Prospects for Higgs properties determination at the LHC

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The strategies recently developed to study Higgs boson properties at the LHC are reviewed. It is shown how to obtain model-independent determinations of couplings to fermions and gauge bosons by exploiting different production and decay channels. We consider in some detail the case of Weak Boson Fusion Higgs production with $H \rightarrow bb$ as well as the prospects for the determination of the Higgs self-coupling at the SLHC.

1. Introduction

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 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow 4l$ will allow a direct mass measurement at the 0.1\% level over a wide range of masses \cite{1}, the total width can only be determined with about 10\% accuracy by direct measurement of the decay $H \rightarrow ZZ^{(*)} \rightarrow 4l$ for $m_H > 200$ GeV, (the Higgs width for lower Higgs masses being too small with respect to the detector resolution). As it will be shown below, an indirect measurement of the total width can be performed also in the low mass region by exploiting the available production and decay mechanisms at the LHC. Several studies have been performed to improve on the strategy originally proposed in ref. \cite{2} for the determination of the Higgs boson properties. Moreover, the first analyses of the LHC potential for the Higgs self-coupling determination have been worked out. We will briefly review the progress recently made in this field. The main focus will be on the mass window 115-200 GeV, which is the one preferred by electroweak precision data and partially by supersymmetry.

2. Higgs couplings to fermions and gauge bosons

In principle, the Higgs coupling to a given fermion family $f$, could be obtained from the following relation:

$$ R(H \rightarrow f\bar{f}) = \int Ldt \cdot \sigma(pp \rightarrow H) \cdot \frac{\Gamma_f}{\Gamma}, $$

where $R(H \rightarrow f\bar{f})$ is the Higgs production rate in a given final state, $\int Ldt$ is the integrated luminosity, $\sigma(pp \rightarrow H)$ is the Higgs production cross section, while $\Gamma$ and $\Gamma_f$ are the total and partial Higgs widths respectively. A measurement of the Higgs production rate in a given channel allows the extraction of the partial width for that channel which in turn gives the coupling $g_f$ of the Higgs to the decay particles involved ($\Gamma_f \sim g_f^2$), provided that the Higgs production cross-section and the total Higgs width are known from the 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 the total Higgs cross-section and width cancel in the ratios (as well as the luminosity and all the 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 produc-
tion, are extremely important to provide complementary information and to 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 $gg \to H, (H \to \gamma\gamma, ZZ, WW)$ [1,3–5], $qq \to qqH, (H \to \gamma\gamma, \tau\tau, WW)$ [6–10], $pp \to t\bar{t}H, (H \to bb, WW, \tau\tau)$ [11–14] and $pp \to WH, H \to bb$ [15]. 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 $WW \to H$ and $ZZ \to H$ production mechanisms. However, since the couplings of a scalar Higgs boson to the $Z$ and $W$ gauge bosons are closely related by 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 rely on the SM value $\Gamma_Z/\Gamma_W = z_{SM}$. Under this hypothesis, every production and decay channel provides a measurement of the ratio $Z_j^{(i)} = \Gamma_i \Gamma_j / \Gamma$, where $i = g, W, t$ indicates the particles involved in the production process while the index $j = b, \tau, W, Z, g, \gamma$ is referred to the decay process. In case of $m_H < 140$ GeV, the above mentioned channels allow to express the individual rates $\Gamma_i, \Gamma_b, \Gamma_{\tau}, \Gamma_W, \Gamma_Z$ and $\Gamma_\gamma$ as functions of the observables $Z_j^{(i)}$ and of the total Higgs width $\Gamma$ [14]. With the additional assumption that the total width is saturated by the known channels $\Gamma = \Gamma_b + \Gamma_\tau + \Gamma_W + \Gamma_Z + \Gamma_g + \Gamma_\gamma$ (otherwise new processes would be observed independently of any precision study), an expression for $\Gamma$ can be obtained in terms of the measured quantities $Z_j^{(i)}$ [14]. Figure 1 [14] summarizes the relative accuracy on the individual rates $\Gamma_i$ expected in the model-independent scenario as well as in a scenario with $\Gamma_b/\Gamma_\tau$ 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 $gg \to H$ channel, of 5% for the $qq \to qqH$, and of 10% for the $pp \to t\bar{t}H$ 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 while 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, with the Higgs boson decaying only to gauge bosons, allow an indirect determination of $\Gamma_W$ and $\Gamma$ with a precision of the order of 10% [2,17]. 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 $Z_j^{(g)}/Z_j^{(W)}$ [17], and it can even be tested with

\[ Z_j^{(g)}/Z_j^{(W)} \]

In a very recent paper [16] the importance of the weak boson fusion processes, with $H \to VV$, has been pointed out, with the aim of testing possible anomalous $HVV$ couplings.
the same level of accuracy for lower Higgs boson masses by comparing the two ratios $Z_b^{(W^H)} / Z_b^{(t)}$ and $Z_\tau^{(W)} / Z_\tau^{(t)}$ [14]. For $m_H > 140$ GeV, with luminosities of the order of 300 fb$^{-1}$, the ratio $\Gamma_t / \Gamma_g$ can be tested in a model-independent way through a measurement of $Z_W^{(t)} / Z_W^{(q)}$ [13].

3. $H \rightarrow b\bar{b}$ via Weak Boson Fusion

As is clear from Figure 1, the most poorly known coupling turns out to be the $Hb\bar{b}$ Yukawa coupling, which can be at best determined with an uncertainty at the 20% level (without any assumption on the ratio $\Gamma_b / \Gamma_\tau$). To improve the analysis of the $Hb\bar{b}$ Yukawa coupling, one can consider the decay of an Higgs, produced via Weak Boson Fusion, into $b\bar{b}$ pairs [18]. We report below the main results of that study.

Signal and background event estimates are based on a leading order partonic calculation of the matrix elements (ME) obtained with the event generator ALPGEN [19]. The background sources considered include:

1. QCD production of $b\bar{b}jj$ final states, where $j$ indicates a jet originating from a light quark ($u, d, s, c$) or a gluon;

2. QCD production of $jjjj$ final states;

3. associated production of $Z^*/\gamma^* \rightarrow b\bar{b}$ and light jets, where the invariant mass of the $b\bar{b}$ pair is in the Higgs signal region either because of imperfect mass resolution, or because of the high-mass tail of the intermediate vector boson;

along with multiple interaction events ($pp \oplus pp, pp \oplus pp \oplus pp...$) giving rise to final states of the kind $b\bar{b}jj$ and $jjjj$. In order to satisfy the requirements of optimization of the signal significance, or sensitivity $(S/\sqrt{B})$, and compatibility with trigger and data acquisition constraints, different selection criteria have been considered. As can be seen in ref. [18], the sensitivity can be as large as 5 for Higgs masses close to the exclusion limit given by LEP searches but the ratio $S/B$ is only a fraction of a percent. This implies that the background itself will have to be known with accuracies at the permille level. There is no way that this precision can be obtained from theoretical calculations. The background should therefore be determined entirely from data. The large rate of $b\bar{b}jj$ from single and multiple interactions and the smoothness of their mass distribution in the signal region will allow to estimate their size with enough statistical accuracy, without significant systematic uncertainties.

The situation is potentially different in the case of the backgrounds from the tails of the $Z$ decays. The $Z$ mass peak is sufficiently close to $m_H$, especially in the case of the lowest masses allowed by current limits, to possibly distort the $m_{b\bar{b}}$ spectrum and spoil the ability to accurately reconstruct the noise level from data. These backgrounds rates are at most comparable to the signal at low $m_H$. A 10% determination of these final states, which should be easily achievable using the $(Z \rightarrow \ell^+\ell^-)jj$ control sample and folding in the detector energy resolution for jets, should therefore be sufficient to fix these background levels with the required accuracy.

Concerning the multiple interactions, in the simplest case of two overlapping events ($pp \oplus pp$), there are four possible combinations of events leading to a $b\bar{b}jj$ background: $jjjj \oplus (b\bar{b})$, $(jj) \oplus (j_bj_b)$, $(jj_b) \oplus (jj_b)$ and $(bb) \oplus (b\bar{b})$, where $(ab) \equiv pp \rightarrow ab$, and $j_b$ represent a jet given by a light quark or a gluon identified as a $b$-jet, because of a mistagging efficiency $\epsilon_{fake}$ of the order of 0.01%-0.05%. A large contribution comes from events of the type $(jj_b) \oplus (jj_b)$, where the $bb$ mass spectrum has a broad peak in the middle of the signal region. The absolute rate of these events (of the order of the signal rate, when using the lower transverse momentum threshold of 60 GeV) can be determined if the distribution of the beam-line $z$ vertex separation between the two overlapping events can be determined with a resolution of the order of 5-10 mm. These events are significantly reduced in number when using the higher threshold of 80 GeV for the forward jets.

Table 1 summarizes the accuracy reachable in the $B(H \rightarrow b\bar{b})$ and in the $Hb\bar{b}$ Yukawa coupling for the case of two different event selections (described in detail in ref. [18]), assuming that the
coupling $HWW$ is the one predicted by the Standard Model or determined in other reactions studied in the literature. An integrated luminosity of 600 fb$^{-1}$ is considered. The $H \to b\bar{b}$ decay in the

| $m_H$ (GeV) | 115 | 120 | 140 |
|------------|-----|-----|-----|
| (a) $\delta \Gamma_{b}/\Gamma$ | 0.33 | 0.35 | 0.71 |
| $\delta \gamma_{Hbb}/\gamma_{Hbb}$ | 0.58 | 0.51 | 0.56 |
| (b) $\delta \Gamma_{b}/\Gamma$ | 0.20 | 0.19 | 0.37 |
| $\delta \gamma_{Hbb}/\gamma_{Hbb}$ | 0.36 | 0.30 | 0.29 |

Table 1

The statistical significance of the determination of the branching ratio $\Gamma_{b}/\Gamma$ and of the $b$-quark Yukawa coupling in the configurations (a) and (b) (see ref. [18] for a detailed description of the two different event selections), for an integrated luminosity of 600 fb$^{-1}$. The $p_{T}$ cut on jets is $p_{T} > 60$ GeV. The case of $p_{T} > 80$ GeV, presented in ref. [18], doesn’t affect sizeably the results. Here $\epsilon_{fake} = 0.01$.

WBF channel could be used together with other processes already examined in the literature for a model independent determination of the ratio of Yukawa couplings $\gamma_{Hbb}/\gamma_{H\tau\tau}$ [20].

As a conclusion of the analysis presented in ref. [18], the $H \to b\bar{b}$ channel produced in association with two jets is suggested as an additional channel to be exploited for interesting measurements of the Higgs couplings to fermions.

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 $\lambda^{SM}_{H} = 3m_{H}^{2}/v$, $\lambda^{SM}_{HHHH} = 3m_{H}^{2}/v^{2}$. A direct measurement of $\lambda_{HH}$ 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 $\lambda_{HH}$. In the literature the following SM channels have been considered [21]: inclusive $HH$ production dominated by the partonic process $gg \to HH$; vector boson fusion $qq \to VV \to qH\bar{H}$, associated production with $W$ or $Z$ bosons $qq \to VH\bar{H}$; associated production with top-quark pairs $gg/q\bar{q} \to t\bar{t}HH$. 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 [21]. 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 backgrounds has been performed for the $gg \to HH$ channel [22], both for a standard LHC luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ [23] and for a possible future upgrade of the luminosity to $10^{35}$ cm$^{-2}$s$^{-1}$ [22]. Among all possible decay channels, the most interesting one turned out to be $gg \to HH \to W^{+}W^{-}W^{+}W^{-} \to l^{\pm}\nu_{l}l^{\pm}\nu_{l}$, which has a good branching ratio for $m_{H} \geq 170$ 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, $tW$, $WWjj$ including the resonant channel $W(H \to WW)jj$ and $t\bar{t}t\bar{t}$. By applying the cuts described in ref. [22], the number of events for signal and backgrounds are summarized in Table 2 for an integrated luminosity of 6000 fb$^{-1}$, where a signal significance of 5.3 (3.8) $\sigma$ for $m_{H} = 170$ (200) GeV can be reached, optimistically assuming that the main parameters of the detector performance will remain the same as those expected at $10^{34}$ cm$^{-2}$s$^{-1}$. This would lead to a determination of the total production cross-section with a statistical uncertainty of $\pm 20\%$ ($\pm 26\%$) for $m_{H} = 170$ GeV (200 GeV), allowing a determination of $\lambda_{HH}$ with statistical errors of 19% (25%) [22]. In the case of 300 fb$^{-1}$
Table 2

| $m_H$ (GeV) | Signal | $t\bar{t}$ | $W^\pm Z$ | $W^\pm W^\mp W^\pm$ | $ttW^\pm$ | $ttt\bar{t}$ | $S/\sqrt{B}$ |
|------------|--------|------------|-----------|----------------|----------|----------|-----------|
| 170        | 350    | 90         | 60        | 2400           | 1600     | 30       | 5.4       |
| 200        | 220    | 90         | 60        | 1500           | 1600     | 30       | 3.8       |

Expected numbers of signal and background events after all cuts for the $gg \to HH \to 4W \to l^+l^-4j\nu\nu$ final state, for $\int L = 6000$ fb$^{-1}$ [22].

only the non-vanishing of the Higgs self-coupling could be established at 95% C.L. for $150 < m_H < 200$ GeV [23].

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. 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. The main results of a very recent analysis of the $H \to b\bar{b}$ channel in Weak Boson Fusion production have been reviewed, pointing out its importance for the determination of the $Hbb$ Yukawa coupling. The potential of the LHC in the determination of the Higgs self-coupling has been recently investigated, but only with an integrated luminosity of 6000 fb$^{-1}$, and in the mass range $170 \leq m_H \leq 200$ GeV a quantitative study could be performed.

Acknowledgements

The authors wish to thank F. Gianotti, K. Jakobs for useful discussions and M.L. Mangano, M. Moretti and R. Pittau for fruitful collaboration. FP wishes to thank the organizers for the kind invitation and for the pleasant atmosphere during the Workshop.

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