HIGGS PHYSICS AT THE LHC*

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This is a non exhaustive overview of Higgs physics at the LHC.

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1. Introduction

In the Standard Model, the electroweak symmetry breaking is provided by the Higgs mechanism [1]. This mechanism predicts the existence of a scalar particle, the Higgs boson (H), which has so far eluded detection. Direct searches performed at LEP put a lower limit on the H mass at 114.4 GeV/c^2 [2]. Precision observables are also sensitive to the H mass through virtual effects. Within the Standard Model, this allows to set an upper limit on the H mass at 186 GeV/c^2 (at 95% CL) [3].

In the following, we concentrate on "low" H mass (M_H) boson searches at the LHC (mostly $M_H < 200$ GeV/c^2), which is the region favoured in the Standard Model. Note that Supersymmetry, the most favoured extension of the Standard Model, also requires a light Higgs boson.

This paper is organised as follows:

- The first section summarises H production at the LHC and decay, as well as the experimental conditions.
- The second section discusses the observation of the Standard Model H.
- The third section is devoted to the measurement of the properties of H.
- The last section summarises the investigations of the Higgs sector of supersymmetric theories.
- Diffractive Higgs production [4] at LHC is not covered here.

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2. Higgs boson production and decay

2.1. Higgs boson production at the LHC

The main production mechanisms of H in 14 TeV proton–proton collisions are, by order of importance: gluon–gluon fusion via a top quark loop, vector boson fusion (VBF), associated production with top quark pair ($t\bar{t}H$), associated production with W or Z boson (WH, ZH). There have been many progresses in the recent years in the QCD computations of these processes [5, 6]. All of them are available either at NLO (next to leading order) or NLLO, and H production properties (like transverse momentum distribution) are also available. It should be noted that the NLO corrections to the gluon–gluon fusion are fairly large, increasing the cross-section by a factor almost two, and that the recent NNLO computations confirm this increase and show also a stabilisation of the cross-section. Fig. 1 shows the cross-sections for the different production processes as a function of the H mass. The typical uncertainties on the predicted cross-sections are $\approx$ 10–20% for the gluon–gluon fusion, $\approx$ 5% for the VBF process, $\approx$ 10–20% for the $t\bar{t}H$ process and $\approx$ 5% for the WH, ZH processes.

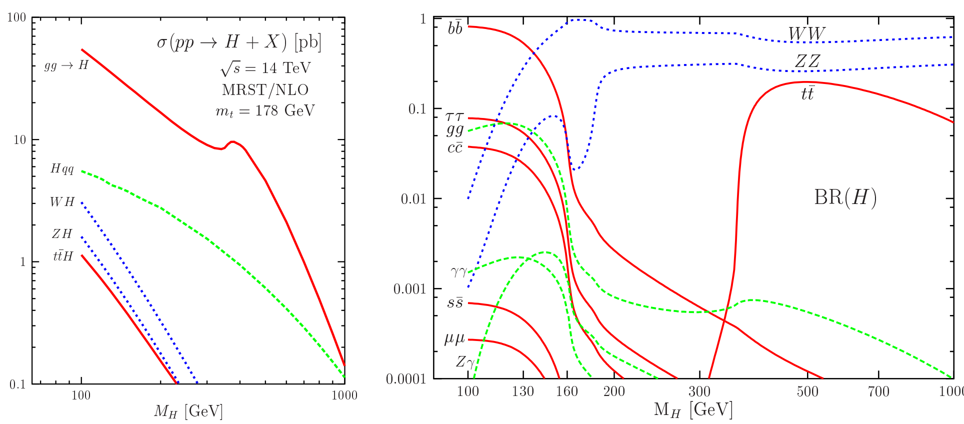

Fig. 1. Higgs production cross-sections and branching ratios (from [6]).

2.2. Higgs boson decay

The dominant H decays are the heaviest particles kinematically accessible: fermion–antifermion pair, mostly $b\bar{b}$, which is dominant up to a H mass of $\approx$ 140 GeV/c^2 (in this mass range, $\tau\tau$ decay has $\approx$ 10% BR); $WW(^*)$, $ZZ(^*)$ (where one or both W, Z can be off shell), this is the dominant decay mode above 140 GeV/c^2; loop mediated decays to two photons, through W and top quark loops, are much smaller but play an important role in the H

observation as will be shown latter. Fig. 1 shows the H branching ratios as a function of the mass. The total width is much smaller than experimental resolution up to $\approx$ 200 GeV/c^2 but then grows very rapidly.

2.3. Experimental conditions and detectors

The first LHC run with 900 GeV centre of mass energy (no acceleration) is expected to end in 2007. Collisions at the full 14 TeV center of mass energy will start in 2008, with a luminosity increasing to reach 10^{33}cm^{-2}s^{-1} (called "low luminosity" phase). It is expected that about 30 fb^{-1} of integrated luminosity will be collected under these conditions. The luminosity will then increase to reach the design value of 10^{34}cm^{-2}s^{-1} ("high luminosity" phase), with $\approx$ 300 fb^{-1} collected during 2014–2015. In the low luminosity phase, the pile-up of additional proton–proton interactions in the same bunch crossing is about 2 to 4, while it reaches up to 25 at high luminosity (bunch crossings are taking place every 25 ns). The H signal production cross-sections are several order of magnitude below the main processes: $\approx$ 80 mb for the total inelastic cross-section, few μb for high (>100 GeV) transverse energy inclusive jet production, several tens of nb's for W and Z inclusive production. So trigger issues (not discussed in details in this review) are critical and should always be kept in mind. In the following, we will emphasise the low luminosity phase for the H observation. The CMS and ATLAS detector descriptions can be found elsewhere [7, 8]. The key points for H searches are powerful e, photon, muon, tau and b-jet identification [9] (especially with very good rejections against light flavour jets) and very good photon and lepton energy measurements (typically 1–2% resolution in the 25–50 GeV energy range), as well as good jets and transverse missing momentum reconstruction.

3. Observing the Standard Model Higgs boson

3.1. Overview

The strategy to detect H follows the production and branching ratios, as well as the background levels:

- Gluon–gluon fusion is the dominant production, but is only accessible if H does not decay to jets (which is overwhelmed by QCD backgrounds). Thus at low mass one has to rely on the two photon decay mode (even the tau decay mode is probably very hard to extract from the backgrounds). Above 130 GeV/c^2, $ZZ(^*)$, $WW(^*)$ decays can be used, leading to four leptons and two leptons signatures.
- VBF production: This production mode offers a distinct signature with two "forward" jets allowing better background rejection. The $\tau\tau$ decay mode in the low mass region becomes accessible.

- $t\bar{t}H$ production: Leptons from top decays allow to trigger efficiently the event. Detailed event reconstruction allows background reduction and the observation of the $b\bar{b}$ decay at low mass. Other H decay modes could be observed with high luminosity.

- WH, WZ production: Two photons and WW^* decays can be observed at high luminosity.

In the following, we discuss more in details few selected channels. General reviews of all the channels can be found in Refs. [10–12].

3.2. The two photons channel

This channel in interesting in the mass range 100–140 GeV/c^2. One is looking for a narrow peak over a smooth background. The key points are *(i)* a good mass resolution, around 1% (since the intrinsic H width is negligible) which comes from excellent energy resolution of the electromagnetic calorimeter and the ability to reconstruct the primary vertex position, and *(ii)* a good photon identification to reduce the jet background below the true photon level. These aspects are studied with detailed full simulations of the detectors based on GEANT. The irreducible background from prompt diphoton production is now computed at NLO [13, 14]. This computation agrees with Tevatron data. The availability of NLO computation for the background allows also to use in a consistent way NLO cross-sections for the signal. ATLAS and CMS have different strong points for this analysis (better energy resolution in CMS, better photon identification and primary vertex reconstruction in ATLAS). Overall the sensitivities are similar if the same input cross-sections are used. In a simple cut based analysis, one is just counting events in a mass window after kinematical cuts. Several ways to optimise this analysis have been explored by ATLAS and CMS. In CMS, kinematic information and photon isolation are added as discriminating variables in the analysis. In ATLAS, the transverse momentum of the photon pair and the angular distribution are used in a likelihood analysis. This improves typically by 30–40% the expected signal significance. These improvements as well as the impact of using NLO cross-sections for signal and background are summarised in the Table I. The differences in the CMS results between the ECAL TDR [15] and the recent study come from better NLO background computation and up-to-date detector simulation. In the ATLAS numbers, the systematic error from fitting the background is not included. This is expected to be $\approx 10\%$ effect on the significance. All these numbers have to be taken with a grain of caution, as the exact level of background will only be known from the data.

TABLE I

Signal significance in the two photon channel,
for 30 fb^{-1} and a H mass of 130 GeV/c^2.

CMS (using NLO rates)		
Ecal TDR	new "cut"	new "optimised"
7.5	6.0	8.2
ATLAS (stat. error only)		
Physics TDR (LO)	new NLO "cut"	new NLO "likelihood"
3.9	6.2	8.7

Dividing events according to the production modes (asking for additional jet, VBF production signature, $t\bar{t}H$ associate production, *etc.*..) could further increase the discovery potential. See [16] for more details on this channel.

3.3. The four leptons channel

This channel is promising in the mass range above 130 GeV, where the ZZ^* decay mode starts to have an observable rate. The key points are very good electron and muon identification and energy resolution. The irreducible background comes from continuum ZZ^* production. The quark annihilation component is known at NLO, 20% should be added to account for the gluon fusion contribution (box diagram). Potentially large reducible backgrounds arise from non-isolated leptons from b decays from the $Zb\bar{b}$ and $t\bar{t}$ productions (the latter is also non resonant). These backgrounds are reduced by isolation and impact parameter cuts. Typical rejections larger than 100 are achieved and this allows to reduce these backgrounds below the irreducible one. This channel is very clean but suffers from low statistics, especially near 130 GeV and 160–170 GeV. See [17] for more details on this channel.

3.4. The WW(*) channel

The main interest of this channel in the gluon fusion process is near 160 GeV H mass, where the branching ratio to WW becomes close to 100%. Both W are required to decay to lepton (electron or muon). The backgrounds arise from $t\bar{t}$ production which can be rejected by strong jet veto and WW continuum which is rejected using angular correlation to distinguish the signal (the decay of a spin 0 particle) from the background. As there are two neutrinos in the final state, the H mass cannot be reconstructed. This is therefore a counting experiment where one has to rely on accurately estimating the background level in the signal region. To achieve this goal dedicated control regions are used to normalise the background and to extrapolate to the signal region. The new developments in this analysis are the inclusion of the gluon fusion contribution to the continuum (small increase in the total background, but shape more similar to the signal) and the computation of both $t\bar{t}$ and single top contributions at NLO. See [18] for more details on this channel.

3.5. The VBF channels

The VBF H boson production has two distinct signatures which can be used to reduce backgrounds: two "forward" tagging jets of transverse momentum around half the W mass with a pseudo-rapidity separation of about 5 units, and no jet radiation in the central region between these two jets, because of the absence of colour flow between the tagging jets. A typical selection for VBF events is thus to ask for two jets above ≈ 40 GeV transverse momentum, with a pseudo-rapidity separation 4.4 and a large invariant mass and to apply a jet veto in the central region. The jet veto cut is expected to reject about 70% of QCD induced backgrounds [19], but is also sensitive to underlying event activity and pile-up effects on the signal. VBF channels have thus been investigated so far only for the "low luminosity" phase.

For low H mass, the VBF production followed by decay to a tau pair is a promising discovery channel. Final states in which both taus decay to leptons or one tau decays to lepton and one to hadrons are considered. In the second case, hadronic tau identification plays an important role. The typical selection, in addition to the VBF generic cuts discussed above, asks for the H decay products to be located in the central region between the tagging jets and apply a cut on the missing transverse momentum (coming from the neutrinos from the tau decays). Even if there are three or four neutrinos in the final state, the H mass can still be reconstructed thanks to the collinear approximation: neglecting the tau mass and assuming that the neutrino directions coincide with the visible tau decay products, the energies of the two taus can be computed from the missing transverse momentum. The resolution on the reconstructed H mass is limited by the missing transverse momentum resolution and is typically 10–13 GeV/c^2. The dominant background in this channel is the production of Z+2 jets followed by Z decays to tau pairs. It should be noted that the background under the H signal is dominated by "on shell" Z with large resolution rather than by intrinsic high mass Drell–Yan events. For this channel, it is important to notice that large control samples of Z+jets will be available with Z decays to electrons and muons. This will allow to study signal free background control samples and investigations of the jet veto rejection.

The other important VBF channel is when the H decays to $WW(^*)$, leading to a dilepton final state (or a lepton plus two jets final state) in addition to the tagging jets. Compared to the dilepton search in the gluon fusion process, the VBF specific cuts allow to reach a better signal over background ratio. The need in accurately predicting the background rate is reduced, however, the backgrounds are more complicated in the VBF analysis.

3.6. Overall sensitivity and comments

Fig. 2 shows the overall discovery potential of ATLAS [11] and CMS [12] for the Standard Model H.

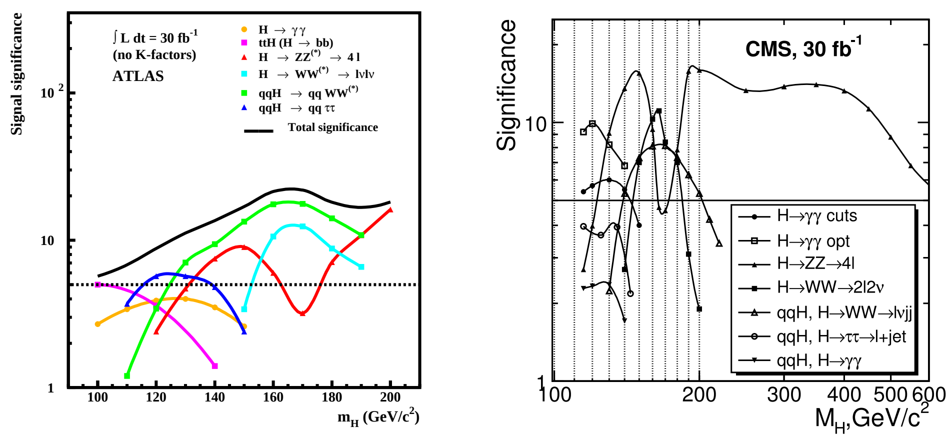

Fig. 2. ATLAS and CMS discovery potential for the Standard Model Higgs boson.

Note that the ATLAS sensitivity shown here is based on LO estimates of the signal cross-sections. Using NLO cross-sections (which has a large impact on the gluon fusion channels), the two experiments have similar sensitivities. As expected, in the region 200–500 GeV$/c^2$, the golden four lepton mode provides an "easy" Higgs discovery. The situation becomes more complicated in the very large mass range (strongly disfavoured in the Standard Model). The most delicate point is the low H mass range. However, even for a H mass of 115 GeV$/c^2$, several channels can be combined and there is already a good discovery potential with 10 fb^{-1} of integrated luminosity. This assumes that detector performances and background systematics are under control. It is therefore important to have for each channel a clear procedure to estimate the background from the data. These issues are briefly summarised in Table II.

TABLE II

Examples of required background systematics and how to get the background from the data. The channels are ranked from "easy" to "more difficult".

Channel	Background	S/B	Bkg syst for 5σ	Technique
Four leptons	$ZZ\,, Zbb\,, t\bar{t}$	300–600%	60%	Side-bands
$\gamma\gamma$	$\gamma\gamma\,, \gamma q$	3–5%	0.8%	Mass side-bands
VBF $H \to \tau\tau$	Zjj ($t\bar{t}$)	50–200%	10–40%	Mass side-bands (beware of Z mass tails)
$t\bar{t}H\,, H \to bb$	$ttbb\,, ttjj$	30%	6%	Mass side-bands anti b-tagging
$H \to WW$	$WW^*\,, t\bar{t}$	30–150%	6–30%	No mass peak Bkg from control regions

4. Measuring the properties of the Higgs boson

4.1. Higgs boson mass and width

The H mass is easy to measure from the two photons or the four lepton decay modes. The accuracy will be limited by systematic uncertainties on lepton and photon energy scales, most likely around 0.1%. The H width can be directly measured with a meaningful accuracy only above 200 GeV/c^2.

4.2. Spin and CP

In the Standard Model, the quantum numbers of the H are 0^{++}. The observation of H decay to two photons, or the production through gluon fusion would exclude the spin one possibility. For a H mass above 200 GeV/c^2, the spin and CP can be studied directly from angular correlations in the four lepton decay mode [20]. Alternate hypothesis like spin 1 or spin 0 and CP $= -1$ can be excluded at more than three sigmas for all masses above 200 GeV/c^2 and an integrated luminosity of 100 fb^{-1}. At lower masses, the H spin can be investigated in the WW^* to dilepton channel, provided the background could be subtracted accurately enough. Information on the CP properties of the HWW coupling can also be studied from the VBF processes.

4.3. Coupling measurements

For this topic, we discuss here the "low" H mass regime (below 180 GeV/c^2). This analysis can be decomposed in several steps and is based on the rates observed in the various accessible (production mode)$\times$(decay channel) [21]:

- Assuming spin 0 for the Higgs, the observed rate (after background subtraction and efficiency correction) can then be converted in $\sigma\times$BR. The typical acuracies range between 10 and 100% depending on the channel, with the expected systematic uncertainties taken into account.
- Assuming that the same Higgs boson is observed in all channels, these measurements can be converted in ratio of BR.
- Assuming that there are no new particles in the loops and no enhanced couplings to light fermions, all rates and BR can be expressed as a function of five basic couplings, to W, Z, top, b and τ. The "absolute" scale of these couplings is not directly accessible, but one can measure ratio of couplings (for instance normalized to the W coupling). The expected accuracies are 5 to 50% on the ratio of the couplings squared.

The most difficult measurement appears to be the b quark Yukawa coupling. This is based only on the $t\bar{t}H$ channel and could be improved if other channels involving Higgs boson decay to $b\bar{b}$ are found feasible.

4.4. Self-coupling

Measuring the H self-coupling would provide a test of the Higgs potential in the Standard Model, where the H trilinear coupling is directly predicted from the H mass. This study requires measuring H pair production and is very challenging because of the very small signal cross-section (≈ 20 fb before BR). For a H mass around 150–180 GeV/c^2, the most promising channel is the four W final state leading to same sign leptons (from two of the W's) and jets (from the others two W's) [22]. However, the background (for instance from $t\bar{t}$ production) could be severe and more studies are needed to definitevely assess the feasibility of this channel, taking into account systematic uncertainties. Given the very low signal rate, this is an example where the very high luminosity of a LHC upgrade could be required.

5. Investigating the Higgs sector of supersymmetric theories

5.1. Introduction

In supersymmetric theories (SUSY) the Higgs sector is richer than the one of the Standard Model. We consider the MSSM case with CP conservation (CP violating scenario have also been investigated but are not discussed here). This model contains two Higgs doublets, which leave five physical states after electroweak symmetry breaking, three neutrals: h, H (CP even), A (CP odd) and two charged: $H^{\pm}$. At tree level, the Higgs sector is described by only two parameters which can be choosen to be the A boson mass M_A and $\tan\beta$) (the ratio of the v.e.v. of the two doublets) and the lightest Higgs boson (h) is always lighter than the Z. Large radiative corections significantly complicate this picture, introducing dependencies on other SUSY parameters, and increasing the upper bound on the h mass. Few typical scenarios are defined, fixing the SUSY parameters and leaving only M_A and $\tan\beta$) as parameters. In the following, we will concentrate on the "M_h max" scenario from [23].

5.2. Application of Standard Model searches

Standard Model searches can be applied with the proper scaling of the production cross-section and branching ratio. This is mostly relevant for h searches when it is SM like (especially in the large M_A region) but also for H searches at low M_A. In this context, the VBF production channel followed by $\tau\tau$ decay is very promising.

5.3. Direct searches of heavy neutral Higgs bosons

H, A are degenerate in mass in most of the relevant parameter space. The cross-section of the process $gg \to bbH$, A scales like $\tan^2\beta$. The main search strategy consists in looking for decays to tau pairs (BR $\approx$ 10%). All possibilities of final state are considered: lepton–lepton, lepton–hadron, hadron–hadron. Large transverse missing momentum is required and the Higgs mass is reconstructed using the collinear approximation. Depending on the cases, the soft b produced in association with the Higgs can explicitly be tagged or not. The main backgrounds are Z/Drell–Yan, $t\bar{t}$, W+jets and QCD multijet events (for the hadron–hadron final state, where powerful tau identification is required). The sensitivity of this channel is shown in Fig. 3 for CMS. Higgs decays to muon pairs can also be used at "low" M_A and high $\tan\beta$, especially in the "intense" coupling regime where h, H, A are almost degenerate in mass. However, despite the good muon momentum resolution, it is almost impossible to separate the three contributions.

5.4. Direct searches of charged Higgs bosons

The dominant production mechanism is $gg \to \bar{t}bH^+$ (where the intermediate t is either on shell or off shell), and the most promising channel is $H^+ \to \tau\nu$. The final state consists in one hadronic tau, three jets and missing transverse momentum. The dominant backgrounds are $t\bar{t}$ and W–t production. The transverse mass of tau and missing momentum exhibits a clear edge at the H^+ mass. The sensitivity of this channel is shown in Fig. 3 for CMS.

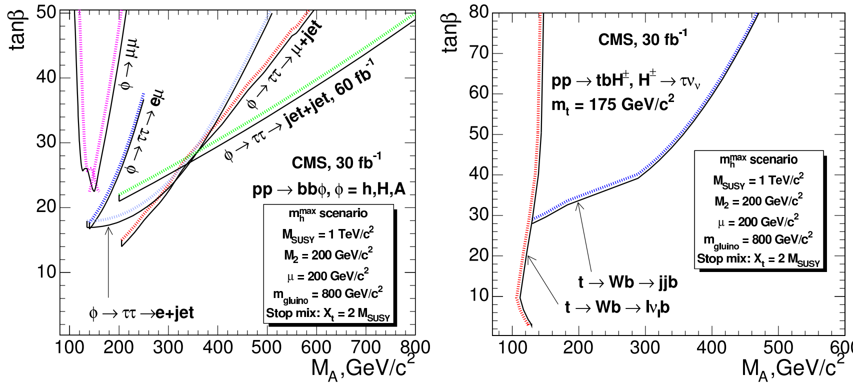

Fig. 3. Region in the M_A, $\tan\beta$ plane accessible using the $\tau\tau$ final state for H, A decays (left). Region where the $H^{\pm}$ can be observed in the tau decay mode (from [12]) (right).

5.5. Overall sensitivity and comments

Fig. 4 shows the summary of the MSSM Higgs sector in the "$\mathrm{M_h}$ max" scenario [24].

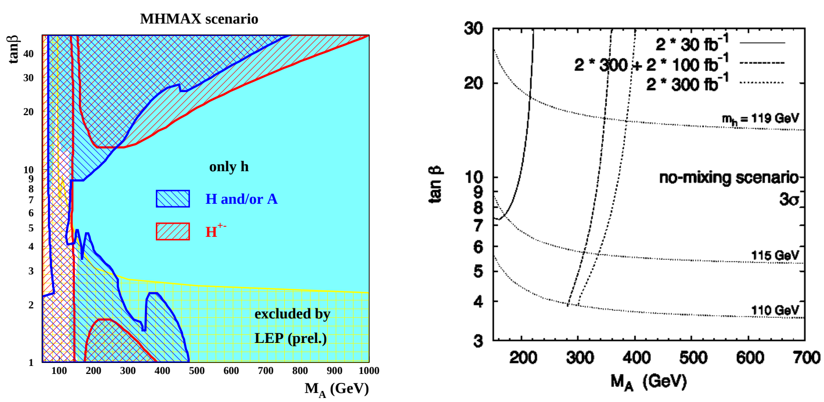

Fig. 4. Observation of the MSSM Higgs sector in the M_A, $\tan\beta$ plane (ATLAS, 300 fb^{-1}) (left). Region of the M_A, $\tan\beta$ plane where more than 3σ deviation from the SM couplings can be observed for h (right).

The good news is that at least one Higgs boson can be seen in all the parameter space (the same conclusion also holds for other MSSM scenarios). The bad news is that only one Higgs boson is seen in a significant part of the parameter space. Measurements of coupling properties would allow to distinguish the MSSM hypothesis from the Standard Model one up to

$M_A \approx 300$–400 GeV$/c^2$ (see Fig. 4). Searches of Higgs boson decays to supersymmetric particles could help to complete the picture but are more model dependent. The situation can also be more complicated in further extensions of the Model like the NMSSM [25].

6. Conclusions

Higgs physics at the LHC has now been studied for more than 15 years. The Standard Model Higgs boson should not elude observation. 10 fb^{-1} of luminosity could be enough for a discovery, provided detector performances and background systematics are under control. Detailed studies of the Higgs boson properties will require more statistics but a wide range of measurements are possible at the LHC. Note that study of longitudinal vector boson scattering at high mass is also an important part of the LHC program if the Standard Model Higgs is not found (what else is responsible for the electroweak symmetry breaking?) and also if the Standard Model Higgs boson is observed (does it regularize this rate as expected?). The MSSM Higgs sector is also well covered at the LHC, but one might be unlucky and only observe a "Standard Model" like h, and one should stay open to more complicated scenario. Finally, in a few years from now, we should have from the data the answer to most of these questions.

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