Physics during the first two years of the LHC

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Physics during the first two years of the LHC

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Abstract. The CERN Large Hadron Collider (LHC) presents the most extraordinary challenges that particle physics has ever faced. By colliding high-intensity proton beams at a centre-of-mass energy of 14 TeV, it will explore in great detail the previously unaccessible territory of the TeV scale. We discuss the LHC physics goals and potential during the first two years of operation, and outline the fundamental questions that it might be able to address by the end of 2009.

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1. Introduction

The CERN Large Hadron Collider (LHC) will start operation in November 2007. The present time is characterized by very intense activities to complete the installation and commissioning of the machine and experiments, and by increasing expectations for the imminent data taking phase.

The LHC [1] will provide pp collisions at the unprecedented centre-of-mass energy $\sqrt{s} = 14 \text{ TeV}$. According to the present plans, the design luminosity $L = 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ should be achieved in 2010, while in the first two years of operation the luminosity should increase gradually from $L \sim 10^{29} \text{ cm}^{-2} \text{s}^{-1}$ to $L \sim 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$. The machine will also deliver heavy ion collisions, for instance lead–lead collisions at the colossal centre-of-mass energy of about 1000 TeV.

Four main experiments will take data at the LHC: two general-purpose detectors, ATLAS and CMS, which have a very broad physics programme; an experiment, LHCb, dedicated to the study of B-hadrons and CP (charge-parity) violation; an experiment, ALICE, which will study ion–ion and p–ion collisions. Here only the ATLAS and CMS experiments are discussed in some detail, since their physics goals address directly the exploration of the TeV scale.

The present LHC schedule, which has been revised in June 2006, foresees first pp collisions at $\sqrt{s} = 900 \text{ GeV}$ in November 2007. The reduced centre-of-mass energy is due to the fact that only two out of the eight machine sectors can realistically be commissioned for 14 TeV operation before the end of 2007. This short (few weeks at most) low-energy pilot run will be used to debug the machine and the experiments, and will be followed by a three-month shutdown at the beginning of 2008, during which the commissioning of the remaining six sectors will be completed. First collisions at $\sqrt{s} = 14 \text{ TeV}$ are expected in June 2008 and will mark the beginning of the first physics run. Integrated luminosities of about 1 fb$^{-1}$ should be accumulated by the end of 2008, and 5–10 fb$^{-1}$ by the end of 2009 [1], although there are several uncertainties on this plan, related e.g. to the time needed to bring the machine to stable operations and to ramp up the instantaneous luminosity.

The LHC is a 30-year project. First discussions took place in a historical workshop held in Lausanne in 1984 [2], detector construction started in the mid 90s, operation will begin in 2007 and data taking will last more than ten years. Since 1984, our understanding of particle physics has evolved significantly, driven by the observation of neutrino oscillations, by the extremely precise and detailed electroweak results from the CERN and SLAC electron–positron colliders LEP and SLC, by the discovery and measurement of the top quark at the Tevatron, and by the extensive parton distribution measurements at the HERA electron–proton collider at DESY. The high-energy operation of LEP2 has pushed the lower limit on the Higgs boson mass far beyond the most optimistic expectations. These results have served to confirm the standard model (SM) at the permil level of accuracy, while the need for physics beyond the SM has become more apparent. Thus, the motivation for the LHC as the machine which will explore in detail the TeV scale, and its physics potential, have become stronger and stronger with time.

Particle physics and the planning for future facilities would greatly benefit from a quick determination of the scale of new physics. Therefore, the first two years (2008–2009) of data taking at the LHC design energy, which are the subject of this article, are going to be crucial for the future of our discipline.
This paper is organized as follows. Section 2 outlines the strategy to understand the detectors and undertake the first physics measurements in the initial phases of the LHC operation. Some opportunities for early discoveries are described in section 3, while section 4 is devoted to the conclusions.

2. First data and first measurements

Understanding unprecedented and complex detectors like ATLAS [3] and CMS [4] in the harsh LHC environment will require a lot of time and a lot of data. Although huge experience has been gained in the pre-collision phase [5] with test-beam activities and cosmics runs, the final commissioning of the experiments, from basic debugging to the level of performance required by the LHC physics goals, can only be addressed in situ with pp data.

We note that understanding the detectors and measuring the main SM physics processes must proceed hand in hand, since the two aspects are highly correlated. Therefore, the most urgent goals to address as soon as first collisions become available are the following.

1. Commission the detectors and triggers in the LHC environment, as well as tune the software tools (e.g. simulation, reconstruction). At the very beginning, minimum-bias and QCD jet production will provide huge samples for a first shake-down of the experiments and first calibration and alignment campaigns. Later on, more constraining physics channels, such as the gold-plated $Z \rightarrow \ell\ell$, will be used for more detailed studies, e.g. to set the absolute electron and muon energy scales of the electromagnetic calorimeters (ECALs) and tracking detectors respectively. As another example, $t\bar{t}$ events can be used to establish the absolute jet energy scale and to understand the b-tagging performance of the inner detectors.

2. Perform extensive measurements of the main SM physics processes at $\sqrt{s} = 14 \text{ TeV}$, e.g. cross-sections and event features for minimum-bias, QCD di-jet, $W$, $Z$, $t\bar{t}$ production, etc, to be compared to the predictions of Monte Carlo simulations. Typical initial precisions may be 10–20% for cross-section measurements, perhaps 7–10 GeV on the top-quark mass, and will likely be limited by systematic uncertainties already with integrated luminosities as low as 100 pb$^{-1}$. These measurements are important on their own, but also because processes like $W/Z + \text{jets}$, $t\bar{t}$ and QCD multi-jet production are omnipresent backgrounds to a large number of new physics channels.

This phase will take time but is crucial to prepare a solid road to discovery.

2.1. The 2007 run at $\sqrt{s} = 900 \text{ GeV}$

Figure 1 shows the numbers of events per experiment expected from several SM physics processes, as a function of the number of days of data taking at $\sqrt{s} = 900 \text{ GeV}$. An instantaneous luminosity $L = 10^{29} \text{ cm}^{-2} \text{s}^{-1}$, as foreseen by the LHC machine team, has been assumed. A total overall data taking efficiency of 30% (taking into account both machine and detector down-time) has been included, as well as trigger and event selection efficiencies for the individual channels. Hence, the numbers of events shown in figure 1 give the size of the data samples actually available for detector and physics studies.
Two main conclusions can be drawn. Firstly, in only a few days of data taking ATLAS and CMS could collect millions of minimum-bias events, as well as $\sim 10^5$ jets with transverse momentum $p_T$ above 15 GeV (of these, 1–2% are expected to come from the fragmentation of $b$-quarks). With these data, the experiments should be able to undertake first calibration, alignment and performance studies of the full initial detectors and make some physics measurements (QCD jet cross-sections, features of minimum-bias events, structure of the underlying event in di-jet production, etc). These physics measurements in an energy range already explored should in turn return useful feedback about the detector behaviour (e.g. the tracking reconstruction efficiency) and on the adequacy of the software tools. Secondly, very few events containing high-$p_T$ leptons will be produced in this first low-energy run, even in the very optimistic case of several weeks of data taking (at most a few hundred $J/\Psi \rightarrow \mu\mu$, $Y \rightarrow \mu\mu$ and a handful of $W \rightarrow e\nu$, $Z \rightarrow \ell\ell$ events). These samples are perhaps sufficient to observe some of these particles, but too small to allow detailed studies of e.g. the absolute momentum scale of the tracking detectors.

An example of the potential use of the 2007 data is discussed in section 2.3.

2.2. First data samples at $\sqrt{s} = 14$ TeV

Collisions at $\sqrt{s} = 14$ TeV will become available in summer 2008. Figure 2 shows the expected numbers of events in ATLAS, after all analysis cuts and as a function of integrated luminosity, for some basic SM processes, the so-called ‘candles’: leptonic $W$ and $Z$ decays and semi-leptonic $t\bar{t}$ final states. It can be seen that with only 100 pb$^{-1}$, which can be collected in a few days of data taking at an initial luminosity $L \sim 10^{32}$ cm$^{-2}$ s$^{-1}$, samples of $10^6$ $W \rightarrow e\nu$, $\mu\nu$ are expected, as well as $\sim 10^5$ $Z \rightarrow ee$, $\mu\mu$ and almost 1000 $t\bar{t} \rightarrow b\ell\nu bjj$. These samples are comparable in size to those recorded so far by the Tevatron experiments CDF and D0, hence very interesting detector and physics studies shall be performed with so much (or even less) integrated luminosity. Some examples are discussed below.
2.3. Understanding the detector performance

An illustration of the detector performance to be expected on ‘day one’, i.e. at the moment when data taking will start, is presented in table 1. These predictions are based on construction specifications and quality checks, on the known precision of the hardware calibration and alignment systems, on test-beam measurements and on simulation studies. The initial uniformity of the ECALs should be at the level of 1% for the ATLAS liquid-argon calorimeter and 3% for the CMS crystals, where the difference comes from the different technologies and from the limited time available to CMS for test-beam measurements. Prior to data taking, the jet energy scale may be established to about 10% from a combination of test-beam measurements and simulation studies. The tracker alignment in the transverse plane is expected to be known at the level of 20 \( \mu m \) in the best case from surveys, from the hardware alignment systems, and from studies with cosmic muons.

This performance should be significantly improved as soon as the first data become available (see last column in table 1) and, thanks to the huge LHC event rates, the ultimate statistical precision should be achieved in principle after a few weeks of data taking. Then the painful battle with the systematic uncertainties will start.

The strategy to calibrate the ATLAS and CMS ECALs is discussed here as an example (the alignment procedure of tracking devices is described in [6]).

One of the most stringent requirements for the LHC ECALs is to provide a mass resolution of about 1% in the hundred GeV range, needed to observe a possible \( H \rightarrow \gamma \gamma \) signal as a narrow peak on top of the huge \( \gamma \gamma \) irreducible background (see section 3.3). This demands a response uniformity, i.e. a channel-to-channel intercalibration, at the level of \(~0.5\%\) over the
Table 1. Examples of expected ATLAS and CMS detector performance at the time of the LHC start-up, and of physics samples which will be used to improve this performance.

| Expected performance on ‘day one’ | Data samples (examples) to improve the performance |
|-----------------------------------|---------------------------------------------------|
| ECAL uniformity (∼1% (∼3%) in ATLAS (CMS)) | Minimum-bias, $Z \rightarrow ee$ |
| Electron energy scale (∼2%) | $Z \rightarrow ee$ |
| HCAL uniformity (3%) | Single pions, QCD jets |
| Jet energy scale (≤10%) | $Z(\rightarrow \ell\ell) + jet$, $W \rightarrow jj$ in $t\bar{t}$ events |
| Tracker alignment (20–200 $\mu$m in $R\phi$) | Generic tracks, isolated $\mu$, $Z \rightarrow \mu\mu$ |

full calorimeter coverage ($|\eta| < 2.5$). Achieving this goal is challenging, and can hopefully be accomplished through the steps outlined below.

The CMS barrel ECAL consists of about 61000 crystals arranged in 36 super-modules. The intrinsic crystal-to-crystal response non-uniformity is ∼8%, coming mainly from variations in the scintillation light yield. Laboratory characterization of the individual crystals during assembly, test-beam measurements of six super-modules with high-energy electron beams, as well as pre-calibration of all of the super-modules with cosmic muons will allow this non-uniformity to be reduced to about 3% before data taking starts. The latter is therefore the initial performance to be expected on ‘day one’ (see table 1).

A further step toward the ∼0.5% intercalibration goal can be achieved with the 2007 data. The barrel ECAL can be divided into 170 $\eta$-rings (where $\eta$ is the pseudorapidity), each one containing 360 crystals. The crystals belonging to a given ring can then be intercalibrated by taking advantage of the azimuthal ($\phi$) symmetry of the energy deposited by physics events. The left panel in figure 3 shows that, by measuring the azimuthal energy flow in about 18 million minimum-bias events (which in principle can be recorded in a few days of data taking in 2007), the crystal-to-crystal response variation should be further reduced from the initial 3% to about 1.5% for rings in the central part of the barrel. Hence the systematic limit coming from the inhomogeneity of the upstream tracker material (which increases with rapidity) will be hit rather quickly.

The ring-to-ring intercalibration requires more data and a ‘calibration sample’ like $Z \rightarrow ee$ events, where the $Z$ mass provides a precise energy-scale constraint. The right panel in figure 3 shows that the barrel part of ECAL should be intercalibrated to a close-to-the-goal level of ∼0.6% with 2 fb$^{-1}$ of data, i.e. hopefully by mid 2009.

The ATLAS ECAL is a lead–liquid argon detector consisting of about 200000 channels. Tight construction specifications, e.g. on the thickness of the absorber plates and of the liquid-argon gaps, and on the uniformity of the pulses delivered by the electronics calibration system, ensure that the detector is uniform ‘by construction’ to about 2%. This has been verified with test-beam measurements of 15% of the final calorimeter modules (the module size in the barrel is $\Delta \eta \times \Delta \phi = 1.4 \times 0.4$, for a total of about 3000 electronic channels) performed with high-energy electron beams. For all tested modules, the response non-uniformity was found to be about 1.5% initially, i.e. at the end of the construction chain, and better than 0.5% (0.6%) in the barrel (end-caps) after calibration with test-beam data (see figure 4). In the complete experiment, response variations from module to module, as well as other sources of non-uniformities (coming e.g. from...
**Figure 3.** Left panel: crystal-to-crystal intercalibration precision of the CMS ECAL [7] achievable with 18 million minimum-bias events, as a function of rapidity (open circles). The dots show the limit coming from the inhomogeneity of the upstream material. Right panel: ring-to-ring intercalibration precision achievable in the barrel CMS ECAL [4] as a function of the average number of $Z \rightarrow ee$ events per ring (370 events correspond to an integrated luminosity of 2 fb$^{-1}$).

the upstream material), will be corrected *in situ* using $Z \rightarrow ee$ events. Detailed studies [3] indicate that, since the calorimeter is quite uniform already on ‘day one’ for the reasons mentioned above, a sample of 10$^5 Z \rightarrow ee$ events, which should become available with an integrated luminosity of $\sim$200 pb$^{-1}$ (see figure 2), should be sufficient to intercalibrate the full detector to the required few permil level.

2.4. Examples of first physics measurements

Thanks to the huge LHC centre-of-mass energy, large samples of interesting data should become available after only a few weeks of operation in 2008, as shown in figure 2. We note that for some SM physics processes ten days of data taking at the LHC at $L = 10^{32}$ cm$^{-2}$ s$^{-1}$ correspond, in terms of event statistics, to ten years of operation at previous machines.

On the theoretical and phenomenological side, a lot of progress has been made recently, so that for instance the production cross-sections for $W$, $Z$, $t\bar{t}$ events, the three ‘candles’ to be measured at the beginning, are known today to the few-percent level. Furthermore, the recent developments of matrix-element Monte Carlo generators (e.g. Alpgen [9], MC@NLO [10]) consistently interfaced to parton-shower packages have marked big improvements in the agreement between the Tevatron data and the theory prediction for processes like $W +$ jets production. This is very encouraging for the preparation of LHC physics, since $W +$ jets, $Z +$ jets, $t\bar{t} +$ jets are omnipresent backgrounds to most searches for new physics.

In contrast, other processes are much less well known today, in particular the basic process, generic pp collisions (minimum-bias events), because these are a mixture of soft and hard physics.
Figure 4. Energy response of three modules of the ATLAS barrel ECAL, as a function of the hit cell number in the $\eta$-direction, as measured from a position scan with high-energy test-beam electrons [8]. The various symbols indicate different $\phi$ rows.

This is illustrated in figure 5, which shows the multiplicity of charged particles at $\eta = 0$, as a function of the machine centre-of-mass energy. The extrapolation of existing measurements to the LHC energy using phenomenological models which all reproduce the lower-energy data indicates an uncertainty of more than 50% on the LHC prediction. Larger uncertainties are expected from other models. However, minimum-bias events are good candidates to very early measurements at the LHC. A sample of $\sim 10^4$ events, which can be recorded in a few hours of data taking, is sufficient, in terms of statistics, to measure the charged particle multiplicity and spectra with enough precision to understand the basic features of generic pp collisions and to discriminate between different models.

QCD jets are also abundantly produced at the LHC, thanks to the huge enhancement of the low-x gluon structure function at 14 TeV. Access to the TeV energy range will be possible already with an integrated luminosity of only 100 pb$^{-1}$, since a few hundred events with $p_T$ (jet) $\geq$ 1 TeV are expected in such a data sample.

With 100 pb$^{-1}$, the $W$ and $Z$ cross-sections should be determined with a precision of $\sim 10\%$ (dominated by the uncertainty on the knowledge of the absolute luminosity). Furthermore, measurements of angular distributions of leptons from $W$ and $Z$ decays, which can be made with an experimental precision of $\sim 4\%$ with 100 pb$^{-1}$ of good data, should improve the existing...
Figure 5. Average charged particle multiplicity at $\eta = 0$ in minimum-bias events, as a function of centre-of-mass energy [11]. The symbols indicate experimental measurements, the curves are the predictions of different models.

Constraints on parton distribution functions (PDFs), in particular on the gluon distribution at low $x$, and therefore provide discrimination among the presently-allowed sets of PDFs [12].

As another example of initial measurement of SM physics, it has been shown [13] that a $t\bar{t}$ signal can be observed with few pb$^{-1}$ of data, with a simple analysis and a detector still in the commissioning phase. In turn such a signal can be used to improve the knowledge of the detector performance and physics. The feasibility of this early measurement is due to the large cross-section (≈250 pb) for the gold-plated semileptonic $t\bar{t} \rightarrow b\ell\nu bjj$ channel (where $\ell = e, \mu$) and the clear signature of these events. A simple analysis [14], based on a sample of $t\bar{t}$ events fully simulated with GEANT4, required an isolated electron or muon with $p_T > 20$ GeV, large missing transverse energy, and four and only four jets with $p_T > 40$ GeV in the final state. The additional constraint that two of the jets have an invariant mass compatible with the $W$ mass was imposed. The resulting mass spectrum of the three jets giving the highest $p_T$ of the top quark is presented in figure 6. It should be noted that no b-tagging of two of the jets was required, assuming (conservatively) that the performance of the vertex detector would not be well understood at this early stage. Figure 6 shows that, even in these pessimistic conditions, a clear top signal should be observed above the background. An integrated luminosity of less than 30 pb$^{-1}$, which should be collected by summer 2008, would be sufficient to this purpose.

An initial top sample will be a very useful tool to understand several aspects of the detector performance. For example, the two b-jets in the final state can be used to study the efficiency of the b-tagging procedure, and the jet energy scale of the experiment can be established in a preliminary way from the reconstructed $W \rightarrow jj$ mass peak.
Figure 6. Three-jet invariant mass distribution for events selected as described in the text, as obtained from a full simulation of the ATLAS detector. The dots with error bars show the expected signal from $t\bar{t}$ events plus the background, the dashed curve indicates the background alone. The number of events corresponds to an integrated luminosity of $50\text{ pb}^{-1}$. Courtesy of W Verkerke.

Furthermore, with a few hundred pb$^{-1}$ of data, the top-quark production cross-section could be initially measured with a precision of $\sim 20\%$ and the mass to 7–10 GeV (whereas the ultimate LHC precision is expected to be $\sim 1\text{ GeV}$). Also, the $p_T$ spectrum of the top quark is very sensitive to higher-order QCD corrections, and this feature can be exploited to test the theory and tune the Monte Carlo generators.

3. Opportunities for ‘early’ discoveries

Only after the steps outlined in section 2 have been fully addressed, can the LHC experiments hope to extract convincing signals of new physics from their data. Three examples are discussed below, ranked by increasing difficulty for discovery in the first year(s) of operation: an easy case, namely a graviton decaying into an $e^+e^-$ pair; an intermediate case, supersymmetry (SUSY); and a difficult case, a light SM Higgs boson.

3.1. Extra-dimension gravitons

A narrow resonance of mass about 1 TeV decaying into $e^+e^-$ pairs, such as the gravitons ($G$) predicted by Randall–Sundrum extra-dimension theories [15], is probably the easiest object to discover at the LHC. Indeed, if the couplings to SM particles are reasonable, and branching ratios for decays into electron pairs are minimally at the percent level, large enough signals are
expected with integrated luminosities of less than 1 fb$^{-1}$ for masses up to $\sim 1$ TeV. In addition, the signal would appear as a narrow mass peak on top of a much smaller, smooth and well-known Drell–Yan background, as shown in figure 7, and not just as an excess of events in the tails of a distribution.

Understanding the nature of the observed resonance, e.g. whether it is a graviton or a heavy gauge boson $Z'$, will require more time. It has been shown [17] that, with an integrated luminosity of 100 fb$^{-1}$, the angular distribution of the electron pairs in the final state can provide discrimination between a spin-1 $Z'$ and a spin-2 graviton.

3.2. Supersymmetry

If SUSY has something to do with stabilizing the Higgs mass, new particles are expected at the TeV scale, and some of them (e.g. squarks and gluinos) could be discovered rather quickly. This is because of the huge production cross-section at 14 TeV for squarks and gluinos, which are strongly-interacting particles, with about ten events per day expected in each experiment at instantaneous luminosities of only $10^{32}$ cm$^{-2}$ s$^{-1}$ and for squark/gluino masses as large as $\sim 1$ TeV. In addition, cascade decays of (heavy) squarks and gluinos should give rise to clear-signature final states, containing several high-$p_T$ jets, leptons and, in $R$-parity conserving models, large missing transverse energy coming from the escaping stable neutralinos ($\chi_1^0$). Figure 8 shows that with only 100 pb$^{-1}$ of data, and provided the detectors and the numerous backgrounds are well understood (see below), ATLAS and CMS should be able to discover gluinos up to masses beyond 1 TeV, whereas the ultimate LHC reach extends up to masses of 2.7 TeV. Rather quickly, therefore, the LHC could provide indications about the energy scale and spectrum of new physics, and therefore about the needed energy of future colliders. Indeed, if squarks and gluinos are
discovered at the LHC with only 100 pb$^{-1}$, SUSY is relatively light, therefore a good part of the spectrum (e.g. charginos, neutralinos, sleptons) should be accessible for detailed measurements at a 1 TeV International Linear Collider (ILC) [19]. On the other hand if nothing is found at the LHC with 100 pb$^{-1}$ of well-understood data, it is likely that SUSY, if it exists at all, is too heavy to be detected at an ILC because, under the assumption of gaugino-mass unification, the lightest supersymmetric particle (the lightest neutralino $\chi^0_1$) would be heavier than 300 GeV, as shown in figure 8.

It should be noted that understanding the detectors and the backgrounds at the level needed to discover SUSY will take time, and will likely require a larger amount of data than 100 pb$^{-1}$. Techniques to reject fake sources of missing transverse energy coming from instrumental effects, as well as to measure backgrounds from SM processes using ‘control’ samples from the data themselves, have been successfully developed and deployed by the Tevatron experiments. Studies of similar methods by the LHC experiments indicate that 1 fb$^{-1}$ of data or less should be sufficient to control these backgrounds at the required level (see [3] and [4] for more details). Therefore it may be possible to extract a convincing SUSY signal at the LHC by the end of 2008.

3.3. Standard model Higgs boson

Figure 9 shows the integrated luminosity per experiment, as a function of the Higgs boson mass, needed to discover a possible Higgs signal (5$\sigma$ excess required) or to exclude it at the 95% CL.
by combining both experiments. Two conclusions can be drawn from these projections. Firstly, with a few fb\(^{-1}\) of well-understood data the LHC can say the final word about the SM Higgs mechanism, i.e. discover the Higgs boson or exclude it over the full allowed mass range.

Secondly, ignoring masses much larger than 200 GeV, which are disfavoured by the present electroweak data (the Winter 2007 fit, including the LEP2 direct mass limit and the most recent measurements of the \(W\) and top-quark masses from the Tevatron, gives \(m_H < 182\) GeV at the 95% CL), two regions can be identified. If the Higgs mass is around 180 GeV (or larger), discovery should be easier thanks to the gold-plated \(H \rightarrow 4l\) channel. As shown in figure 10, the expected signal sample is tiny for integrated luminosities of a few fb\(^{-1}\), but these events are very pure (since the background is small) and should cluster in a narrow mass peak. About 1 fb\(^{-1}\) of data could be enough for discovery, combining both experiments and provided that the detectors are well understood. This may well happen by mid 2009.

If, on the other hand, the Higgs mass is around 115–120 GeV, i.e. just above the experimental lower limit set by LEP, more luminosity is needed and observation of a possible signal is less straightforward. This is because in this mass region the experimental sensitivity is equally shared by three different channels (\(H \rightarrow \gamma\gamma\), \(t\bar{t}H\) production with \(H \rightarrow b\bar{b}\), and Higgs production in vector-boson fusion followed by \(H \rightarrow \tau\tau\)) which all require close-to-ultimate detector performance and a control of the huge backgrounds at the few percent level. As mentioned in section 2.3, a response uniformity of the ECAL of \(\sim 0.5\)\% is needed to extract a narrow \(H \rightarrow \gamma\gamma\) mass peak on top of the huge irreducible \(\gamma\gamma\) background. Powerful b-tagging is the key performance issue for the \(t\bar{t}H\) channel, because there are four b-jets in the final state which all need to be tagged in order to reduce the background. Finally, efficient and precise jet reconstruction over ten rapidity units (\(|\eta| < 5\)) is required for the \(H \rightarrow \tau\tau\) channel,
Figure 10. The expected $H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$ signal in CMS [4] for a Higgs mass of 200 GeV on top of the backgrounds, for an integrated luminosity of 5.8 fb$^{-1}$. The results of one simulated experiment are shown as dots.

since tagging the two forward jets accompanying the Higgs boson and vetoing additional jet activity in the central region of the detector are necessary tools to suppress the background. In conclusion, convincing evidence for a very light ($m_H \lesssim 120$ GeV) SM Higgs boson at the LHC is not likely to come before the end of 2009.

4. Conclusions

The LHC will start operation in about one year, and particle physics will enter a new epoch, hopefully the most glorious and fruitful of its history. Given the compelling motivations for new physics in the TeV region, coming mainly from the SM being incomplete already at this energy scale, one can anticipate a profusion of exciting (and perhaps unexpected . . .?) results from a machine able to explore the TeV region in detail.

Accelerator and experiments of unprecedented complexity, technology and performance are needed to achieve this goal. Installation and commissioning of these instruments are progressing at full speed, marked almost weekly by impressive achievements, toward first collisions at $\sqrt{s} = 900$ GeV at the end of 2007 and at $\sqrt{s} = 14$ TeV in the second half of 2008.

With the very first pp data at 14 TeV (a few to a few hundred pb$^{-1}$) the most urgent tasks will be: to commission the detectors, as well as the trigger, software and computing systems; to understand SM physics at $\sqrt{s} = 14$ TeV; to measure the main backgrounds to possible new physics processes.

More excitingly, the LHC could offer major discoveries already in the first one-to-two year(s) of operation, depending mainly on what scenario nature has chosen and on the machine luminosity performance. TeV-scale gauge bosons and SUSY may be found rather quickly, whereas a light Higgs boson could be observed by mid-end 2009. Hence, first indications of the scale and shape of new physics may well become available by the end of 2009.

With more time and more data, the LHC will be able to explore the highly-motivated TeV scale in detail, with a direct discovery potential up to particle masses of $\sim5$–6 TeV. Hence, it
will provide definitive answers about the SM Higgs mechanism, SUSY, and other TeV-scale predictions that have resisted experimental verification for decades. Perhaps more importantly, the LHC will likely tell us which are the right questions to ask and what is the best strategy for the future of our field.

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