Prospects for Higgs search at the LHC
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The present status of theoretical calculations for signal and background processes relevant to the Higgs boson search at the LHC is reviewed, with special emphasis on recent developments. The issue of Higgs properties determination at the LHC is addressed.

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1. Introduction

The search for the Higgs boson will be one of the primary goals of the LHC experiments. The main Higgs production channels at the LHC are gluon fusion, weak boson fusion (WBF) and $ttH$ and $VH (V = W, Z)$ associated productions. Complete analyses with full detector simulation within the experimental collaborations have shown that, with only 10 fb\textsuperscript{−1} of integrated luminosity per experiment, corresponding to one year of running at low luminosity ($\mathcal{L} = 10^{33}$ cm\textsuperscript{−2} s\textsuperscript{−1}), there is a signal significance above the 5$\sigma$ level over a wide range of Higgs masses, the most difficult region being the window between the lower bound given by LEP and 140 GeV \[1\].

Recent detailed simulations, with realistic experimental conditions of the WBF processes, have proved the importance of these channels to improve significantly the sensitivity in that difficult region \[2,3\]. Crucial to this aim, on the experimental side, are the forward jet reconstruction and central jet veto efficiencies. On the theoretical side, a large amount of work has been done to reduce the uncertainties on theoretical predictions, both for the signals and the backgrounds. Further studies have been performed to improve on the strategy originally proposed in ref. \[4\] for the determination of Higgs boson properties, such as couplings to fermions and gauge bosons, and total width. Moreover, very recently, the first analyses on the LHC potential for the Higgs self-coupling determination have been carried out. In the following the present status of theoretical calculations and of the prospects for Higgs properties determination is reviewed. The main focus will be on the mass window 115-200 GeV, which is the preferred one by electroweak precision data and also partially by supersymmetry. During the last year a lot of effort has been concentrated on the Standard Model (SM) Higgs boson, but the strategies and results can be translated to the lightest scalar Susy Higgs. For these reasons this brief review deals only with the case of the SM Higgs boson.

2. Theoretical calculations

In order to disentangle a signal from backgrounds, a good understanding of uncertainties in theoretical predictions is necessary. Predictions based on leading order (LO) calculations are plagued by considerable uncertainties due to the strong dependence on the renormalization and factorization scales, introduced by the QCD coupling and the parton densities. At present the QCD corrections, at least at next-to-leading order (NLO), are known for all production channels, the most recent calculations being the NNLO calculation for the gluon fusion process in the limit of heavy top-quark mass \[5,6\] and the NLO corrections for the process $pp/p\bar{p} \rightarrow ttH + X$ \[7\]. The

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Theoretical predictions. In the case of higher-order corrections reduce the renormalization and factorization scale dependence of the theoretical predictions. In the case of $pp/\bar{p}p \to tH+X$, the NLO corrections increase the rate by roughly 20% with respect to the LO predictions over the entire intermediate Higgs mass range at the LHC. In the case of Higgs production through gluon fusion, the NLO corrections give a $K$ factor of the order of 2, so that NNLO corrections are needed \[ [8] \]. At present, the uncertainties arising from QCD uncertainties (combining the residual scale dependence with the error from parton distribution functions) can be estimated to be of the order of $\pm 20\%$ for gluon fusion, $\pm 5\%$ for WBF, and $\pm 10\%$ for associated production.

Concerning the backgrounds, several processes with low final state parton multiplicity (corresponding to important irreducible backgrounds) are available at NLO, namely $q\bar{q} \to \gamma \gamma$ [8], $pp(p) \to Wb\bar{b}$, $pp(p) \to Zb\bar{b}$ [10], $pp(p) \to Wjj$, $pp(p) \to Zjj$ [13], $pp(p) \to VV$ [2] and QCD $H+jj$ production via gluon fusion [13]. Some of these calculations are already implemented in NLO Monte Carlo programs. In the case of multiparton final states, the methods developed up to now for NLO calculations cannot be applied, because of the complexity of the calculations for processes with many external legs. Recently some effort has been devoted to the realization of LO Monte Carlo event generators based on exact matrix element calculations, suitably interfaced to the shower evolution Monte Carlo programs producing the real final state hadrons [14,15,16,17,18].

3. Higgs couplings to fermions and gauge bosons

The LHC will allow not only the discovery of the Higgs boson, but also the study of its properties, such as mass, width and couplings to fermions and gauge bosons. While the decay channels $H \to \gamma \gamma$ and $H \to ZZ^{(*)} \to 4l$ will allow a direct mass measurement at the 0.1% level over a wide range of masses, the total width can only be determined with about 10% accuracy by direct measurement with the decay $H \to ZZ^{(*)} \to 4l$ for $m_H > 200$ GeV; the Higgs width for lower Higgs masses being too small with respect to the detector resolution. As will be shown below, by exploiting the available production and decay mechanisms at the LHC, an indirect measurement of the total width can be performed also in the low mass region. In principle, the Higgs coupling, for instance to a given fermion family $f$, could be obtained from the following relation:

$$R(H \to ff) = \int L dt \cdot \sigma(pp \to H) \cdot \frac{\Gamma_f}{\Gamma_t},$$

where $R(H \to ff)$ is the Higgs production rate in a given final state, which can be measured experimentally, $\int L dt$ is the integrated luminosity, $\sigma(pp \to H)$ is the Higgs production cross section, and $\Gamma$ and $\Gamma_f$ are the total and partial Higgs widths respectively. Hence, a measurement of the Higgs production rate in a given channel allows the extraction of the partial width for that channel, and therefore of the Higgs coupling $g_f$ to the involved decay particles ($\Gamma_f \sim g_f^2$), provided that...
the Higgs production cross-section and the total Higgs width are known from theory. Aiming at model-independent coupling determinations, one needs to consider ratios of couplings, which are experimentally accessible through the measurements of ratios of rates for different final states, because in the ratio the total Higgs cross-section and width cancel (as well as luminosity and all QCD uncertainties related to the initial state). In spite of the fact that the gluon fusion mechanism is the leading scalar Higgs production mode at the LHC, other subleading production modes, such as weak boson fusion and associated production, are extremely important to provide complementary information and allow unique determinations of ratios of Higgs boson couplings. Up to now detailed studies on signal and backgrounds for several channels have been performed, namely $gg \rightarrow H, (H \rightarrow \gamma\gamma, Z, W W) [1,19,20,21]$, $qq \rightarrow qH, (H \rightarrow \gamma\gamma, \tau\tau, W W) [22,23,24,25,26,27]$, $pp \rightarrow tH, (H \rightarrow bb, W W, \tau\tau) [28,29,30]$ and $pp \rightarrow WH, H \rightarrow bb [31]$. Each process depends on two Higgs couplings, one from the Higgs boson production and one from the Higgs boson decay, with the exception of the weak boson fusion channels, for which it is experimentally impossible to distinguish between $WW \rightarrow H$ and $ZZ \rightarrow H$ production mechanisms. However, since the couplings of a scalar Higgs boson to the $Z$ and $W$ gauge bosons are closely related to the electroweak $SU(2)$ gauge symmetry, which has been very successfully tested by the LEP experiments, and since in a large class of models the ratio of $HWW$ and $HZZ$ couplings is identical to the one in the SM, including the MSSM, it is reasonable to assume $\Gamma_Z/\Gamma_W = z_{SM}$. Under this hypothesis, every production and decay channel provides a measurement of the ratio $Z_j^{(i)} = \Gamma_i/\Gamma_j$, where $i = g, W, t$ indicates the production process and $j = b, \tau, W, Z, g, \gamma$ indicates the decay process. For the case $m_H < 140$ GeV, the above mentioned channels allow us to express the individual rates $\Gamma_i$ and the total Higgs width $\Gamma$ [30]. With the additional assumption that the total width is saturated by the known channels $\Gamma = \Gamma_g + \Gamma_\gamma + \Gamma_W + \Gamma_Z + \Gamma_{W} + \Gamma_\gamma$ (otherwise new processes would be observed independently of any precision study), an expression for $\Gamma$ can be obtained in terms of measured quantities, namely [30]

$$\sqrt{\Gamma} = \frac{1}{\sqrt{Z_W^{(W)}}} \left[ Z_W^{(W)} (1 + \frac{Z_W}{Z_\gamma}) \right] + Z_W^{(W)} (1 + z_{SM}) + \frac{Z_W^{(W)}}{Z_\gamma} + Z_\gamma.$$ 

Figure [1] [30] summarizes the relative accuracy on the individual rates $\Gamma_i$ expected in the model-independent scenario as well as in a scenario with $\Gamma_b/\Gamma_t$ fixed to its SM value, assuming a total integrated luminosity of 200 fb$^{-1}$. The upper plots show the accuracies obtained without including any theoretical systematic error, while the lower plots show the same accuracies when a systematic theoretical error of 20% for the $gg \rightarrow H$ channel, of 5% for the $qq \rightarrow qH$, and of 10% for the $pp \rightarrow tH$ and $pp \rightarrow WH, H \rightarrow bb$ channel are included. As can be seen, the total Higgs width can be indirectly determined in the low mass region with a precision of the order of 30% in a model-independent way, and the Higgs couplings can be determined with accuracies between 7% and 25%. In the case of $140 < m_H < 200$ GeV, the gluon fusion, weak boson fusion and $t\bar{t}H$ associated production processes can be exploited, with the Higgs boson decaying only to gauge bosons, allowing an indirect determination of $\Gamma_Z$ and $\Gamma$ with a precision of the order of 10% [32]. In this Higgs mass range, however, there is no handle to study the Higgs Yukawa couplings to $b$ quarks and $\tau$ leptons. The assumption $\Gamma_Z/\Gamma_W = z_{SM}$ can be tested at the 20–30% level for $m_H > 130$ GeV by measuring the ratio $Z_Z^{(g)}/Z_W^{(g)}$ [33], and it can even be tested with the same level of accuracy for lower Higgs boson masses by comparing the two ratios $Z_W^{(WH)}/Z_W^{(t)}$ and $Z_W^{(WW)}/Z_W^{(t)}$ [34]. For $m_H > 140$ GeV, with luminosities of the order of 300 fb$^{-1}$, the ratio $\Gamma_t/\Gamma_b$ can be tested in a model-independent way through a measurement of $Z_W^{(W)}/Z_W^{(g)}$ [35].
Table 1
Expected numbers of signal and background events after all cuts for the $gg \rightarrow HH \rightarrow 4W \rightarrow l^+l^-4j\nu\nu$ final state, for $\int \mathcal{L} = 6000 \text{ fb}^{-1}$.

| $m_H$ (GeV) | Signal | $tt$ | $W^+W^-Z$ | $W^+W^-W^-$ | $ttWW^+$ | $ttt\tau$ | $S/\sqrt{B}$ |
|-------------|--------|-----|----------|-------------|----------|---------|-----------|
| 170         | 350    | 90  | 60       | 2400        | 1600     | 30      | 5.4       |
| 200         | 220    | 90  | 60       | 1500        | 1600     | 30      | 3.8       |

4. Higgs self-couplings

A complete determination of the parameters of the SM would require the measurement of the Higgs self-couplings. These include trilinear and quadrilinear interactions. In the SM the corresponding couplings are fixed at LO in terms of the Higgs mass and vacuum expectation value $v$, namely $\lambda_{HHH}^{SM} = 3m_H^2/v$, $\lambda_{HHH}^{SM} = 3m_H^2/v^2$. A direct measurement of $\lambda_{HHH}$ could be obtained via the detection of Higgs pair production, where a contribution is expected from the production of a single off-shell Higgs which decays into a pair of Higgses. This contribution is always accompanied by diagrams where the two Higgs bosons are radiated independently, with couplings proportional to the Yukawa couplings or the gauge couplings. As a result, different production mechanisms will lead to different sensitivities of the $HH$ rate to the value of $\lambda_{HHH}$. In the literature the following SM channels have been considered: inclusive $HH$ production, dominated by the partonic process $gg \rightarrow HH$; vector boson fusion $qq \rightarrow qV^*V^* \rightarrow qgHH$, associated production with $W$ or $Z$ bosons $qg \rightarrow VH$; associated production with top-quark pairs $gg/qg \rightarrow t\bar{t}HH$. With the exception of the gluon fusion process, which has a total cross section at the level of few tens of fb, the cross section for all other channels is of the order of 1 fb over the intermediate Higgs mass range. Given these low production rates, and the potentially large backgrounds associated to the $HH$ final states, a quantitative study of the Higgs self-coupling is very hard at the LHC. Recently a study of signal and background has been performed for the $gg \rightarrow HH$ channel, both for a standard LHC luminosity of $10^{34}\text{ cm}^{-2}\text{s}^{-1}$ and for a possible future upgrade of the luminosity to $10^{36}\text{ cm}^{-2}\text{s}^{-1}$. Among all possible decay channels, the most interesting one turned out to be $gg \rightarrow HH \rightarrow W^+W^-W^+W^- \rightarrow l^+\nu jjl^+\nu jj$, which has a good branching ratio for $m_H \geq 170\text{ GeV}$. The like-sign lepton requirement is essential to reduce the high-rate opposite-sign lepton final states from Drell–Yan and $t\bar{t}$ production. Potential backgrounds to the considered signature are given by $t\bar{t}$+jets, $WZ$+jets, $t\bar{t}W$, $WWWjj$ including the resonant channel $W(H \rightarrow WW)jj$ and $ttt\tau$. By applying the cuts described in ref. [34], the number of events for signal and backgrounds are summarized in Table 1 for an integrated luminosity of 6000 fb$^{-1}$, where a signal significance of $5.3 (3.8)$ $\sigma$ for $m_H = 170 (200)\text{ GeV}$ can be reached, optimistically assuming that the main parameters of the detector performance will remain the same as those expected at $10^{34}\text{ cm}^{-2}\text{s}^{-1}$. This would lead to a determination of the total production cross-section with a statistical uncertainty of $\pm 20\% (\pm 26\%)$ for $m_H = 170\text{ GeV} (200\text{ GeV})$, allowing a determination of $\lambda_{HHH}$ with statistical errors of $19\% (25\%)$. In the case of 300 fb$^{-1}$ only the non-vanishing of the Higgs self-coupling could be established at 95% C.L. for 150 GeV $< m_H < 200\text{ GeV}$.

5. Summary

During the last few years there has been a dramatic improvement in both theoretical and experimental studies of several Higgs boson production and decay channels at the LHC. On the theoretical side, the corrections at NLO (in one case even at NNLO) have been calculated for the main Higgs production processes and for many irreducible backgrounds. Several LO Monte Carlo event generators based on exact matrix elements have been developed very recently to give pre-
diction for multiparton final states, which represent important backgrounds for several Higgs signatures. On the experimental side, complete simulations, including full detector simulation, have been carried out for all production processes, pointing out the relevance of the weak boson fusion processes as discovery channels in the low Higgs mass region. Considering all channels, a signal significance above $5\sigma$ over the entire mass spectrum is well established already with only $10\ \text{fb}^{-1}$ of integrated luminosity per experiment.

A strategy has been designed to study, in a model-independent way, the Higgs couplings to fermions and bosons, which allows also, with little theoretical assumption, an indirect determination of the total Higgs width. Recently the potential of the LHC in the determination of the Higgs self-coupling has been investigated, but only with an integrated luminosity of $6000\ \text{fb}^{-1}$, and in the mass range $170 \leq m_H \leq 200\ \text{GeV}$ a quantitative study could be performed.

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