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

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ABSTRACT

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. $\Gamma(H \to VV)$ is approximately proportional to the product of the Higgs boson coupling and the vector boson width. Γ_Z is well measured, but Γ_W gives an uncertainty on $\Gamma(H \to WW)$ which is not negligible. The ratio of branching ratios, $\text{BR}(H \to WW)/\text{BR}(H \to ZZ)$ measured by a combination of ATLAS and CMS at LHC is used herein to extract a width for the W boson of $\Gamma_W = 1.8^{+0.4}_{-0.3}$ GeV by assuming Standard Model couplings of the Higgs bosons. This dependence of the branching ratio on Γ_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 κ 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 Prophecy4f [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 2495.2 ± 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.

$$\Gamma(H \to V^*V^*) = \frac{1}{\pi^2} \int_0^{M_H^2} \frac{dq_1^2 M_V \Gamma_V}{(q_1^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \times \int_0^{(M_H - q_1)^2} \frac{dq_2^2 M_V \Gamma_V}{(q_2^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \Gamma_0. \quad (1)$$

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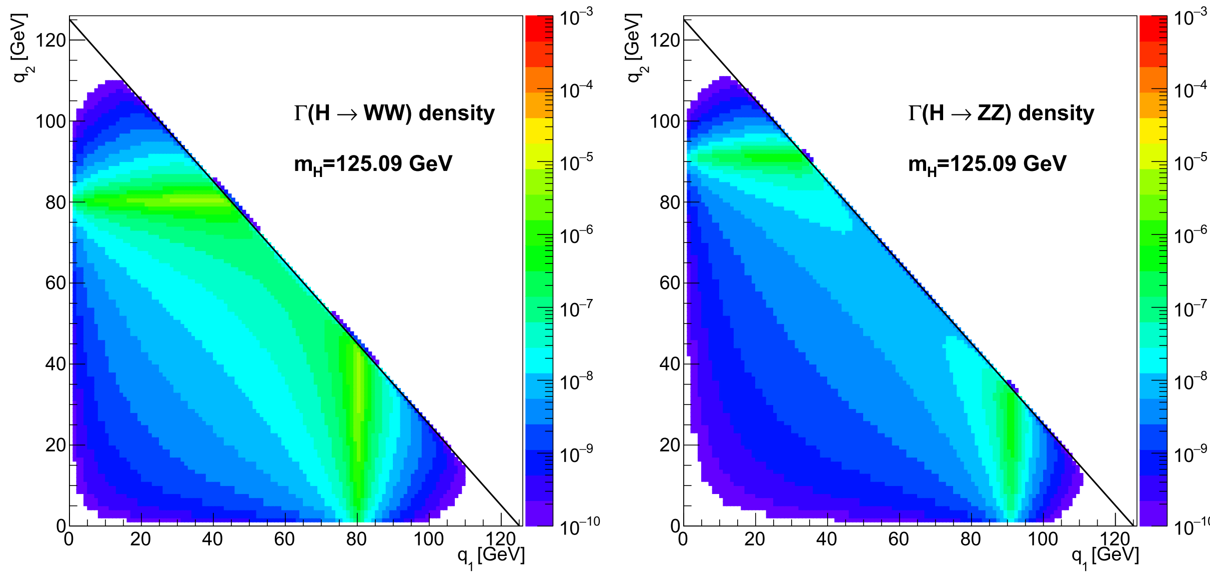

Fig. 1. The partial width densities of the Higgs boson into WW (left) and ZZ (right), in GeV per GeV^2.

In this formula Γ_0 is

$$\Gamma_0 = \delta'_V \frac{G_F M_H^3}{16\sqrt{2}\pi}\sqrt{\lambda(q_1^2, q_2^2, M_H^2)}\left(\lambda(q_1^2, q_2^2, M_H^2) + \frac{12q_1^2 q_2^2}{M_H^4}\right) \quad (2)$$

where $\lambda(x, y, z) = (1 - x/z - y/z)^2 - 4xy/z^2$ and δ'_V has different values depending upon the vector boson: $\delta'_W = 2$ and $\delta'_Z = 1$ [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 Γ_V 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 $\Gamma(H \to WW) = 0.853$ MeV and $\Gamma(H \to ZZ) = 0.107$ 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 Γ_W. This supports the

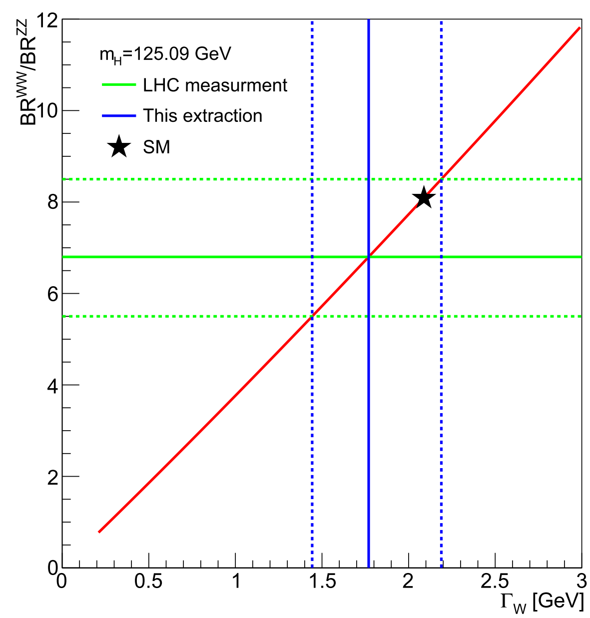

Fig. 2. The ratio $\text{BR}^{WW}/\text{BR}^{ZZ}$ as a function of the W boson width, with all other parameters fixed. The LHC measurement of the ratio of Higgs boson branching ratios $\text{BR}(H \to WW)/\text{BR}(H \to ZZ)$, the extracted Γ_W, and the SM expectation.

1% correction via a scaling of the ratio to the full calculation. The equation is numerically inverted to find Γ_W. This is:

$$\Gamma_W = 1800^{+400}_{-300}\text{MeV} \quad (3)$$

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 Γ_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 $\Gamma(H \to ZZ)$. 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 changing 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 *llll* final state [17]. A conservative estimate of the impact is made by changing m_H by 3.4 GeV, which gives a 3 MeV shift in the extracted Γ_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 combination of these, 1%, gives the largest uncertainty on Γ_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 testing the SM. The alternative, of using the experimentally measured value, should be considered. The current 2% uncertainty on Γ_W corresponds to a 2% uncertainty on the expected $\Gamma(H \to WW)$.

Under the alternate hypothesis that the ratio of the Higgs boson 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 Γ_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 presumably a combination of two experiments will be better. At this point a 2% error on Γ_W would have a significant impact on the physics interpretation.

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