Probing New Physics by the Tail of the Off-shell Higgs via Polarization Tagging

Based on Work with Seung J. Lee, Myeonghun Park (arXiv:1812.02679)
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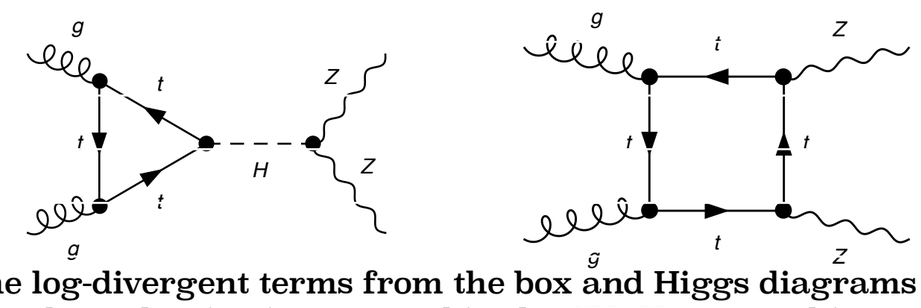
Abstract

Off-shell Higgs at the high mass tail may shed light on the underlying mechanism of the electroweak symmetry breaking. In the Standard Model, there is an exact cancellation of the logarithmic divergence between the box and Higgs-mediated triangle diagrams due to unitarity, such that the $gg \to ZZ$ (WW) process in the SM is dominated by the V_TV_T transverse-mode. The cancellation can be delayed to a higher scale, when there is sufficiently large new physics contribution resulting in V_LV_L longitudinal mode, which is commonly the case when the Higgs sector is modified. Thus the V_LV_L final states in the high mass tail can be utilized as a sensitive probe for new physics. In this letter, we propose to utilize the information in angular observables to maximize the hint of a new physics hiding in the polarization of gauge bosons.

Introduction

Vector boson pair production could be categorized into TT (transverse-transverse), TL(transverse-longitudinal), and LL(longitudinal-longitudinal) modes. In the Standard Model (SM), Z boson pair production is mostly from $qq \to ZZ$ process, dominated by TT mode. For $gg \to ZZ$, the destructive interference between the massive quark box-loops and triangle-Higgs diagrams leaves the total cross section dominated by TT mode as well.



The log-divergent terms from the box and Higgs diagrams cancel exactly, and unitarity restored in the SM. However, this exact cancellation may be delayed in the presence of new physics (NP) at a scale probable by the LHC. In this case, a modification of $gg \to V_LV_L$ amplitude can be established from 1) a change in Higgs propagator 2) introduction of a new propagator 3) a variation in hV_LV_L form factor. These cases are portrayed with following examples, and tagging the LL mode in the tail of off-shell Higgs provides a sensitive probe to all these NP scenarios.

New Physics Examples

A. Higgs Portal Light Scalar

A Higgs portal light scalar with mass of $m_S > m_h/2$, which evades constraints from Higgs invisible decay searches, would contribute through loop effects to the Higgs self energy, and modify the m_{ZZ} distribution at high energy scale. To study, we write a simplified Lagrangian of a SM plus a complex scalar in the form:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \partial_\mu S \partial^\mu S^* - \mu^2 |S|^2 - \kappa |S|^2 |\Phi|^2 .$$

At Next Leading Order (NLO), the scalar S modifies the Higgs propagator through loop. The deviation from the SM at high energy becomes apparent in the LL mode as expected. We set the benchmark point with $\kappa = 9$ and $m_S = 80$ GeV, where κ is set to be largest value allowed by current experimental search.

B. Broad-Width Heavy Scalar

Another example is a heavy scalar S that decays to ZZ, with amplitude proportional to its mixing with the SM Higgs. We take a representative example of an additional real scalar:

$$\mathscr{L} \ni \mathscr{L}_{\rm SM} - \mu_S S |\Phi|^2 .$$

Through mixing, all the Higgs couplings to the other SM particles are rescaled by $\cos\theta$, while the SXX couplings are $\sin\theta$ times the SM Higgs coupling value. We take the scalar mass at $M_S = 700$ GeV and $\sin\theta = 0.4$ as still allowed by current Higgs data, and assume a relatively broad width $\Gamma_S = 140$ GeV which manifests large interference.

C. Quantum Critical Higgs

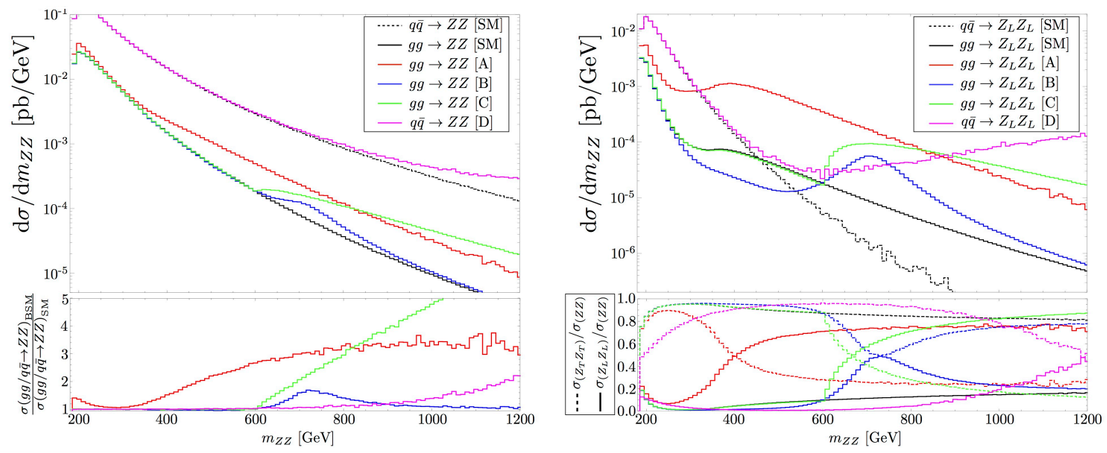
Quantum critical Higgs type of models typically predict a higher scale continuum which modify the Higgs off-shell region. In general, the Higgs couplings to other SM particles could depend on the details of the UV theory, the conformal symmetry breaking and the scale.

We consider a minimal scenario where the propagator of the physical Higgs field and the hZZ coupling are modified as,

$$G_h(p) = -\frac{iZ_h}{(\mu^2 - p^2 - i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}}$$

$$g_{hZZ} = -\frac{(\mu^2)^{2-\Delta} - (\mu^2 - p^2)^{2-\Delta}}{\hat{s}} g^{\rm SM}_{hZZ} .$$

The non-standard hZZ form factor arises from gauge invariant form of the Higgs two-point function. The continuum scale u and the anomalous dimension Δ are the two new parameters in this case. u =600 GeV and Δ =1.6 are chosen as benchmark point. We show the differential $m_{\{4l\}}$ distribution below for total and in LL-mode below for all relevant processes.



Analysis and Results

We use MadGraph to generate $gg(qq) \to ZZ \to e^- e^+ u^- u^+$ events. Generator level cuts are applied as, $p_{T\{l\}} > 10$ GeV, $\eta_{\{l\}} < 2.5$, $m_{\{ll\}} > 50$ GeV, and $m_{\{4l\}} > 560$ GeV. We further require in the final state a pair of electrons and muons with basic cuts,

$$80 < m_{ll} < 100 \text{ GeV}, \quad m_{4l} > 600 \text{ GeV} . \qquad \text{(Basic Cuts)}$$

The generic NP signal is $gg \to h^* \to 4l$ -like, dominated by LL mode. Backgrounds are the SM $qq \to ZZ$, $gg \to ZZ$ processes, dominated by TT mode in the high mass scale.

Besides the polar angle cut $\cos\theta_1$ on the leading Z decay, another useful variable is $\cos\theta^*$, the angle between the Z from $u^- u^+$ pair, and the beam line in the center of mass frame. The angular cuts are:

$$|\cos\theta^*| < 0.7, \quad |\cos\theta_1| < 0.68. \qquad \text{(Angluar Cuts)}$$

To further suppress the qq-initiated background and maximize the sensitivity to new physics, we perform a 6-variable BDT analysis. The significance at HL-LHC for our benchmark scenarios are:

Significance	case A	case B	case C
with basic cuts	2.01	0.634	4.71
with basic + angle cuts	2.32	0.838	5.78
with basic cuts + BDT	2.45	0.92	7.01

We study the the high mass tail region of the $pp \to ZZ \to 4l$ channel, which is sensitive to modification to the Higgs sector. We point out that the deviation is mostly detectable in the LL-mode of Z bosons. Thus the sensitivity over a general class of NP models would be improved by suppressing TT-mode utilizing simple angular cuts, as we show for three NP benchmark cases. We would also like to point out that, our method of improvement is applicable to all di-boson and Higgs associated production channels, and a combined search would accumulatively improve the sensitivity for NP at the tail of the off-shell Higgs. Inclusion of these additional channels could be extended from our study.