1

Status of and Early Expectations from the LHC

J. Mnich

Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

The Large Hadron Collider (LHC) at CERN will start operation in the second half of 2008 at the highest energy ever reached at particle colliders. Two intense proton beams will provide a centre-of-mass energy of 14 TeV and high luminosities permiting precision measurements as well as the study of new processes expected at the TeV scale like the production of Higgs boson or supersymmetric particles. We present the status of the machine and the two large multi-purpose detectors ATLAS and CMS together with the physics expectations for the first years of data taking.

1.1 Status of the LHC and the Detectors

The LHC [1] is one of the largest scientific instruments ever built, installed in the 27 km tunnel in the Geneva area used in 1990 already for the Large Electron Positron collider (LEP). The machine poses several new technological challenges which required many years of research and development work. One example are the dipole magnets to keep the 7 TeV protons on a circular orbit. In total 1232 of these superconducting magnets providing a bi-directional filed of 8.3 Tesla are to be installed in the bending sections of the tunnel. The last of the dipoles was brought into the tunnel in April 2007 marking the achievement of an important milestone of the project [2].

All superconducting magnets must be cooled down to 1.9 Kelvin by supraliquid helium requiring one of the largest cryogenic plants. These installations have been completed and in spring of 2007 one out of eight LHC sectors was completely cooled down to the required temperature. In summary, the construction of the LHC is on schedule and is expected to be completed in the first half of 2008 at which point the first proton beams can be injected to start the machine commissioning.

Four large particle detectors are under construction in world-wide collaborations to detect and analyze the collissions. Two of these, ALICE and LHC-B are specialized apparatus to study in the first case collisions of heavy nuclei - which can also be brought into collision in the LHC - which will give insight into a new state of matter, the quark-gluon plasma. The LHC-B experiment is conceived as large spectrometer to study the physics of b-quarks and in particular effects from CP violation.

In the following we shall concentrate on the two large multi-purpose detctors ATLAS [3] and CMS [4] which are designed to study a broad range of physics which is expected or might reveal at the new energy frontier. The most noticeable feature of the ATLAS detector is the large air toroid magnet equipped with high precision muon chambers. Inside the steel-scintillator hadron calorimeter resides a solenoid providing a 2 Tesla field for the inner detectors: a liquid argon calorimeter and the tracking system consisting of straw tubes with transistion radiation detection capabilities, silicon strip and pixel detectors. The latter includes about 10^8 readout channels providing 15 μm spatial resolution. The main components of the ATLAS detector are meanwhile installed in the experimental cavern and the experiment is taking cosmic ray data to prepare the acquisition system for proton collisions.

The magnetic system of CMS consists of a large solenoid with an iron return yoke which is equipped with muon chambers. The coil surrounds all other detector components starting from outside with a copper-scintillator hadron and lead-tungsten crystal electromagnetic calorimeter. The tracking system contains consists of the largest exisiting silicon strip detector complemented by a pixels rather similar to ATLAS. In contrast to other experiments the main components of CMS are assembled on the surface and lowered into the tunnel in large pieces weighting up to 2000 t. These operations are meanwhile sucessfully accomplished and the detector is close to completion. A comparison of mechanical parameters of both detectors is shown in table 1.1.

Table 1.1. Size comparison of the ATLAS and CMS detectors.

	ATLAS	CMS
length	≈ 44 m	≈ 22 m
diameter	≈ 25 m	≈ 15 m
weight	≈ 7 000 t	≈ 12 000 t

1.2 Experimental challenges

The LHC combines the two most important virtues for high energy physics experiments: highest energy and large luminosities in the range from 10^{33} cm^{-2}s^{-1} as goal for the first years of operation up to 10^{34} cm^{-2}s^{-1} at a later stage. These figures pose extreme challenges to the detectors. To reach the design luminosity two times 2835 bunches each containing about 10^{11} protons

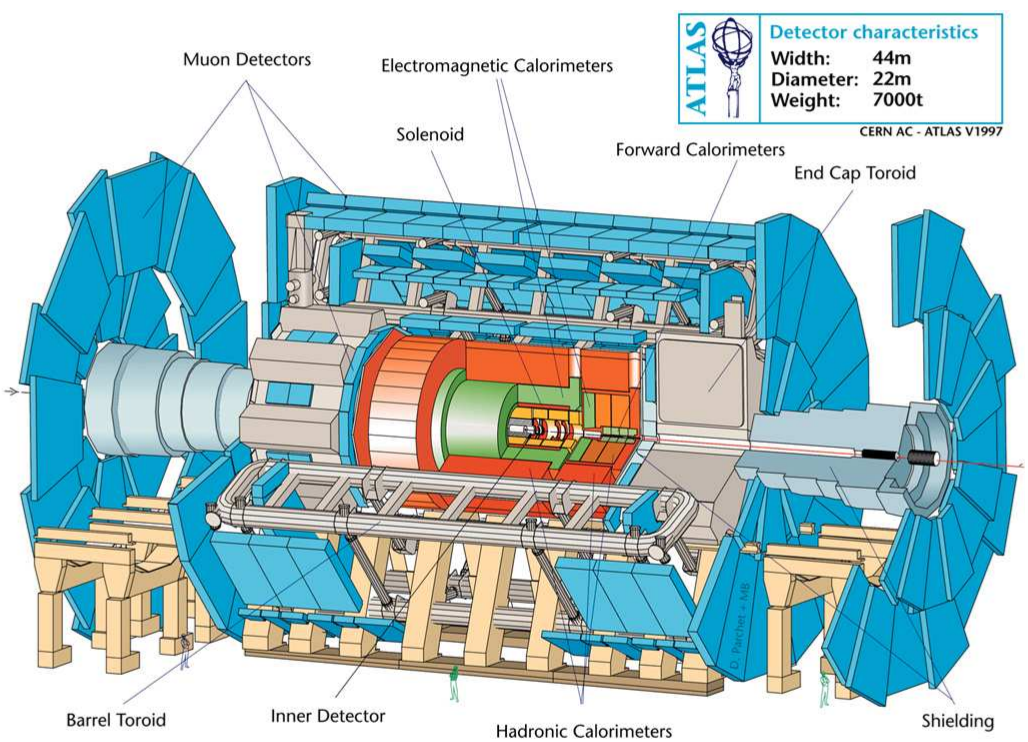

Figure 1.1. Layout of the ATLAS detector.

will circulate in opposite sense and collide every 25 ns in the centre of the detectors. As only a small fraction, about 100 Hz, of the collisions can be permanently stored for detailed analyses a sophisticated and very reliable trigger systems are required. In addition, every bunch collision entails on average 35 simultaneous pp interaction resulting in about 1500 charged tracks. This poses the problem of identifying the products of the interesting, relatively rare hard scattering event from the rest.

1.3 LHC schedule

The initial performance of a new complex scientific device as the LHC is very difficult to predict. Therefore the following estimates should be considered as an indication for a possible, realistic scenario which is subject to many unknowns. The current schedule foresees to have first beams in the LHC ring by summer 2008 such that first collisions could take place in the autumn of this year. If the commissioning phase runs as expected luminosites of the order of 10^{32} cm^{-2}s^{-1} might be reached allowing for an integrated 2008 data sample corresponding to 0.1 fb^{-1}. These data will be

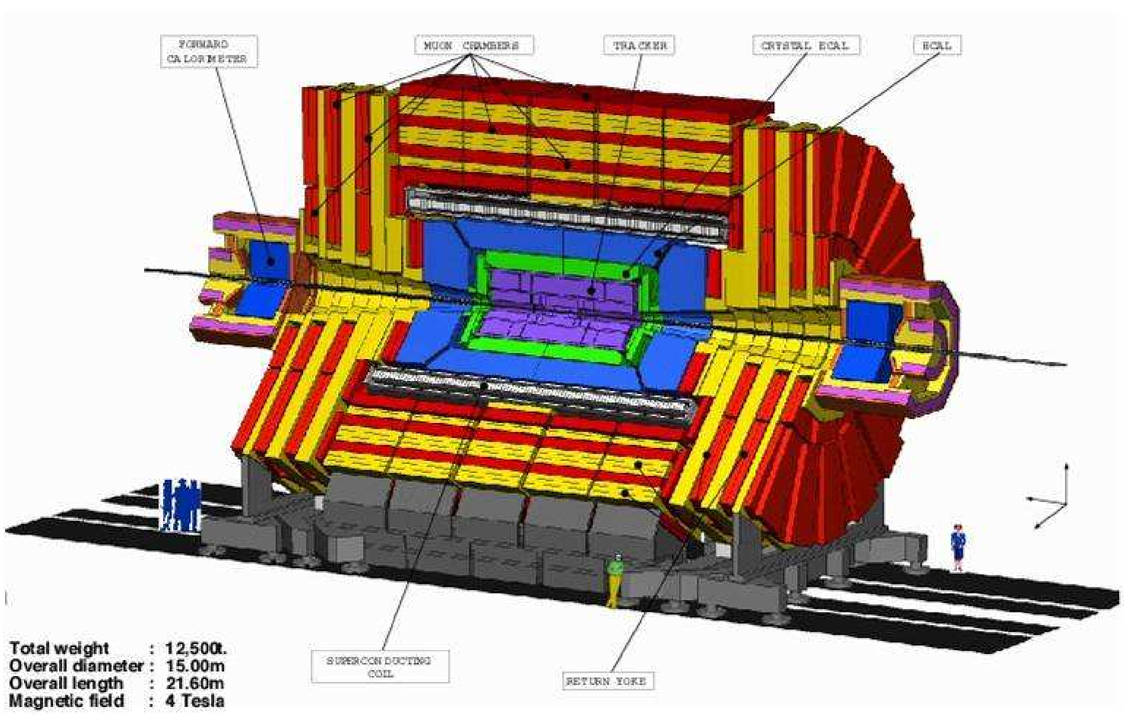

Figure 1.2. Layout of the CMS detector.

extremely useful for the commissioning and understanding of the detectors and will allow establishing high cross section signals like W/Z and perhaps $t\bar{t}$ production.

In 2009 the machine parameters will be pushed further towards the nominal values and one might expect to reach towards the end of the running period luminosities of 10^{33} cm^{-2}s^{-1} resulting in an integrated value of 1 fb^{-1}. As discussed below which such a data samples many meaningful tests and perhaps discoveries of new physics can be done provided that the detectors are understood to a sufficient level.

In the following years routine operation at $1-2\cdot10^{33}$ cm^{-2}s^{-1} should be established collecting a data sample of 30 fb^{-1} which suffices for precision tests of the Standard Model (SM) and discoveries. For example the question if Higgs bosons exist should be definitely answered using these data. At around 2011 or later operation at the design luminosity of 10^{34} cm^{-2}s^{-1} is foreseen yielding approximately 100 fb^{-1} per year to study rare processes of what then will be new Standard Model then. Beyond 2015 plans are discussed to increase the luminosity even further by an order of magnitude, called Super LHC (SLHC). This would however required major upgrades of the machine as well as the detectors.

1.4 Physics at the LHC

Cross sections of various Standard Model (SM) processes in $p\bar{p}$ and pp collisions as a function of the energy are compared in figure 1.3 [5]. For instance the production cross sections for the heavy gauge bosons W and Z and $t\bar{t}$ quark pairs are significantly larger at the LHC than at the Tevatron because of the higher energy. Already during the low luminosity phase of the LHC this results in large production rates as can be seen from the right scale of this plot. Approximately 200 W, 50 Z bosons and one $t\bar{t}$ pair will be produced every second. Also a light SM Higgs boson would be generated at a rate of one per minute. Even when taking into account reasonable values for selection efficiencies and the branching ratios into clean leptonic final states (electrons and muons) it is evident from these numbers that large data samples will be acquired shortly after the start-up of the collider. Besides providing excellent means to calibrate and understand the detectors these data samples will allow many precision measurements.

The two collaborations have studied in detail their physics potential at the LHC and developed analysis strategies [6, 7].

1.4.1 QCD and Jet Physics

Hadron colliders are a predestined tool for probing strong interactions and the physics of jets. The observable spectrum of transverse jet energies (E_T) at the LHC ranges from about 200 GeV to several TeV with the corresponding cross sections varying over 11 orders of magnitude. These samples will allow to probe QCD at the smallest distance scales and provide information on a possible quark substructure [8].

Already with data samples of the order of 0.1 fb^{-1} statistical sensitity beyond 2 TeV will be available eclipsing the results from the Tevatron experiments [7]. The crucial issue here is the control of the experimental jet energy scale which has to be achieved to a sufficient level before such analyses can turn into one of the first physics results at the LHC.

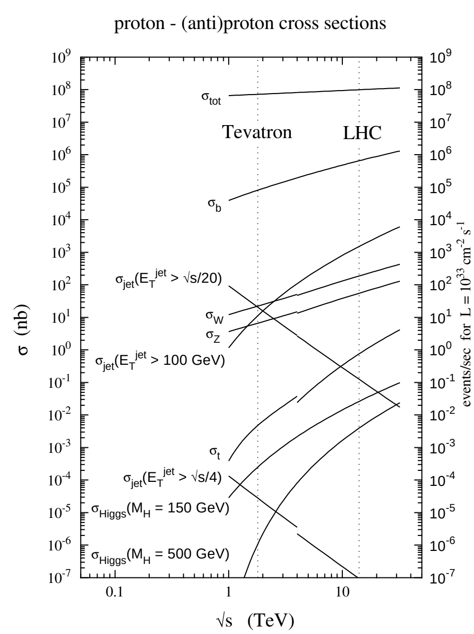

Figure 1.3. Cross sections of various SM processes in (anti)proton-proton collision in the Tevatron and LHC energy ranges.

1.4.2 Electroweak Physics

The LHC will abundantly produce W and Z bosons which through their leptonic decays provide relatively clear signatures and are readily identifiable. As an example fig. 1.4 shows the expected experimental distribution of the electron transverse energy in selected $W \to e\nu$ decays together with the small background contributions.

W and Z events will thus provide an excellent tool to understand and calibrate the detector and in a second step the experiments will be able to study the properties of W and Z bosons and to complement and extend the tests of the electroweak theory performed so far at e^+e^-- and $p\bar{p}$-colliders. For instance, detailed studies [6, 7] show that the LHC experiment have the potential to further improve the error on m_W beyond the anticipated uncertainty of about 20 MeV from final LEP and Tevatron Run II data. A very good understanding of the detector and improved theoretical calculation are required to achieve this goal.

The high energy makes the LHC also an ideal place to study di-boson

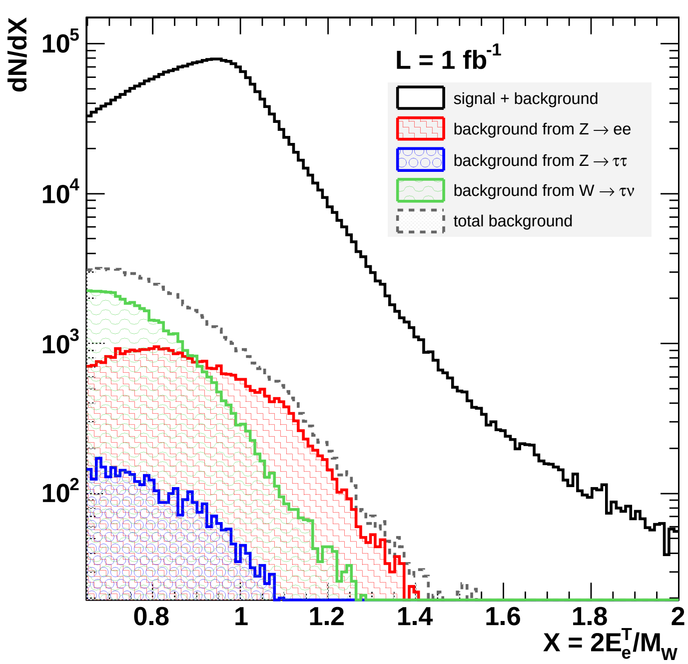

Figure 1.4. Expected transverse energy spectrum of electrons scaled to the W mass in the channel $W \to e\nu$ together with the contributions from background sources (CMS).

production from which information on the triple gauge boson vertices can be deduced. In the SM two such vertices, $WW\gamma$ and WWZ exist whereas all others, in particular those involving only the neutral bosons γ and Z, do not.

In particular also final states with two heavy gauge bosons, i.e.WZ and ZZ, will be copiously produced at the LHC and their leptonic decays will allow a clean event selection. This is illustrated in Fig. 1.5 which shows the mass distribution of the Z candidate in selected WZ events together with the background. It has been shown that less than 1 fb^{-1} are required to firmly establish the SM signal of WZ and ZZ production [7]. The analysis of these events will then contribtue to tests of triple gauge couplings.

1.4.3 Physics of the Top Quark

The LHC is also a real top quark factory which will permit precision measurements of the properties of the heaviest SM fermion. Contrary to the Tevatron the dominant production process for top quark pairs is gluon

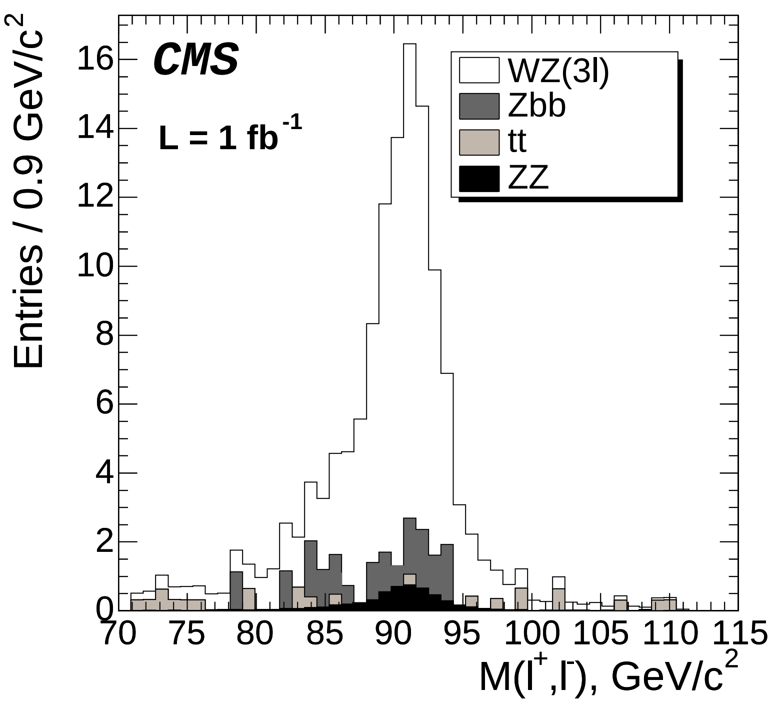

Figure 1.5. Selection of leptonic WZ final states in 1 fb^{-1}: The di-lepton mass closest to the Z hypothesis is shown for signal and background.

fusion gg $\rightarrow$ t$\bar{\text{t}}$ contributing with about 87% much more than quark annihilation q$\bar{\text{q}}$ $\rightarrow$ t$\bar{\text{t}}$. The top quark decays to almost 100% into a b quark and a W boson such that the signature of a top pair is given by the decay topology of the W pair in addition to the two b quarks in the final state. The experimentally cleanest modes are characterised by the leptonic (electron or muon) decay of one or both W bosons which are refered to as semi-leptonic and di-lepton channel, respectively. The experiments will be able to establish a t$\bar{\text{t}}$ signal very quickly with relatively low integrated luminosity. As an example Fig. 1.6 shows the result of a selection for 0.1fb^{-1} [9] revealing an unambigous signal over the background. It should be noted that analyses of top quarks require a rather complete understanding of the detector as top event signatures rely on jets, leptons, missing transverse energy and b-tagging. Thus studies of top events can be considered a prerequisite before establishing the presence of new physics signals. Concerning precision studies of the SM the experiments estimate to be able to measure the top mass to a precision of about 1 GeV which will significantly improve the sensitivity to electroweak radiative corrections.

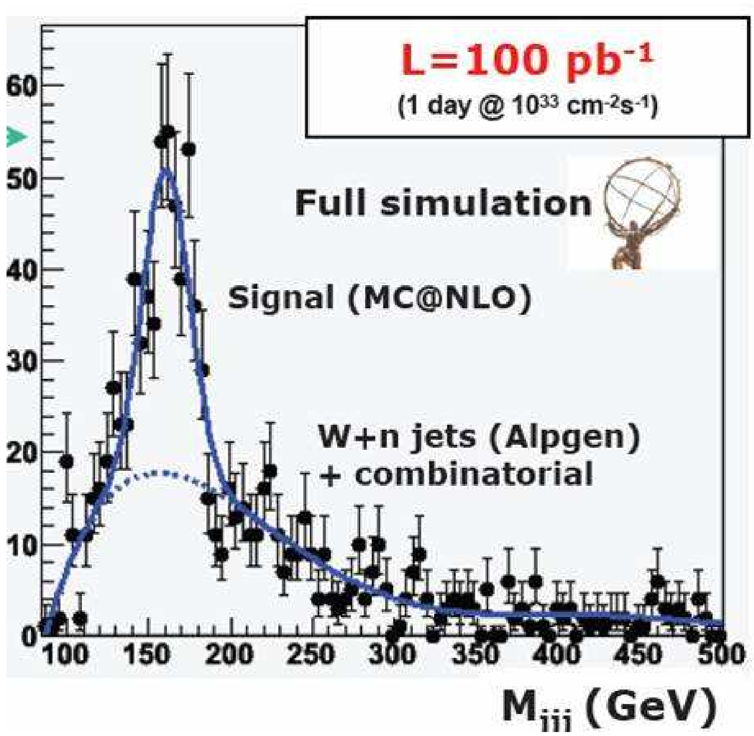

Figure 1.6. Early selection of top pairs in the semi-leptonic channel by ATLAS.

1.5 Search for New Physics

The time scale for discoveries exploiting new facilities like the LHC is not necessarily determined by ramp-up of luminosity and the accumulated data samples but rather by progress and level of understanding of the detectors. Issues like detector malfunctions, calibration and alignment need to be understood by careful analyses of the data. Experience shows that particularly difficult objects which requiring more detailed investigations are jets, in particular their energy calibration, and detectors in the forward region. Both govern the uncertainties on the missing transverse energy (MET), which is an important signature for many new physics channels like for example supersymmetry but at the same time a rather complicated experimental variable. In addition to detector effects like noise, malfunctioning channels and inter-calibrations, and beam related background, at the LHC effects from pile-up and the underlying event, i.e. the remnant of the hard parton-parton interaction, must be well understood.

On the other hand measurements based on lepton signatures, in particular muons, provide clean signatures which are rather insensitive to details of the detector behaviour. Despite the fact that leptonic branching ratios are often smaller, the first solid measurements are expected based on muons and electrons in the final state.

An example is the Drell-Yan production of muon pairs where the statistical sensitity with 1 fb^{-1} at the LHC is exceeding the expected final result of the Tevatron experiments as the higher energy compensates for the lower luminosity (see figure 1.7). A new Z' boson could be seen in such a mass plot already at low luminosity and imperfect momentum resolution based on a crude initial alignment of the detector.

1.5.1 Search for the Standard Model Higgs Boson

The experimental search for Higgs bosons will be a central point of the LHC programme and the experiments will definitely answer the question if a Higgs boson exists. The sensitivity of the experiments covers the allowed mass range from the experimental limit of 114 GeV [10] to the largest theoretically allowed value of 1 TeV.

The most difficult Higgs mass values are just above the experimental limit because here the dominant decay channel $H \to b\bar{b}$ cannot be exploited due to the enormous b-quark background from QCD production. The most promising channel is $H \to \gamma\gamma$ which however has a low branching order of only about 10^{-3} and thus requires larger integrated luminosity. At around 140 GeV Higgs decays into heavy gauge bosons become dominant which provide clean signatures through their leptonic decays resulting in lower luminosities required to establish a Higgs signal. This is illustrated in figure 1.8 which summarises the achievable statistical significance as a function of m_H. An integrated luminosity of 30 fb^{-1}, corresponding to three years operation at 10^{33} $cm^{-2}s^{-1}$, is sufficient to discover the SM Higgs with a significance of five standard deviations independent of its mass. Large parts of the allowed mass region can be explored with significantly less luminosity.

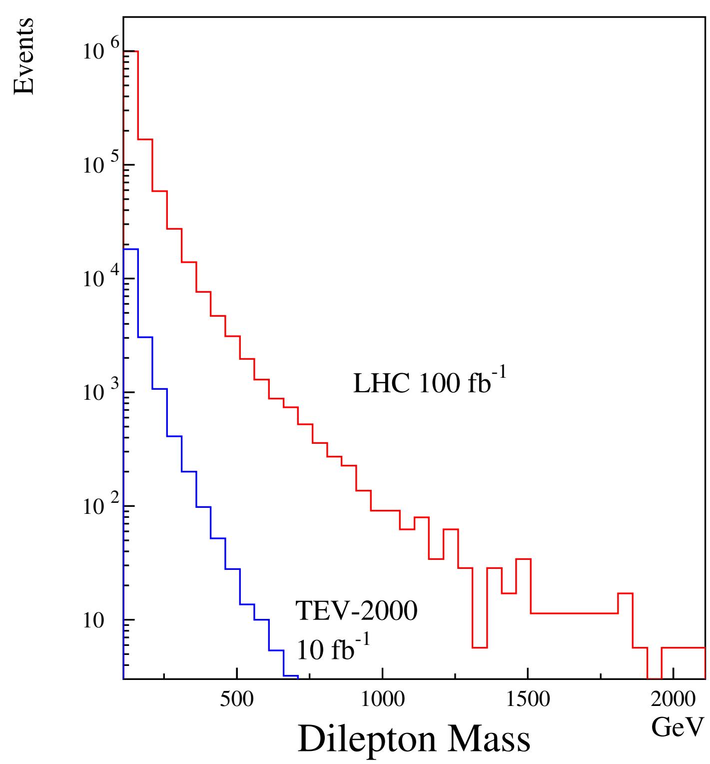

Figure 1.7. Comparison of event rate in Drell-Yan lepton pair production at LHC and the Tevatron as of function of mass. Scaling down the rates shows that the LHC sensitity with 1 fb^{-1} is equal or excceding the expected final Tevatron result.

As can be seen from figure 1.8 he most favourable region is around $m_{\rm H} \approx 160$ GeV where the decay into W pairs becomes dominant. With only 30 $\rm fb^{-1}$ of well understood such a Higgs could be discovered.

1.5.2 Search for Supersymmetry

If they exist in the accessible mass range supersymmetric (SUSY) particle would be copiously produced at the LHC, either through strong (scalar quarks and gluinos) or electroweak (scalar leptons and boson partners) interactions. In most scenarios investigated R-parity is conserved and lightest SUSY particle, produces at the end of the decay chain, escapes detection leaving a signature of missing transverse energy. Signatures thus depend on the details of the model and the particles produces but in general they consists of multi-lepton and jets accompanied by MET. The experiments will therefore look for deviations from the SM expectation in such distributions to establish the production of SUSY particles and determine the mass scale.

Detailed studies of the studies of the data are required to control back-

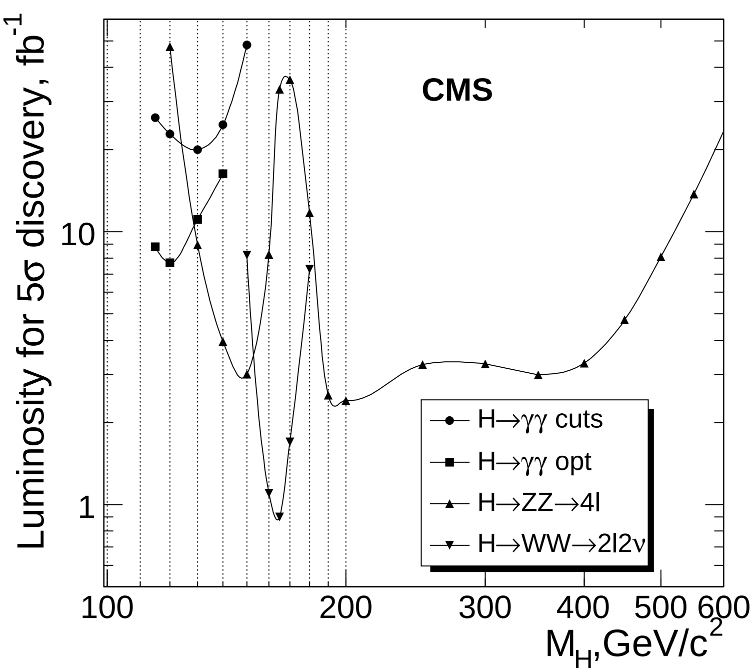

Figure 1.8. The integrated luminosity needed for a 5σ discovery of the SM Higgs boson as a function of mass.

grounds, in particular for the difficult MET signature. For example from the well measureable process $\mathrm{Z} \rightarrow Z \rightarrow \mu\mu$ + jets and the known branching ratios SM background with MET signature from $\mathrm{Z} \rightarrow \nu\nu$ + jets can be determined from data without relying on Monte Carlo simulations. Once this and many other questions are answered the LHC experiments will quickly be sensitive to mass scales in the TeV range through such inclusive searches. Figure 1.9 shows the reach in the mass parameters m_0 and $m_{1/2}$ for 1 fb^{-1} which by far exceeds the limits posed to date by other experiments.

1.6 Summary and Conclusions

The LHC and the detectors are on schedule to start operation in the second half of 2008. At this point particle physics will enter a new era with exper-

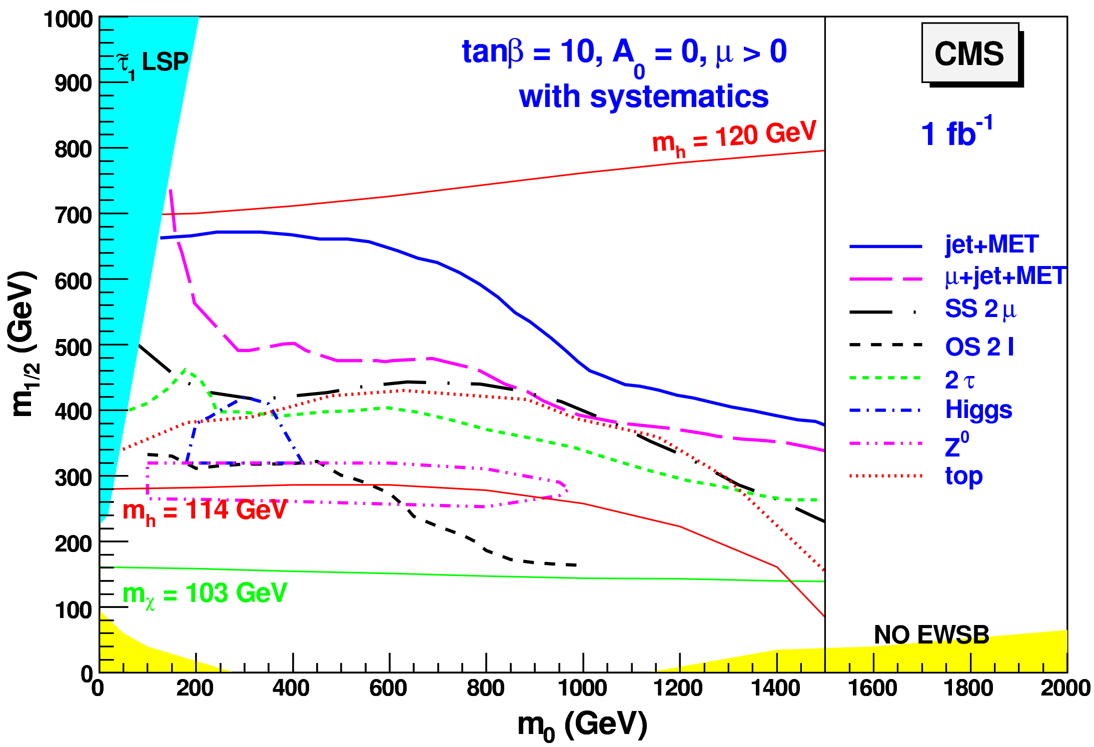

Figure 1.9. Regions in the m_0 and $m_{1/2}$ plane showing the CMS reach in inclusive SUSY analyses for 1 fb^{-1} [7].

iments in an energy regime where fundamental questions like the origin of mass, intimately linked to the existence of Higgs bosons, and the presence of new symmetries like SUSY will be answered. As the first data are required to commission and understand the sophisticated detectors and the harsh experimental environment already for 2009 significant physics results can be expected provided that start-up proceeds according to schedule. Precision measurement of the SM as well as the dicovery of the Higgs boson and other new particles are possible under favourable conditions already in the first years.

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