Probing the Sign of hZZ Coupling

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Introduction

- After the discovery of a scalar resonance at the LHC in 2012, its resemblance to the Standard Model (SM) Higgs scalar has been under constant experimental scrutiny.
- CMS and ATLAS present the information about the Higgs couplings in the form of Higgs signal-strengths which, in most cases($h \to \gamma\gamma$ is an exception where the relative sign of tth and WWh couplings can be resolved), is not sensitive to the sign of the tree-level Higgs couplings. So
- Here we discuss a method to systematically resolve the relative sign between the hWW and hZZ couplings.

Wrong-Sign Limit(WSL)

- We define the Higgs coupling modifiers as

$$\kappa_X^h = \frac{g_{XXh}}{g_{XXh}^{\rm SM}}\,, \tag{1}$$

where 'X' is a generic symbol for the SM fermions and massive vector bosons and g_{XXh} represents the strength of the trilinear coupling at the tree-level. Here, h in the denominator denotes the SM Higgs boson, and h in the numerator denotes h_{125}, the observed resonance at 125 GeV. If $\kappa_X^h = 1$ for all X, we can identify h_{125} with h.

- The wrong sign limit is defined as the case $\kappa_W^h = -\kappa_Z^h = 1$
- it is possible to construct models that accommodate this scenario while keeping $\rho = 1$ at the tree-level and hence it becomes imperative to build a strategy to experimentally probe it[1].

[1] Chiang and Yagyu, Phys. Lett. B 786 (2018) 268–271

Wrong Sign Limit (WSL)

- In this context, it was suggested[2,3] that one should look into process like $e^+e^- \to W^+W^-h$ which will involve an interference between the hWW and hZZ vertices allowing us, in principle, to experimentally determine the relative sign between κ_W^h and κ_Z^h.
- A similar strategy was adopted by the ATLAS and CMS Collaborations[4,5], where the Wh production in the vector boson fusion (VBF) channel was analyzed and subsequently it was concluded that the 'wrong-sign' limit with $\kappa_W^h = -\kappa_Z^h = 1$ is excluded with significance greater than 8σ.
- All such conclusions, however, come with an important caveat which is the underlying assumption that the processes under investigation are mediated by the SM-particles only.
- In principle, new physics can contribute to such processes and cancel the energy growths and lead to such null results but they are constrained by direct search constraints.

[2] Chiang, He, and Li, JHEP 08 (2018) 126
[3] Hamdellou and Ahriche, J. Phys. Conf. Ser. 1766 (2021), no. 1 012019
[4] CMS Collaboration, CMS-PAS-HIG-23-007 (2023)
[5] ATLAS Collaboration, Aad et al., arXiv:2402.00426

Relevance of our work

- This is where our current work becomes relevant.
- Our approach relies on the fact that, in a setting that respects unitarity, any deviation from the SM couplings will violate unitarity[6,7,8] and therefore will require the intervention of new physics (NP). The wrong-sign arrangement will also necessitate the presence of new interactions beyond the SM (BSM).
- The energy scale beyond which unitarity is violated ($\Lambda_{\rm UV}^{\rm max}$) may be interpreted as the upper limit on the masses of the new nonstandard particles required for restoration of unitarity.
- Moreover, the strengths of these new interactions cannot be arbitrary as they need to satisfy the unitarity sum rules[9].
- Such estimates of the coupling strengths of the new particles can then be used to place lower bounds on the masses of BSM particles ($\Lambda_{\rm NP}^{\rm min}$) using the data from direct searches at the LHC.
- If $\Lambda_{\rm NP}^{\rm min} > \Lambda_{\rm UV}^{\rm max}$ then we may conclude that the NP scenario accommodating the wrong-sign possibility is ruled out.

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[6] Joglekar, Annals Phys. 83 (1974) 427
[7] Horejsi, World Scientific, 1994
[8] Bhattacharyya, Das, and Pal, Phys. Rev. D 87 (2013) 011702
[9] Gunion, Haber, and Wudka, Phys. Rev. D 43 (1991) 904–912

Unitarity Violation in $W_L^+ W_L^- \to Z_L Z_L$ Scattering

- To illustrate our bottom-up approach explicitly, we first note that in the limit $\kappa_W^h = -\kappa_Z^h = 1$ the $W_L^+ W_L^- \to Z_L Z_L$ (the subscript 'L' stands for longitudinal polarization) scattering amplitude will violate unitarity.

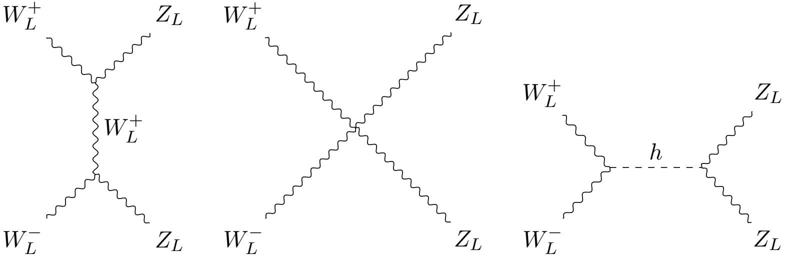

Figure: The Feynman diagrams for the $W_L W_L \to Z_L Z_L$ scattering process which are mediated by the 125 GeV neutral Higgs (h) and weak vector bosons.

- This is because the quadratic remnant energy growths from the gauge diagrams will no longer be canceled by the SM-Higgs mediated diagrams (see Fig. 1 for the Feynman diagrams).

Unitarity Violation in $W_L^+ W_L^- \to Z_L Z_L$ Scattering

- The resulting amplitude will be:

$$\mathcal{M}_{W_L W_L \to Z_L Z_L} \equiv 16\pi a_0 = \frac{g^2 E^2}{M_W^2}\left(1 - \kappa_W^h \kappa_Z^h\right) + \mathcal{O}(1) , \qquad \text{for} \quad E \gg M_W , \quad (2)$$

  where E is the CM energy and a_0 is the zeroth partial wave amplitude.

- Requiring $a_0 \leq 1$, we may conclude that unitarity will be violated for energies beyond

$$\Lambda_{\rm UV}^{\rm max} = \sqrt{\frac{4\pi v^2}{\left|1 - \kappa_W^h \kappa_Z^h\right|}} = \sqrt{2\pi}\, v \approx 620 \text{ GeV} , \quad (3)$$

  where in the final steps we set $\kappa_W^h = -\kappa_Z^h = 1$ and $v \approx 246$ GeV as the electroweak vacuum expectation value (VEV).

- Therefore, the effects of new BSM interactions must set in before $\Lambda_{\rm UV}^{\rm max}$.

Parameterising the New Physics

- Let us parametrize the set of new couplings that will, presumably, come to reinstate unitarity, as follows

$$\mathscr{L}_{\text{NP}} = \sum_{k=1}^{N_n} H_k \left(\kappa_W^{H_k} g M_W W^{\mu +} W_\mu^- + \frac{\kappa_Z^{H_k}}{2} \frac{g M_Z}{\cos\theta_w} Z^\mu Z_\mu - \kappa_f^{H_k} \frac{m_f}{v} \bar{f} f \right) + \left(\sum_{k=1}^{N_c} \delta_k \frac{g M_W}{\cos\theta_w} W_\mu^+ Z^\mu H_k^- + \sum_{k=1}^{N_d} \xi_k \frac{g M_W}{2} W_\mu^+ W^{\mu +} H_k^{--} + \text{h.c.} \right) \quad (4)$$

where g is the $SU(2)_L$ gauge coupling, θ_w is the weak mixing angle, M_W and M_Z are the W and Z-boson masses respectively, and m_f is the mass of the fermion, f. We've assumed a single coupling modifier for all fermions. The numbers N_n, N_c and N_d represent the number of nonstandard neutral, singly-charged and doubly-charged scalars respectively.

Unitarity Sum Rules

- From $WW \to WW$ and $WW \to ZZ$ scattering amplitudes we get the following sum rules:

$$1 - \left(\kappa_W^h\right)^2 - \sum_{k=1}^{N_n} \left(\kappa_W^{H_k}\right)^2 + \sum_{k=1}^{N_d} \xi_k^2 = 0\,, \tag{5a}$$

$$1 - \kappa_W^h \kappa_Z^h - \sum_{k=1}^{N_n} \kappa_W^{H_k} \kappa_Z^{H_k} + \sum_{k=1}^{N_c} \delta_k^2 = 0\,. \tag{5b}$$

- Similarly, from $\bar{f}f \to WW$ and $\bar{f}f \to ZZ$ amplitudes we find

$$1 - \kappa_f^h \kappa_W^h - \sum_{k=1}^{N_n} \kappa_f^{H_k} \kappa_W^{H_k} = 0\,, \tag{6a}$$

$$1 - \kappa_f^h \kappa_Z^h - \sum_{k=1}^{N_n} \kappa_f^{H_k} \kappa_Z^{H_k} = 0\,. \tag{6b}$$

Unitarity Sum Rules

- The direct search channels of interest are $pp \xrightarrow{VBF} H_1 \to VV$ and $pp \xrightarrow{ggF} H_1 \to VV$
- New scalars should be allowed by these direct search constraints to appear before $\Lambda_{\rm UV}^{\rm max}$.
- In the limit, $\kappa_W^h = -\kappa_Z^h = 1$, Eqn. (7) becomes

$$\sum_{k=1}^{N_n} \kappa_W^{H_k} \kappa_Z^{H_k} = 2 + \sum_{k=1}^{N_c} \delta_k^2 \,. \qquad (7)$$

  Here, we must try to reduce the magnitude of the product $\kappa_W^{H_k} \kappa_Z^{H_k}$ without compromising the unitarity sum rules. Thus, in Eqn. (7), having $\delta_k \approx 0$ would lead to the least stringent bounds from direct searches
- In what follows, we intend to verify that from such considerations, the lower limits from direct searches always lie *above* the upper limit set by unitarity. In this way we shall conclude that non-observation of new BSM resonances in direct searches at the LHC together with the constraints from unitarity can potentially rule out the wrong-sign scenario with $\kappa_W^h = -\kappa_Z^h = 1$.

One Tier of BSM Higgs

- To begin with, let us investigate whether it is possible to accommodate the wrong-sign possibility with just one tier of BSM scalars ($N_{n,c,d} = 1$). Working under the assumption $\delta_1 \approx 0$, the sum rules of Eqns. (5) and (6), in the limit $\kappa_W^h = \kappa_f^h = -\kappa_Z^h = 1$, become

$$\kappa_W^{H_1} \kappa_Z^{H_1} = 2\,, \tag{8a}$$

$$\left(\kappa_W^{H_1}\right)^2 = \xi_1^2\,, \tag{8b}$$

$$\kappa_W^{H_1} \kappa_f^{H_1} = 0\,, \tag{8c}$$

$$\kappa_Z^{H_1} \kappa_f^{H_1} = 2\,. \tag{8d}$$

- Quite clearly, the above relations cannot be satisfied simultaneously for finite values of $\kappa_Z^{H_1}$. As the next step, one may try to leverage the experimental uncertainties in κ_W^h and κ_f^h (denoted by ϵ_W and ϵ_f respectively) to accommodate the $\kappa_Z^h = -1$ possibility and obtain a finite value for $\kappa_Z^{H_1}$.
- Using $\kappa_W^h = 1 \pm \epsilon_W$, $\kappa_f^h = 1 \pm \epsilon_f$ and $\kappa_Z^h = -1$ in the sum rules of (5) and (6) we will obtain the minimum possible value of $\kappa_Z^{H_1}$ as follows

$$\kappa_Z^{H_1} \approx \frac{2}{\sqrt{(\epsilon_W + \epsilon_f)}}\,. \tag{9}$$

One Tier of BSM Higgs

- Current 2σ limits on ϵ_W and ϵ_f stand at 14% and 19% respectively[10]. Using these numbers, the most conservative lower limit on m_{H_1}, from $pp \xrightarrow{VBF} H_1 \to ZZ$ searches as shown in Fig. 2, is found to be around 2.5 TeV.

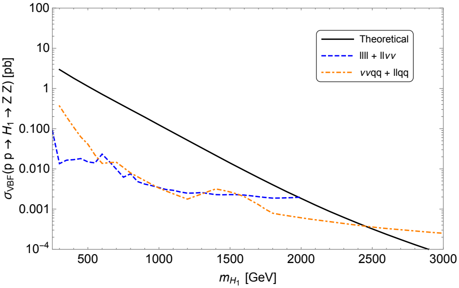

Figure: *The direct search bound on m_{H_1} arising from $pp \xrightarrow{VBF} H_1 \to ZZ$ for coupling strength given by (9). The blue and orange lines represent the experimental upper limits*[12]*. To draw the solid black curve (theoretical cross section using the coupling strength given by (9)) we used the FeynRules and the MadGraph packages.*

[10] CMS Collaboration, Tumasyan et al., Nature 607 (2022), no. 7917 60–68

[11] ATLAS Collaboration, ATL-PHYS-PUB-2023-007 (2023)

[12] ATLAS Collaboration, ATL-PHYS-PUB-2023-007 (2023)

One Tier of BSM Higgs

- This limit is much above the unitarity violation scale given by

$$\Lambda_{\rm UV}^{\rm max} = \sqrt{\frac{4\pi v^2}{\left|1-\kappa_W^h\kappa_Z^h\right|}} = \sqrt{\frac{4\pi v^2}{|2-\epsilon_W|}} \approx 650 \text{ GeV}\,. \tag{10}$$

- Thus, taking the experimental uncertainties in $\kappa_{W,f}^h$ is not sufficient to allow $\kappa_Z^h = -1$.

Two Tiers of Neutral Higgs

- As a final attempt, we consider the possibility of having WSL with multiple tiers of BSM scalars.
- We illustrate this scenario by having two tiers of neutral BSM scalars (H_1 and H_2). The intent behind this strategy is to allot just enough coupling strengths to the lighter BSM scalar (say H_1) so that it can be allowed before $\Lambda_1^{\rm max} \approx 620$ GeV from direct searches. After this, we hope that the assigned values of $\kappa_X^{H_1}$ will raise the second stage unitarity violation scale, $\Lambda_2^{\rm max}$, sufficiently so that H_2 can be comfortably accommodated within $\Lambda_2^{\rm max}$ without being in conflict with the direct search bounds.
- The unitarity sum rules are as follows,

$$\kappa_W^{H_1}\kappa_Z^{H_1} + \kappa_W^{H_2}\kappa_Z^{H_2} = 2\,, \tag{11a}$$

$$\left(\kappa_W^{H_1}\right)^2 + \left(\kappa_W^{H_2}\right)^2 = \xi_1^2\,, \tag{11b}$$

$$\kappa_W^{H_1}\kappa_f^{H_1} + \kappa_W^{H_2}\kappa_f^{H_2} = 0\,, \tag{11c}$$

$$\kappa_Z^{H_1}\kappa_f^{H_1} + \kappa_Z^{H_2}\kappa_f^{H_2} = 2\,. \tag{11d}$$

Two Tiers of Neutral Higgs

Our analysis can be summed up in a few steps as follows,

- (a) Scan over $\kappa_X^{H_1}$ within the ranges

$$\kappa_{W,Z,f}^{H_1} \in [-1, 1] \,, \tag{12}$$

and check if H_1 can be allowed by the direct searches constraints at $m_{H_1} = 620$ GeV. We have considered the search channels $pp \xrightarrow{VBF} H_1 \to VV$ and $pp \xrightarrow{ggF} H_1 \to VV$ for this purpose.

- (b) Having obtained a set of $\kappa_X^{H_1}$ for which H_1 is allowed at $m_{H_1} = 620$ GeV, we can find the second stage unitarity violation scales for the different scattering amplitudes as follows:

$$\Lambda_{WW\to ZZ}^{\max} = \sqrt{\frac{4\pi v^2}{\left|2 - \kappa_W^{H_1}\kappa_Z^{H_1}\right|}} \,, \tag{13a}$$

$$\Lambda_{WW\to WW}^{\max} = \sqrt{\frac{8\pi v^2}{\left|\xi_1^2 - (\kappa_W^{H_1})^2\right|}} \,, \tag{13b}$$

where ξ_1 can be solved using the unitarity sum rules of Eqns. (5) and (6). The lowest of the above is interpreted as $\Lambda_2^{\max}$ before which the effects of H_2 must set in.

Two Tiers of Neutral Scalars

- The set of $\kappa_X^{H_1}$ also allows us to solve for ξ_1 and $\kappa_X^{H_2}$, required to complete the unitarity sum rules of Eqns. (5) and (6). We then use this set of $\kappa_X^{H_2}$ to scan over m_{H_2} to find the lower bounds on m_{H_2} from $pp \xrightarrow{VBF} H_2 \to VV$ and $pp \xrightarrow{ggF} H_2 \to VV$ direct searches.
- As we can see from Fig. 3, $(m_{H_2})_{\rm min}$ always lies above $\Lambda_2^{\rm max}$ implying that the possibility of accommodating $\kappa_W^h = -\kappa_Z^h = 1$ with two tiers of neutral nonstandard scalars is also ruled out from the combined constraints of unitarity and direct searches.
- The reason behind this can be understood from the fact that rather small values of $\kappa_X^{H_1}$ can be allowed (check the range on the horizontal axis in Fig. 3) in order to keep $m_{H_1} < 620$ GeV safe from the direct searches. Consequently, the unitarity violation scale of (3) hardly gets relaxed for $\Lambda_2^{\rm max}$ as may be seen in the red region in Fig. 3. Therefore, for this strategy to work, one may need an unusually large number of nonstandard scalars.

Two Tiers of Neutral Higgs

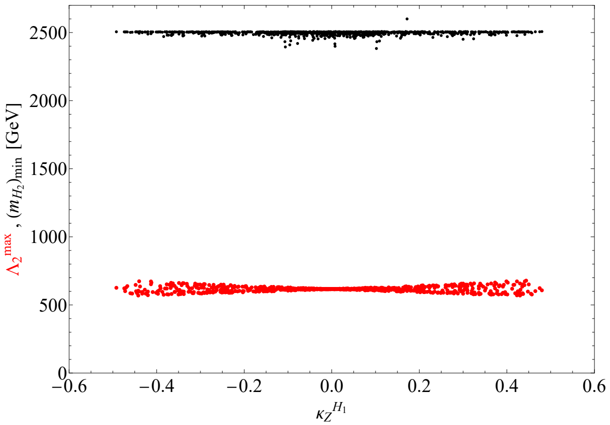

Figure: *The unitarity violation scale ($\Lambda_2^{\max}$) for the second tier Higgs and the direct search limits on the second tier Higgs mass, $(m_{H_2})_{\min}$, plotted against $\kappa_Z^{H_1}$ as red and black regions respectively. We have used the ATLAS bounds to extract the experimental limits.*

Conclusion

- We have discussed a complementary method to probe the sign of the hZZ coupling, which, unlike the existing studies, is immune to the concerns regarding UV completion.
- Our approach is based on the realization that the wrong-sign hZZ coupling will bring in unitarity violation which will necessitate existence of new particles with masses in the sub-TeV regime.
- Moreover, the coupling strengths of these new particles can be inferred from the unitarity sum rules. As shown, these new particles should be well within the reach of the LHC and, if they are not observed in the direct searches, the wrong-sign hZZ coupling will be severely constrained.
- We have been able to show that even with two tiers of nonstandard neutral scalars brought in to restore unitarity, the wrong-sign hZZ coupling cannot be accommodated.
- Most importantly, our current analysis exemplifies the fact that the so called *null* results in the direct searches can be translated into nontrivial information regarding the couplings of the SM-like Higgs boson thereby providing us with important insights about mechanism of electroweak symmetry breaking.

Thank you