and reduce it to hundreds of megabytes per second for storage [12]. The many petabytes that will be generated per year per experiment have to be distributed for offline analysis to scientists located across the globe. This data management problem motivated the development of the so-called 'computing grid'.

### ($a$) *The conceptual design of the ATLAS and CMS experiments*

Arguably, the most important aspect of experiment design and layout at hadron colliders is the choice of the configuration of the magnetic field for the measurement of the momentum of muons. Large bending power is needed to measure, with sufficient precision, the momentum of charged particles. This forces a choice of superconducting technology for the magnets.

The required performance of the muon system, and hence the bending power, is defined by narrow states decaying into muons and by the need for an unambiguous determination of the electric charge of muons of a momentum of approximately $1\,\mathrm{TeV\,c^{-1}}$. This requires a momentum resolution of $\Delta p/p \approx 10$ per cent at $p = 1\,\mathrm{TeV\,c^{-1}}$.

ATLAS (figure 6$a$,$b$) chose a large superconducting toroid with $B \approx 0.6\,\mathrm{T}$, $L \approx 4.5\,\mathrm{m}$, giving a sagitta, $s \approx 0.5\,\mathrm{mm}$ for $p_\mu = 1\,\mathrm{TeV\,c^{-1}}$. The design momentum

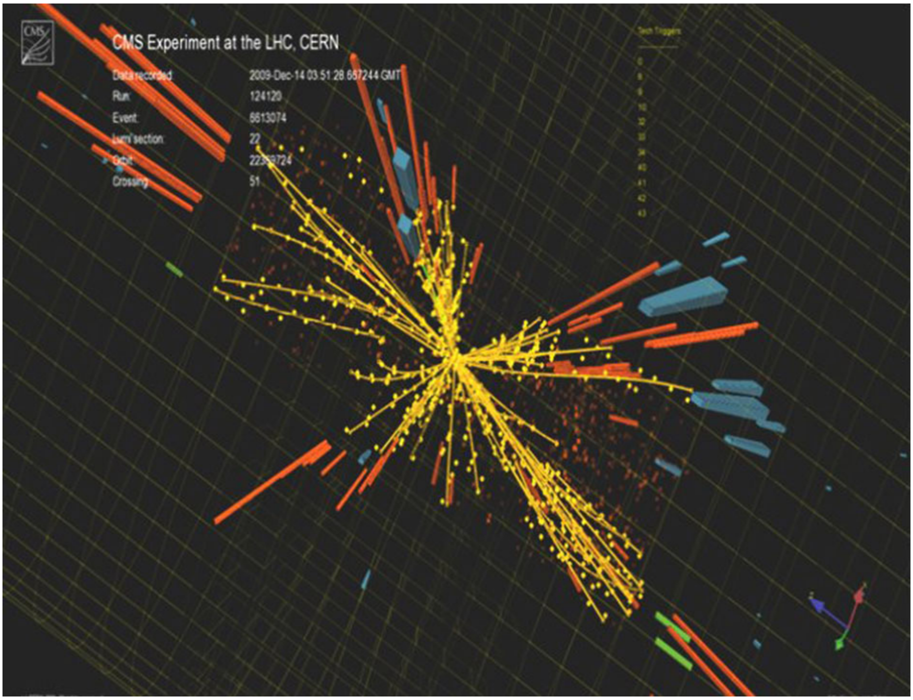


Figure 7. An event display of a proton–proton collision in CMS illustrating the inner tracking detector hits and the energy deposits in the electromagnetic calorimeter (red) and the hadron calorimeter (blue). The height of the red and blue towers is indicative of the energy deposited. The muon system is not displayed. The production of 'jets' is evident from the collimated bunches of particles. (Online version in colour.)

resolution implies that the sagitta has to be measured with a precision of ≈50 µm. Each of the eight coils in the barrel region measures about 26 m in length and 5 m in width.

A large bending power can also be obtained for a modestly sized magnet by employing a high-field superconducting solenoid, a choice made by CMS (figure 6*c*,*d*), as the bending starts at the primary vertex. This implies that in CMS for the muon momentum to be measured with the same precision as stated above the sagitta has to be measured with a precision of ≈100 µm. A favourable length–radius ratio is necessary to ensure a good momentum resolution in the forward region as well.

The manufacture of the muon chambers was a big challenge for both ATLAS and CMS because the chambers have to cover a surface area of about 10 000 $m^2$ while being able to measure the position of a muon with a precision of better than 100 µm. Aligning the chambers and imposing strict quality control were critical when they were being built and installed. Indeed, it is the muon spectrometer that defines the overall dimensions of the ATLAS and CMS experiments. ATLAS has a diameter of 22 m and a length of 46 m, and weighs some 7000 tonnes. CMS is about half this length with a diameter of 14.6 m, but it weighs in at 14 000 tonnes because of its magnet return yoke, which is made of iron.

The most powerful way to 'see' the event topology is by using the inner tracker (figure 7). The principal role of the inner tracker is to measure the momentum of charged tracks with minimal disturbance. The figures of merit are the track finding efficiency, the momentum resolution and the secondary vertex resolution (for particles such as B mesons that live long enough to have the point of decay distinct from the point of proton–proton interaction). The inner tracker also plays a crucial role in the identification of electrons, taus and b-jets. The ATLAS and CMS tracking detectors at the LHC have to deal with very high particle fluxes ($\approx 2 \times 10^{10}$ particles per second emerging from the interaction point) and a very short time between bunch crossings (25 ns). The target momentum resolution, 1 per cent at $100\,\mathrm{GeV\,c^{-1}}$, for charged particles is almost an order of magnitude better than was needed at the experiments on the LEP collider at CERN. This is attained by deploying Si microstrip detectors, and gas detectors such as straw tubes, complemented by high space-resolution Si-pixel detectors close to the point where beams cross.

The technologies for the electromagnetic calorimeter in both experiments were chosen to address the need for very good energy resolution as well as good radiation hardness. At the time, there were few technologies possible; ATLAS chose a lead–liquid argon sampling calorimeter using a novel 'accordion-like' mechanical structure, and CMS chose a fully active lead tungstate scintillating crystal calorimeter deploying some 75 000.

## 7. Summary

The physics requirements for the ATLAS and CMS experiments can now be summarized as follows.

— Good charged particle momentum resolution and reconstruction efficiency in the inner tracker; efficient b/$\tau$-jet identification requiring pixel detectors close to the beamline.

— Good electromagnetic energy resolution, good di-photon and di-electron mass resolution (less than 1% at $100\,\mathrm{GeV\,c^{-2}}$), wide geometric coverage ($|\eta| < 2.5$), correct localization of the primary interaction vertex, $\pi^0$ rejection and efficient photon and lepton isolation at high luminosities.

— Good muon identification and momentum resolution over a wide range of momenta in the region $|\eta| < 2.5$, good di-muon mass resolution (less than 1% at $100\,\mathrm{GeV\,c^{-2}}$) and an ability to determine unambiguously the charge of muons with $p_\mathrm{T}$ less than $1\,\mathrm{TeV\,c^{-1}}$.

— Good $E_\mathrm{T}$ and di-jet mass resolution. This requires hadron calorimeters with a large geometric coverage ($|\eta| < 5$) and with fine lateral segmentation ($\Delta\eta \times \Delta\phi \sim 0.1$).

The conceptual design of ATLAS and CMS was driven by the anticipated but undiscovered physics at the new and special energy scale of the LHC. These experiments [13] should allow the discovery of almost anything Nature has in store at this energy scale. For this reason, ATLAS and CMS are rightly labelled 'general-purpose detectors'. These are instruments unprecedented in scale and complexity, and many technologies have been pushed to their limits or were invented/developed for these experiments. Their construction required a long and painstaking effort on a worldwide scale. After 20 years, from conception to construction and commissioning, the second half of this journey—that of extraction of physics—has started in earnest. It is particularly important to note that both ATLAS and CMS (and indeed the other LHC experiments) are meeting the physics-driven design requirements set by the ambitious desires of their designers and builders.

A new era in modern physics has been launched and exciting times lie ahead. Many results are now pouring out of the ATLAS and CMS experiments [14]. All the expectations still are that what shall be found at the LHC will reform our understanding of Nature at the most fundamental level.

Only experiments reveal/confirm Nature's inner secrets and it is very apt to recall at this meeting the words of a past President of the Royal Society, Sir Isaac Newton, who said

> To me there has never been a higher source of earthly honour or distinction than that connected with advances in science.

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