Trilinear Higgs Self Coupling in the Inert Higgs Doublet Model

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Abstract

In order to verify the mechanism of mass generation, the Higgs boson couplings with gauge bosons as well as fermions have to be determined with sufficient accuracy. Moreover, precise determination of the hhh and hhhh couplings is essential to determine the structure of the Higgs potential.

The triple Higgs self-coupling can be, measured directly in pair-production of the Higgs boson at LHC with high luminosity: pp→ $hh \to b\bar{b}\gamma\gamma$,pp→ $hh \to \bar{b}b\tau^+\tau^-$ At e^+e^- International Linear Collider $e^+e^- \to Zhh$, $e^+e^- \to W^+W^-\nu\bar{\nu} \to hh\nu\bar{\nu}$

Introduction

The ATLAS and CMS collaborations have been reported , by collecting the data of 7 TeV and 8 TeV run, the discovery of a new boson with mass around $125-126$ GeV in the $\gamma\gamma$, ZZ^* and WW^* channels. This result have been confirmed by CDF and $D0$ collaborations at Tevatron in the process $p\bar{p} \to Wh \to l\nu b\bar{b}$. Since this particle decays into two bosons, the possibility that this discovery corresponds to a fermion is therefore ruled out. Spin-1 particle is ruled out since according to Landau-Yang theorem a spin one particle cannot decay into 2 photons. We have only two possibilities, spin-0 particle or a spin-2 like particle. Both ATLAS and CMS have been reported results of the spin and parity studies, this particle have $J^P = 0^+$.

The Inert Higgs Doublet Model

The IHDM is one of the most simplest extensions beyond the SM. This model consists of adding a doublet H_2 to the SM with no interactions with the fermions, i.e with an unbroken Z_2 symmetry. Under this symmetry all the SM particles are even while H_2 is odd, i.e : $H_2 \to -H_2$. The parametrization of the doublets is given by :

$$H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}, H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix} \quad (1)$$

with G^0 and G^+ are the Goldstone bosons eaten up by the $W^\pm$ and Z^0 to aquire their masses. v is the vacuum expectation value (VEV) of the SM Higgs doublet H_1.
The most general renormalizable, gauge invariant and CP invariant potential is given by :

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + H.c.\right] \quad (2)$$

Note that because of the unbroken Z_2 symmetry, this potential have no mixing terms like $\mu_{12}(H_1^\dagger H_2 + h.c)$. The hermicity of the potential implies that the parameters $\lambda_i, i = 1, \cdots, 4$ are real while the phase in λ_5 can be absorbed by a suitable redefinition of the fields H_1 and H_2. After spontaneous symmetry breaking of the group $SU(2)_L \otimes U(1)_Y$ down to $U(1)_Q$, we have in the spectrum of this five additional particles : two CP even H^0 and h where the latter is the SM Higgs boson, a CP odd A^0, a pair of charged scalars $H^\pm$. their masses are given by :

$$\begin{aligned} m_h^2 &= -2\mu_1^2 = 2\lambda_1 v^2 \\ m_{H^0}^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 \\ m_{A^0}^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2 \\ m_{H^\pm}^2 &= \mu_2^2 + \frac{1}{2}\lambda_3 v^2 \end{aligned} \quad (3)$$

This model involves 8 independent parameters : 5λ, 2μ and v. one parameter is eliminated by the minimization condition and the VEV is fixed by the W boson mass. Finally, we have 6 independent parameters which we choose as follow :

$$\{\mu_2^2, \lambda_2, m_h, m_{H^\pm}, m_{H^0}, m_{A^0}\} \quad (4)$$

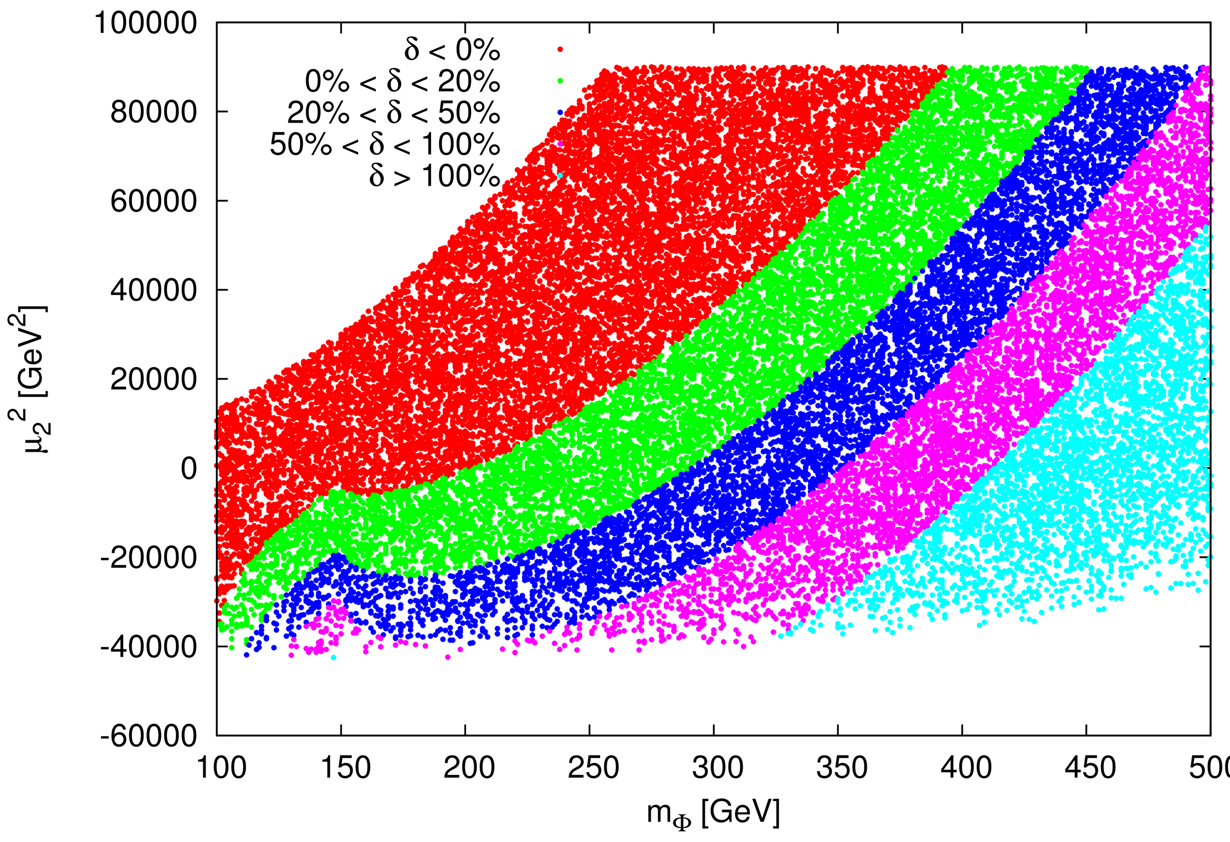
The Trilinear Higgs Self Coupling in the IHDM

We calculate in this section the one-loop radiative corrections to the trilinear Higgs self-coupling in the IHDM. This coupling is given at the tree-level by :

$$\lambda_{hhh} = \frac{-3m_h^2}{v} \quad (5)$$

The one-loop effects from the Standard Model (SM) are studied in several papers. These effects are dominated by the top quark loops which gives 10% as a maximum of these corrections. New physics effects have been analyzed in the context of the MSSM and the THDM. It was found that these effects can enhance significately this coupling in a wide range of the parameter space. Furthermore, these corrections depend on the model and hence any deviation from the SM tree level relation (5) relation by at least 20% would not only be an evidence for new physics but also guide us to which new physics is discovered.
We have calculated the corrections to the tree level formula (5) in the Feynman gauge including all the particles in the loops. This calculation was done with the help of FeynArts and FormCalc packages. Numerical evaluation of the one-loop integrals have been done with LoopTools. We define the ratio $\Delta\Gamma_{hhh}$ by the above formula :

$$\Delta\Gamma_{hhh} = \frac{\lambda_{hhh}^{loop} - \lambda_{hhh}^{tree}}{\lambda_{hhh}^{tree}} \quad (6)$$



$e^+e^- \to hhZ$ in the IHDM

Measurement of the cross-section of $e^+e^- \to hhZ$ offers the information of the trilinear Higgs self-couplings.
At the one-loop order, the cross section can be obtained by interfering the amplitudes of tree level diagrams with those arising at the one-loop.
Writing the amplitude as follow :

$$\mathcal{M} = \mathcal{M}_{\text{tree}} + \mathcal{M}_{\text{loop}} \quad (7)$$

The squared amplitude at the one-loop level is then :

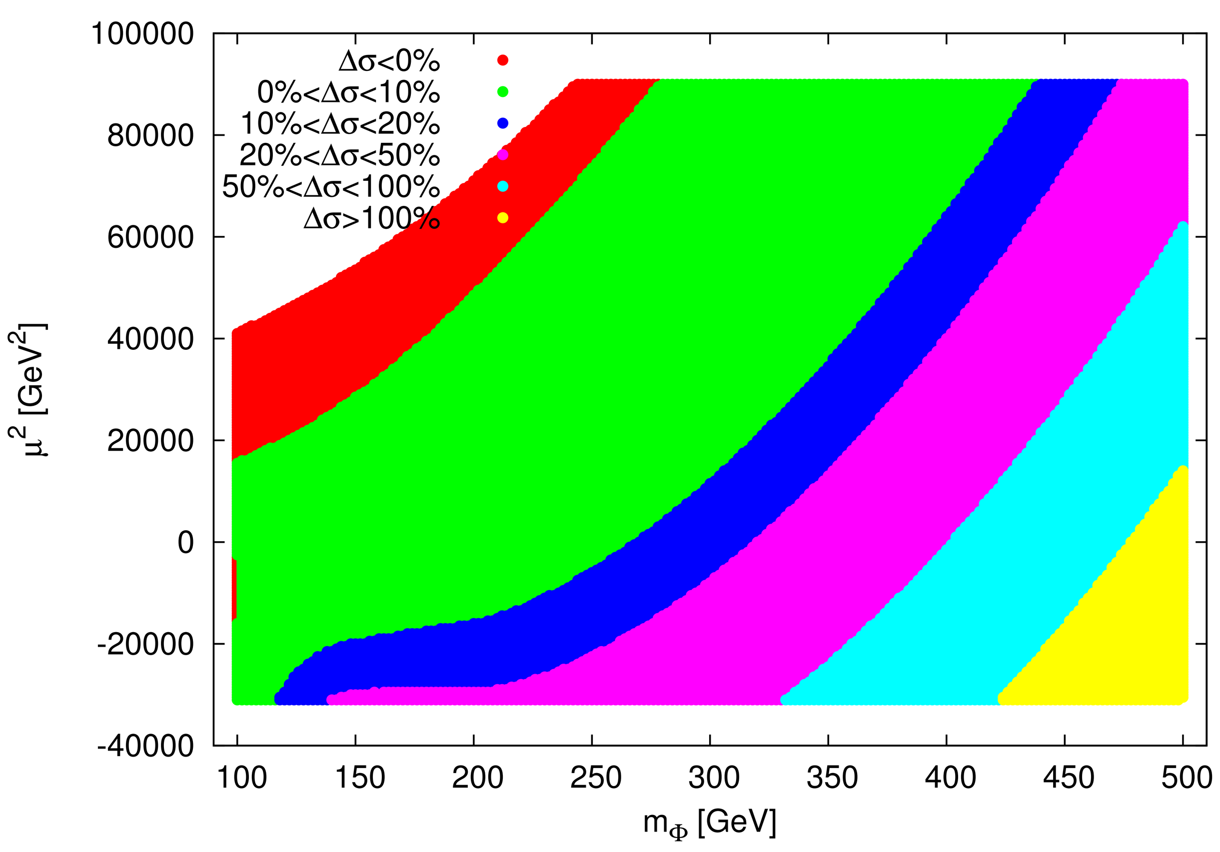
$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{tree}}|^2 + 2\text{Re}\{\mathcal{M}_{\text{tree}}^*\mathcal{M}_{\text{loop}}\} + \mathcal{O}(\alpha^2) \quad (8)$$

Thus, the cross section is written as :

$$\sigma = \frac{1}{(2\pi)^2}\int \prod_{k=1}^{3} \frac{d^3\mathbf{p}_k}{2E_k}\delta^{(4)}(q_1 + q_2 - p_1 - p_2 - p_3) \sum_{\text{spin, pola.}} |\mathcal{M}|^2 \quad (9)$$

where q_1 and q_2 are the 4-momenta of the incoming particles (electrons and positrons), p_1, p_2 and p_3 are the momenta of the outgoing particles and the factor $\frac{1}{(2\pi)^2}$ arises from the flux of the initial particles. We define the ratio $\Delta\sigma$ by :

$$\Delta\sigma = \frac{\sigma_{\text{total}} - \sigma_{\text{tree}}}{\sigma_{\text{tree}}} = \frac{\sigma_{\text{loop}}}{\sigma_{\text{tree}}} \quad (10)$$



Conclusions

- In 2015 the LHC will restart with an energy of 14 TeV in the center of mass to study the properties of this new resonance.
- The process $e^+e^- \to hhZ$ is interesting and of importance mainly because it gives access to the measurement of the triple Higgs coupling.
- The triple Higgs coupling could be a good probe of physics. beyond SM.

References

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