CP Asymmetries in Higgs decays to ZZ at the LHC

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Abstract. We examine the effect of a general HZZ coupling through a study of the Higgs decay to leptons via Z bosons at the LHC. We discuss various methods for placing limits on additional couplings, including measurement of the partial width, threshold scans, and asymmetries constructed from angular observables. We find that only the asymmetries provide a definitive test of additional couplings. We further estimate the significances they provide.

1. Introduction

The verification of the Higgs mechanism as the cause of electroweak symmetry breaking and the discovery of the Higgs boson is the next big goal of particle physics. However, it is not enough to simply find a new resonance in the Higgs search channels at the next generation of colliders. One must ensure that this resonance is indeed the Higgs boson by measuring its properties: its CP and spin, to demonstrate its predicted scalar nature; its couplings to known particles, to verify that these couplings are proportional to the particle's mass; and the Higgs self couplings, in order to reconstruct the Higgs potential itself. This will be a challenging programme and will not be fully realised at the Large Hadron Collider (LHC) (e.g. the quartic Higgs self coupling will be out of reach). However, such an analysis will be crucial in our investigation of electroweak symmetry breaking in scenarios where the suspected Higgs boson is all we find at the LHC, as well as scenarios where new physics is discovered. In the former case, testing for deviations from the Standard Model (SM) may provide clues to resolving some of the SM's long standing problems; in the latter case, the Higgs boson properties will provide essential information on the nature of the new physics.

It is interesting to note that the Higgs boson's CP (and spin) is intimately related to its couplings to other SM particles, since its scalar or pseudoscalar nature allow or forbid certain tensor structures in the Higgs boson couplings. In this report, we investigate the tensor structure of the HZZ vertex in order to shed some light on the Higgs boson's CP. We write down the most general tensor vertex for this coupling and investigate how the additional terms influence the decay $H \to ZZ^{(*)} \to 4$ *leptons* at the LHC. For a more detailed description of this analysis, see Ref.[1].

The most general vertex for a spinless particle coupling to a pair of Z bosons, with four-momenta q_1 and q_2, is given by,

$$V^{\mu\nu}_{HZZ} = \frac{igm_Z}{\cos\theta_W}\left[a\,g_{\mu\nu} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\,\epsilon_{\mu\nu\alpha\beta}\,\frac{p^\alpha k^\beta}{m_Z^2}\right], \tag{1}$$

where $p = q_1 + q_2$ and $k = q_1 - q_2$, θ_W denotes the weak-mixing angle and $\epsilon_{\mu\nu\alpha\beta}$ is the totally antisymmetric tensor with $\epsilon_{0123} = 1$. The CP conserving tree-level Standard Model coupling is recovered for $a = 1$ and $b = c = 0$.

Terms containing a and b are associated with the coupling of a CP-even Higgs, while that containing c is associated with that of a CP-odd Higgs boson. The simulanteous appearance of a non-zero a (and/or b) together with a non-zero c would lead to CP violation. In general these parameters can be momentum-dependent form factors that may be generated from loops containing new heavy particles or equivalently from the integration over heavy degrees of freedom giving rise to higher dimensional operators. The form factors b and c may, in general, be complex, but since an overall phase will not affect the observables studied here, we are free to adopt the convention that a is real.

2. The total width

One method of investigating the tensor structure of the HZZ coupling is to examine the threshold behaviour of the decay $H \to ZZ^*$ [2]. Notice that the additional terms in the vertex all have a momentum dependence and will vanish at threshold. The SM term does not, and although the SM width will still vanish at threshold due to a shrinking phase space, it will have a much steeper slope than a pure CP-odd state. This can be seen in Figure 1 which shows the dependence of the partial width of a 150 GeV Higgs boson on the virtuality of the most virtual Z boson. Notice that the pure CP-even (SM) (solid black curve) and pure CP-odd (dashed blue curve) states are easily distinguishable. However, when one has a CP-violating combination of couplings (dot-dashed red curve) the SM terms will be dominant near threshold and it is very difficult to distinguish from the SM.

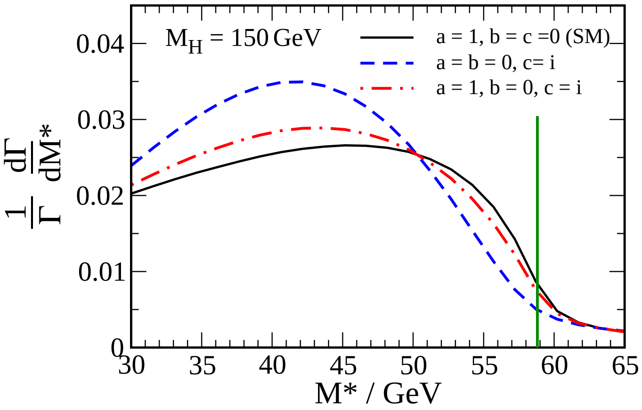

Figure 1. The dependence of the Higgs decay width on the virtuality of the most virtual Z boson.

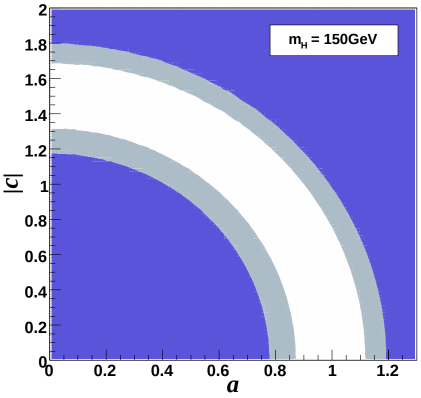

Figure 2. The deviation of the width from the SM prediction.

Alternatively, one could examine the magnitude of the total decay width for $H \to ZZ^* \to 4$ *leptons* to see if it differs from the SM. For the vertex of Equation 1, the dependence on the coefficients a, b and c is given by,

$$\frac{\partial^2 \Gamma_H}{\partial q_1^2 \partial q_2^2} \sim \beta \left\{ a^2 \left[\beta^2 + \frac{12 q_1^2 q_2^2}{m_H^4} \right] + |b|^2 \frac{m_H^4}{m_Z^4} \frac{\beta^4}{4} + |c|^2 \frac{8 q_1^2 q_2^2}{m_Z^4} \beta^2 + a \Re e(b) \frac{m_H^2}{m_Z^2} \beta^2 \sqrt{\beta^2 + \frac{4 q_1^2 q_2^2}{m_H^4}} \right\}, \tag{2}$$

where β is the usual Lorentz boost factor for the Z-bosons. (Notice that the only term with a linear β dependence (from the phase space) is proportional to a^2, illustrating the principle described above for the threshold scan.) If additional terms are present one expects them to increase or decrease the width according to this equation. We used the ATLAS study of Ref. [3,4] (including cuts and efficiencies) to estimate the number of signal and background events for the SM and CP-violating scenarios (scaling the signal according to Equation 2). In Figure 2 we plot the number of standard deviations from the SM that the CP-violating scenario would imply, for a 150 GeV Higgs boson and an integrated luminosity of $300\,\mathrm{fb}^{-1}$ (we set $b = 0$ for simplicity). The white area represents scenarios where the significance of the deviation is less than $3\,\sigma$, the light blue/grey region represents a $3 - 5\,\sigma$ deviation, while the dark blue/grey region represents a greater than $5\,\sigma$ deviation. This measurement would allow one to rule out much of the $a - |c|$ parameter space, but does not allow one to definitively rule out (or place significant limits on) the CP-odd coupling $|c|$. A SM-like rate is perfectly consistent with a large value of $|c|$ and a small value of a.

3. Asymmetries as a probe of CP violation

To definitively ascertain whether or not extra tensor structures are present in the HZZ vertex one is better served by measuring asymmetries which vanish when such terms are absent. Such an asymmetry can be constructed from an observable, $\mathcal{O}$, based on the angles of the final state leptons,

$$\mathcal{A} = \frac{\Gamma(\mathcal{O} > 0) - \Gamma(\mathcal{O} < 0)}{\Gamma(\mathcal{O} > 0) + \Gamma(\mathcal{O} < 0)} \,. \tag{3}$$

The choice $\mathcal{O} = \cos\theta_1$, where θ_i is the angle between lepton i and its parent Z's direction of travel, as measured in the Z rest frame, provides an asymmetry proportional to $a\,\Im m(c)$. Unfortunately, for this particular choice the asymmetry is rather small (always $\lesssim$ 7%), making it a rather poor discriminant. However, other observables can be constructed which do much better. For example, $\mathcal{O}_5 = \sin\theta_1 \sin\theta_2 \sin\phi[\sin\theta_1 \sin\theta_2 \cos\phi + \cos\theta_1 \cos\theta_2]$, where ϕ is the azimuthal angle between the two planes formed by lepton-antilepton pairs, provides a good test of non-zero $\Re e(c)$, with an asymmetry, $\mathcal{A}_5$, sometimes as large at 15%. We calculated the significance with which non-zero $\Re e(c)$ would manifest at the LHC by taking the number of signal and background events from the ATLAS study. Since the contamination of the asymmetry from the background is rather minimal we use the number of events after the initial selection cuts, but before applying additional isolation and impact parameter cuts to remove the irreducible backgrounds. The significance, for a 150 GeV Higgs boson and a total luminosity of $300\,\mathrm{fb}^{-1}$, is shown in Figure 3, and we see this asymmetry would provide a $3(5)\,\sigma$ exclusion limit for $\Re e(c) \gtrsim 0.66(1.28)$. See Ref.[1] for further details, including additional asymmetries and an analysis for $m_H = 200$GeV.

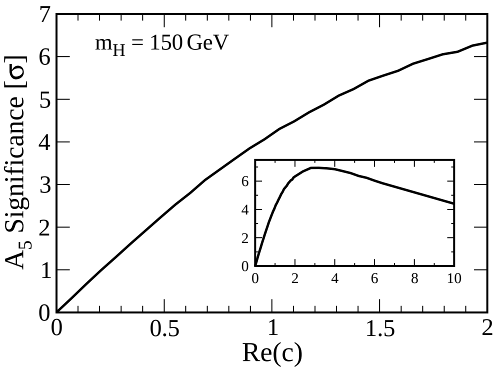

Figure 3. The significance of the deviation from zero of the asymmetry $\mathcal{A}_5$.

References

[1] R. M. Godbole, D. J. Miller and M. M. Muhlleitner, arXiv:0708.0458 [hep-ph].

[2] S. Y. Choi, D. J. Miller, M. M. Muhlleitner and P. M. Zerwas, Phys. Lett. B **553** (2003) 61 [arXiv:hep-ph/0210077].

[3] ATLAS Collaboration, *ATLAS Detector and Physics Performance: Technical Design Report*, Vol. 2, CERN-LHCC-99-15 (1999).

[4] M. Hohlfeld, *On the determination of Higgs parameters in the ATLAS experiment at the LHC*, ATL-PHYS-2001-004.