Snowmass2021 - Letter of Interest

Measuring Higgs Self-couplings with $V_LV_L \to V_LV_Lh$

Thematic Areas: (check all that apply □/■)

■ (EF01) EW Physics: Higgs Boson properties and couplings
□ (EF02) EW Physics: Higgs Boson as a portal to new physics
□ (EF03) EW Physics: Heavy flavor and top quark physics
■ (EF04) EW Precision Physics and constraining new physics
□ (EF05) QCD and strong interactions: Precision QCD
□ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF07) QCD and strong interactions: Heavy Ions
□ (EF08) BSM: Model specific explorations
□ (EF09) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders
□ (Other) *[Please specify frontier/topical group]*

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Abstract: (maximum 200 words)

It was proposed in reference[1] that we can measure Higgs couplings through processes with the external states as longitudinal vector bosons, instead of the Higgs boson directly, if the number of external states are more than four. In this letter we set follow up this proposal to study the measurement of Higgs self-couplings with subprocess $V_LV_L \to V_LV_Lh$. The theoretical framework is SMEFT. Our plan is two-folded. First, in order to disentangle unphysical energy increase from longitudinal vector polarizations and physical energy increase from derivative coupling from higher dimensional operators, we analyze the amplitude under Goldstone equivalence theorem, trying to understand the contribution of dim-6 operators to the amplitude, compared to the SM only. Second, we carry out a more careful simulation analysis of the corresponding process in LHC: $pp \to jjV_LV_Lh$.

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1 Introduction

It remains a great task to measure the self-couplings of the Higgs boson with greater precision, which is intimately related to our understanding of hierarchy problem, the origin of EW symmetry breaking, the nature of EW phase transition and etc[5 2]. The traditional approach to measure Higgs couplings is to choose the process with the largest cross section that have Higgs bosons as final states, so that we can accumulate enough luminosity to analyze the data. In LHC, it's the di-Higgs production through gluon fusion[6 7]. In ref[1], the authors proposed a new approach. They claim we can measure Higgs self-couplings through processes with longitudinal vector bosons, by making use of the fact that $V_L \sim \phi$[9 10 11 12] in high energy limit. As claimed by the authors of ref[1], this approach is especially effective if the number of external vector bosons increases. Taking the example of our concern in this letter, $pp \to jjV_LV_Lh$ has sub-process $V_LV_L \to V_LV_Lh$, in which there are 4 longitudinal vector bosons. The claim is that the precision of Higgs self-couplings in this channel is comparable to the well-studied di-Higgs channel. This raises puzzles and further questions: First, the energy increase of longitudinal polarization vectors is unphysical, would be canceled after summing over all Feynman diagrams. This is the basic argument for Goldstone equivalence theorem[9 10 11 12]. Thus, it's confusing how increasing the number of longitudinal vector bosons can boost the amplitude. Second, the collider simulation of the process $pp \to jjV_LV_Lh$ in ref[1] is very primitive. Even if the conclusion of ref[1] is correct at the amplitude level. It's still very important to devote a careful analysis to the process to really understand how precise the channel can be. A crucial step would be good choices of final states and cuts to minimize background.

Based on summary above, the plan of our project is two-folded. First, we carry out a thorough analytical analysis of the process $V_LV_L \to V_LV_Lh$ in high energy limit. Second, we carry out a careful collider analysis of, for example, $pp \to jjW_L^{\pm}W_L^{\pm}h$.

2 Amplitude

To analyze the amplitude of $V_LV_L \to V_LV_Lh$ in high energy limit. We use SMEFT to capture the effects of new physics in high energy scale. Since the energy increase of longitudinal polarization vectors are unphysical, it's important to disentangle this unphysical energy increase from physical increase in Feynman diagrams from dim-6 operators. Thus we take Goldstone equivalence theorem by replacing V_L with the corresponding Goldstone boson ϕ. The real object of our analysis is then the amplitude of $\phi_L\phi_L \to \phi_L\phi_Lh$.

In the physical picture of Goldstone equivalence, the relevant dim-6 Lagrangian terms that contribute to $VV \to VVh$, ignoring CP violating terms, are,

$$\begin{aligned} \mathcal{L}_{\text{dim}-6} \quad = \quad & -C_6(\Phi^\dagger\Phi)^3 + C_{\Phi_1}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + C_{\Phi_2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)^*(\Phi^\dagger \overleftrightarrow{D}_\mu\Phi) \\ & +C_{\Phi^2W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + C_{\Phi^2B^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + C_{\Phi^2WB}\Phi^\dagger\tau^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ & +C_{W^3}\epsilon^{abc}W^{a\nu}_\mu W^{b\rho}_\nu W^{b\mu}_\rho \end{aligned} \tag{1}$$

It was claimed in ref[1] that for BSM scale being Λ, the ratio of BSM and SM contributions to the amplitude is

$$\frac{\mathcal{A}_{BSM}}{A_{SM}} \sim \frac{E^2}{\Lambda^2} \tag{2}$$

Our goal is to confirm the Eq.(2) (or reject it) through direct calculations, and gain a more complete physical understanding. In order to cross check, we also use FeynArts[13] to evaluate the amplitude and compare with our results from direct analytical calculations.

3 Simulation

For the collider simulation, the first task is to evaluate the total cross section with and without dim-6 operators, and understand how Wilson coefficients, especially C_6, are measured. Second, we need good choices of final states and cuts to minimize the background. Third, making use of the results of amplitude in the last section, we can make use of the distributions of the cross section and improve our precision.

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