

LHC Detectors: Commissioning and Early Physics

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Abstract. After a machine-commissioning phase in summer 2008, the Large Hadron Collider (LHC), 27 km long, at CERN (Geneva/Switzerland) will begin colliding protons at a center-of-mass energy of 14 TeV, becoming the world's highest energy particle collider. The main goals of the LHC are the search for the Higgs boson, the last particle remaining undiscovered of the standard model of particle physics, and the search for physics "beyond the standard model". This report summarizes the commissioning challenges of the major experiments and highlights some of the early physics prospects of the LHC.

1. Introduction

The Large Hadron Collider (LHC) is a proton-proton collider with a center of mass energy of 14 TeV and a design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Beam crossings are 25 ns apart and at design luminosity there are on average 23 interactions per crossing. 10 fb^{-1} of integrated luminosity are expected to be collected in a year of data taking at the initial low ($10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) luminosity and 100 fb^{-1} in a year of data taking at the nominal one. To support the 7 TeV proton beams, 1,232 8.4 Tesla superconducting dipoles and 736 quadrupoles are installed in the underground tunnel, whose circumference is 26.6 km. Installation of the dipoles magnets in the tunnel was completed in March 2007. The interconnecting of the magnets and installation of other components will take up the rest of the year. A first octant sector has been cooled down to 1.9 degrees Kelvin. According to the new machine schedule [1], the machine will be completed by April 2008 and the first collisions at 14 TeV are expected in early summer 2008.

The physics potential of the LHC is unprecedented. It will allow scientists to study the TeV scale region directly and in detail. The LHC is expected to elucidate the electroweak symmetry breaking mechanism (EWSB) and provide evidence of physics beyond the standard model (SM). Besides the direct searches for physics beyond the SM, precision studies of the heavy-flavor sector could lead to indirect evidence of new physics, for example through an enhancement of otherwise very rare decays. In particular, the very copious production of Bs mesons will make it possible to complement the measurements at the B factories currently in operation. The flavor-mixing parameters that appear in the Cabbibo-Kobayashi-Maskawa (CKM) matrix will be measured using several decay channels, leading to a better understanding of CP violation in the B sector. Finally, the LHC will also make it possible to cause heavy ions to collide. The unprecedented energy densities achieved in these collisions are expected to lead to the formation of new forms of partonic matter, most notably a quark-gluon plasma. The properties of this new state of matter, as well as the phase transition to hadronic matter, will be the subject of intense research.

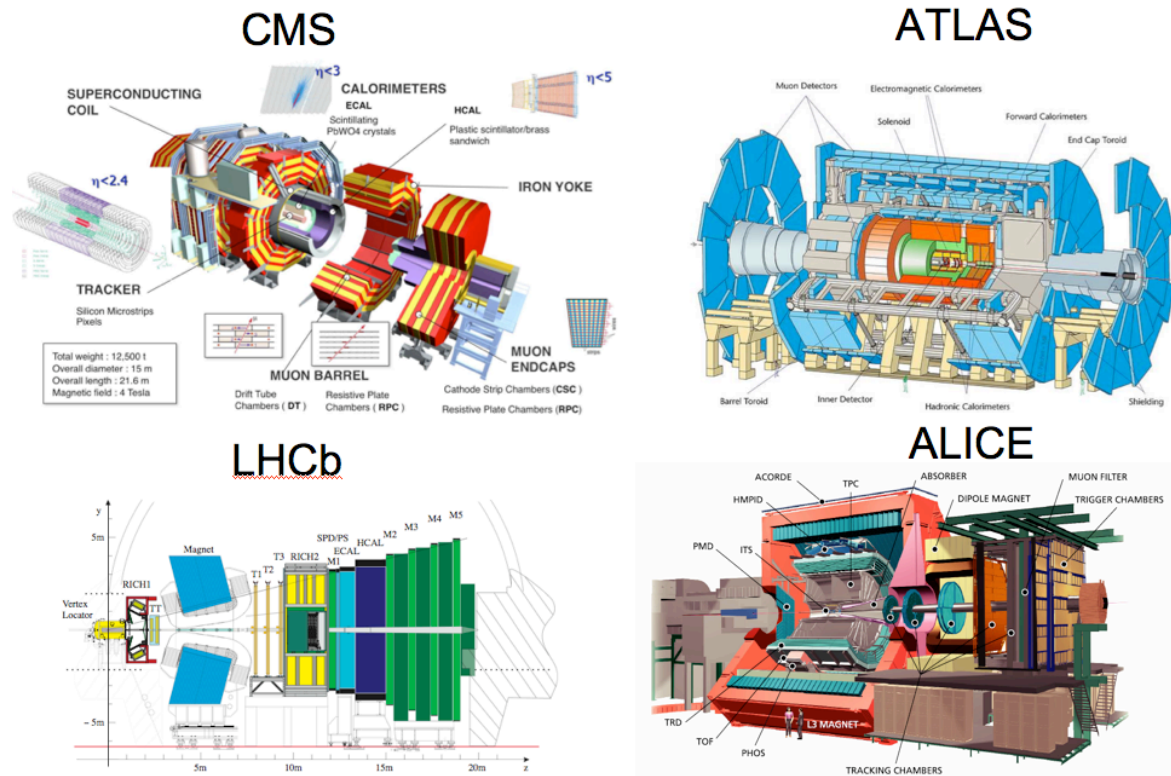


Figure 1. Schematic views of the CMS, ATLAS, LHCb, and ALICE detectors

2. LHC Experiments

The physics program of the LHC will be pursued by six experiments: ALICE[2], ATLAS[3], CMS[4], TOTEM[5], LHCb[6], and LHCf. The core of the program consists of two general-purpose detectors (ATLAS and CMS) and the two special-purpose experiments ALICE (heavy-ion physics) and LHCb (b physics). The installation schedules of the experiments are consistent with the machine schedule outlined in [1]. It is expected that all important detector components will be installed in time for the start-up of the LHC machine in the summer of 2008. In the following, I present a brief overview of the detector design of the four major LHC experiments.

2.1. The CMS Detector

A schematic drawing of the Compact Muon Solenoid Experiment (CMS) is shown in Figure 1. The total weight of the apparatus is 12,500 tons. The detector, which is cylindrical, has a length and diameter of 21.6 m and 14.6 m, respectively. The overall size is set by the muon tracking system, which in turn makes use of the return flux of a 4 Tesla superconducting solenoid 13 m long and 5.9 m in diameter. The core of the magnet coil is also large enough to accommodate the inner tracker and the calorimetry inside. The tracking volume is given by a cylinder 5.8 m long and 2.6 m in diameter. To deal with high-track multiplicities, CMS employs 10 layers of silicon-microstrip detectors, which provide the required granularity and precision. In addition, three layers of silicon pixel detectors are placed close to the interaction region to improve the measurement of the impact parameter of charged-particle tracks and the position of secondary vertices. The EM calorimeter (ECAL) uses lead tungstate (PbWO_4) crystals with coverage in pseudorapidity of up to $|\eta| < 3.0$. The ECAL is surrounded by a brass/scintillator sampling hadron calorimeter with coverage up to $|\eta| < 3.0$. This central calorimetry is complemented by a “tail catcher” in the barrel region. Coverage up to a pseudorapidity of 5.0 is provided by an iron/quartz-fiber calorimeter. The Cerenkov light emitted in the quartz fibers is

detected by photomultipliers. The forward calorimeters ensure full geometric coverage for the measurement of the transverse energy in the event.

2.2. The ATLAS Detector

ATLAS stands for “a toroidal LHC apparatus.” With a length of 46 m and a diameter of 25 m, ATLAS is the largest of all LHC experiments. Like CMS, ATLAS is a general purpose detector with the following features: very good calorimetry, including electron and photon identification and measurement, Jets, and MET reconstruction; high precision muon momentum measurement; efficient tracking at high luminosities for lepton momentum measurements, electron ID and photon ID, and heavy-flavor ID; and triggering and measurement at low-pt thresholds. Although ATLAS is similar to CMS in performance and physics goals [7–10], the technical design chosen for each detector is somewhat different [3, 4]. Figure 1 shows a schematic view of the ATLAS detector.

2.3. The LHCb Detector

LHCb is the Large Hadron Collider experiment for precision measurement of CP violation and rare decays of beauty particles. Figure 1 shows the layout of the LHCb detector. The basic composition of the spectrometer remains unchanged from that of the Technical Proposal [5] produced in 1998. It consists of the dipole magnet, beam pipe, Vertex Locator, tracking system, and two Ring Imaging Cherenkov detectors (RICH-1 and RICH-2) with three radiators, a calorimeter system, and a muon system.

2.4. The ALICE Detector

The ALICE detector is designed to fully exploit the heavy ion operation of the LHC. It is installed in the former L3 cavern and re-uses the L3 magnet system. Its main element is a big-time projection chamber of approximately 90 m³, which will allow the reconstruction of several thousand tracks per unit of rapidity. Further emphasis is given to particle identification. Figure 1 shows a schematic view of the ALICE detector.

3. Commissioning of the Experiments

The commissioning of the LHC machine and detectors of unprecedented complexity, technology, and performance will be one of the biggest challenges in the next year. Only with well-commissioned experiments will it be possible to open the door to the new physics world.

All experiments are expected to be ready by the summer of 2008. Once they are fully installed in the underground cavern, a comprehensive program of commissioning has to be carried out in order to optimize the detector’s performance and prepare it for an optimal exploitation of its physics potential. The main commissioning goals of the experiments are (1) efficient operation of the trigger and DAQ; (2) tracker and muon alignment; and (3) calorimeter calibration. Once these goals are achieved, the commissioning of higher-level physics tools and objects such as b-tagging, jets, and missing E_T can proceed. With enough physics, cosmics and beam-halo/gas events can be accumulated, and many important commissioning tasks can even be performed during the very early startup phase. Trigger and DAQ can be timed in and synchronized and their data integrity can be checked. The trigger algorithms can be debugged and improved. Calorimeter systems can be calibrated to $\sim 2\%$. Tracks from cosmic and beam halo muons as well as collision tracks can be used to align the silicon-based tracking systems and the muon detectors.

From a general commissioning point of view, three distinct phases can be identified, which give access to complementary data sets (see also 11 for more information):

- **No beams:** Accumulation of large samples of cosmic muons, which are very beneficial for tracker and muon barrel alignment, for example.
- **Single beams:** Single beams give rise to beam halo muon and beam-gas events. The near-horizontal beam halo muons can be used for tracker and muon end-cap alignment. Beam-gas interactions can be used for various commissioning tasks.
- **Colliding beams:** LHC collisions will provide a cocktail of physics events, depending on the specific luminosity. For commissioning purposes, muons and electrons from W, Z decays, minimum bias, and QCD jet events are useful.

Parts or all of the installed sub-detectors can be commissioned and pre-calibrated well before the first LHC collisions. For example, cosmic-ray muons will be used by all detectors to obtain initial alignment and calibration constants, mainly for the barrel parts. These muons are also very useful for debugging and mapping dead-channels.

An example of a comprehensive pre-collision commissioning campaign is the Magnet Test and Cosmic Challenge (MTCC) of the CMS experiment.

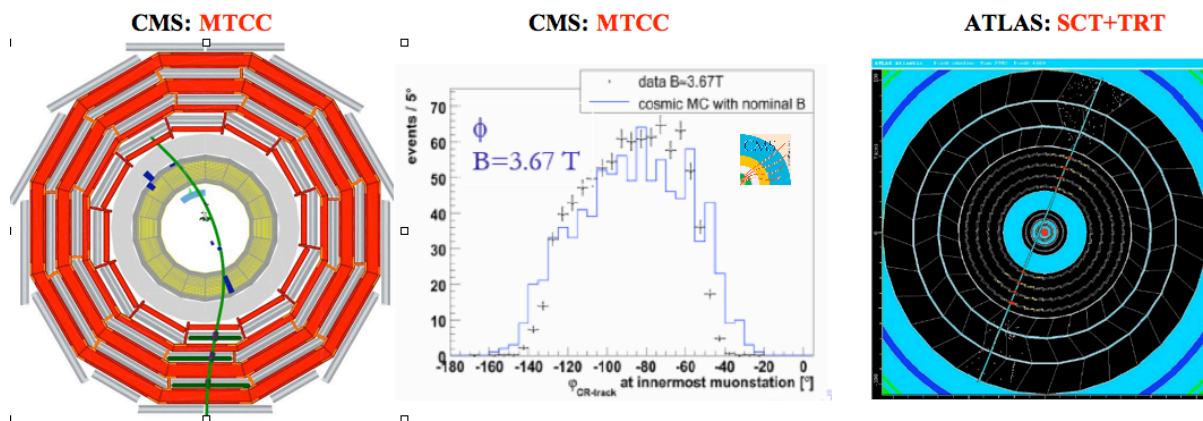


Figure 2. Left: characteristic event display of a cosmic muon that left signatures on all four active CMS detector elements (tracker, ECAL, HCAL, and the muon detector). Middle: comparison of cosmic Monte Carlo with data recorded during the CMS MTCC. Right: cosmic muon traversing the ATLAS inner tracking system.

The objective of the MTCC was the recording, offline reconstruction, and display of cosmic muons in the four subsystems of CMS (tracker, ECAL, HCAL and muon detector) with the magnet operating at its full strength of 4T. During the test, 25 million cosmic triggered events were recorded with the principal subdetectors active, of which 15 million events have a stable field of ≥ 3.8 T. Data-taking efficiency reached over 90% for extended periods. Several thousand of these events correspond to the “4-detector” benchmark, and the whole data sample will provide useful understanding and calibration of the combined detector and software performance (see, e.g., Figure 2, middle plot). A characteristic event display of a cosmic muon that left signatures in all four active detector elements (tracker, ECAL, HCAL and muon detector) is shown in Figure 2 (left plot). The trajectory shown represents the measurement of the stand-alone muon reconstruction. In the inner detector, this trajectory coincides well with the ECAL, HCAL, and tracker measurements within the expected uncertainties, demonstrating that the propagation of the stand-alone muon information was successfully carried out. The MTCC was executed in the second half of 2006 and is a major milestone in the commissioning of the CMS experiment. It is also a very good example for the currently ongoing commissioning activities utilizing cosmic muons in the other experiments. Figure 2 (right plot) shows an example of a cosmic muon that traverses the ATLAS inner detector.

The final commissioning of the experiments will be carried out with collision data samples. During the early start-up phase of the machine, the available collision data will be completely dominated by minimum bias and QCD jet events. At most, a few hundred W, Z events can be expected in this very early phase. Once the luminosity approaches values of $> 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, we will see substantial rates of W^\pm , Z events. Large samples of high pT muons and electrons from these events can thus be accumulated within a short time and used for high-precision alignment and other precise commissioning tasks, among other things.

4. Early Physics

According to the current schedule of the machine, the first delivered luminosity will be around $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. At this point there will be no problem with pile-up, due to the lower bunch currents, and the trigger will have a large acceptance for all medium and high pT processes. However, even at a relatively low integrated luminosity, say 10 pb^{-1} , many di-jet, W, Z, and top quark events will have been recorded. At any energy and luminosity, soft hadronic interactions, often called “minimum bias” events, will be the most common types of event. Since they set the scale for background and reconstruction, measuring their properties will be the top priority for the experiments. In general, the understanding of the standard model (SM) processes will be crucial in the early search for new physics at the LHC. Therefore, a considerable effort will be invested to measure the SM processes precisely at the early days of machine operation. Only with a good understanding of the SM background will it be possible to proceed with the search for new physics at the LHC. In the following, I outline three important search activities that are broadly representative of the many analyses that will be carried out with the first ATLAS and CMS data ($\sim 1 \text{ fb}^{-1}$).

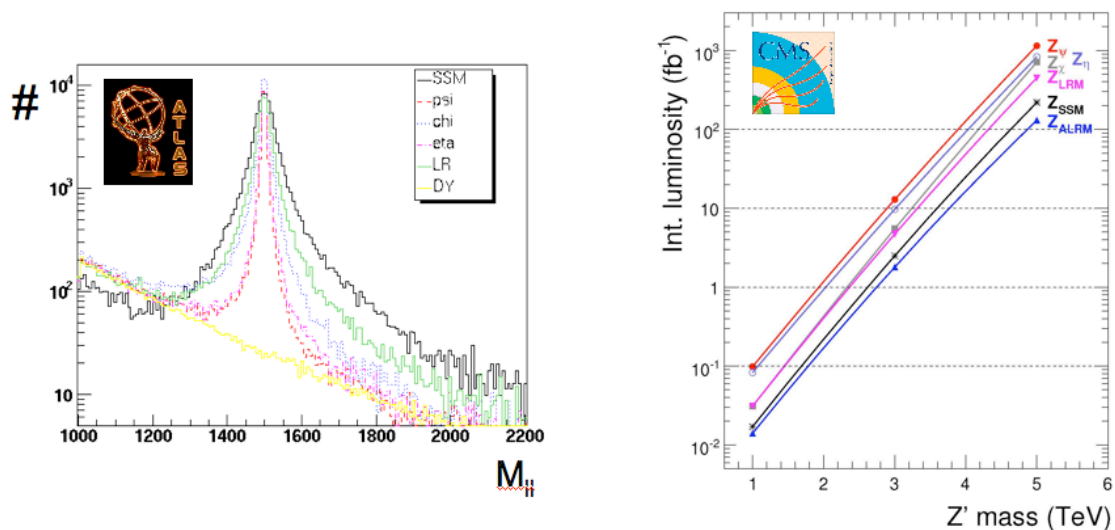


Figure 3. Z' resonance reconstructed with the ATLAS detector with an invariant mass of 1.5 TeV for various models (left plot). Integrated luminosity needed for a 5 sigma Z' discovery in CMS, plotted as a function of the Z' mass for different Z' models (right plot).

4.1. Di-lepton Resonances

One of the most promising signals for new physics in the first data is high mass lepton pairs. Such heavy resonances, here generically referred to as Z' , appear in models like the little Higgs model and the Randall-Sundrum model, or in universal extra-dimension models (just to name a few). If these new particles have SM-like couplings to lepton and quarks, then one expects sizable production cross-sections and branching ratios to e^+e^- and $\mu^+\mu^-$, resulting in very clear signatures above a low and well-defined Drell-Yan continuum background. The right plot in Figure 3 shows the invariant mass

distribution of various Z' models with a mass of 1.5 TeV. At only 100 pb^{-1} , a discovery of Z' with masses around 1 and 2 TeV is possible (see Figure 3, left plot). Once the existence of such a heavy resonance is established, it will be most exciting to analyze the subsequent data and discriminate between the various models that predict such an object. Possible approaches will be measuring forward-backward asymmetries in the case of a Z' or looking for other hints of extra dimensions, such as large amounts of missing energy or very energetic isolated photons.

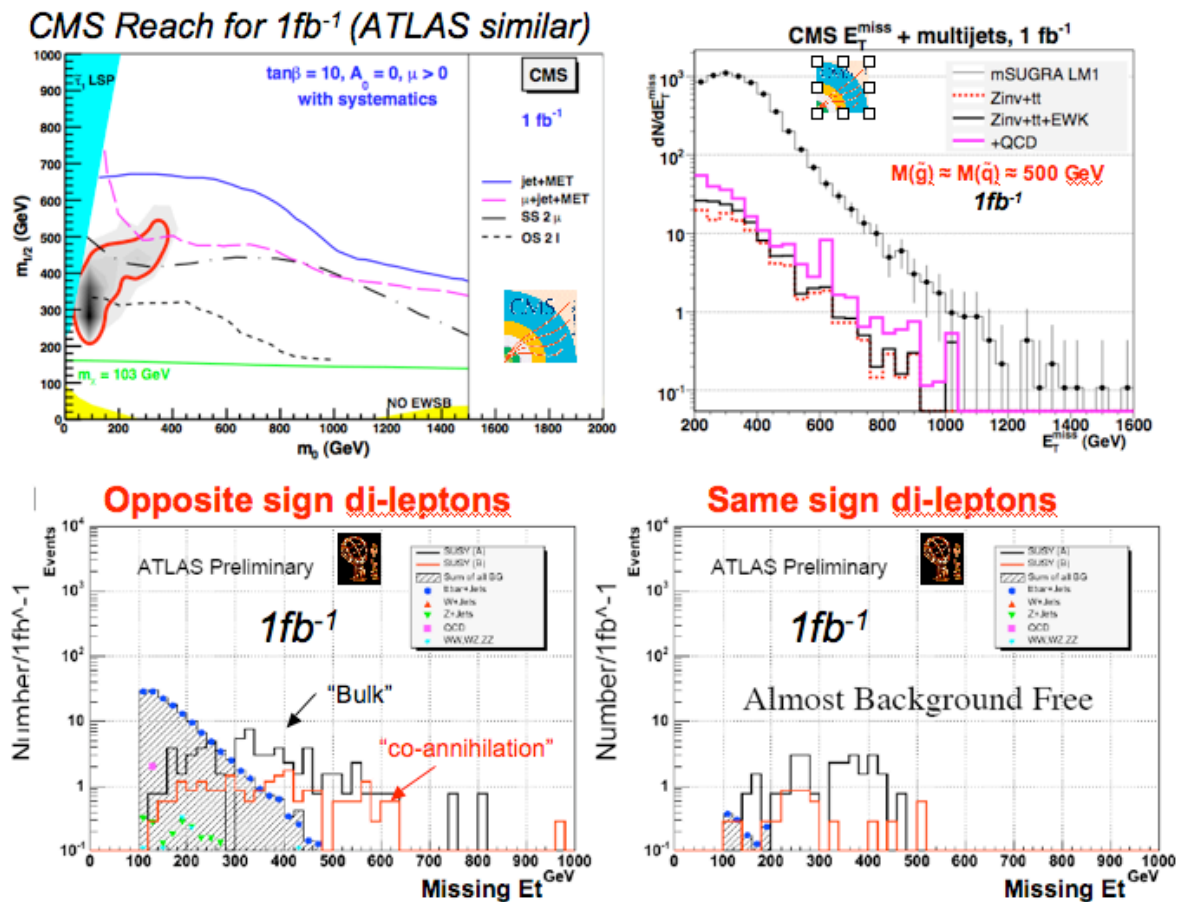


Figure 4. Regions of the m_0 - m_{12} plane showing the CMS SUSY reach. The dark region represents the preferred parameter space obtained from a fit to high-precision indirect constraints (top-left plot). SUSY (CMS benchmark point LM1) signal and SM background distribution for the search jets and missing transverse energy (top-right plot). Opposite-sign di-leptons (lower-left plot) and same-sign di-leptons (lower-right plot) signal and background distribution from ATLAS. All plots are for 1fb^{-1} .

4.2. Supersymmetry

Supersymmetry predicts that each known particle has a sparticle partner with the same couplings but a spin difference of $\frac{1}{2}$ (i.e., fermions have boson partners and vice versa). Low-energy supersymmetry leads one to expect these particles to be produced in present and future colliders. So far the Tevatron has not found any evidence for sparticles, but since their masses in the most conservative SUSY models are expected (at least in part) to be well below a few TeV, they should show up at the LHC. In fact they could show up very rapidly when the machine is turned on. Cross sections vary from about 100 pb to 10 fb for sparticle masses varying from 500 GeV to 1 TeV . Hence about $100,000$ to 10

sparticles can be produced with 1 fb⁻¹ of data. If the sparticle masses are below 1 TeV, then the first signatures could be observed in the very first years (2008, 2009) of LHC operation. A search for SUSY in early data must be robust (able to cope with background uncertainties and a non-optimal detector) and general yet efficient. Excellent opportunities exist in final states with high E_T jets and significant missing transverse energy. In order to suppress the QCD background and facilitate triggering, it is possible to further demand one or more high p_T leptons. Such final states typically arise in the decay chains of squarks and gluinos, which will be copiously produced at the LHC, if kinematically allowed. Standard model backgrounds to the SUSY search mainly stem from top quark-pair production, Z or W boson production in association with jets, and QCD jet production. Examples for jets, missing transverse energy, and 0,2 lepton distribution are shown in Figure 4. This figure (top-left plot) shows also the SUSY discovery reach of the CMS experiment for 1fb⁻¹. The dark region in this plot shows the “preferred” parameter region obtained from a fit of present precision data and heavy flavor variables within the constrained MSSM [12]. Clearly this region will be probed with the very first data.

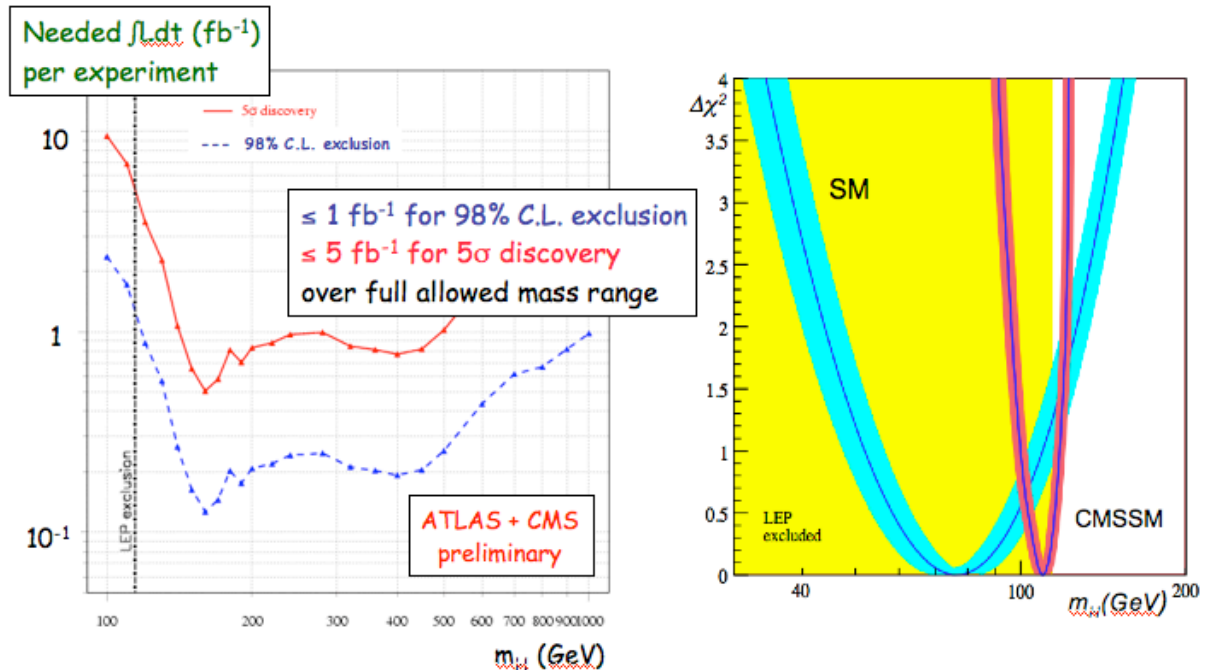


Figure 5. Combined ATLAS and CMS experimental search reach for the SM-like Higgs as a function of the Higgs mass (left plot). Indirect prediction of the Higgs boson mass in the SM [13] and the constraint MSSM [12] (right plot).

4.3. SM-like Higgs Boson

One of the key questions in particle physics is the origin of electroweak symmetry breaking. The most elegant explanation within the SM is a Higgs field with at least one scalar particle, the Higgs boson. The reach of the LHC search has been largely optimized for finding the SM-like Higgs particle or proving its non-existence. The combined experimental reach of ATLAS and CMS is shown in Figure 5 for the most significant channels. A few fb⁻¹ will suffice to discover the SM Higgs if the mass is around 165 GeV or if the mass of the Higgs is between 200 and 400 GeV/c². For Higgs masses around 114 to 130 GeV, around 10 fb⁻¹ will be needed to establish a discovery of this particle. In particular this low-mass region is very interesting because it is favored by many of the popular theoretical models. As shown in the right plot of Figure 5, not only the SM [13] but also the constraint MSSM [12] prefers Higgs-mass values below 150 GeV. A discovery of the Higgs boson in this mass region

will likely require a combination of several decay channels such as $H \rightarrow \gamma\gamma$, $t\bar{t}H \rightarrow b\bar{b}l\nu b\bar{b}j\bar{b}b$, and $q\bar{q}H \rightarrow q\bar{q}\tau\tau$. Therefore, a sound understanding of the corresponding backgrounds and detector performance will be crucial for a discovery (or proof of non-existence) of the SM-like Higgs boson at low mass.

5. Summary

The next few years will be very exciting for particle physics. In the summer of 2008 the LHC will start exploring the TeV energy scale for the first time, with a direct discovery potential up to several TeV. We may be able to discover new physics signatures at the LHC with the very first data. Furthermore, the hunt for the Higgs will finally come to an end but the potential of discovering it at the very early days of LHC operation will strongly depend on its mass. However, it is clear that eventually we will get an answer to this question, so long outstanding, of the existence of an SM-like Higgs boson.

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