Prospects for the Determination of Higgs Boson Properties at the LHC

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Abstract. The prospects for the determination of the properties of a hypothetical boson discovered at the Large Hadron Collider using measurements to be performed with the ATLAS and CMS detectors are summarized. The properties that are discussed are the mass of the boson, its width, the strength of its couplings to fermions, the strength and structure of its couplings to gauge bosons and its spin and CP quantum numbers.

1 Introduction

The determination and testing of the theory underlying electroweak symmetry breaking and the description of particle masses is one of the main objectives of the ATLAS and CMS experiments at the Large Hadron Collider (LHC). Monte Carlo studies indicate [1,2] that the discovery of the Higgs boson associated with the symmetry breaking mechanism of the Standard Model, if it exists, will be possible over the full mass range that has not yet been excluded. Due to the variety of suggested extensions of the Standard Model and alternative descriptions of electroweak symmetry breaking, however, the discovery of a particle by itself is unlikely to be sufficient to uniquely identify the model implemented in nature. A systematic measurement of the properties of a newly discovered particle will be important to establish its relation to symmetry breaking, constrain model predictions and exclude alternative models as far as possible.

2 Mass and width of the Higgs Boson

The mass of the Standard Model Higgs boson can be measured with a high precision in the decay channels $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ by direct reconstruction from the measured four-momenta of the final state particles. The expected precision from a fit to the invariant mass distribution for the CMS experiment, taking into account statistical errors only, is shown in Fig.1 (*left*). An integrated luminosity of $30\,\mathrm{fb}^{-1}$, which is expected to be obtained after the first three years of LHC operation, is assumed for the plot. The expected precision is better than 0.3% for Higgs boson masses smaller than about 300 GeV. For the ATLAS experiment, assuming an integrated luminosity of $300\,\mathrm{fb}^{-1}$ and taking into account also the systematic errors on the absolute energy scale, the precision is expected to be 0.1% for Higgs boson masses smaller than 400 GeV. For this result the scale uncertainty for leptons and photons is assumed to be 0.1 %, which is considered a conservative estimate [1]. For larger Higgs boson masses the precision degrades to around 1% at 600 GeV.

If the above decay channels turn out to be suppressed for the particle under study the measurement of the mass will have a larger uncertainty. The invariant mass can be reconstructed in the channel $ttH \to ttbb$ directly from the reconstructed final state, in the channel $H \to WW \to l\nu jj$ by using the mass of the W boson as a constraint and in the channel $H \to \tau\tau$ by using the approximation that the momenta of all decay products of a τ lepton are collinear to the momentum of the τ lepton itself. Finally, in the channel $H \to WW \to ll\nu\nu$ the mass can be extracted from a fit to the distribution of the transverse mass of the lepton-neutrino system.

The expected precision of a measurement of the Standard Model Higgs boson width for masses larger than 200 GeV with the ATLAS experiment for an integrated luminosity of $300\,\mathrm{fb}^{-1}$ is shown in Fig.1. The precision is expected to be better than 8% for masses larger than about 270 GeV. For Higgs boson masses smaller than 200 GeV the observed width of the Higgs resonance peak will be dominated by the detector resolution and a direct measurement of the width will not be possible. Also, at the LHC some decay channels of the Higgs boson such as $H \to gg$ and the decay to quarks lighter than b will not be observable and for some decay channels such as $H \to b\bar{b}$ the experimental uncertainties will be large. Therefore, the width cannot be determined in a model-independent way from the observed decay rates. However, an indirect determination using assumptions about the model can be performed in this mass region, as discussed in Sec.3.

3 Measurement of couplings of a CP even scalar boson

The prospects for the measurement of the couplings of a CP even scalar Higgs boson candidate to fermions

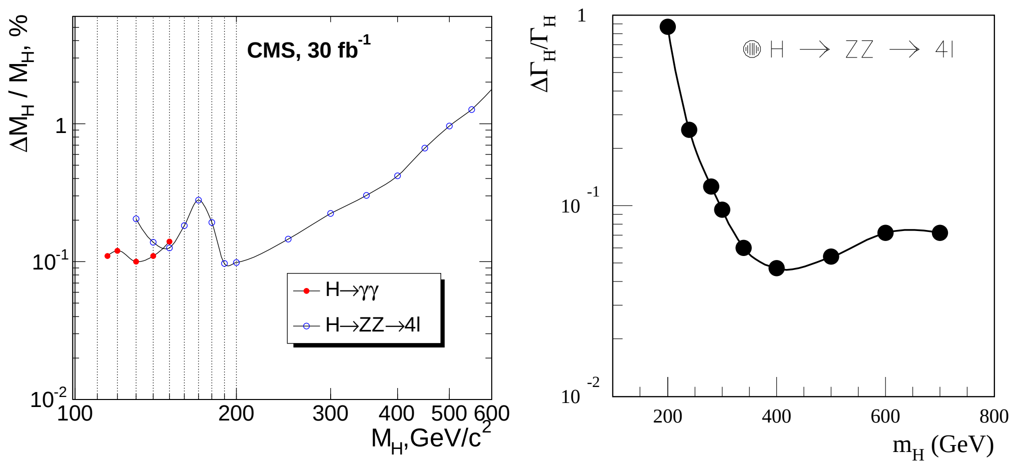

Fig. 1. Expected precision, taking into account statistical errors only, of the measurement of the Higgs boson mass with the CMS experiment [2] (*left*) and expected precision for the measurement of the Higgs boson width with the ATLAS experiment for an integrated luminosity of $300\,\mathrm{fb}^{-1}$ [1] (*right*).

Table 1. Production and decay channels and corresponding mass ranges used for the fit of fermion and gauge boson couplings.

Production	Decay	Mass range
Gluon Fusion	$H \to ZZ^{(*)} \to 4l$	(110 - 200) GeV
	$H \to WW^{(*)} \to l\nu l\nu$	(110 - 200) GeV
	$H \to \gamma\gamma$	(110 - 150) GeV
Weak Boson Fusion	$H \to ZZ^{(*)} \to 4l$	(110 - 200) GeV
	$H \to WW^{(*)} \to l\nu l\nu$	(110 - 190) GeV
	$H \to \tau\tau \to l\nu\nu l\nu\nu$	(110 - 150) GeV
	$H \to \tau\tau \to l\nu\nu \mathrm{had}\nu$	(110 - 150) GeV
	$H \to \gamma\gamma$	(110 - 150) GeV
$t\bar{t}H$	$H \to WW^{(*)} \to l\nu l\nu(l\nu)$	(120 - 200) GeV
	$H \to b\bar{b}$	(110 - 140) GeV
	$H \to \tau\tau$	(110 - 120) GeV
WH	$H \to WW^{(*)} \to l\nu l\nu(l\nu)$	(150 - 190) GeV
	$H \to \gamma\gamma$	(110 - 120) GeV
ZH	$H \to \gamma\gamma$	(110 - 120) GeV

and gauge bosons were studied [3,4] by performing a likelihood fit to the expected numbers of events taken from ATLAS analyses for the channels listed in Tab.1. Sources of systematic errors that were taken into account in the fit are the luminosity, detector effects, the background normalization and theoretical uncertainties on the cross sections. The event rate in a given channel can be approximated [4] as

$$\sigma(H) \cdot \mathrm{BR}(H \to x) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma} \qquad (1)$$

with the partial width Γ_p describing the production process and the partial width Γ_x describing the decay.

Since the total width of the boson in the considered mass range is not known it is not possible to extract the partial widths and coupling constants from the observed event rates in a completely model-independent way. Under the assumption that only one boson contributes to the observed signal it is possible to perform a fit of ratios of partial widths. The results are shown in Fig.2 for an integrated luminosity of $300\,\mathrm{fb}^{-1}$. For the weak boson fusion channels only $30\,\mathrm{fb}^{-1}$ were assumed because the analyses of weak boson fusion rely on the reconstruction of jets in directions close to the beam axis and a veto against additional jets in the central part of the detector, both of which have only been studied in detail for the initial low-luminosity phase of LHC operation for which $30\,\mathrm{fb}^{-1}$ are expected. The ratios are taken with respect to the partial width Γ_W because the $H \to WW$ channel has a relatively high precision over the whole mass range used in the fit. The expected precisions for the ratios Γ_Z/Γ_W and Γ_γ/Γ_W lie between 10% and 35%. For Γ_τ/Γ_W and Γ_b/Γ_W the relative uncertainties lie between 30% and 60%.

By making the additional assumption that the partial widths to weak bosons are not larger than in the Standard Model ($\Gamma_V < \Gamma_V^{\mathrm{SM}}$), which is justified in any model containing only Higgs doublets and singlets, the Higgs boson width can be constrained from above. The width is also constrained from below by the likelihood [3], permitting a fit of the couplings and the width. The results are shown in Fig.2. The expected precisions are typically around 20% - 30%. With the exception of the Higgs boson coupling to b quarks the expected precisions are all better than 50%. The fit also allows for a determination of new contributions to the loops describing $H\gamma\gamma$ and Hgg couplings and an invisible width of the Higgs boson by including $\mathit{\Gamma}_\gamma$, $\mathit{\Gamma}_g$ and a new $\mathit{\Gamma}_{inv}$ in the fit. The results for these contributions are also shown in Fig.2. The expected precisions are comparable to those for the couplings.

The likelihood function used for the fit can be used to calculate the expected discrepancy of the fit results

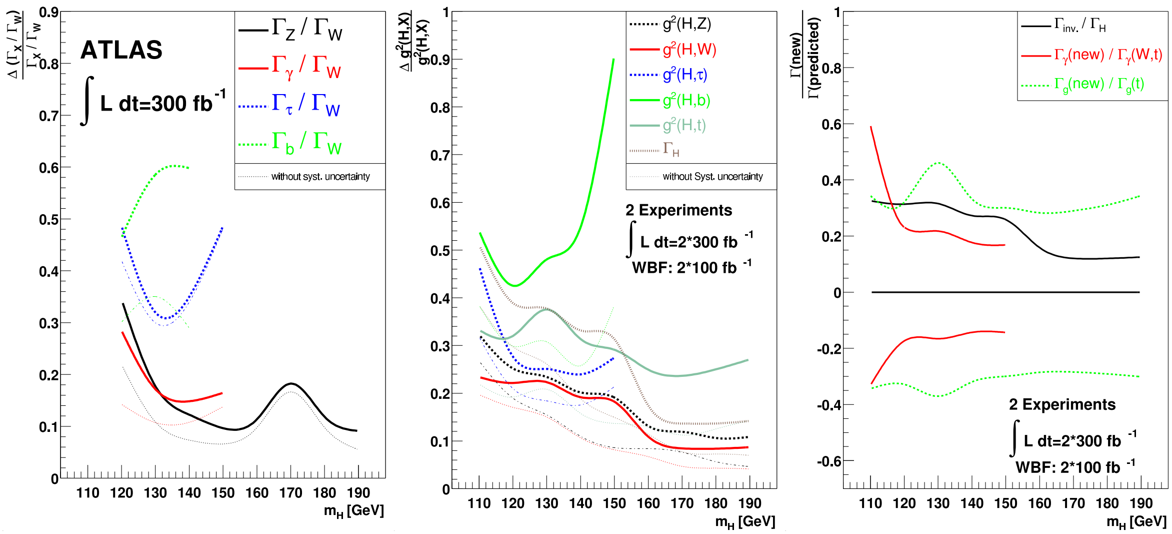

Fig. 2. Expected precision of the measurement of relative partial widths [3] (*left*) using a likelihood fit under the assumption that only one boson contributes to the observed signal (only 30 fb^{-1} were assumed for the weak boson fusion channels). Expected precision of the measurement of absolute couplings and the width of the boson (*middle*) and expected precision of the measurement of additional partial widths [4] (*right*) using a likelihood fit under the additional assumption $\Gamma_V < \Gamma_V^{\mathrm{SM}}$.

for a Standard Model Higgs boson from the expectations in the Minimal Supersymmetric Standard Model (MSSM). Results for the expected exclusion of regions in the MSSM parameter space for several benchmark scenarios are shown in [4].

4 Determination of spin and CP quantum numbers

The Landau-Yang theorem [5] implies that the spin-1 hypothesis for the Higgs boson can be excluded if the decay $H \to \gamma\gamma$ is observed.

The spin and CP quantum numbers of the Higgs boson can be studied in the channel $H \to ZZ \to 4l$ [6, 2] by using the angular distributions of the decay leptons. The sensitive observables that are used are the angle ϕ between the planes spanned by the two lepton pairs and the angle θ between the momentum of a negatively charged lepton in the rest frame of the corresponding Z boson and the momentum of that Z boson in the rest frame of the Higgs boson. The prospects for the exclusion of non-Standard Model combinations of spin and CP quantum numbers with the ATLAS experiment have been studied [6] by performing fits of parametrizations to the angular distributions. The resulting expected deviation from the Standard Model expectation divided by the expected error for the Standard Model case is given as the significance in Fig.3. The angle θ ("Polarisation") provides a good discrimination against the scalar CP odd case and, for masses larger than about 230 GeV, against the spin-1 cases. For smaller masses near 200 GeV the angle ϕ ("Plane Angle") contributes significantly to the combined significance.

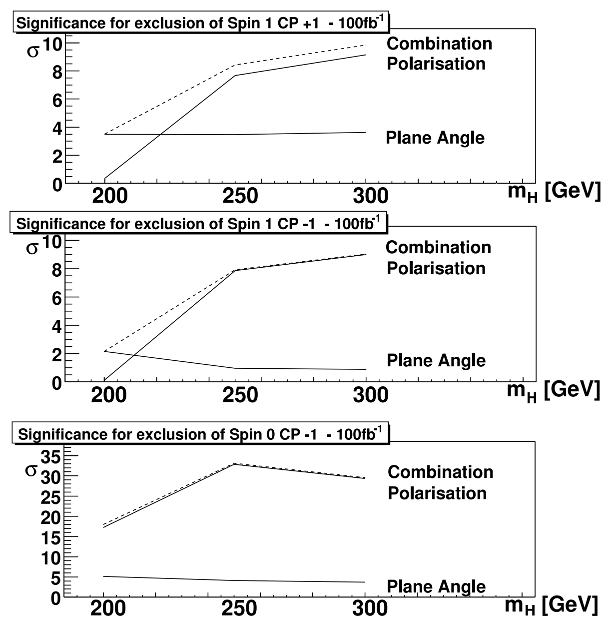

Fig. 3. Expected deviation of fit results for different combinations of spin and CP quantum numbers of the Higgs boson from the Standard Model expectation divided by the uncertainty expected for the Standard Model case [6].

5 Determination of the structure of HVV couplings

The most general coupling of a spin-0 boson to vector bosons contains, in addition to the Standard Model coupling which is proportional to the metric tensor $g^{\mu\nu}$, a CP even and a CP odd term proportional to combinations of the momenta of the participating particles. In the Standard Model the additional terms are

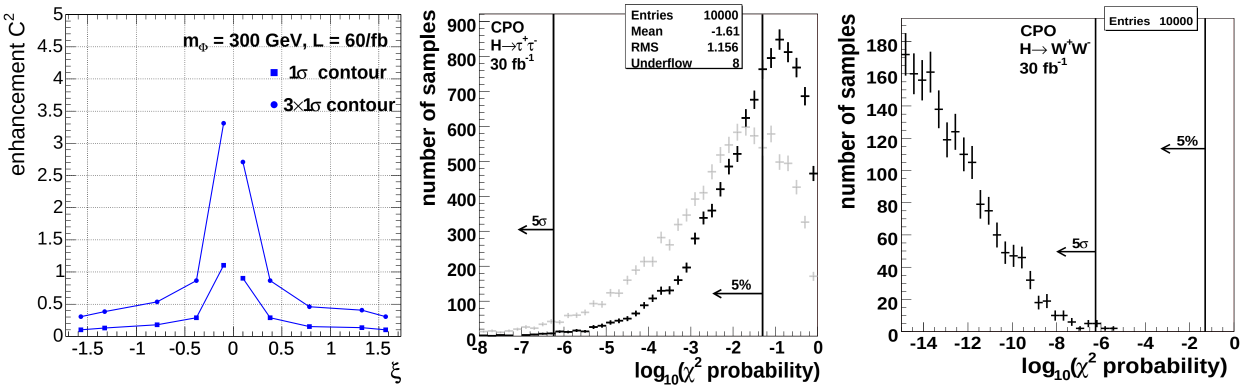

Fig. 4. Enhancement factor for the cross section required for the exclusion of the Standard Model hypothesis versus the parameter ξ (see text) [2] (*left*). Distributions, obtained by performing a series of pseudo-experiments, of the χ^2 probability of the hypothesis of a purely CP odd effective coupling for a Higgs boson mass of 120 GeV (*middle*) and for a Higgs boson mass of 160 GeV [7] (*right*). The gray distribution is obtained if backgrounds are neglected.

zero at tree level. They can be introduced by adding dimension-5 terms to the Lagrangian, examples being the Standard Model effective Hgg and $H\gamma\gamma$ couplings.

The prospects for the measurement of a contribution of $\tan\xi/m_Z^2$ times the CP odd effective coupling in addition to the Standard Model coupling were studied [2] for the CMS experiment. In the study the angular distributions of the leptons in the channel $H \to ZZ \to 4l$ as described in Sec.4 were used. For the case of a Higgs boson mass of 300 GeV and assuming an integrated luminosity of 60 fb^{-1} the enhancement factor for the cross section required for the exclusion of the Standard Model hypothesis for a given value of the parameter ξ is shown in Fig.4.

The structure of the coupling of the Higgs boson to vector bosons can also be studied in the weak boson fusion process. The sensitive observable that is used is the difference $\Delta\phi_{jj}$ between the azimuthal angles of the tagging jets which originate from the scattered quarks. The prospects for the exclusion of the hypotheses of a purely CP even or a purely CP odd effective coupling for a Standard Model Higgs boson with the ATLAS experiment were studied [7] by performing a χ^2 test in the distribution of $\Delta\phi_{jj}$. The results of the hypothesis test for a series of pseudo-experiments for the hypothesis of a purely CP odd effective coupling and for a Higgs boson mass of 120 GeV in the decay channel $H \to \tau\tau$ and a Higgs boson mass of 160 GeV in the decay channel $H \to WW$, assuming an integrated luminosity of 30 fb^{-1} in each case, are shown in Fig.4. For the case of a Higgs boson mass of 120 GeV an exclusion at a 95% confidence level is observed in more than half of the pseudo-experiments. For the case of a Higgs boson mass of 160 GeV the observed χ^2 probability almost always corresponds to more than $5\,\sigma$.

The prospects for the measurement of a contribution by the CP even effective coupling in addition to the Standard Model coupling were studied [7] by performing a likelihood fit to the $\Delta\phi_{jj}$ distribution. This fit is sensitive to the interference between the effective coupling and the Standard Model coupling. In a normalization such that a coupling of 1 reproduces the Standard Model cross section for a purely effective coupling the expected standard deviation for the coupling from the fit, assuming an integrated luminosity of 30 fb^{-1}, is 0.20 for a Higgs boson mass of 120 GeV using the $H \to \tau\tau$ channel and 0.09 for a Higgs boson mass of 160 GeV using the $H \to WW \to ll\nu\nu$ channel.

6 Summary

The ATLAS and CMS experiments offer not only a good discovery potential for the Higgs boson but also promising prospects for the determination of its properties. The measurement of the Higgs boson mass is expected to reach a precision around 0.1% over a large range of masses. The width is expected to be measurable with a precision better than 10% for masses above 250 GeV. Higgs boson couplings and width are expected to be measurable under mild theoretical assumptions with typical precisions of a few 10% in the mass range below 200 GeV. Non-Standard Model combinations of Spin and CP quantum numbers are expected to result in significant deviations from Standard Model expectations for Higgs masses above 200 GeV. The vector boson fusion channel offers good prospects for the study of CP properties of the Higgs boson and the structure of Higgs-vector boson couplings, also in the range of Higgs masses below 200 GeV.

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