Status and prospects from the LHC

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Abstract. This article reviews the status of the CERN Large Hadron Collider and associated experiments as of July 2010. After a brief discussion of the progress in accelerator and experiment commissioning, the LHC physics landscape is presented, together with a selection of the experimental results achieved so far. Finally the prospects for the 2010-11 LHC physics run are reviewed, with an emphasis on possible discoveries in the Higgs and supersymmetry sectors.

1. The Large Hadron Collider and experiments
The Large Hadron Collider (LHC) is a high-luminosity proton-proton and heavy ion collider installed in the 27km tunnel that formerly housed the CERN LEP electron-positron collider. The LHC and its associated experiments are designed to shed light on many of the unsolved questions in fundamental physics, some of whose solutions predict new phenomena at the TeV energy scale. After around twenty years of design, construction, installation and commissioning, the LHC and experiments were finally ready to begin operations in September 2008, when part of the accelerator was damaged in a commissioning accident caused by a faulty magnet interconnect. A year of repair and consolidation followed, and the LHC began operations in earnest in November 2009, with first collisions at a centre-of-mass energy $\sqrt{s} = 900\text{ GeV}$ happening on 23rd November, and first 7 TeV collisions on 31st March 2010.

The LHC interaction points host four major experiments—ATLAS, CMS, LHCb and ALICE, and several smaller ones. ATLAS and CMS are large general-purpose detectors designed to explore the full range of LHC proton-proton physics, including both searches for new particles and precision measurements. The LHCb experiment is dedicated to exploring the physics of heavy flavours ($b$ and $c$ quarks), in particular the violation of charge-parity (CP) symmetry. ALICE is a dedicated heavy ion experiment, focused on studying the very high multiplicity of particles produced in the collisions of lead nuclei during special LHC running periods. CMS and ATLAS will also participate in these runs, the first of which is scheduled for late 2010.

After having achieved the first pilot 7 TeV $pp$ collisions, the main goal of the accelerator team for 2010 is to fully commission the machine and increase the intensity step-by-step, ideally reaching an instantaneous luminosity of $L = 10^{32}\text{ cm}^{-2}\text{s}^{-1}$ by the end of the 2010 running period. This should open the way to accumulating 1 fb$^{-1}$ in 2011, before the accelerator is shut down in 2012 for work on improving the magnet interconnects ready for $\sqrt{s} = 14\text{ TeV}$ running in 2013. The step-by-step approach has resulted in alternating periods of machine commissioning and physics data accumulation, as clearly visible in the integrated luminosity history plots shown in Figure 1. The machine team started with a small number of colliding bunches with $2 \times 10^{10}$ p/bunch, then commissioned the ‘squeeze’ (tightening the focus of the beams at the interaction...
points) to increase the collision rate. An intense period of commissioning with nominal intensity bunches \((1 \times 10^{11} \text{ p/bunch})\) then followed, with the number of bunches being increased to 13 per beam in July, giving instantaneous luminosities of about \(1 \times 10^{30} \text{ cm}^{-2} \text{s}^{-1}\). At the time of the PASCOS 2010 conference, over 200 nb\(^{-1}\) had been delivered to each experiment.

A key parameter for safe machine operation is the stored energy per beam; in July this had reached about 1 MJ per beam, around the maximum energy seen in other proton accelerators such as HERA and the Tevatron, and enough to cause significant damage to the accelerator if the beam is lost in an uncontrolled way. The next step therefore involves a period of sustained, stable running to gain operational experience and build confidence in the machine protection systems, before moving onto larger numbers of bunches. These will be injected in closely spaced bunch trains, with the aim of having routine operation with several hundred bunches by the end of 2010. This is still far below the LHC design goal of 2808 bunches/beam for an instantaneous luminosity of \(L = 10^{34} \text{ cm}^{-2} \text{s}^{-1}\), but should allow a data sample of \(\mathcal{O}(100 \text{ pb}^{-1})\) to be accumulated by the end of October, before the LHC switches to lead ions for a short heavy-ion commissioning run in November.

2. The LHC physics landscape

Most of the new physics signals which ATLAS and CMS are searching for have very small production cross-sections, implying that they will give rise to rare events which have to be detected amongst an overwhelming background of Standard Model physics processes. The rates for some typical processes at the LHC design energy and luminosity are given in Table 1, from which it can be seen for example that a 100 GeV Higgs boson is expected to be produced about once in every 10\(^{10}\) collisions. Much of the early data analysis work at LHC therefore focuses on building up a thorough understanding of the more common Standard Model physics processes, and how they are reconstructed and measured in the detectors. Many interesting studies can be performed with these data, and some of the processes also serve as ‘standard candles’ allowing the calibration of the detectors to be verified and improved.

Although the full LHC discovery potential will only be reached after several years of high-luminosity running, even the \(\mathcal{O}(100 \text{ pb}^{-1})\) expected in 2010 will allow a discovery reach significantly beyond that of the Fermilab Tevatron in many areas. Current Tevatron search limits are typically based on \(\mathcal{O}(5 \text{ pb}^{-1})\) of \(p\bar{p}\) data at \(\sqrt{s} = 1.96 \text{ TeV}\), so the LHC enjoys a factor
Table 1. Approximate expected rates for some physics processes in LHC pp collisions at $\sqrt{s} = 14$ TeV and $L = 10^{34}$ cm$^{-2}$s$^{-1}$.

| Process                                      | Rate ($\sqrt{s} = 14$ TeV) |
|----------------------------------------------|-----------------------------|
| Inelastic pp collision                       | $10^9$ Hz                   |
| $b$-quark pair production                    | $10^6$ Hz                   |
| Jet production, $E_T > 250$ GeV              | $10^3$ Hz                   |
| $W \to \ell\nu$                              | $10^2$ Hz                   |
| Top-quark pair production                    | 10 Hz                       |
| Standard Model Higgs, $m_H = 100$ GeV        | 0.2 Hz                      |

3.6 advantage in energy, balanced by a expected factor of approximately 50–100 less integrated luminosity in 2010, improving to 5–10 at the end of 2011. The potential gain over the Tevatron depends on the ratio of parton luminosities at the energy scale $X$ appropriate for the production of a state of mass $M_X$, and whether that state is produced primarily in gluon-gluon ($gg \to X$) or quark-antiquark ($q\bar{q} \to X$) processes [1]. For example, the production of a 160 GeV Higgs boson is dominated by $gg$ and gains a factor 15 in cross-section from the increased centre-of-mass energy. Top quark pair production ($m_X = 2 \times 175$ GeV) becomes $gg$ dominated at LHC, and gains a factor of 20 compared to the $q\bar{q}$-dominated production at the Tevatron. A possible 1 TeV $Z'$ state gains a factor 100, opening up new territory even with 100 pb$^{-1}$ of LHC data. There are therefore significant chances for a discovery even with early LHC data, if the new physics lies just beyond the Tevatron search limits.

3. Commissioning the experiments

Once first collisions were delivered, initially at $\sqrt{s} = 900$ GeV, one run at 2.36 TeV and then at 7 TeV, the experiments focused on completing the commissioning of their detectors, trigger and offline computing systems. These had already been intensively exercised over the preceding few years with cosmic rays and other dedicated tests, but benefited greatly from the gradual increase in LHC luminosity over the first weeks and months of accelerator commissioning.

The tracking and particle identification detectors began to see the ‘zoo’ of Standard Model hadrons from the first LHC runs: $K^0_s \to \pi^+\pi^-$, $\phi \to K^+K^-$, $\Lambda^0 \to p^+\pi^-$ and even $\Omega^- \to \Lambda^0K^-$ were quickly reconstructed. Similarly, the calorimeters began to see signatures such as $\pi^0 \to \gamma\gamma$, $\eta, \omega \to \pi^+\pi^-\pi^0$ and later $J/\psi \to e^+e^-$, together with $J/\psi \to \mu\mu$ in the muon detectors. As well as acting as commissioning signals, precise measurements of the production rates of all these particles are useful in tuning Monte Carlo models. The first physics runs also allowed the experiments to start commissioning their missing transverse energy ($E_T^{\text{miss}}$) reconstruction—this is based on the vector sum of calorimeter energy deposits resolved into the transverse plane. Since the initial state of colliding protons has no significant momentum component transverse to the beam direction, large values of $E_T^{\text{miss}}$ indicate ‘unbalanced’ events, with transverse momentum being carried away by undetected particles (such as neutrinos). The $E_T^{\text{miss}}$ measurement is of vital importance in many analyses, but requires that ‘fake’ $E_T^{\text{miss}}$ from inefficient or noisy calorimeter cells, miscalibration or cracks first be thoroughly understood.

All the LHC experiments employ complex multi-stage trigger systems to select the most interesting pp collisions online and reduce the rate to around 200 Hz (in the case of ATLAS and CMS) for recording and offline analyses. Since the actual pp collision rate already exceeded 200 Hz after the first few runs, it has been crucial to commission the trigger systems as soon as possible to keep up with the data-taking rates. These triggers are typically based on a first level
of hardware triggers, making use of only a subset of event information, followed by software-based high-level triggers (HLTs) running on farms of standard computers. The experiments started with low-threshold level-1 triggers and the HLTs running in pass-through mode (i.e. not rejecting any events), allowing the efficiencies of higher-threshold trigger chains to be studied on unbiased data samples before they need to be enabled in rejection mode. More selective triggers have been implemented step-by-step, with the aim of always filling the available data recording bandwidth irrespective of the LHC luminosity.

The worldwide LHC Grid computing effort has also worked very well in the initial data-taking phase, with $O(1\text{ GB/s})$ of data being recorded and distributed to the $>100$ Tier-1 and Tier-2 sites. Data has been analysed by 1000s of individual users throughout the geographical spread of the collaborations, in parallel with data reprocessing with improved calibrations and the large-scale production of Monte Carlo simulation samples.

4. Minimum bias and QCD measurements

The most basic process in proton-proton collisions is $pp \rightarrow X$, composed of a mixture of elastic, diffractive and inelastic processes, collectively referred to as ‘minimum bias’. In practice, the exact mixture of processes sampled depends on the experiments’ triggers, which are typically sensitive to activity on either one or both sides of the detector. All of the LHC experiments have measured the charged particle multiplicity in such collisions, as a function of pseudorapidity $\eta$ and particle $p_T$; measurements from ALICE of the multiplicity distribution in $pp$ collisions at 0.9, 2.36 and 7 TeV are shown in Figure 2(left) [2, 3]. As expected, the overall event charged particle multiplicity increases with $\sqrt{s}$; however existing Monte Carlo models tuned at the Tevatron tend to underestimate the overall multiplicity and predict a harder $p_T$ spectrum than in the data. Work has already started on incorporating first LHC data in such model tunes, which should lead to a better description of this data.

CMS and ALICE have also shown measurements of Bose-Einstein correlations (BEC) in minimum bias events. These correlations are manifested as an enhancement of the density of pairs of identical bosons (e.g. $\pi^+\pi^+$) close in phase space, i.e. with four-momentum $p_1 \approx p_2$. They can be characterised by studying the particle pair density $dN/dQ$ where $Q = \sqrt{-(p_1 - p_2)^2}$ with respect to a reference distribution $dN/dQ_{\text{ref}}$ constructed to be free of
two-particle correlations. The reference distribution can be constructed from the data by taking opposite charged pairs (e.g. $\pi^+\pi^-$) after correcting for resonance decays, by reflecting particles from the opposite hemisphere, by mixing events, or by using a Monte Carlo simulation sample without BEC. Figure 2(right) shows an example from CMS of BEC measured at $\sqrt{s} = 0.9$ and $2.36$ TeV with respect to combination of reference samples [4]. The correlations can be parameterised in terms of the size and strength of a source emitter, and both CMS and ALICE [2] data show that the emitter size increases as a function of the number of charged particles in the event.

Hard interactions between the quarks and gluons in the colliding protons produce events with characteristic dijet and multijet structure. These interactions dominate the event sample with large total transverse energy, and were seen right from the first LHC runs at $\sqrt{s} = 7$ TeV. The jets are reconstructed primarily in the experiments’ calorimeters, and provide an essential tool in understanding and calibrating the calorimeter response, as well as a sensitive probe of QCD models. Figure 3 shows measurements of the multiplicity of jets reconstructed in 1 $\text{nb}^{-1}$ of 7 TeV ATLAS data [5], together with the dijet invariant mass spectrum, compared to the predictions of the Pythia [6] leading-order Monte Carlo generator. Once the jet energy scale systematic is fully understood, by using $e.g.$ energy balance in dijet and later $\gamma$-jet events, these distributions will be used to set limits on possible deviations from the behaviour expected from QCD. For example, Figure 3(right) shows a CMS simulation study of the effect of a contact interaction term with scale $\Lambda = 3$ TeV [7]; this produces a clear enhancement at high dijet invariant mass which would be visible already with a few $\text{pb}^{-1}$ of data.

As well as the hard interaction giving rise to quark and gluon jets, the experiments are beginning to study the ‘underlying event’ which comes from other components of the $pp$ interaction, $e.g.$ initial and final state gluon radiation, the remnants of the proton which do not participate in the hard scattering, and multiple parton interactions. The properties of the underlying event are expected to be approximately independent of the activity in the hard scattering. This hypothesis can be studied by using the leading (highest-$p_T$) track to define an event direction in the transverse plane correlated to the hard scattering, and looking at the distributions of charged particles in towards, transverse and away regions with respect to this direction, as shown in Figure 4(left). Densities of charged particles in these regions have been measured by ATLAS [8], and are shown in Figure 4(right). It can be seen that the particle density as a function of $p_T$ reaches a plateau in the transverse region, whilst it continues to increase in the
towards and away regions, which are populated more strongly by the hard scattering. However, other variables in the transverse region are correlated with the leading track $p_T$, indicating possible contributions from components other than the beam remnant. These studies can be used to tune Monte Carlo models and are important in understanding the background to jets in high $p_T$ events.

5. Early flavour physics

The large $b\bar{b}$ production cross-section at LHC ($O(100 \mu b)$ at $\sqrt{s} = 7\text{ TeV}$) makes the LHC a true $b$-factory, with $b$-hadron production rates in excess of any previous collider. The dedicated LHCb experiment has been optimised to fully exploit the potential of LHC for precision $b$ (and $c$) physics, in particular in the area of CP-violation studies. Many of these studies require the study of $b$-hadron decays involving $J/\psi$ mesons, and LHCb has already shown reconstructed $J/\psi \to \mu\mu$ decays in the first few nb$^{-1}$ of data, as shown in Figure 5(left). These mesons are produced both directly (‘prompt’ $J/\psi$ production) and in the decay of $b$-hadrons, and the two components can be separated by reconstructing the proper decay time of the $J/\psi$ from measurements of its lifetime and distance from the event primary vertex. The latter relies on precise tracking measurements using the LHCb VELO silicon vertex detector. Figure 5(right) shows that the separate contributions can already be separated, with the exponential decay of the $b$-hadron component allowing the average $b$-lifetime to be measured [9]. With more statistics, these samples will allow the study of quarkonium production, spectroscopy and polarisation, and $b$-physics in both inclusive and exclusive modes. The $J/\psi \to \mu\mu$ decays are also very useful for studying the detector calibration, alignment and magnetic field maps.

LHCb is also starting to reconstruct exclusive charm decays, for example $D^*$ mesons via the decay $D^{*+} \to D^0\pi^+$, with $D^0 \to K^-\pi^+$ or the rarer decay mode $D^0 \to K^-K^+$. Due to the small $D^*-D$ mass difference, the $\pi^+$ produced directly in the $D^*$ decay produces a very narrow peak in the $m_{\pi^-K^-\pi^+} - m_{K^-\pi^+}$ mass spectrum and also tags the flavour ($D^{*+}$ or $D^{*-}$) of the parent meson. Studying the time-dependent decay rates of $D^*$ into the various final states provides access to $D^0$-$\bar{D}^0$ mixing and CP-violation observables. LHCb has already reconstructed several 100s of the rare $D^0 \to K^+K^-$ mode, and should have a sample ten times larger than that of BaBar with 100pb$^{-1}$ [10]. The experiment is also starting to reconstruct significant numbers of semi-exclusive semileptonic $b$-hadron decays such as $B \to D^0\mu\nu X$ and $B_s \to D_s\mu\nu X$. These
will provide a complementary measurement of the $b\bar{b}$ production cross-section to that using $b \to J/\psi X$ decays, access to $B^0-\bar{B}^0$ oscillations measurements and calibration of flavour tagging algorithms [10].

6. Vector boson and top quark production

Beyond the production of high-$p_T$ jets, the next early physics milestone for ATLAS and CMS is the observation of the electroweak vector bosons $W$ and $Z$, through their leptonic decays $W \to \ell \nu$ and $Z \to \ell \ell$ ($\ell$ represents an electron or muon). $W$-boson production is the dominant source of high-$p_T$ leptons, which tend to be more isolated than the low-$p_T$ leptons produced from the decays of $b$- and $c$-flavoured hadrons in jets. The production of a neutrino $\nu$ in $W$ boson decay also gives rise to significant missing transverse energy $E_T^{\text{miss}}$, which can be used to enhance the $W$ signal.

ATLAS and CMS both observed $W$ production in the first few nb$^{-1}$ of data, using selections based on requiring isolated high-$p_T$ leptons and significant $E_T^{\text{miss}}$. Since the longitudinal (parallel to the beam axis) component of the neutrino momentum cannot be measured, the $W$ mass cannot be reconstructed. Instead, the experiments make use of the transverse mass $m_T$, defined as:

$$m_T = \sqrt{2p_T^{\ell}p_T^{\nu}(1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

where the $E_T^{\text{miss}}$ vector is used as an estimate of the neutrino transverse momentum $p_T^{\nu}$. Figure 6 shows distributions of $m_T$ measured by ATLAS in the electron channel [11], and CMS in the muon channel [12]; clear Jacobian peaks around the $W$ mass are visible, smeared due to the use of $m_T$ rather than $m$. The numbers of observed events are consistent with the expectations from the Standard Model.

The $Z$ boson production rate is about a factor 10 smaller than that for $W$, and the first few events have been observed in both $Z \to ee$ and $Z \to \mu\mu$. As can be seen from Figure 7 showing the mass distribution of $Z$ boson candidates in CMS [12], the expected background is much smaller than for $W$, and the selected event sample is dominated by the continuum $q\bar{q} \to Z/\gamma^* \to \ell\ell$ Drell-Yan process, which has a resonant peak at the $Z$ mass. Due to the clean signature with low background and the well-determined $Z$ mass, with more statistics such event samples will be extremely useful for calibrating the detectors' energy response and uniformity. They can also be used for measuring the efficiency of both trigger and offline reconstruction/identification algorithms, by selecting events using only one lepton from the $Z$, and studying the properties of the other lepton in an unbiased way (the so-called ‘tag and probe’ technique).
Figure 6. Distributions of the $W$ boson transverse mass $m_T$, measured in early data by ATLAS in the electron channel (left) and CMS in the muon channel (right).

Figure 7. Distributions of the $Z$ candidate mass reconstructed by CMS in $ee$ (left) and $\mu\mu$ (right) channels.

With $O(3000)$ $W$ and $O(300)$ $Z$ bosons per lepton flavour expected in each pb$^{-1}$ of data, many precision measurements should become possible already in 2010. For example, the production rates of $W^+$ and $W^-$ bosons are not equal because of the dominance of $u$ over $d$ valence quarks in the proton. Predictions for the asymmetry $A(\eta)$ defined as:

$$A(\eta) = \frac{N(W^+ \rightarrow \ell^+\nu) - N(W^- \rightarrow \ell^-\nu)}{N(W^+ \rightarrow \ell^+\nu) + N(W^- \rightarrow \ell^-\nu)}$$

depend in detail on the parton density functions (PDFs) assumed for the proton, and the level of precision achievable with 100 pb$^{-1}$ is already enough to improve on current PDF uncertainties, see Figure 8(left) [13]. $W$ and $Z$ bosons can also be produced in association with one or more hard jets—each extra jet ‘costing’ approximately a factor of $\alpha_s$. With 1 fb$^{-1}$, 1000s of events will be produced up to $Z+4$ jets, see Figure 8(right), and the resulting distributions of jet
Figure 8. Expected $W \rightarrow \mu \nu$ charge asymmetry measurement as a function of $\eta$, assuming 100 pb$^{-1}$ of CMS data at $\sqrt{s} = 10$ TeV (left); expected jet multiplicity distribution in association with $W$ boson production in 1 fb$^{-1}$ of simulated ATLAS data at $\sqrt{s} = 10$ TeV (right).

multiplicities and momenta can be used to provide sensitive tests of QCD and Monte Carlo models [14]. These events are also a significant background to many analyses of final states involving high $p_T$ leptons, jets and $E_T^{miss}$, for example top quark physics and many new physics searches.

Beyond the $W$ and $Z$ bosons, the last and heaviest known outpost of the Standard Model is the top quark, so far seen only at the Tevatron. The top quark is expected to be produced most copiously in pairs ($t\bar{t}$), and decays almost exclusively as $t \rightarrow Wb$. The $t\bar{t}$ decay topologies are therefore determined by the decay modes of the $W$, and include the dilepton state $t\bar{t} \rightarrow \ell\nu b\ell\nu b$ ($\ell = e$ or $\mu$) with a branching ratio of 5%, and the semileptonic final state $t\bar{t} \rightarrow \ell v b j j b$ with a branching ratio of 30%. Both decay modes give rise to events with isolated leptons, $E_T^{miss}$ and jets, some with $b$-flavour. The $e-\mu$ dilepton mode is the cleanest, as can be seen in Figure 9(left), which shows the expected composition of $e-\mu$ dilepton events as a function of jet multiplicity in a CMS simulation study at $\sqrt{s} = 10$ TeV. However, at $\sqrt{s} = 7$ TeV, only a few dilepton events are expected per pb$^{-1}$ of data. The semileptonic final states have higher rate, and also allow the reconstruction of the hadronic top mass $m_{jjb}$ from three of the four jets—this will provide confirmation that the observed object is the 173 GeV top quark also seen at Fermilab. This state suffers from higher background, principally from $W$+jet events, as can be seen from the ATLAS simulation study shown in Figure 9(right). The background can be significantly reduced if $b$-tagging can be applied, only a small fraction of the $W$+jets background having $b$-flavoured jets. As of July 2010, both ATLAS and CMS were eagerly awaiting the first $t\bar{t}$ candidate events.

Once the initial $t\bar{t}$ signal is established and the production cross-section measured (to an expected precision of 10–20% with 100 pb$^{-1}$), the LHC precision top physics program can begin. With the 1 fb$^{-1}$ expected in 2011, the top quark sample will significantly exceed that available at the Tevatron, allowing $e.g.$ the top quark mass to be measured with a statistical error well below 1 GeV using the $m_{jjb}$ distribution or a full kinematic fit. The key will be to control systematic errors to the same level, especially those related the jet energy scale, for both light and $b$-flavoured jets. With enough data statistics, alternative techniques less dependent on jet energies will also be used, $e.g.$ use of the lepton $p_T$ and $b$-decay length distributions, or the very
clean measurements possible in $t \to b \to J_\psi$ decays.

Electroweak single top production will also be intensively studied in the first years at LHC; as at the Tevatron, complex multivariate techniques will be required to extract the signal from the dominant $W$+jets (with heavy flavour) and $t\bar{t}$ backgrounds. Simulations studies [15] indicate that $200 - 1000$ pb$^{-1}$ will be required at $\sqrt{s} = 7$ TeV to establish the dominant $t$-channel production mechanism, but background characterisation studies can start already with the 2010 data.

7. Higgs, supersymmetry and beyond
The prospects for an early discovery of the Standard Model Higgs boson at LHC depend crucially on the Higgs mass $m_H$. The first chance will come using the $H \to WW$ decay mode in the mass range $150 < m_H < 180$ GeV, where the Higgs boson is produced either in the gluon fusion mode, or via the fusion of $W$ or $Z$ bosons produced in the initial state (vector boson fusion or VBF). The analysis requires two high $p_T$ leptons and large $E_T^{miss}$ from the $W$ decays, and a veto on additional jets in the central region to suppress $t\bar{t}$ background. The sensitivity in the VBF mode can be enhanced by requiring additional forward jets from the quarks radiating the bosons. The remaining background is dominated by $WW$ diboson and $W$+jets. Figure 10(left) shows the significance achievable in CMS with 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV [16]; a 3–5$\sigma$ signal is expected for $150 < m_H < 180$ GeV.

For larger $m_H$, the $H \to ZZ \to 4\ell$ channel is most promising—with sufficient data statistics, the Higgs signal stands out clearly over the continuum background from ZZ diboson production. But for 1 fb$^{-1}$, the sensitivity is limited to cross-sections a few times larger than that of the Standard Model, see Figure 10(right). An intriguing possibility is that of a 4th generation of Standard Model-like quarks: in this case, the $gg \to H$ production cross-section is enhanced by a factor 9, irrespective of the $t'$ quark mass, rendering the Higgs boson observable up to about $m_H = 400$ GeV [16]. At low $m_H$ below the $H \to WW$ threshold, a variety of channels contribute, including $H \to \gamma\gamma$. In this channel, the Higgs is visible as a small peak over a large continuum background from direct $\gamma\gamma$ production and $\gamma$-jet production with a misidentified jet. With 1 fb$^{-1}$, a sensitivity of 4–6 times the Standard Model cross-section can be achieved depending on $m_H$ [16, 17].

Early LHC data also offers some sensitivity to the neutral Higgs bosons of the Minimal
Supersymmetric Standard Model (MSSM) if the Higgs vacuum expectation value ratio \( \tan \beta \) is large. In this case, the \( A, H \) and \( h \) are produced preferentially in association with \( b \)-quarks, and can be seen in the \( A, H, h \rightarrow \tau \tau \) decay mode. With 1 fb\(^{-1}\), low mass Higgs bosons can be seen for \( \tan \beta > 20 \) [16].

In the most widely-studied \( R \)-parity conserving supersymmetry (SUSY) models, squark and gluino pairs will be copiously produced at LHC, decaying into a variety of final states. These are characterised by multiple jets, \( E_T^{\text{miss}} \) due to the escaping lightest supersymmetric particle which is neutral, non-interacting and stable, and sometimes one more leptons depending on the decay mode. The most important issues in early SUSY searches are a good performance of \( E_T^{\text{miss}} \) measurements, to minimise ‘fake’ \( E_T^{\text{miss}} \) caused by detector problems or resolution tails, and the understanding of Standard Model backgrounds, particularly those from \( t\bar{t} \) and \( W^+ \) jets. These background processes often contribute in ‘pathological’ ways which are difficult to simulate, \textit{e.g.} when one lepton is missed or badly reconstructed, so need to be evaluated using data control samples wherever possible. Studies show that sensitivities to 500 GeV squarks and gluinos, just beyond the Tevatron limits, can be achieved with 100-500 pb\(^{-1}\) using final states with and without leptons [16, 18].

An alternative strategy involves looking for events with two like-sign leptons, also in association with jets and \( E_T^{\text{miss}} \). Such selections tend to have lower signal efficiency, but also much lower Standard Model backgrounds, mainly from \( t\bar{t} \) events where the second lepton comes from a \( b \)-hadron decay, or is a misreconstructed fake. This technique also offers the possibility for significant improvements over the current Tevatron limits with 1 fb\(^{-1}\) [16], but in all cases, LHC data at \( \sqrt{s} = 14 \) TeV will be needed to probe for SUSY particles at the 1 TeV mass scale.

Many other exotic physics scenarios can be probed with the early LHC data. For example, several models predict high-mass \( W \) or \( Z \)-like objects which decay in similar ways to the Standard Model bosons: \( W' \rightarrow \ell \nu \) and \( Z' \rightarrow \ell \ell \). Limits at the Tevatron are now constrained by the available centre-of-mass energy to around 1 TeV, and these should be overtaken with 7 TeV LHC data samples of around 20 pb\(^{-1}\) (\( W' \)) and 100 pb\(^{-1}\) (\( Z' \)). Models with large extra dimensions predict an excess of high-mass diphoton events, where the sensitivity beyond the Tevatron can be achieved with as little as 50 pb\(^{-1}\) [16]. Finally, searches for resonances or other deviations in...
the dijet mass spectrum can provide sensitivity to quark compositeness or excited quarks, again in the first year of LHC datataking.

8. Conclusions
After many years of development, construction, installation and commissioning, the LHC physics era has finally begun. The commissioning of the LHC accelerator at $\sqrt{s} = 7$ TeV is going very well, and no major performance limitations have been encountered so far. The LHC team has a clear plan towards operation at an instantaneous luminosity of $L = 10^{32}$ cm$^{-2}$s$^{-1}$ near the end of 2010, and an integrated luminosity of 1 fb$^{-1}$ per experiment in 2011, before a major shutdown in 2012 to prepare for 14 TeV operation. The experiments are working very well, triggering and recording data with high efficiency, and analysing it effectively using the worldwide Grid computing environment.

The first LHC physics results have already been derived, with measurements of basic event properties in the new energy regime. The heavy flavour and jet physics programs have started, $W$ and $Z$ boson production observed and ATLAS and CMS are on the verge of observing top quark production. The integrated luminosity profile is such that first results on new physics searches can be expected already at the end of 2010, whilst extending the Higgs boson search beyond the current Tevatron limits will also require the 2011 data sample.

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