The sensitivity of the Higgs boson branching ratios to the W boson width

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The Higgs boson branching ratio into vector bosons is sensitive to the decay widths of those vector bosons because they are produced with at least one boson significantly off-shell. \( \Gamma(H \rightarrow VV) \) is approximately proportional to the product of the Higgs boson coupling and the vector boson width. \( \Gamma_Z \) is well measured, but \( \Gamma_W \) gives an uncertainty on \( \Gamma(H \rightarrow WW) \) which is not negligible. The ratio of branching ratios, \( \text{BR}(H \rightarrow WW)/\text{BR}(H \rightarrow ZZ) \), measured by a combination of ATLAS and CMS at LHC is used herein to extract a width for the \( W \) boson of \( \Gamma_W = 1.8^{+0.3}_{-0.3} \) GeV by assuming Standard Model couplings of the Higgs bosons. This dependence of the branching ratio on \( \Gamma_W \) is not discussed in most Higgs boson coupling analyses.

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1. Introduction

The Higgs boson discovered at LHC[1,2] has been the subject of combined mass[3] and couplings [4] analyses by the ATLAS and CMS collaborations. The couplings analysis uses the so-called \( \kappa \) framework of the LHC Higgs cross-section working group [5,6], and relies upon the cross-section and branching ratio calculations contained therein. This includes the properties of the vector bosons, \( W \) and \( Z \), for which the masses reported in the RPP [7], are used to extract pole masses of \( m_Z = 91.15349 \) GeV and \( m_W = 80.36951 \) GeV in Ref. [6]. In addition, and especially relevant for this letter, the vector boson widths are calculated from their masses and assuming the Standard Model (SM), to be \( \Gamma_Z = 2495.81 \) MeV and \( \Gamma_W = 2088.56 \) MeV. The partial widths of the Higgs boson in \( WW \) and \( ZZ \) states are calculated from these using HDECAY [8,9] and PROPHECY [10,11] which incorporate dominant NLO effects.

The use of the theoretically expected \( W \) boson width is not discussed in Ref. [6], it is merely stated. It is not obvious that this is the best motivated assumption when looking for beyond the Standard Model (SM) effects in Higgs boson properties. The primary purpose of this document is to highlight that assumption.

The widths of the \( Z \) and \( W \) bosons have also been measured experimentally. The \( Z \) boson width was measured at LEP [12] to be \( 2495.7 \pm 2.3 \) MeV. The \( W \) boson width has been measured at LEP 2 [13] and the Tevatron [14] to give a combined result of \( \Gamma_W = 2085 \pm 42 \) MeV [7]. In consequence, effects due to the vector boson width uncertainties are dominated by those from the \( W \) boson.

The Higgs boson partial widths and branching ratios are not experimentally accessible at the LHC, where only products of production and decay can be studied. However, the ratio of the branching ratios to \( WW \) and \( ZZ \), is measurable, and it is presented in Ref. [4]. The measured value of \( \text{BR}^{WW}/\text{BR}^{ZZ} \) is \( 6.8^{+1.7}_{-1.3} \). The SM value given in Ref. [6] is 8.09.

The measured rate of Higgs bosons into diphoton pairs could also provide information. However additional assumptions would have to be made about the particles in the loop, complicating the interpretation.

2. Analysis of the widths

The full calculation of the Higgs boson partial widths in the SM is rather complex. However, the results are tabulated in Ref. [6], and the approach taken here is to use a leading-order approximation [15], and then scale its results to those in Ref. [6] for the nominal input parameters. The calculation is reproduced below.

\[
\Gamma(H \rightarrow V^+V^-) = \frac{1}{\pi} \int_0^{M_H^2} dq_1^2 M_V \Gamma_V \left( \frac{q_1^2 - M_V^2}{(q_1^2)^2 + M_V^2 \Gamma_V^2} \right) \int_0^{(M_H - q_1)^2} dq_2^2 M_V \Gamma_V \left( \frac{q_2^2 - M_V^2}{(q_2^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \right) \Gamma_0.
\]
In this formula $\Gamma_0$ is

$$\Gamma_0 = \delta_\nu \frac{G_F M_H^2}{16 \sqrt{2\pi}} \sqrt{\lambda(q_1^2, q_2^2, M_H^2)} \left( \lambda(q_1^2, q_2^2, M_H^2) + \frac{12q_1^2q_2^2}{M_H^4} \right)$$

(2)

where $\lambda(x, y, z) = (1-x/z-y/z)^2 - 4xy/z^2$ and $\delta_\nu$ has different values depending upon the vector boson: $\delta_\nu = 2$ and $\delta_\nu = 1$ [15]. This calculation assumes the SM coupling strengths to the $W$ and $Z$ boson.

Fig. 1 shows the density of the partial width of the Higgs to vector boson pairs in the $(q_1, q_2)$ plane. The doubly resonant point is not kinematically accessible, and in consequence all the available space is in a region far from the pole of at least one of the integrals. This means the factor $\Gamma_\nu$ in equation (1) does not cancel in the integral.

The numerical evaluation uses the parameters from the LHC Higgs cross-section working group as given in the introduction and was done using root [16]. To check the calculation it is first evaluated at $m_H = 126$ GeV because Ref. [6] provides partial widths at this mass. The values obtained are 0.941 MeV for $WW$ and 0.119 MeV for $ZZ$. These are respectively 97% and 98% of the values from the reference, 0.974 MeV and 0.122 MeV. This 2–3% discrepancy with the full calculation shows that the higher order effects are not large.

Having tested the implementation, the partial widths are found at $m_H = 125.09$ GeV. They are $\Gamma(H \rightarrow WW) = 0.853$ MeV and $\Gamma(H \rightarrow ZZ) = 0.107$ MeV.

The ratio of the partial widths gives directly the ratio of the branching ratios, 7.99. This is about 1% lower then the 8.09 contained in Ref. [6] and the difference is assumed to come from the more complete calculation used in that document. The 2–3% changes in the $WW$ and $ZZ$ widths have largely cancelled in the ratio. A scale factor of 1.01 is applied to subsequent evaluations.

The ratio $\text{BR}^{WW}/\text{BR}^{ZZ}$ as a function of the $W$ width, ignoring the uncertainties on all the other parameters, is shown in Fig. 2. Had the Higgs boson decayed to two on-shell bosons the width would scarcely have entered. If both vector bosons had been virtual, as is the case for a Higgs boson of 100 GeV or less, the dependence would have been roughly quadratic. With the actual mass there is one real and one virtual gauge boson and the width is, to a good approximation, proportional to $\Gamma_W$. This supports the 1% correction via a scaling of the ratio to the full calculation. The equation is numerically inverted to find $\Gamma_W$. This is:

$$\Gamma_W = 1800^{+400}_{-300}\text{MeV}$$

(3)

2.1. Errors from the extraction procedure

The Higgs boson mass of $125.09 \pm 0.21 \pm 0.11$ GeV has the largest mass uncertainty in the formula. It changes the extracted value of $\Gamma_W$ by around 0.2 MeV, which is clearly negligible, and similarly the $W$ and $Z$ boson masses contribute negligible uncertainty.

The $Z$ boson width is known to 2 per mile, and this translates to a 2 MeV uncertainty on the prediction of $\Gamma(H \rightarrow ZZ)$. This is far below the precision achievable at LHC and is ignored here. The
width of the Higgs boson could also influence this result by chang-
ing the relative suppression of \(WW\) and \(ZZ\) states. The tightest
model-independent upper limit on the \(H\) boson width is 3.4 GeV
from the CMS studies in the \(\text{III} \) final state \([17]\). A conservative es-
timate of the impact is made by changing \(m_H\) by 3.4 GeV, which
gives a 3 MeV shift in the extracted \(\Gamma_W\). This is again negligible.

There is a 1% correction made in the double ratio between the
first order calculation used here and the full calculation. However,
the measured value is compatible with the SM expectation, and so
the calculation has been corrected to the full calculation at least in
some part of the range. The total calculational error is expected to
be dominated by the uncertainty with which both the \(WW\) and
\(ZZ\) partial widths are calculated, 0.5% \([6]\). A pessimistic combina-
tion of these, 1%, gives the largest uncertainty on \(\Gamma_W\), 20 MeV.

In summary, the total error of the extraction is estimated to be
20 MeV, which is negligible in comparison with the experimental
error.

3. Discussion and outlook

The partial width \(\Gamma(H \to VV)\) is proportional to the full width
of the vector boson involved. While it is possible to impose the
SM expectation, this seems to this author a restrictive way of test-
ing the SM. The alternative, of using the experimentally measured
value, should be considered. The current 2% uncertainty on \(\Gamma_W\)
corresponds to a 2% uncertainty on the expected \(\Gamma(H \to WW)\).

Under the alternate hypothesis that the ratio of the Higgs bo-
son couplings to vector bosons is given by the SM then \(\Gamma_W =
1800^{+400}_{-300}\) MeV has been extracted. A conservative 20 MeV error
on the \(W\) boson width is estimated due to uncertainties on the
calculation of the partial widths to \(WW\) and \(ZZ\).

The uncertainty on this derivation of \(\Gamma_W\) is thus dominated by
the errors on the Higgs boson \(WW\) and \(ZZ\) measurements and
will remain so at HL-LHC. Various projections for these in the
future exist. For example, ATLAS concluded \([18]\) that 5% and 4%
errors on the \(H \to WW\) and \(H \to ZZ\) signal strength, respectively,
were possible using 3000 fb\(^{-1}\) if theoretical systematic errors are
ignored. Some of these theoretical errors will cancel in the ratio,
so an error approaching 7% error might be achievable, and pre-
sumably a combination of two experiments will be better. At this point
a 2% error on \(\Gamma_W\) would have a significant impact on the physics
interpretation.

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