A major goal of the future Large Hadron Collider will be the Higgs boson search. In this paper the discovery potential is described as a function of the Higgs mass showing that a Standard Model Higgs boson can be discovered after less than two years of running of the collider. The MSSM Higgs searches and the precision achievable on the measurement of the Higgs boson parameters are also discussed.

1 Introduction

The main focus of the experiments at the future proton-proton Large Hadron Collider (LHC) at CERN will be the investigation of the nature of the electroweak symmetry breaking, and therefore the search for the Higgs boson. Two general purpose experiments, ATLAS and CMS, have been designed to study collisions at the LHC, and have been optimized to cover a large spectrum of possible physics signature, accessible at the high luminosity and center-of-mass energy of the (LHC).

Detailed simulations of both experiments have been performed to demonstrate that the Higgs should be discovered regardless of its mass which is an unknown parameter of the Standard Model. The Higgs can be produced at the LHC through several mechanisms, whose individual cross section is plotted in Fig. 1 (left) as a function of the Higgs mass \( m_H \). It can be seen that the inclusive production dominates over the entire mass range, followed by \( Hqq \), while the production in association with a W, Z, or \( tt \) pair has a sizeable contribution for \( m_H \leq 200\) GeV. The branching fractions of the Higgs decays vary as a function of \( m_H \) as shown in Fig. 1 (right).
2 LHC running scenarios and cross sections

Throughout the paper, it is assumed that an initial luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$ (hereafter called low luminosity) can be achieved at the LHC. It is expected that this value should rise, during the first two years of operation, to the design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ (hereafter called high luminosity). Integrated luminosities of about $10\text{fb}^{-1}$, $30\text{fb}^{-1}$, $100\text{fb}^{-1}$, $300\text{fb}^{-1}$ should therefore be collected after one year, three years, four years and less than ten years of data taking, respectively.

The physics performance has been evaluated using the following assumptions: (i) Despite the considerable progress in the calculation of higher order QCD corrections over the last years, these corrections (K-factors) are not known for all signal and background processes of interest. Therefore, the studies presented here, have consistently and conservatively refrained from using K-factors, resorting to Born-level predictions for both signal and backgrounds. (ii) The non diffractive inelastic cross section has been assumed to be 70 mb. At low (high) luminosity, this leads on average to a superposition of 2.3 (23) minimum bias events per crossing on top of the hard collision. These so called pile-up contribution have been included for both low and high luminosity. (iii) Physics process have been simulated with the Pythia Monte Carlo program, including initial- and final-state radiation, hadronization and decays. Although many results have been obtained using a fast simulation of the detectors, all key performance characteristics have been evaluated with a full GEANT simulation, both at low and high luminosity.

3 The search for the Higgs boson

The Standard Model Higgs boson is searched for at the LHC in various decay channels, the choice of which is given by the signal rates and the signal-to-background ratios in the various mass regions. The search strategies and background rejection methods have been established through many studies over the past years.

The overall sensitivity for the discovery of a Standard Model Higgs boson over the mass range from 80 GeV to 1 TeV is shown in Fig. 2 (left). This sensitivity is given for individual channels as well as for the combination of the various channels, assuming integrated luminosities of $30\text{fb}^{-1}$ for the ATLAS experiment. The combined sensitivity for both ATLAS and CMS is shown in Fig. 2 (right) for $10\text{fb}^{-1}$, $30\text{fb}^{-1}$ and $100\text{fb}^{-1}$. A Standard Model Higgs boson can be discovered at the LHC over the full mass range from the LEP2 lower limit up to the TeV range with a high significance. A $5\sigma$ discovery could already be achieved over the full mass range after the first two years of running at low luminosity. Over a large fraction of the mass range the discovery of a Standard Model Higgs boson will be possible in two or more independent
channels.

The main channels which will be used at the LHC to look for a Standard Model Higgs boson can be classified depending on $m_H$ as follow:

- **Low mass region ($m_H < 130$ GeV).** The search of the Standard Model Higgs boson is challenging in this mass region. Even though its natural width is narrow, the backgrounds from $t\bar{t}$, $\gamma\gamma$, and $W/Z+jets$ production are relatively large and thus, an excellent detector performance in terms of energy resolution and background rejection is required. Two decays modes are experimentally important in this region: $H \rightarrow b\bar{b}$ and $H \rightarrow \gamma\gamma$. The first one has a branching ratio close to 100% in most of this region, and therefore inclusive Higgs production followed by $H \rightarrow b\bar{b}$ has a large cross-section ($\approx 20$ pb). However, since the signal-to-background ratio for the inclusive production is smaller than $10^{-5}$, it will be impossible to observe this channel above the QCD background and even to select it at the trigger level. On the other hand, the associated production $t\bar{t}H, WH, ZH$, with $H \rightarrow b\bar{b}$ and with an additional lepton coming from the decay of the accompanying particles, has a much smaller cross section ($< 1$ pb) but gives rise to final states which can be extracted from the background.

The $H \rightarrow \gamma\gamma$ channel has a branching ratio at the level of $10^{-3}$ and therefore a small cross-section ($\approx 50$ fb). However, the signal-to-background ratio ($\approx 10^{-2}$) is much more favorable than for the inclusive $b\bar{b}$ channel.

In addition it has been recently suggested that the statistical significance can be increased by searching for a Higgs boson produced through vector boson fusion, e.g. with two forward emitted jets accompanying it in the final state. The detection of those two energetic jets provides a powerful tool for background rejection.

- **Intermediate mass region ($130$ GeV $< m_H < 2m_Z$).** The most promising channels for the experimental searches are $H \rightarrow ZZ^{(*)} \rightarrow 4l$ and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$, the latter can be studied both using inclusive and associated W production.

- **High mass region ($m_H > 2m_Z$).** This is the best region to discover a Higgs boson signal at the LHC, since the $H \rightarrow ZZ \rightarrow 4l$ channel gives rise to a gold plated signature,
almost background free. For very large masses ($m_H > 500$ GeV) searches for this decay mode will be supplemented by searches for other channels, such as $H \rightarrow ZZ \rightarrow ll\nu\nu$ and $H \rightarrow WW \rightarrow l\nu jj$ (where $j$ stands for hadronic jet), which have larger branching ratios and therefore can compensate for the decrease in the production cross-section.

The experimental techniques used to extract a possible signal above the backgrounds and the LHC discovery potential are illustrated here.

3.1 $H \rightarrow \gamma\gamma$

This channel should allow observation of a Higgs boson over the mass region up to 150 GeV. The branching ratio for this channel is of the order of $0.1\div0.3\%$ as the Higgs is coupled to photons only through a $W$ loop. The final state consists of two high-$p_T$ photons ($p_T \approx 50$ GeV), despite the simple signature, this is the most challenging channel for the performance of the LHC electromagnetic calorimeters and has indeed driven the design and the technology choices for these detectors. The reason is that there are two large backgrounds to fight. (i) The $\gamma\gamma$ production through QCD diagrams, which is an irriducible background without a resonant structure, and decreases smoothly with the invariant mass of the two photons. The $\gamma\gamma$ cross-section is about 60 times larger than the $H \rightarrow \gamma\gamma$ cross-section in the region $m_{\gamma\gamma} \approx 100$ GeV. Therefore, excellent detector energy and angular resolution are needed in order to extract a narrow resonant peak above the overwhelming continuum background. (ii) The reducible $\gamma$-jet and jet–jet production, where one or both jets fake a photon. This happens when a quark fragments into a very hard $\pi^0$ plus a few other particles which are too soft to be detected. The two photons from the subsequent $\pi^0$ decay are very close in space because the parent $\pi^0$ is usually produced with a large boost. For instance, for a $\pi^0$ of $p_T \approx 50$ GeV the distance between the two decay photons is smaller than 1 cm at the front face of the electromagnetic calorimeters ($\approx 150$ cm from the interaction point). Although the probability for a jet to fragment into a single isolated $\pi^0$ is small, the cross section for $\gamma$jet and jet–jet production is $\approx 10^6$ times larger than the cross section for the $\gamma\gamma$ continuum. Therefore a jet rejection of at least 1000 is required to suppress this background to well below the irreducible $\gamma\gamma$ background. Fig. 3 shows the expected $H \rightarrow \gamma\gamma$ signal in ATLAS above the continuum (reducible and irreducible) $\gamma\gamma$ background, for a Higgs mass of 120 GeV and an integrated luminosity of 100 fb$^{-1}$. About 1000 events are expected in the Higgs peak. Also shown is the expected signal in CMS for $m_H = 130$ GeV, after background subtraction. The CMS significance should be about 15% better than the ATLAS significance, due to a better energy resolution of the electromagnetic calorimeter.

3.2 $H \rightarrow b\bar{b}$

The $H \rightarrow b\bar{b}$ decay channel can be searched for only if the Higgs boson is produced in association with other particles. In particular the $t\bar{t}H$ associated production is promising in terms of statistical significance achievable. The final state is considerably complex, since it consists of two $W$-bosons and four $b$-jets. For trigger purposes, one of the $W$ bosons is required to decay leptonically, whereas the other one is assumed to decay into a $q\bar{q}$ pair. In order to reliably extract the signal, the analysis requires that both top quarks be fully reconstructed. This method reduces considerably the large combinatorial background in the signal events themselves, since two of the $b$-jets are associated to the top decays, and therefore the remaining two should come from the Higgs boson decay. The signal should appear as a peak in the $b\bar{b}$ invariant mass distribution, above the various background processes.
3.3 $H \rightarrow ZZ^{(*)}$

This channel, which can be observed at the LHC over the mass region 120–700 GeV, gives rise to a very distinctive signature, consisting of four leptons whose invariant mass is consistent with the nominal Higgs boson mass.

The expected backgrounds, and therefore the search criteria, depend on the Higgs mass. If $m_H > 2m_Z$, then both $Z$ bosons in the final state are real and two pairs of leptons with the same flavor and opposite sign should have an invariant mass compatible with the $Z$ mass. In this region the backgrounds, such as the irreducible $pp \rightarrow ZZ \rightarrow 4l$, are small.

For $m_H < 2m_Z$, on the other hand, the backgrounds are large. In addition to the already mentioned $pp \rightarrow ZZ \rightarrow 4l$ continuum, there are two potentially dangerous reducible backgrounds: $t\bar{t} \rightarrow 4l + X$ and $Zb\bar{b} \rightarrow 4l + X$ with two leptons coming from semileptonic decays of two $b$-quarks. These backgrounds can be rejected by asking the invariant mass of at least one lepton pair to be compatible with the $Z$ mass, by requiring that all leptons be isolated (leptons from the $b \rightarrow lX$ decays are usually non-isolated), and by requiring that all leptons come from the interaction vertex (leptons from $b$-quark decay are produced at $\approx 1$ mm from the vertex due to the long $B$-hadrons lifetime).

The signal significance expected in each experiment varies between three and 25 for an integrated luminosity of 30 fb$^{-1}$, over the Higgs mass range 120–700 GeV. For larger masses, the production cross-section decreases fast and the width increases, and the branching ratio into four lepton final states is too small to allow observation of this channel. Other channels should be used for $m_H > 700$ GeV, such as $H \rightarrow ZZ \rightarrow ll\nu\nu$ or $H \rightarrow WW \rightarrow l\nu l\nu$ which have a larger branching fractions.

3.4 $H \rightarrow WW^{(*)}$

For Higgs boson masses close to 170 GeV, the signal significance in the $H \rightarrow ZZ \rightarrow 4l$ channel is reduced, due to the suppression of the $ZZ^*$ branching ratio as the $WW$ decay mode opens up. The best candidate for Higgs boson discovery in the mass range 150–190 GeV is the channel $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$. Due to the presence of two neutrinos in the final state, it is possible to reconstruct only the Higgs transverse mass, and the signal can not be observed as a clear mass peak. The transverse mass distribution for the signal and for the backgrounds is shown in Fig. 4 for an Higgs mass of 150 GeV, assuming an integrated luminosity of 30 fb$^{-1}$. The
The observation of a Higgs signal is based on a counting experiment, and the systematic on the knowledge of the total background yield is crucial. A 5% systematic uncertainty on the total number of background events is assumed here, and used to derive the statistical significance for the channel.

To confirm the discovery one can exploit production processes where the Higgs boson is produced in association with a W boson. This channel provides a distinctive signature with 3 W bosons in the final state and with a low level of background, but with a lower –by a factor of about 10– event rate. Using this associated production channel the statistical significance is worse than in the inclusive channel, however a good signal to background ratio (of the order of 2) can be achieved so that the results are not so sensitive to the precise knowledge of the absolute normalization of the backgrounds.

The final state in which all the W bosons decay into lepton pairs and that in which two of them decay leptonically and one hadronically have been studied. In the latter case, to obtain the needed rejection against the t\bar{t} production followed by a di-lepton decay as well as against many other physics backgrounds with opposite sign leptons in the final state, it is required that the two charged leptons have the same sign.

4 Supersymmetric Standard Model Higgs

The LHC experiments have also a large potential in the investigation of the Minimal Supersymmetric Standard Model (MSSM) Higgs sector. If the SUSY mass scale is large and supersymmetric particles do not appear in the Higgs decay products, the full parameter space in the conventional \((m_A, \tan \beta)\) plane should be covered. The 5\(\sigma\) discovery contour curves are shown in Fig. 5 for individual channels and for integrated luminosities of 300 fb\(^{-1}\). In addition to the channels discussed for the Standard Model case, the MSSM Higgs search relies heavily on the \(H/A \to \tau\tau, \mu\mu\) channel, and on the charged Higgs decays. Over a large fraction of the parameter space more than one Higgs boson and/or more than one decay mode would be accessible.

The interplay between SUSY particles and the Higgs sector has also been addressed in the ATLAS studies. SUSY scenarios have an impact on the discovery potential through the opening of Higgs-boson decays to SUSY particles (mostly for H and A) and through the presence of
SUSY particles in loops.

5 Determination of the Standard Model Higgs boson parameters

Assuming that a Standard Model Higgs boson will have been discovered at the LHC, the potential for the precision measurement of the Higgs parameters (mass, width, production rates, branching ratios) is discussed in this section. Such measurements should give further insights into the electroweak symmetry-breaking mechanism and into the way the Higgs couples to fermions and bosons, and, in some cases, should allow a distinction between a Standard Model and a MSSM Higgs boson.

5.1 Measurement of the Higgs boson mass and width

The ultimate experimental precision with which the Higgs boson mass will be measured in shown in Fig. 6 for the ATLAS detector and assuming 300 fb$^{-1}$ of integrated luminosity. The results obtained in the various decay channels as well as the combination of all channels are given. The quoted precision includes the statistical error in the determination of the peak position, coming from both the limited number of signal events, the error on the background subtraction, and the systematic error on the absolute energy scale. The latter is conservatively assumed to be 0.1% for decay channels which contain leptons or photons and 1% for decay channels containing jets. Fig. 6 indicates that the Higgs mass can be measured with a precision of 0.1% up to masses of 400 GeV. For larger masses the precision deteriorates because the Higgs boson width becomes large and the statistical error increases.

The Higgs boson width can be experimentally obtained from a measurement of the width of the reconstructed Higgs peak, after unfolding the contribution of the detector resolution. This direct measurement is only possible for Higgs boson masses larger than 200 GeV, above which the intrinsic width of the resonance becomes comparable or larger than the experimental mass resolution. This is the mass region covered mainly by the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decays. Over the range $300 < m_H < 700$ GeV, the precision of the measurement is approximately constant and of the order of 6%.
5.2 Measurement of the Higgs boson rate

The measurement of the Higgs boson rate in a given decay channel provides a measurement of the production cross-section times the decay branching ratio for that channel. Such measurement in some cases would help to disentangle between Standard Model and MSSM Higgs scenarios.

The statistical error on such measurements is expected to be smaller than 10% over the mass region 120–600 GeV using the $\gamma\gamma$, $b\bar{b}$ and $4l$ final states. The main systematic error comes from the knowledge of the luminosity and background subtraction. Fig. 6 shows the expected experimental uncertainty on the Higgs boson rates, for various production and decay channels and for two assumptions on the luminosity uncertainty. By performing these measurements for several channels, one can obtain several constraints on the Higgs boson couplings.

6 Conclusions

The ATLAS and CMS experiments at the LHC should discover a Higgs boson (with significance above 5) over the full allowed mass region from the limit set by previous machines up to the theoretical bound of 1 TeV, after less than two years of operation.

Different channels cover different mass regions, but over most of the mass range more than one channel should be observed, thus giving robustness to the discovery and hints to understand the nature of the signal.

If a Standard Model Higgs boson will be observed at the LHC, then ATLAS and CMS should be able to measure its mass with a precision of $\approx 0.1\%$ and to study its coupling to SM particles with a $\approx 10\%$ precision.

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