MEASUREMENT OF HIGGS PROPERTIES AT THE LHC

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A SM-like Higgs boson can be produced in a variety of channels at the LHC. By combining information from production via gluon fusion and weak boson fusion, various partial widths and the total Higgs boson width can be extracted. Expected accuracies for 200 fb^{-1} of data are in the 10% range.

1 Introduction

One of the prime tasks of the LHC will be to probe the mechanism of electroweak gauge symmetry breaking. Beyond observation of the various CP even and CP odd scalars which nature may have in store for us,[1,2] this means the determination of the couplings of the Higgs boson to the known fermions and gauge bosons, i.e. the measurement of Htt, Hbb, $H\tau\tau$ and HWW, HZZ, $H\gamma\gamma$ couplings, to the extent possible.

Clearly this task very much depends on the expected Higgs boson mass. For $m_H > 200$ GeV and within the SM, only the $H \to ZZ$ and $H \to WW$ channels are expected to be observable, and the two gauge boson modes are related by SU(2). A much richer spectrum of decay modes is predicted for the intermediate mass range, i.e. if a SM-like Higgs boson has a mass between the reach of LEP2 ($\lesssim$ 110 GeV) and the Z-pair threshold. The main reasons for focusing on this range are present indications from electroweak precision data, which favor $m_H < 250$ GeV,[3] as well as expectations within the MSSM, which predicts the lightest Higgs boson to have a mass $m_h \lesssim 130$ GeV. Recently, an analysis of Higgs coupling measurements at the LHC was completed for this intermediate mass range[4] and in this talk I sumarize the results.

Table 1: Number of events expected for $qq \to qqH$, $H \to WW^{(*)} \to \mu^\pm e^\mp \not{p}_T$ in 200 fb^{-1} of data, and corresponding backgrounds.[9] The expected relative statistical error on the signal cross section is given in the last line.

m_H	120	130	140	150	160	170	180	190
N_S	136	332	592	908	1460	1436	1172	832
N_B	136	160	188	216	240	288	300	324
$\Delta\sigma_H/\sigma_H$	12.1%	6.7%	4.7%	3.7%	2.8%	2.9%	3.3%	4.1%

2 Survey of intermediate mass Higgs channels

The total production cross section for a SM Higgs boson at the LHC is dominated by the gluon fusion process, $gg \to H$, which largely proceeds via a top-quark loop. Thus, inclusive Higgs searches will collectively be called "gluon fusion" channels in the following. Three inclusive channels are highly promising for the SM Higgs boson search,[1,2]

$$gg \to H \to \gamma\gamma\,, \qquad \text{for} \quad m_H \lesssim 150 \text{ GeV}\,, \tag{1}$$

$$gg \to H \to ZZ^* \to 4\ell\,, \qquad \text{for} \quad m_H \gtrsim 130 \text{ GeV}\,, \tag{2}$$

and

$$gg \to H \to WW^* \to \ell\bar{\nu}\bar{\ell}\nu\,, \qquad \text{for} \quad m_H \gtrsim 130 \text{ GeV}\,. \tag{3}$$

The $H \to \gamma\gamma$ signal can be observed as a narrow and high statistics $\gamma\gamma$ invariant mass peak, albeit on a very large diphoton background. A few tens of $H \to ZZ^* \to 4\ell$ events are expected to be visible in 100 fb^{-1} of data, with excellent signal to background ratios (S/B), ranging between 1:1 and 6:1, in a narrow four-lepton invariant mass peak. Finally, the $H \to WW^* \to \ell\bar{\nu}\bar{\ell}\nu$ mode is visible as a broad enhancement of event rate in a 4-lepton transverse mass distribution, with S/B between 1:4 and 1:1 (for favorable values of the Higgs mass, around 170 GeV).

Additional, and, as we shall see, crucial information on the Higgs boson can be obtained by isolating Higgs production in weak boson fusion (WBF), i.e. by separately observing $qq \to qqH$ and crossing related processes, in which the Higgs is radiated off a t-channel W or Z. Specifically, it was recently shown in parton level analyses that the weak boson fusion channels, with subsequent Higgs decay into photon pairs,[5,6]

$$qq \to qqH,\ H \to \gamma\gamma\,, \qquad \text{for} \quad m_H \lesssim 150 \text{ GeV}\,, \tag{4}$$

into $\tau^+\tau^-$ pairs,[6,7,8]

$$qq \to qqH,\ H \to \tau\tau\,, \qquad \text{for} \quad m_H \lesssim 140 \text{ GeV}\,, \tag{5}$$

or into W pairs [6,9]

$$qq \to qqH,\ H \to WW^{(*)} \to e^\pm \mu^\mp \not{p}_T\,, \qquad \text{for} \quad m_H \gtrsim 120 \text{ GeV}\,, \tag{6}$$

can be isolated at the LHC. The weak boson fusion channels utilize the significant background reductions which are expected from double forward jet tagging[10] and central jet vetoing techniques,[11] and promise low background environments in which Higgs decays can be studied in detail.

An example of expected events rates (after cuts and including efficiency factors) are summarized in Table 1 for the $qq \to qqH$, $H \to WW^{(*)} \to e^\pm \mu^\mp \not{p}_T$ signal. The rates and ensuing statistical errors of the signal cross section are given for 100 fb^{-1} of data collcted in both the ATLAS and the CMS detector. The statistical accuracy with which the signal cross sections of the processes in Eqs. (1-6) can be determined is shown in Fig. 1a).

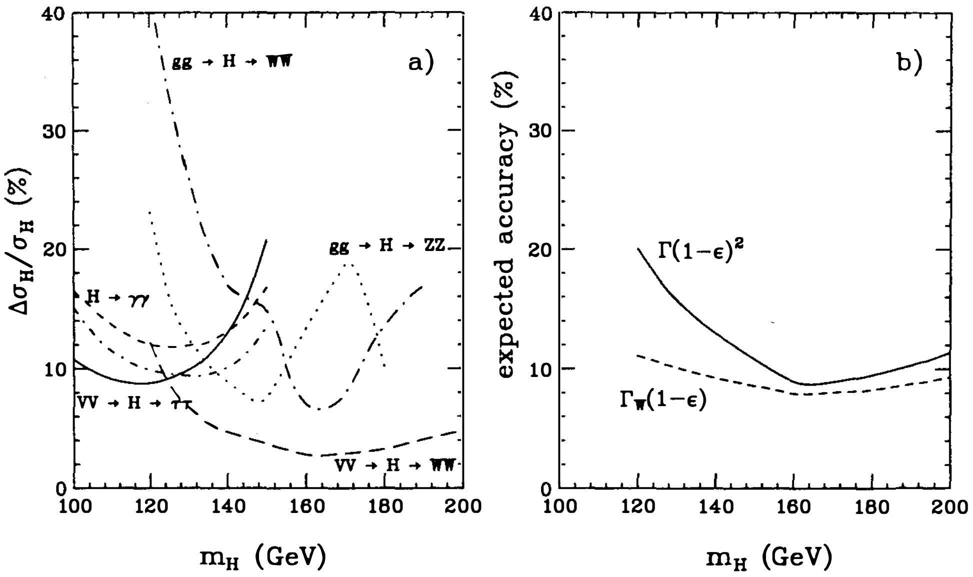

Figure 1: Relative accuracy expected at the LHC with 200 fb^{-1} of data. a) Cross section times branching fraction for several inclusive modes (dotted and dash-dotted lines) and WBF channels (dashed and solid lines). b) Extracted total width (solid line) and $H \to WW$ partial width (dashed line).

3 Measurement of Higgs properties

In order to translate the cross section measurements of the various Higgs production and decay channels into measurements of Higgs boson properties, in particular into measurements of the various Higgs boson couplings to gauge fields and fermions, it is convenient to rewrite them in terms of partial widths of various Higgs boson decay channels. The Higgs-fermion couplings g_{Hff}, for example, which in the SM are given by the fermion masses, $g_{Hff} = m_f(m_H)/v$, can be traded for $\Gamma_f = \Gamma(H \to \bar{f}f)$. Similarly the square of the HWW coupling ($g_{HWW} = gm_W$ in the SM) or the HZZ coupling is proportional to the partial widths $\Gamma_W = \Gamma(H \to WW^*)$ or $\Gamma_Z = \Gamma(H \to ZZ^*)$. $\Gamma_\gamma = \Gamma(H \to \gamma\gamma)$ and $\Gamma_g = \Gamma(H \to gg)$ determine the squares of the effective $H\gamma\gamma$ and Hgg couplings. The Higgs production cross sections are governed by the same squares of couplings, hence, $\sigma(VV \to H) \sim \Gamma_V$ (for $V = g,\ W,\ Z$). Combined with the branching fractions $B(H \to ii) = \Gamma_i/\Gamma$ the various signal cross sections measure different combinations of Higgs boson partial and total widths, $\Gamma_i\Gamma_j/\Gamma$.

The production rate for WBF is a mixture of $ZZ \to H$ and $WW \to H$ processes, and we cannot distinguish between the two experimentally. In a large class of models the ratio of HWW and HZZ couplings is identical to the one in the SM, however, and this includes the MSSM. We therefore assume that 1) the $H \to ZZ^*$ and $H \to WW^*$ partial widths are related by SU(2) as in the SM, i.e. their ratio, z, is given by the SM value, $z = \Gamma_Z/\Gamma_W = z_{SM}$. Note that this assumption can be tested, at the 15-20% level for $m_H > 130$ GeV, by forming the ratio $B\sigma(gg \to H \to ZZ^*)/B\sigma(gg \to H \to WW^*)$.

With W, Z-universality, the three weak boson fusion cross sections give us direct measurements of three combinations of (partial) widths,

$$X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma} \qquad \text{from} \quad qq \to qqH,\ H \to \gamma\gamma\ , \tag{7}$$

$$X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma} \qquad \text{from} \quad qq \to qqH,\ H \to \tau\tau\ , \tag{8}$$

$$X_W = \frac{\Gamma_W^2}{\Gamma} \qquad \text{from} \quad qq \to qqH,\ H \to WW^{(*)}\ , \tag{9}$$

In addition the three gluon fusion channels provide measurements of

$$Y_\gamma = \frac{\Gamma_g \Gamma_\gamma}{\Gamma} \qquad \text{from} \quad gg \to H \to \gamma\gamma\ , \tag{10}$$

$$Y_Z = \frac{\Gamma_g \Gamma_Z}{\Gamma} \qquad \text{from} \quad gg \to H \to ZZ^{(*)}\ , \tag{11}$$

$$Y_W = \frac{\Gamma_g \Gamma_W}{\Gamma} \qquad \text{from} \quad gg \to H \to WW^{(*)}\ . \tag{12}$$

When extracting Higgs couplings, the QCD uncertainties of production cross sections enter. These can be estimated via the residual scale dependence of the NLO predictions and are small (of order 5%) for the WBF case,[12] while larger uncertainties of about 20% are found for gluon fusion.[13]

A first test of the Higgs sector is provided by taking ratios of the X_i's and ratios of the Y_i's. QCD uncertainties, and all other uncertainties related to the initial state, like luminosity and pdf errors, cancel in these ratios. They test W, Z-universality, and compare the $\tau\tau H$ Yukawa coupling with the HWW coupling. Typical errors on these cross section ratios are expected to be in the 15 to 20% range. Accepting an additional systematic error of about 20%, a measurement of the ratio Γ_g/Γ_W, which determines the Htt to HWW coupling ratio, can be performed, by measuring the cross section ratios $B\sigma(gg \to H \to \gamma\gamma)/\sigma(qq \to qqH)B(H \to \gamma\gamma)$ and $B\sigma(gg \to H \to WW^*)/\sigma(qq \to qqH)B(H \to WW^*)$.

Beyond the measurement of coupling ratios, minimal additional assumptions allow an indirect measurement of the total Higgs width. First of all, the τ partial width, properly normalized, is measurable with an accuracy of order 10%. The τ is a third generation fermion with isospin $-\frac{1}{2}$, just like the b-quark. In many models, the ratio of their coupling to the Higgs is given by the τ to b mass ratio. In addition to W, Z-universality we thus assume that (2) $y = \Gamma_b/\Gamma_\tau = y_{SM}$ and, finally, (3) the branching ratio for unexpected channels is small, i.e. $\epsilon = 1 - (B(H \to b\bar{b}) + B(H \to \tau\tau) + B(H \to WW^{(*)}) + B(H \to ZZ^{(*)}) + B(H \to gg) + B(H \to \gamma\gamma) \ll 1$.

With these three assumptions consider the observable

$$\begin{aligned} \tilde{\Gamma}_W &= X_\tau(1+y) + X_W(1+z) + X_\gamma + Y_W \\ &= \Big(\Gamma_\tau + \Gamma_b + \Gamma_W + \Gamma_Z + \Gamma_\gamma + \Gamma_g\Big)\frac{\Gamma_W}{\Gamma} = (1-\epsilon)\Gamma_W\ . \end{aligned} \tag{13}$$

$\tilde{\Gamma}_W$ provides a lower bound on $\Gamma(H \to WW^{(*)}) = \Gamma_W$. Provided ϵ is small (within the SM and for $m_H > 110$ GeV, $\epsilon < 0.04$ and it is dominated by $B(H \to c\bar{c})$), the determination of $\tilde{\Gamma}_W$ provides a direct measurement of the $H \to WW^{(*)}$ partial width. Once Γ_W has been determined, the total width of the Higgs boson is given by

$$\Gamma = \frac{\Gamma_W^2}{X_W} = \frac{1}{X_W}\Big(X_\tau(1+y) + X_W(1+z) + X_\gamma + \tilde{X}_g\Big)^2 \frac{1}{(1-\epsilon)^2}\ . \tag{14}$$

The extraction of the total Higgs width, via Eq. (14), requires a measurement of the $qq \to qqH, H \to WW^{(*)}$ cross section, which is expected to be available for $m_H \gtrsim 115$ GeV.[9] Consequently, errors are large for Higgs masses close to this lower limit but decrease to about 10% for Higgs boson masses around the WW threshold. Results are shown in Fig. 1b) and look highly promising.

4 Summary

With an integrated luminosity of 100 fb^{-1} per experiment, the LHC can measure various ratios of Higgs partial widths, with accuracies of order 10 to 20%. This translates into 5 to 10% measurements of various ratios of coupling constants. The ratio Γ_τ/Γ_W measures the coupling of down-type fermions relative to the Higgs couplings to gauge bosons. To the extent that the $H\gamma\gamma$ triangle diagrams are dominated by the W loop, the width ratio $\Gamma_\tau/\Gamma_\gamma$ probes the same relationship. The fermion triangles leading to an effective Hgg coupling are expected to be dominated by the top-quark, thus, Γ_g/Γ_W probes the coupling of up-type fermions relative to the HWW coupling. Finally, for Higgs boson masses above ≈ 120 GeV, the absolute normalization of the HWW coupling is accessible via the extraction of the $H \to WW^{(*)}$ partial width in weak boson fusion.

These measurements test the crucial aspects of the Higgs sector. The HWW coupling, being linear in the Higgs field, identifies the observed Higgs boson as the scalar responsible for the spontaneous breaking of $SU(2) \times U(1)$: a scalar without a vacuum expectation value does not exhibit such a trilinear coupling at tree level. The measurement of the ratios of g_{Htt}/g_{HWW} and $g_{H\tau\tau}/g_{HWW}$ then probes the mass generation of both up and down type fermions. Thus the LHC can do much more than mereley discover the Higgs: it can give us detailed and reasonably precise information on the dynamics of electroweak symmetry breaking.

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