Unitarity Bound In Composite Two Higgs Doublet Models

Emine Yildirim
University of Southampton
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Work (in progress) in Collaboration with:
Stefania De Curtis, Stefano Moretti, and Kei Yagyu

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Outline

The Idea of Composite Two Higgs Doublet Model

$\Rightarrow$ Higgs boson arises as a pseudo- Nambu-Goldstone boson (pNGB) from a strong dynamics.

$\Rightarrow$ The Composite 2 Higgs Doublet Model (C2HDM) based on $SO(6)/SO(4) \times SO(2)$ coset which generates 8 pNGBs.

$\Rightarrow$ According to CCWZ prescription, effective kinetic Lagrangian is given by:

$\mathcal{L}_{kin} = \frac{f^2}{4}(d_\alpha^{\hat{a}})_\mu (d_\alpha^{\hat{a}})^\mu \quad (d_\alpha^{\hat{a}})_\mu = i \ tr(U^\dagger D_\mu U T_\alpha^{\hat{a}})$

where U is NG boson matrix and $T_\alpha^{\hat{a}}$ with $\alpha = 1, 2$ and $\hat{a} = 1, \ldots, 4$ are the eight broken generators of $SO(6)/SO(4) \times SO(2)$.

$\Rightarrow$ Modified Higgs to gauge boson coupling from SM prediction:

$$\frac{\lambda_{hW^+W^-}^{C2HDM}}{\lambda_{hW^+W^-}^{SM}} = \sqrt{1-\xi}$$

where $\xi = \frac{v^2}{f^2}$ with $v \simeq 246 GeV$.

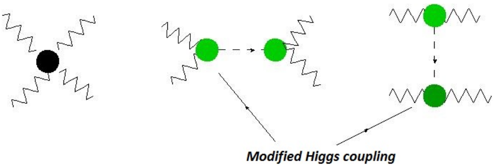
Perturbative Unitarity In $W_L W_L$ Scattering

$\Rightarrow$ $A(V_L V_L \to V_L V_L)$ grows with energy due to modified $hV_L V_L$, unitarity is lost in the C2HDM.

$\Rightarrow$ S-wave amplitude a_0 for $W_L W_L$ scattering:

$$a_0(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{s}{32\pi v^2}\xi - \frac{1}{8\pi v^2}(m_h^2 \cos^2\theta + m_H^2 \sin^2\theta)(1-\xi)$$

Where, $\theta \to$ angle between CP-even scalar states.



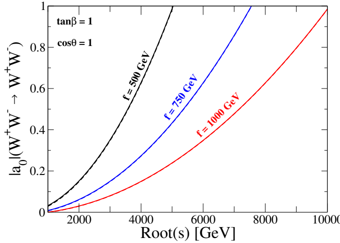


FIG. (right hand side): S-wave amplitude for the $W^+W^- \to W^+W^-$ process as a function of $\sqrt{s}$. The solid (dashed) curve is the result with (without) $\mathcal{O}(\xi s^0)$ term.

Perturbative Unitarity In $(H^+H^- \to H^+H^-)$ Scattering

$$a_0(H^+H^- \to H^+H^-) = \left[\boxed{\frac{s}{32\pi v^2}\xi - \frac{2}{3}\frac{m_{H^\pm}^2}{v^2}\xi} + \boxed{\lambda_{H^+H^-H^+H^-}}\right]$$

From Potential Term

Emerges From Kinetic Term

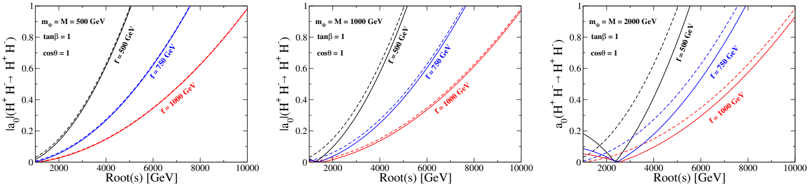


Figure : S-wave amplitude for the $H^+H^- \to H^+H^-$ process as a function of $\sqrt{s}$. The solid (dashed) curve is the result with (without) $\mathcal{O}(\xi s^0)$ term.

$$\lambda_{H^+H^-H^+H^-} = [\frac{2}{v^2}4M^2\cot^2 2\beta - m_h^2(c_\theta + 2\cot 2\beta\sin\theta)^2) - m_H^2(s_\theta - 2\cot 2\beta c_\theta)^2](1 - \frac{\xi}{3})$$
$$+ \frac{4c_{2\beta}}{3v^2 s_{2\beta}^2}[m_h^2(c_\theta s_{2\beta} + 2s_\theta c_{2\beta})s_\theta + m_H^2(2c_\theta c_{2\beta} - s_\theta s_{2\beta})c_\theta]\xi.$$

Unitarity Constraints by Combined All The Channels

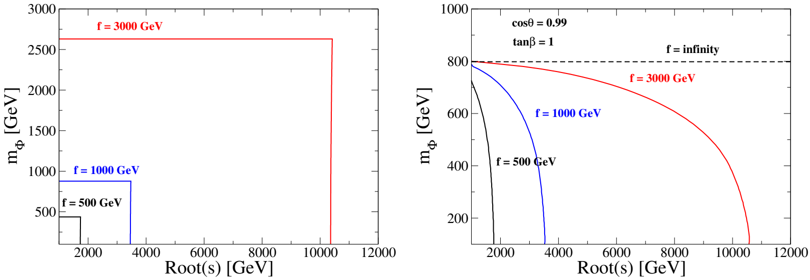


Figure : Bound from unitarity and vacuum stability in the case of $\tan\beta = 1$. The region inside the curves is allowed. We take $\cos\theta = 1$ (left) and 0.99 (right). In both panels, we scan the value of M^2.

Where $m_\phi = m_A = m_H = m_{H^\pm}$ $m_h = 125$ GeV SM-like Higgs.

Conclusion and Outlook

- Contribution from kinetic term gives important difference between E2HDM and C2HDM.
- Because of s dependence in the amplitude, unitarity is violated at a certain energy scale.
- Smaller value of compositeness scale f gives stronger upper bound on $\sqrt{s}$.

Future Work

- We will discuss strong EWSB for C2HDM via Coleman-Weinberg (CW) mechanism. In this project we have assumed we have a CW potential whose structure is the same as the E2HDM, but each of the parameters in the potential comes from a strong sector.
- We tackle the case of the Composite 2HDM, which affords one with a more varied Higgs phenomenology at the LHC as well as a Dark Matter (DM) candidate when one Higgs doublet is inert (no VEV).

Thank You

Backup Slides (I)

$$U = \exp(i\frac{\Pi}{f}) \quad \Pi \equiv \sqrt{2} h_\alpha^{\hat{a}} T_\alpha^{\hat{a}} = -i \begin{pmatrix} O_{4\times 4} & h_1^{\hat{a}} & h_2^{\hat{a}} \\ -h_1^{\hat{a}} & 0 & 0 \\ -h_2^{\hat{a}} & 0 & 0 \end{pmatrix}.$$

$$\begin{aligned}
(d_\alpha^{\hat{1}})_\mu = & -\frac{\sqrt{2}}{f}\partial_\mu h_\alpha^1 - \frac{g}{2f}[(h_\alpha^4 - i h_\alpha^3) W_\mu^+ + (h_\alpha^4 + i h_\alpha^3) W_\mu^-] \\
& - \frac{\sqrt{2} g_Z}{f}\left(\frac{1}{2} - s_W^2\right) h_\alpha^2 Z_\mu - \frac{\sqrt{2} e}{f} h_\alpha^2 A_\mu + \mathcal{O}(1/f^3), \\
(d_\alpha^{\hat{2}})_\mu = & -\frac{\sqrt{2}}{f}\partial_\mu h_\alpha^2 - i\frac{g}{2f}[(h_\alpha^4 - i h_\alpha^3) W_\mu^+ - (h_\alpha^4 + i h_\alpha^3) W_\mu^-] \\
& + \frac{\sqrt{2} g_Z}{f}\left(\frac{1}{2} - s_W^2\right) h_\alpha^1 Z_\mu + \frac{\sqrt{2} e}{f} h_\alpha^1 A_\mu + \mathcal{O}(1/f^3),
\end{aligned}$$

Backup Slides (II) The Analytic Formula Of All The Independent Eigenvalues

$$16\pi a_1^{\pm} = -\frac{3}{2}\frac{\xi s}{\upsilon_{SM}} - \frac{1}{2}[3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2 + (\frac{\xi s}{\upsilon_{SM}} + 4\lambda_3 + 2\lambda_4)^2}],$$

$$16\pi a_2^{\pm} = \pm\frac{1}{2}\frac{\xi s}{\upsilon_{SM}} - \frac{1}{2}[(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2 + (\frac{\xi s}{\upsilon_{SM}} \pm 2\lambda_4)^2}],$$

$$16\pi a_3^{\pm} = \pm\frac{1}{2}\frac{\xi s}{\upsilon_{SM}} - \frac{1}{2}[(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2 + (\frac{\xi s}{\upsilon_{SM}} \pm 2\lambda_5)^2}],$$

$$16\pi a_4^{\pm} = -\frac{\xi s}{\upsilon_{SM}} - (\lambda_3 + 2\lambda_4 \pm 3\lambda_5), \quad 16\pi a_5^{\pm} = \pm\frac{\xi s}{\upsilon_{SM}} - (\lambda_3 \pm \lambda_5),$$

$$16\pi a_6^{\pm} = \pm\frac{\xi s}{\upsilon_{SM}} - (\lambda_3 \mp \lambda_5),$$

$$16\pi a_7^{\pm} = \pm\frac{\xi s}{\upsilon_{SM}} - (\lambda_3 \mp \lambda_4),$$

Backup Slide (III) Simplified Expression for The S- Wave Amplitude

$$\mathcal{M}_c(AB \to CD) = -(g_{AB,CD}P_{AB} + g_{CD,AB}P_{CD})$$
$$+ g_{AC,BD}P_{AC} + g_{BD,AC}P_{BD} + g_{AD,BC}P_{AD} + g_{BC,AD}P_{BC} + \lambda_{ABCD},$$
$$\mathcal{M}_s(AB \to X \to CD) = -\frac{1}{s - m_X^2}(g_{AB,X}P_{AB} - g_{XA,B}P_{XA} - g_{BX,A}P_{BX} - \lambda_{ABX})$$
$$\times (g_{CD,X}P_{CD} - g_{XC,D}P_{XC} - g_{DX,C}P_{DX} - \lambda_{CDX}),$$
$$\mathcal{M}_t(AB \to X \to CD) = -\frac{1}{t - m_X^2}(-g_{AC,X}P_{AC} - g_{XA,C}P_{XA} + g_{CX,A}P_{CX} - \lambda_{ACX})$$
$$\times (-g_{BD,X}P_{BD} + g_{XB,D}P_{XB} - g_{DX,B}P_{DX} - \lambda_{BDX}),$$
$$\mathcal{M}_u(AB \to X \to CD) = -\frac{1}{u - m_X^2}(-g_{AD,X}P_{AD} - g_{XA,D}P_{XA} + g_{DX,A}P_{DX} - \lambda_{ADX}$$
$$\times (-g_{BC,X}P_{BC} + g_{XB,C}P_{XB} - g_{CX,B}P_{CX} - \lambda_{BCX},$$
$$g_{ab,cd} \equiv \frac{\partial^4 \mathcal{L}_{kin}}{\partial(\partial_\mu a)\partial(\partial_\mu b)\partial(c)\partial(d)}, \quad g_{ab,c} \equiv \frac{\partial^3 \mathcal{L}_{kin}}{\partial(\partial_\mu a)\partial(\partial_\mu b)\partial(c)},$$
$$\lambda_{abcd} \equiv -\frac{\partial^4 V}{\partial a \partial b \partial c \partial d} \quad \lambda_{abc} \equiv -\frac{\partial^4 V}{\partial a \partial b \partial c}$$