Search for Higgs Bosons at LHC

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When LHC will start it may still not be clear if a light Higgs boson with a mass below 120 GeV/c² exists. LEP stopped data-taking with the final result of a 2 σ evidence for a Higgs boson with a mass around 115 GeV/c²[1]. TeVatron will be able to exclude a Higgs boson at this mass at the 95% confidence level with 2 fb⁻¹ per experiment (end of the year 2003). If a Higgs boson in the mass range 115–120 GeV/c² exists, however, TeVatron would need ~ 15 fb⁻¹ per experiment for a 5 σ discovery. The projected luminosity for LHC in 2007 is 10 fb⁻¹, sufficient for a 5 σ discovery of a Higgs boson in the mass range 115–120 GeV/c² and at higher masses.

1. Standard Model Higgs Boson Searches

LHC (Large Hadron Collider) is a pp accelerator with a circumference of 27 km which will be built in the existing LEP tunnel. For the year 2006 first collisions of 7 TeV protons with 7 TeV protons are planned. Two general purpose experiments-ATLAS[2] and CMS[3]-are under construction. Higgs boson production at the LHC is dominated by the gluon fusion mechanism $gg \to H$, which is mediated by top and bottom triangle loops. This production process is directly sensitive to the $t\bar{t}H$ coupling. For large Higgs boson masses the vector boson fusion mechanism $WW, ZZ \rightarrow H$ becomes competitive, while for intermediate Higgs boson masses it is about an order of magnitude smaller than gluon fusion. This process is sensitive to the Higgs coupling to the weak vector bosons. The ratio of the two cross sections provides the information how the Higgs couples to fermions and bosons. Higgs-strahlung $W^*/Z^* \rightarrow HW^*/Z^*$ plays a role only for $m_H < 1$ 100 GeV/ c^2 . Another interesting production process for Higgs bosons is the associated Higgs production: $q_i \bar{q_j} \rightarrow WH$ or $q_i \bar{q_j} \rightarrow ZH$, where an off-shell vector boson is produced and radiates a Higgs boson. The last production mechanism is the Higgs bremsstrahlung: $gg, q_i \bar{q_i} \rightarrow t\bar{t}H$ where top quarks are produced and radiate a Higgs boson. The two last production mechanisms have a cross section about 100 times smaller than the gluon fusion process. Figure 1 shows the different Feynman graphs for the production of Higgs bosons at LHC.



Figure 1: Production mechanism for Higgs bosons at LHC: (a) gluon-gluon-Fusion, dominant at low Higgs boson masses, (b) vector boson fusion, dominant at high Higgs boson masses, (c) associated $t\bar{t}H$ production, about 50 times smaller than gluon-gluon fusion, (d) associated *ZH*, *WH* fusion, about 50 times lower than vector boson fusion.

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The strategy to find the Higgs boson changes depending on its mass [4, 5]. For Higgs boson masses below 130 GeV/c² the most significant channels are the decays $H \rightarrow \gamma\gamma$ and $H \rightarrow b\bar{b}$. Between 130 and 180 GeV/c² the decay channels $H \rightarrow ZZ^* \rightarrow 41$ and $H \rightarrow WW^* \rightarrow l^+ \nu l^- \bar{\nu}$ are the expected discovery channels. For larger masses up to 400 GeV/c² $H \rightarrow ZZ^* \rightarrow 41$ provides the easiest discovery signature. For higher Higgs boson masses, additional signatures involving hadronic W and Z decays have been investigated and promising signals have been obtained. These channels will be discussed in detail in the following sections.

Physics processes have been simulated with the PYTHIA[6] Monte Carlo program, including initial- and final-state radiation, hadronization and decays. The signal and background production cross sections are affected by uncertainties due to higher order corrections, structure function parameterizations and event generation. The higher-order QCD corrections to the production cross sections are not known for all signal and background processes. Therefore, the present Higgs studies at ATLAS have consistently and conservatively refrained from using k-factors, resorting to Born-level predictions for both signal and backgrounds. The studies performed by the CMS collaboration are using k-factors. The k-factors, i.e. higher order corrections are of the order of 1.6–1.9 for $gg \rightarrow H$. The uncertainties from parton density functions and NNLO cross sections are estimated to be smaller than 20%.

1.1. $H \rightarrow \gamma \gamma$

The decay $H \rightarrow \gamma \gamma$ is a rare decay mode, only detectable in a limited Higgs mass region where the production cross-section and the decay branching ratio are both relatively large. It is a promising channel for a Higgs search in the mass range of $100 < m_H < 150 \text{ GeV/c}^2$. Excellent energy and angular resolution are required to observe the narrow mass peak above the irreducible prompt $\gamma \gamma$ continuum. Powerful particle identification capability is needed to reject the large jet background.

The direct production of a low mass Higgs is dominated by the qq fusion process. The irreducible background consists of genuine photon pairs via the following three processes: Born $(q\bar{q} \rightarrow \gamma\gamma)$, box $(g \rightarrow \gamma\gamma)$, and quark-bremsstrahlung $(qg \rightarrow q\gamma \rightarrow q\gamma\gamma)$. The production cross section for the sum of the Born and box processes is of the order of 1 pb/GeV/ c^2 in the two-photon mass range around 100 GeV/ c^2 . After isolation cuts, this background amounts to about 50% of the combined Born plus box contribution. The reducible background consists of *iet-iet* and *y-iet* events in which one or both jets are misidentified as photons, as well as $Z \rightarrow e^+e^-$ decays, where both electrons are mistaken as photons. Since the production cross sections for these processes are many orders of magnitude larger than the signal cross sections, excellent photon/jet and photon/electron discrimination are required. The expected $H \rightarrow \gamma \gamma$ signal significances, defined for each mass point as S/\sqrt{B} where S and B are the numbers of accepted signal and background events in the chosen mass window of $\pm 1.4 \sigma$ for an integrated luminosity of 100 fb⁻¹ ranges from 2.4 to 6.5 σ in the mass range 80 < m_H < 130 GeV/c². In addition to the signal events from direct production, events from the associated production of a Higgs boson with a W or Z boson or a $t\bar{t}$ pair have been included in the signal. As an example for the signal reconstruction, Figure 2 shows the expected signal from a Higgs boson with $m_H = 120 \text{ GeV/c}^2$ after an integrated luminosity of 100 fb⁻¹ (high luminosity). The $H \rightarrow \chi \chi$ signal is clearly visible above the smooth background, which is dominated by the irreducible $\gamma\gamma$ background.

The production of the Higgs in association with a *W* or a *Z* boson or with a $t\bar{t}$ pair can be used in addition to the direct $\gamma\gamma$ decay mode to search for a low mass Higgs boson. The production cross section for the associated production is almost a factor 50 lower than for the direct production, leading to much smaller signal rates. If the associated *W*/*Z* boson or one of the top quarks is required to decay leptonically, thereby leading to final states containing one isolated lepton and two isolated photons, the signal-to-background ratio can nevertheless be substantially improved with respect to the direct production. In addition, the vertex position can be unambiguously determined by the lepton charged track, resulting in much better mass resolution at high luminosity than for the case of the direct production. In order to suppress the reducible background from QCD jet and $t\bar{t}$ production and from final-state photon radiation, isolation criteria are applied. The irreducible background has been evaluated by considering the *W* $\gamma\gamma$, *Z* $\gamma\gamma$, $t\bar{t}\gamma\gamma$ and $b\bar{b}\gamma\gamma$ production. By requiring the lepton-photon mass to be above a given threshold the background has been further suppressed. There are also many sources of reducible backgrounds. Final states containing one, two or three jets in association with a lepton or photon, such as $\gamma\gamma - jet$, $\gamma l - jet$,



Figure 2: Expected $H \rightarrow \gamma \gamma$ signal for $m_H = 120 \text{ GeV/c}^2$ for an integrated luminosity of 100 fb⁻¹ (ATLAS Experiment). The signal is shown on top of the irreducible background (left) and after background subtraction (right).

y-jet-jet, l-jet-jet and jet-jet-jet, have been considered. The total reducible background is estimated to be at the level of 20-30% of the irreducible one over the mass range considered (80-140 GeV/c²). The statistical significance in the mass range between 80 to 140 GeV/c² is 4 to 3 σ for an integrated luminosity of 100 fb⁻¹.

For low Higgs boson masses (< 140 GeV/ c^2) the decay width is of the order of keV. The measured mass resolution will be entirely dominated by the energy resolution of the electromagnetic calorimeter used to detect and measure the photons. The mass resolution will be in the order of 1–1.5 GeV/ c^2 at both experiments.

1.2. $H \rightarrow b\bar{b}$

This channel has about a 10 times larger $\sigma \times$ branching ratio (BR) than the $H \rightarrow \gamma \gamma$ mode. Since the direct production, $gg \rightarrow H$ with $H \rightarrow b\bar{b}$, cannot be efficiently triggered nor extracted as a signal above the huge QCD two-jet background, the associated production with a W or Zboson or a $t\bar{t}$ pair remains the only possible process to observe a signal from $H \rightarrow b\bar{b}$ decays. The leptonic decays of the W boson or semi-leptonic decays of one of the top quarks provide an isolated high- p_T lepton for triggering. In addition, requiring this high- p_T lepton provides a large rejection against background from QCD jet production. The Higgs boson signal might thus be reconstructed as a peak in the invariant jet-jet mass spectrum of tagged b-jets.

Contrary to the TeVatron *ZH* production with $Z \rightarrow ll$ is not considered at LHC because it provides a rate about six times lower than the *WH* channel and the signal-to-background ratio would not be significantly improved with respect to the *WH* channel because the main background *Zbb* is only a factor 1.8 smaller than the *Wbb* background.

Besides the *WH* channel the $t\bar{t}H$ is used, for both channels excellent *b*-tagging capabilities are needed to achieve a high efficiency. Using pixel layers at small radii allows to achieve efficiencies around 60% (50%) at low (high) luminosity, for rejection factors of about 100 versus u-jets. The background to the *WH* channel can be divided into three classes:

- Irreducible background from $WZ \rightarrow l\nu b\bar{b}$ and from $Wb\bar{b}$ production.
- Reducible background with at least two *b*-quarks in the final state, which arises predominantly from $t\bar{t} \rightarrow WWb\bar{b}$, and from single top production through $gq \rightarrow t\bar{b}q \rightarrow l\nu b\bar{b} + q$.
- Reducible background containing jets misidentified as *b*-jets, which arises mainly from W + jet production.

It is not clear in all cases how to achieve an accurate knowledge of the various backgrounds from the data. For example the shape and magnitude of the $Wb\bar{b}$ background cannot be obtained directly from the experimental data and one will have to rely on Monte Carlo simulations. If a systematic uncertainty of $\pm 5\%$ on the shape of the $Wb\bar{b}$ background is assumed in the $H \rightarrow b\bar{b}$



Figure 3: Left: Invariant mass distribution, $m_{b\bar{b}}$, of tagged *b*-jet pairs in fully reconstructed $t\bar{t}H$ signal events with a Higgs boson of 120 GeV/c² above the summed background. Assumed is an integrated luminosity of 100 fb⁻¹ (30 fb⁻¹ at low luminosity operation and 70 fb⁻¹ with high luminosity operation). The points with error bars represent the result of a single experiment (ATLAS) and the dashed line represents the background distribution. Right: Invariant mass distribution, $m_{b\bar{b}}$, of signal (dark shaded, $m_H = 115 \text{ GeV/c}^2$) plus background for $L_{\text{int}}=30 \text{ fb}^{-1}$ (CMS experiment) [9].

signal region, the statistical significance is between 3.0 σ (m_H =80 GeV/c²) and 1.7 σ (m_H =120 GeV/c²) for an integrated luminosity of 30 fb⁻¹ (ATLAS Experiment) and assuming a systematic uncertainty of \pm 5 %. on the shape of the $Wb\bar{b}$ background in the $H \rightarrow b\bar{b}$ signal region. In conclusion, the extraction of a signal from $H \rightarrow b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions for the *b*-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself.

The cross section for associated $t\bar{t}H$ production [7, 8] is about the same as for WH production. The final state is however considerably more complex, since it consists of two W bosons and four *b*-jets. For trigger purposes, one of the *W* bosons should decay leptonically, whereas the other one is assumed to decay into a $q\bar{q}$ pair. A signal from $t\bar{t}H$ production can be extracted by a complete reconstruction of both top-quark decays. This solves the large combinatorial problem arising from the presence of four *b*-quarks in the final state. This channel is observable both at low and high luminosity. The signal should appear as a peak in the $m_{b\bar{b}}$ distribution, above the various background processes. The resonant $t\bar{t}Z$ and continuum $t\bar{t}b\bar{b}$ production are the irreducible backgrounds. The W bosons are reconstructed from the jets not tagged as b-jets and from the reconstructed lepton and the neutrino. In the case of the leptonic decay, the W mass constraint is used to determine the longitudinal component of the neutrino momentum. Ambiguities arise in the pairing of the two *W* bosons, with two of the four *b*-jets. These ambiguities are resolved by selecting from all lvb - jjb combinations the one which minimizes $\chi^2 = (m_{jjb} - m_t)^2 + (m_{lvb} - m_t)^2$ $(m_t)^2$. For events passing all kinematic cuts, the $b\bar{b}$ invariant mass, $m_{b\bar{b}}$, is computed and a final cut is applied to select events in a mass window around the nominal Higgs boson mass. The $m_{b\bar{b}}$ distribution for the summed signal and background events is shown in Figure 3 for a Higgs boson mass of 120 GeV/ c^2 and for an integrated luminosity of 100 fb⁻¹ (30 fb⁻¹ at low luminosity operation and 70 fb⁻¹ with high luminosity operation, ATLAS Experiment).

The summed background is shown by the dashed line, and the points with error bars represent the result of a single experiment. A similar study has been done for CMS [9]. Here events are triggered and preselected if there is an isolated lepton ($p_T > 10$ GeV, $|\eta| < 2.4$) and at least six jets ($E_T > 20$ GeV, $|\eta| < 2.5$). In the next step, the best jet configuration in the event has been found by defining an event likelihood function which takes into account the probabilities of jets to be *b*-jets, two reconstructed top masses, one reconstructed *W*-mass and the order of *b*-jet energies. After the best configuration is found with the highest value of the event likelihood function, the signal events are enriched cutting on values of the likelihood functions which take into account *b*-tagging and kinematics of the event. Applying k-factors of 1.9 for $t\bar{t}q\bar{q}$ background and of 1.5 for $t\bar{t}H$ and $t\bar{t}Z$ leads to a signal-to-background ratio S/B = 73% with $m_H = 115 \text{ GeV/c}^2$. In the Standard Model the Higgs boson can be discovered in this channel with 5σ significance for a Higgs mass up to 122 GeV/c² for $L_{int} = 30 \text{ fb}^{-1}$. Figure 3 shows the invariant mass distribution of signal (dark shaded, $m_H = 115 \text{ GeV/c}^2$) plus background for $L_{int} = 30 \text{ fb}^{-1}$.

1.3. $H \rightarrow ZZ^{(*)} \rightarrow 4l$

The decay channel $H \rightarrow l^+ l^- l^+ l^-$ provides a very clean signature for a Standard Model Higgs boson in the mass range from $120 < m_H < 600 \text{ GeV/c}^2$. The signal can be well identified and reconstructed above rather low backgrounds. The branching ratio is larger than for the $\gamma\gamma$ channel and increases with increasing m_H up to $m_H \sim 150 \text{ GeV/c}^2$. For $m_H < 2 \cdot m_Z$, i.e. $H \rightarrow ZZ^* \rightarrow 4l$, the Higgs boson is narrow, hence a good mass resolution for electron and muon final states is essential. Both electrons and muons are considered in the final state, thus yielding *eeee*, $ee\mu\mu$ and $\mu\mu\mu\mu$ event topologies.

The background is composed of three components: ZZ^*/γ^* continuum, this process represents an irreducible background; $t\bar{t}$, this is a reducible background with the largest production cross section and $Zb\bar{b}$. The following kinematic selection cuts were designed to match the lepton triggers and to reject the $t\bar{t}$ and $Zb\bar{b}$ background:

- a. Pseudo-rapidity cut for each lepton: $|\eta_l| < 2.5$.
- b. Transverse momentum, p_T^l , for each lepton should be greater than 7 GeV, and at least two leptons should have p_T^l greater than 20 GeV.
- c. The di-lepton invariant mass of one selected pair of leptons should be consistent with the Z^0 mass: $|M_{ll} M_{Z^0}| < 6$ GeV. This cut rejects most of the non-resonant $t\bar{t}$ background.
- d. The other pair of the leptons should have an invariant mass greater than 20 GeV. This cut considerably reduces both the contributions from cascade decays and the $Z\gamma^*$ background.

The detection efficiencies obtained from the full simulations and reconstructions for different Higgs masses ranges from 34% to 54% for masses between 130 GeV/c^2 and 180 GeV/c^2 .

For the decay into four electrons inner bremsstrahlung degrades the response, yielding a mass resolution for $m_H = 130 \text{ GeV/c}^2$ of 1.4 GeV [4] with 20% of the events in tails of the mass distribution outside $\pm 2\sigma$. For the decay into four muons, the mass resolution using the muon system information alone gives 2 GeV, whereas a combination with the information from the inner tracker will give 1.4 GeV [10, 11] (ATLAS Experiment).

The $H \rightarrow ZZ^* \rightarrow 4$ lepton channel allows a discovery of a Standard Model Higgs boson in the mass range from 130 to 180 GeV/c², already at low luminosity, by combining the electron and muon signatures. The signal-to-background ratios are large and the reducible backgrounds can be kept at the level of 10–20% of the ZZ^* continuum.

Figure 4 shows the invariant mass distribution of the four leptons for the process $H \rightarrow ZZ^* \rightarrow$ 4l. The peaks for $m_H = 130, 150$ and 170 GeV/c^2 are shown over the Standard Model background assuming an integrated luminosity of 100 fb^{-1} for the CMS experiment.

For Higgs boson masses larger than 180 GeV/c² the $H \rightarrow ZZ \rightarrow 4l$ signal would be observed easily above the $ZZ \rightarrow 4l$ continuum background after less than one year of low luminosity operation for $180 < m_H < 600 \text{ GeV/c}^2$. For larger values of m_H , the Higgs boson signal becomes very broad and the signal rate drops rapidly, but a signal in the $H \rightarrow ZZ \rightarrow 4l$ channel could be observed up to $m_H \sim 800 \text{ GeV/c}^2$, possibly even through the WW/ZZ fusion process if jet tagging in the forward regions is required.

1.4. $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

This channel is extremely interesting near the $2m_W$ mass threshold, where the decay $H \rightarrow ZZ \rightarrow 4l$ is suppressed. By applying kinematical cuts on the outgoing leptons, based on different kinematics between the Higgs and the *WW* processes, one can observe a broad excess of events in the spectrum of the transverse dilepton mass, m_T , above the dominant *WW* background with $S/B \sim 1$ [12],[13]. The background consists of the irreducible *WW*^{*} continuum production, where



Figure 4: Invariant mass distribution of the four leptons for the process $H \rightarrow ZZ^* \rightarrow 4$ l. The peaks for $m_H = 130, 150$ and 170 GeV/c² are shown over the Standard Model background assuming an integrated luminosity of 100 fb⁻¹ for the CMS experiment. Right: Transverse mass distribution for a Higgs signal $(M_H = 170 \text{ GeV/c}^2)$ in the $H \rightarrow WW^* \rightarrow l\nu l\nu$ channel (ATLAS experiment) and the total background. The distribution for the background alone is shown separately (dashed line).

both *W*'s decay leptonically, and of the following reducible contributions: (1) $t\bar{t}$ production, (2) Single top production *Wt* and (3) *W*+jet(s) production, with a leptonic *W* decay and a jet faking an electron. The distribution of the transverse mass is shown for all signal and background events passing the selection criteria in Figure 4 for a Higgs mass of 170 GeV/c². In order to evaluate the significance, it has been assumed that a normalization between the Monte Carlo prediction and the data can be performed outside the signal region and that the $t\bar{t}$, the *WW* and the *Wt* backgrounds are known with a systematic uncertainty of $\pm 5\%$. Taking this into account the significance for the signal observation in the ATLAS experiment is found to be above 5 standard deviations in the mass region between 155 and 190 GeV/c² assuming an integrated luminosity of 30 fb⁻¹. The sensitivity to the Higgs mass is given by the upper falling edge of the distribution. It has been estimated that the Higgs mass can be determined with an accuracy of better than ± 5 GeV from this distribution. The CMS collaboration has done a study applying cuts based on the boost and the spin-correlation of the *WW*-system which enables the difficult separation from the irreducible continuum background production. A discovery for $155 < m_H < 180 \text{ GeV/c}^2$ is possible for only 5 fb⁻¹ [14].

1.5. Higgs Production via Weak Gauge Boson Fusion

The largest Higgs production cross-section is predicted for gluon-gluon fusion, but the second largest cross-section is predicted for weak gauge boson fusion, $q\bar{q} \rightarrow q\bar{q}VV \rightarrow q\bar{q}H(V = W, Z)$. With the Higgs boson decaying to $H \rightarrow W^{(*)}W^{(*)} \rightarrow e^{\pm}\mu^{\pm}p_T^{miss}$ a significant Higgs boson signal with an integrated luminosity of 5 fb⁻¹ or less would be seen in the mass range of 130–200 GeV/c². The additional very energetic forward jets in these events can be exploited to significantly reduce the backgrounds. Another feature is the lack of color exchange between the initial-state quark in contrast to most background processes. This channel has been first proposed by Rainwater and Zeppenfeld [15]. This channel is also interesting for a measurement of the $t\bar{t}H/WWH$ coupling ratio. The dominant backgrounds are the production of W pairs, $t\bar{t}$ and $Z \rightarrow \tau\tau$ in association with jets. First studies by ATLAS and CMS including a detector simulation have been performed and are promising. Recently this channel has been investigated as discovery mode for a light Higgs boson with a mass of around 115 GeV/c² [16]. The signal to background ratio is better than 1:1 and allows a 5σ signal with 35 fb⁻¹ of data.

Besides the decay channel described above decays of the Higgs boson to $\tau^+\tau^-$ pairs or $H \rightarrow \gamma\gamma$ are investigated. Both decay channels allow a 5 σ discovery in the mass range of 110–150 GeV/c²

1.6. Heavy Higgs Boson

For Higgs masses in the range $180 < m_H < 700 \text{ GeV/c}^2$, the $H \rightarrow ZZ \rightarrow l^+ l^- l^+ l^-$ decay mode is the most reliable channel for the discovery of a Standard Model Higgs at LHC. The momenta of the final state leptons are high and their measurement does not put severe requirements on the detector performance. Therefore, the Higgs discovery potential in this channel is primarily determined by the available luminosity. The $H \rightarrow ZZ \rightarrow 4l$ becomes nevertheless rate limited around $m_H \sim 700 \text{ GeV/c}^2$. To access Higgs masses up to the TeV mass range one needs also to allow hadronic or neutrino final states. The channels available are $H \rightarrow ZZ \rightarrow ll\nu\nu$, with a rate six times larger than the 4-lepton mode, and with a large missing E_T signature and the $H \rightarrow WW \rightarrow l\nu jj$ mode, with a rate 150 times larger than the the sum of the 4-lepton mode and the $H \rightarrow ZZ \rightarrow ll\nu\nu$ mode. The $WW \rightarrow l\nu jj$ mode provides a discovery potential from 600 to 1000 GeV/c², and a sensitivity to masses down to 300 GeV/c². This mode is complemented by the $ZZ \rightarrow ll\nu\nu$ mode in the mass range from 500-700 GeV/c², thus giving redundancy and robustness to the search in that mass region, and allowing to compare H to WW and H to ZZcouplings.

1.7. Overall Sensitivity to the Standard Model Higgs Searches

The overall sensitivity for the discovery of a Standard Model Higgs boson over the relevant mass range from 80 GeV/c² to 1 TeV/c² is shown in Figure 5. The sensitivity is given in terms of S/\sqrt{B} for the individual channels as well as for the combination of the various channels assuming an integrated luminosity of 30 fb⁻¹. A Standard Model Higgs boson can be discovered in the ATLAS experiment over the full mass range up to ~1 TeV/c² with a high significance. A discovery sensitivity of 5σ can already be reached over the full mass range after a few years of running at low luminosity [4]. No k-factors have been included in the evaluation of the signal significance. This is a conservative assumption, provided the k-factor for the signal process of interest is larger than the square root of the k-factor for the corresponding background process.

Most of the decay channels studied in the mass range below 200 GeV/c^2 are challenging in terms of detector performance. Even though the natural width of the Standard Model Higgs boson in this mass range is narrow, the backgrounds are relatively large and thus, an excellent detector performance in terms of energy resolution and background rejection is required. The $H \rightarrow \gamma \gamma$ decay mode requires high performance of the electromagnetic calorimetry in terms of photon energy resolution, photon direction measurements, and γ/jet separation. Impact parameter measurements in the inner detector are crucial for the discovery of the $b\bar{b}$ decay mode: efficient tagging of *b*-jets with a high rejection against light quark and gluon jets allows a rather clean and complete reconstruction of $t\bar{t}$ final states together with the $b\bar{b}$ mass peak from Higgs boson decays. Finally, excellent performance in terms of the identification, reconstruction and measurement of isolated leptons with $p_T > 7$ GeV is required to discover the Higgs boson in the $H \rightarrow ZZ^* \rightarrow 4l$ channel. For $m_H > 2m_Z$, the dominant discovery channel is the four-lepton channel. In this case the background is small and dominated by irreducible ZZ continuum production. For $m_H > 300 \text{ GeV/c}^2$ the requirements on the detector performance are rather modest in this channel, since the Higgs width is larger than the detector resolution. A high-significance discovery of the Higgs boson can be achieved for Higgs boson masses up to 600 GeV/c^2 over less than one year of data-taking at low luminosity. By combining the two experiments ATLAS and CMS the minimum luminosity required to start seeing a 115 GeV/c² Higgs boson at 5 σ is ~ 10 fb⁻¹ (see Figure 5), which may be achieved after two years of LHC running. Since at most a few weeks of very low luminosity collisions can be envisaged in 2005, and only 1 or 2 fb^{-1} is anticipated in 2006, this presumably means that the LHC could hope to discover a 115 GeV/c^2 Higgs boson after the 2007 run. For higher masses, i.e. for $130 < m_H < 500 \text{ GeV/c}^2$, the discovery is expected to be much faster (a few months of data-taking) thanks to the gold-plated and background-free $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel.



Figure 5: Left: Sensitivity for the discovery of a Standard Model Higgs boson. The sensitivity in terms of S/\sqrt{B} is plotted for individual channels and for a combination as a function of the Higgs mass assuming an integrated luminosity of 30 fb⁻¹ at the ATLAS experiment. Right: The combined sensitivity of the two LHC experiments ATLAS and CMS to a Standard Model Higgs boson, as a function of its mass, for different accumulated luminosities.

2. Determination of the Standard Model Higgs Boson Parameters

The determination of the Higgs boson parameters is a major goal once the Higgs boson will have been discovered. Precision measurements of these parameters allow a deeper understanding of the electroweak symmetry-breaking mechanism. They may also be useful to distinguish a Standard Model Higgs boson from a MSSM Higgs boson. The ATLAS experiment provides excellent tools to measure precisely the Higgs boson parameters like mass, production rates, couplings to bosons and fermions and the total width. A detailed description can be found in [20].

In most of the channels the Higgs boson appears as a resonant peak above the background $(H \rightarrow \gamma \gamma, H \rightarrow ZZ \rightarrow 4l)$, thus the background can be subtracted using control regions outside the resonance. The error on the mass reconstruction includes the statistical error due to the limited number of signal events and the error of the subtraction of the background. The uncertainty on the absolute energy scale introduces a systematic error, which is assumed to be 0.1% for photons and leptons and 1% for each jet. This is a conservative estimate since the ATLAS goal is to determine the absolute energy scale for photons and leptons with a precision of 0.02%.

In the channel $H \rightarrow \gamma \gamma$ the fractional error is found to be 0.2-0.3% for 300 fb⁻¹—this corresponds to about ten years of operation at the LHC—in the mass range of 110 to 150 GeV/c². The channel $H \rightarrow ZZ \rightarrow 4l$ offers the best possibility of determining the mass of the Higgs boson. An accuracy of 0.1% is achievable over the whole mass range of 120 to 400 GeV/c² and an integrated luminosity of $\int \mathcal{L}dt = 300 \text{ fb}^{-1}$. For larger masses the precision deteriorates because the Higgs width becomes large and therefore the statistical error increases. However, even for masses as large as 700 GeV/c² the Higgs mass can be measured with an accuracy of 1%.

Figure 6 shows the fractional errors in the channels considered for an integrated luminosity of $\int \mathcal{L} dt = 300 \,\text{fb}^{-1}$. For the combination of the channels an energy scale uncertainty of $\pm 0.1\%$ is assumed. The goal is to reach an energy scale uncertainty of $\pm 0.02\%$ by determining the scale from $Z \rightarrow ll$.

The determination of the rates in the various production and decay channels allows to set constraints on the couplings and the branching ratios. Using the $H \rightarrow ZZ \rightarrow 4l$ channel a differentiation between Standard Model and MSSM may be feasible, since this channel is suppressed in the MSSM. Furthermore the Higgs width differs from Standard Model to MSSM and thus can also be used for the distinction.

The statistical error on the rate is expected to be smaller than 10% over the mass region 120 to 600 GeV/c² using the $\gamma\gamma$, $b\bar{b}$ and 4 lepton final states. The main systematic error comes from



Figure 6: Relative precision $\Delta M_H/M_H$ of the Higgs mass reconstruction assuming an integrated luminosity of $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ per experiment (ATLAS+CMS). The open symbols correspond to the different channels. The combination of all channels with an uncertainty of 0.1% on the energy scale is represented by the dark triangles.



Figure 7: Relative precision on the measurement of the Higgs boson rate ($\sigma \times BR$) for various channels, as a function of m_H , assuming an integrated luminosity of 300 fb⁻¹. The left figure shows predictions using direct production, the right figure shows the predictions using associated production.

the knowledge of the luminosity, a value of 5% has been considered for the luminosity uncertainty. An additional systematic error of 10% for the $H \rightarrow b\bar{b}$ and 5% for the $H \rightarrow WW$ has been included to take into account the uncertainty on the background subtraction for channels where the background is not completely flat under the peak. Figure 7 shows the expected experimental uncertainty on the Higgs boson rates, for various production and decay channels. The left part displays the results from direct production. Over the mass region 120 to 600 GeV/c², the Higgs boson production rate can be measured with a precision of 7%. The right part gives the results from associated production. Over the mass range of 100 to 200 GeV/c² the expected precision is between 6 and 30%. An integrated luminosity of $\int \mathcal{L}dt = 300 \,\text{fb}^{-1}$ per experiment (ATLAS+CMS) is assumed.

Without any theoretical input only a measurement of coupling ratios will be possible at LHC. From the direct measurement of $\sigma \times BR(H \rightarrow WW^*)$ and $\sigma \times BR(H \rightarrow ZZ^*)$ the ratio of the HWW coupling to the HZZ coupling, g_{HWW}/g_{HZZ} , can be measured with an accuracy of 10–15%. In

10% because of higher order corrections. For both measurements an integrated luminosity of 300 fb⁻¹ per experiment is assumed. Measurements of the boson/fermion couplings are affected by more theoretical constraints and the measurement is restricted at LHC. $g_{HWW}/g_{Ht\bar{t}}$, $g_{HWW}/g_{H\tau\tau}$, $g_{HWW}/g_{Hb\bar{h}}$ can be measured with an error of 15–30%.

The width of the Higgs, can be measured directly above the *ZZ* decay threshold where the width grows rapidly. ATLAS and CMS will be able to measure the Higgs width with a precision of 5 to 6% over the mass range 300–700 GeV/c². The systematical error is dominated by the uncertainty of radiative decays, assumed to be 1.5%. Below 300 GeV/c² the instrumental resolution is larger than the Higgs width Γ_H .

To determine the width of the Higgs boson for masses less than 300 GeV/c^2 , an indirect method, which is proposed in [21], can be used. From rates of $qq \rightarrow qqH$ with $H \rightarrow \gamma\gamma, \tau\tau, WW$ decays assuming a branching ratio of less than 10% for $H \rightarrow c\bar{c}$ and non-standard decays a measurement of the Higgs width in the mass range of 120 to 150 GeV/c^2 is possible with an expected precision of 6 to 20%.

3. Minimal Supersymmetric Standard Model Higgs

There are strong theoretical arguments suggesting that the theory of elementary particles should obey supersymmetry. The most interesting choice for the SUSY model is the one with a minimum number of Higgs fields, the Minimal Supersymmetric Standard Model, MSSM [22]. Extensive simulation work has been done to study the possibilities to search for the MSSM Higgs bosons with the ATLAS detector [4]. The Higgs sector in the MSSM contains two CP-even (h,H), one CP-odd (A) neutral states and one charged (H^{\pm}) state.

At tree level there are two free parameters determining their masses and couplings. Usually m_A and the ratio of the expectation values of the Higgs doublets, $\tan \beta$, are chosen. The investigation of the Higgs sector of the MSSM is complex and one has to deal with a rich spectrum of possible signals. For the benchmark sets of MSSM parameters [23], where M_{SUSY} is fixed to 1 TeV, an extreme configuration of stop mixing parameters (A_t, μ) has been chosen, the so-called minimal mixing scenario $(A_t, \mu \ll M_{SUSY})$. This scenario corresponds to the most pessimistic discovery scenario at the LHC, since these choices for the additional MSSM parameters give the lowest possible upper limit for m_h . This reduces the LHC potential for h-boson discovery in the $h \rightarrow \gamma \gamma$ channel, and also suppresses the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel.

The interest is focussed on the potential of various decay modes accessible also to the Standard Model Higgs: $h \rightarrow \gamma\gamma$, $h \rightarrow b\bar{b}$, $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$, and on modes strongly enhanced at large $\tan\beta$: $H/A \rightarrow \tau^+\tau^-$, $H/A \rightarrow \mu^+\mu^-$. Much attention is given also to other potentially interesting channels such as $H/A \rightarrow t\bar{t}$, $A \rightarrow Zh$, $H \rightarrow hh$. The 5σ discovery contour as determined for the various channels in the (m_A , $\tan\beta$) plane are superimposed in Figure 8 for an integrated luminosity of 10 fb⁻¹ per experiment (ATLAS+CMS). From Figure 8 it can be seen that a large part of the (m_A , $\tan\beta$) plane can be explored in the year 2007. The region between $3 \leq \tan\beta \leq 10$ and $100 \leq m_A \leq 250 \text{ GeV/c}^2$ can not be covered with 10 fb⁻¹ integrated luminosity. For a region $3 \leq \tan\beta \leq 15$ and $m_A \geq 100 \text{ GeV/c}^2$ only the lightest Higgs boson h is accessible. The figure also displays the LEP limit [24] which excludes the region below $\tan\beta < 2.4$ and $m_A \approx 93 \text{ GeV/c}^2$. The details of the contour curves can be affected by changes in some of the parameters in the MSSM model. These studies have selected sets of parameters, for which SUSY particle masses are large, so that Higgs-boson decay to SUSY particles are kinematically forbidden.

At the very high integrated luminosity of 300 fb⁻¹, the ATLAS discovery potential covers the whole parameter space. The overall discovery potential in the $(m_A, \tan\beta)$ plane relies heavily on the $H/A \rightarrow \tau\tau$ channel and on the $t\bar{t}h$ with $h \rightarrow b\bar{b}$ and on the $h \rightarrow \gamma\gamma$ channels. From Figure 8 it can be seen that over a large range of the parameter space more than one Higgs boson is observable and the experiment would be able to distinguish between Standard Model and MSSM. In this Figure an integrated luminosity of 300 fb⁻¹ for the ATLAS experiment is assumed. At



Figure 8: Left: For an integrated luminosity of 10 fb⁻¹ per experiment (ATLAS+CMS), 5σ discovery contour curves in the (m_A , tan β) plane for all Higgs boson signals are shown. Right: Number of Higgs bosons of the MSSM in the plane of tan β versus m_A (maximal scalar top mixing) observable at the LHC with 300 fb⁻¹ of integrated luminosity with ATLAS.

small tan β a large number of channels are accessible allowing a measurement of many couplings including *Hhh* and *AZh*. For almost all cases, the experiment would be able to distinguish between the Standard Model and the MSSM case. The region with $m_A > 250 \text{ GeV/c}^2$ and $4 < \tan \beta < 5 - 10$ is only covered by the $h \rightarrow \gamma \gamma$ and $h \rightarrow b\bar{b}$ channels thus making the distinction very difficult. Over large regions for $m_A > 160 \text{ GeV/c}^2$, all three neutral Higgs bosons, and in some cases also the charged Higgs boson would be discovered with ATLAS. Over most of this region, the *H* and *A* bosons are degenerate in mass and would be very difficult to distinguish. For ~ 10% of the parameter space, i.e. for tan $\beta > 2$ and 90 GeV/c² $< m_A < 130 \text{ GeV/c}^2$, the two neutral Higgs bosons and the charged Higgs boson would be discovered with ATLAS.

4. Summary

The LHC will most probably allow to solve one of the most interesting remaining questions in particle physics: whether one or more Higgs bosons exist or not. By combining the two experiments ATLAS and CMS the minimum luminosity required to observe a 115 GeV/c² Higgs boson with 5 σ significance is ~ 10 fb⁻¹, which may be achieved after two years of LHC running. The availability of two channels, $H \rightarrow \gamma \gamma$ and $H \rightarrow b\bar{b}$, should give robustness to the discovery and should allow the interpretation of the observed signal as indeed coming from a Higgs boson. For higher masses, i.e. for 130 < m_H < 500 GeV/c², the discovery is expected to be much faster (a few months of data-taking) thanks to the gold-plated and background-free $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel.

With a modest integrated luminosity of 30 fb⁻¹, the LHC discovery potential covers a large fraction of the MSSM parameter space in the $(m_A, \tan \beta)$ plane. In most of the MSSM parameter space more than one Higgs boson would be discovered thus allowing a clean distinction between the Standard Model and the MSSM case. If only one Higgs boson can be detected LHC has to measure the properties of the Higgs boson to disentangle Standard Model and MSSM.

The experimental precision with which the Higgs boson mass will be measured assuming 300 fb⁻¹ integrated luminosity for the ATLAS and CMS detector will be 0.1% up to masses of 400 GeV/c². The Higgs boson width can be obtained from a measurement of the width of the reconstructed Higgs peak, over the mass range $300 < m_H < 700$ GeV the precision of the measurement is of the order of 6%. The statistical error on the measurement of the cross section times the branching ratio is expected to be smaller than 10% over the mass region 120-600 GeV/c². By combining these measurements for several channels, one can obtain constraints on the Higgs boson couplings.

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