Theory and Phenomenology of Composite 2-Higgs Doublet Model

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Outline

1. Motivation
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2. Effective Lagrangian In C2HDM
3. Perturbative Unitarity In C2HDM
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The idea of composite two Higgs doublet model

- Higgs boson emerges as a pseudo-Nambu-Goldstone Boson (pNGB) from a new strong interaction at the compositeness scale f.
- The Composite 2 Higgs Doublet Model (C2HDM) based on $SO(6)/SO(4) \times SO(2)$ coset developing 8 pNGBs, which are identified with the (composite) *two Higgs doublet fields*.
- Symmetry breaking occurs in two steps
  1. Spontaneously global symmetry breaking $SO(6) \xrightarrow{f} SO(4) \times SO(2)$ at scale f.
  2. Electroweak symmetry breaking is triggered by coupling of the SM particles to the composite sector via the Coleman-Weinberg (CW) potential at loop levels.
- Minimal composite Higgs model (with a single Higgs doublet) can explain hierarchy problem by its pNGB nature. It's remarkable motivation to study **C2HDM** for describing presence of extra Higgs particles as pNGBs and explain their mass and phenomenological differences.

⇒ The $SO(6)$ invariant effective kinetic Lagrangian, can be constructed by the analogue of the construction in non-linear sigma models developed by Callan-Coleman-Wess-Zumino (CCWZ) as

$$\mathcal{L}_{kin} = \frac{f^2}{4}(d^{\hat{a}}_\alpha)_\mu (d^{\hat{a}}_\alpha)^\mu = \frac{f^2}{4}\mathrm{tr}[D_\mu\Sigma\,(D^\mu\Sigma)^T]$$

$$(d^{\hat{a}}_\alpha)_\mu = i\ tr(U^\dagger D_\mu U T^{\hat{a}}_\alpha), \quad \text{where} \quad \alpha = 1,2.\ \hat{a} = 1,4.$$

where Σ $SO(6)$ adjoint representation **15**-plet under $SO(4)\times SO(2)$

$$U = \exp(i\tfrac{\Pi}{f}),\ \Pi \equiv \sqrt{2} h^{\hat{a}}_\alpha T^{\hat{a}}_\alpha = -i\begin{pmatrix} O_{4\times4} & h^{\hat{a}}_1 & h^{\hat{a}}_2 \\ -h^{\hat{a}}_1 & 0 & 0 \\ -h^{\hat{a}}_2 & 0 & 0 \end{pmatrix},\ \Phi_\alpha \equiv \tfrac{1}{\sqrt{2}}\begin{pmatrix} h^2_\alpha + ih^1_\alpha \\ h^4_\alpha - ih^3_\alpha \end{pmatrix} \equiv \begin{pmatrix} \phi^+_\alpha \\ \phi^0_\alpha \end{pmatrix}$$

$$i(d^{\hat{1}}_\alpha)_\mu + (d^{\hat{2}}_\alpha)_\mu = -\frac{2}{f}\left[\partial_\mu\phi^+_\alpha - i\frac{g}{\sqrt{2}}\phi^0_\alpha W^+_\mu - ig_Z\left(\frac{1}{2} - s^2_W\right)\phi^+_\alpha\right] + \mathcal{O}(1/f^3),$$

Effective Yukawa Lagrangian in C2HDM

$$\mathcal{L}_Y = f\Big[\bar{Q}_L^u(a_u\Sigma - b_u\Sigma^2)U_R + \bar{Q}_L^d(a_d\Sigma - b_d\Sigma^2)D_R$$
$$+\bar{L}_L(a_e\Sigma - b_e\Sigma^2)E_R\Big] + \text{h.c.}$$

where Σ $SO(6)$ adjoint representation **15**-plet under $SO(4)\times SO(2)$.

$$\mathcal{L}_Y = \sum_{f=u,d,e}\frac{m_f}{v_{\rm SM}}\bar{f}\left(\bar{X}_f^h h + \bar{X}_f^H H - 2iI_f\bar{X}_f^A\gamma_5 A\right)f$$
$$+\frac{\sqrt{2}}{v_{\rm SM}}\bar{u}V_{ud}(m_d\bar{X}_d^A P_R - m_u\bar{X}_u^A P_L)d\,H^+ + \frac{\sqrt{2}}{v_{\rm SM}}\bar{\nu}m_e\bar{X}_e P_R\,e\,H^+ + \text{h.c.}$$

	$\bar{X}_u^h$	$\bar{X}_d^h$	$\bar{X}_e^h$	$\bar{X}_u^H$	$\bar{X}_d^H$	$\bar{X}_e^H$	$\bar{X}_u^A$	$\bar{X}_d^A$	$\bar{X}_e^A$
Type-I	ζ_h	ζ_h	ζ_H	ζ_H	ζ_H	ζ_A	ζ_A	ζ_A	ζ_A
Type-II	ζ_h	ξ_h	ξ_h	ζ_H	ξ_H	ξ_H	ζ_A	ξ_A	ξ_A
Type-X	ζ_h	ζ_h	ξ_h	ζ_H	ζ_H	ξ_H	ζ_A	ζ_A	ξ_A
Type-Y	ζ_h	ξ_h	ζ_h	ζ_H	ξ_H	ζ_H	ζ_A	ξ_A	ζ_A

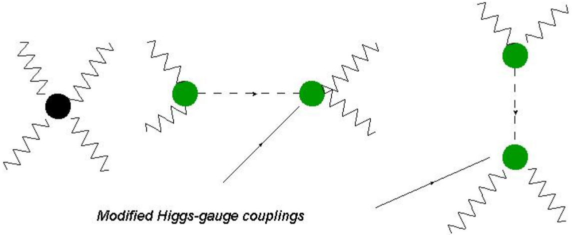
Perturbative Unitarity in C2HDM

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

$$\mathcal{M}(W_L^+ W_L^- \to W_L^+ W_L^-)_{\text{Higgs}}$$
$$= -\frac{s}{2v_{\text{SM}}^2}(1 - c_\phi)(1 - \xi) - \frac{2}{v_{\text{SM}}^2}(1 - \xi)(m_h^2 c_\theta^2 + m_H^2 s_\theta^2) + \mathcal{O}(s^{-1}),$$

where ϕ is the scattering angle and $\xi = \frac{\upsilon^2}{f^2}$ with $\upsilon \simeq 246 GeV$.

$$W_L W_L \to W_L W_L$$



Modified Higgs-gauge couplings

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

$$\mathcal{M}(H^+H^- \to H^+H^-) = \left[\boxed{\frac{s}{2v_{SM}^2}\xi(1+c_\phi)} - \boxed{\frac{m_{H^\pm}^2}{v_{SM}^2}\xi(\frac{2}{3}+4c_\phi)} + \boxed{\lambda_{H^+H^-H^+H^-}} \right] + \mathcal{O}(s^{-1}).$$

Kinetic Term

Kinetic and Potential Term

Emerges From Potential Term

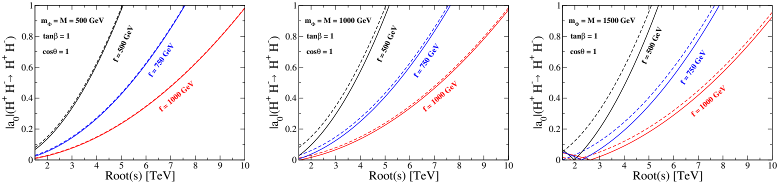


Figure : S-wave amplitude for the $H^+H^- \to H^+H^-$ process as a function of $\sqrt{s}$ in the case of $\cos\theta = 1$, $\tan\beta = 1$ and $f = 500$ (black), 750 (blue) and 1000 GeV (red). The solid (dashed) curves are the results with (without) $\mathcal{O}(\xi s^0)$ term. The left, center and right panels show the results for $m_\Phi(m_A = m_H = m_{H^\pm}) = M = 500$, 1000 and 1500 GeV, respectively.

- $\mathcal{O}(\xi s^0)$ contributions are not so important as long as we consider the case $m_\phi \leq 1$ TeV and $\sqrt{s} \geq m_\phi$.

Perturbative Unitarity in $(G^+G^- \to G^+G^-)$ process with and without $\mathcal{O}(1/s)$ term

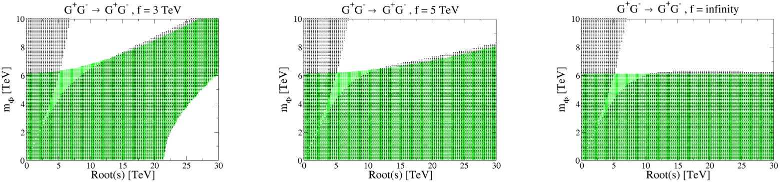


Figure : Allowed regions from perturbative unitarity in the plane $(\sqrt{s}, m_H)$ from $G^+G^- \to G^+G^-$ scattering amplitudes within the C2HDM. We take $\cos\theta = 0.99$, $\tan\beta = 1$ and $m_H = m_A = m_{H^\pm} = M$. The grey regions are obtained by using the exact formulae (with $\mathcal{O}(1/s)$ terms), the green ones by neglecting $\mathcal{O}(1/s)$ terms. The left, center and right panels show the cases with $f = 3000$ GeV, 5000 GeV and infinity (corresponding to the E2HDM).

- If we focus on the region of $\sqrt{s} \geq 1\,TeV$ and $m_\phi \leq 1\,TeV$, $\mathcal{O}(s^0\xi)$ and $\mathcal{O}(s^{-1})$ terms can be neglected safely.

Unitarity Constraint on the parameter space of the C2HDM

Unitarity Bound In All $2 \to 2$ Scalar Scattering Channels

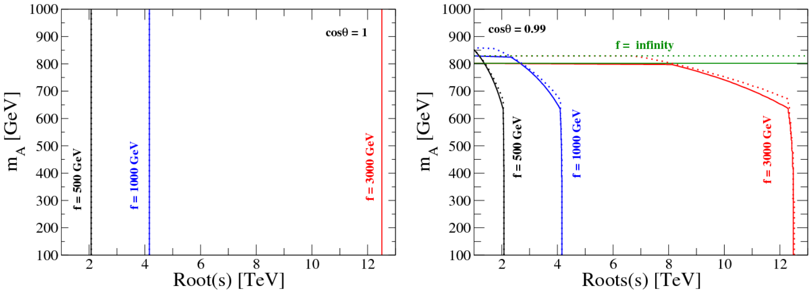


Figure : Constraint on the parameter space of the C2HDM from the unitarity and the vacuum stability in the case of $\tan\beta = 1$ and $m_{H^\pm} = m_A$ for several fixed values of f. The left and right panels show the case with $\cos\theta = 1$ and 0.99, respectively. The lower left region from each curve is allowed. We take the value of m_H to be equal to m_A for the solid curves, while we scan it within the region of $m_A \pm 500$ GeV for the

Phenomenology of C2HDM

Decays of Extra Higgs Boson H

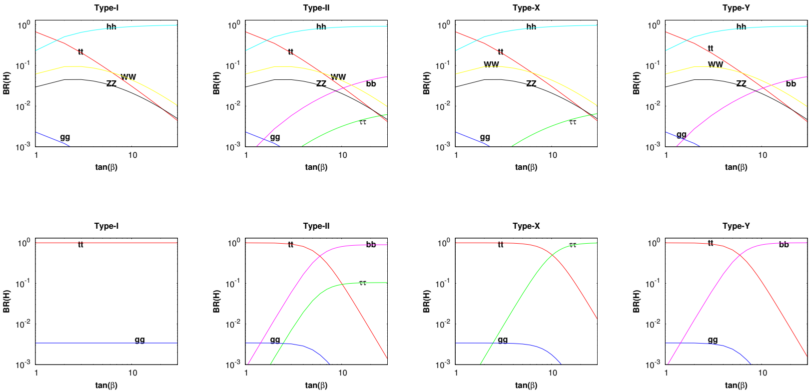


Figure : Branching ratios of H as a function of $\tan\beta$ with $m_\Phi (= m_H = m_A = m_{H^\pm}) = M = 500$ GeV.The upper panels show the results in the E2HDM ($\xi = 0$ and $s_\theta = -0.2$), while the lower ones show the results in the C2HDM ($\xi = 0.04$ and $\theta = 0$)

Mass Dependence of the Branching ratios for Extra Higgs Boson H

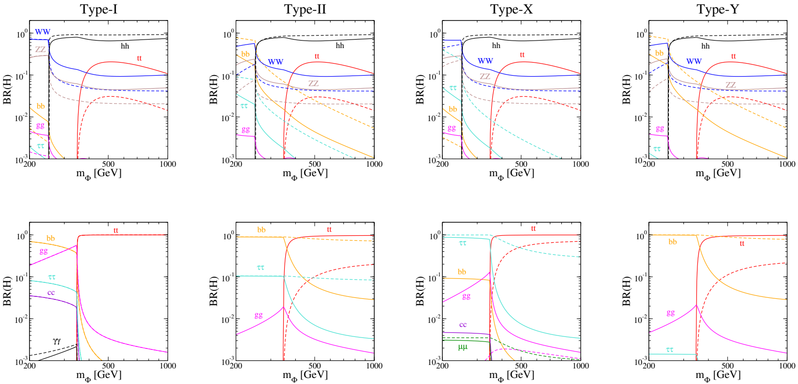


Figure : Branching ratios of H as a function of $m_\Phi (= m_H = m_A = m_{H^\pm})$ with $\tan\beta = 3(10)$ for solid (dashed) curves, $M = m_\Phi$ and $\Delta\kappa_V = -2\%$. The upper panels show the results in the E2HDM ($\xi = 0$ and $s_\theta = -0.2$), while the lower ones show the results in the C2HDM ($\xi = 0.04$ and $\theta = 0$)

$\sigma(gg \to H/A)$ in the C2HDM and E2HDM

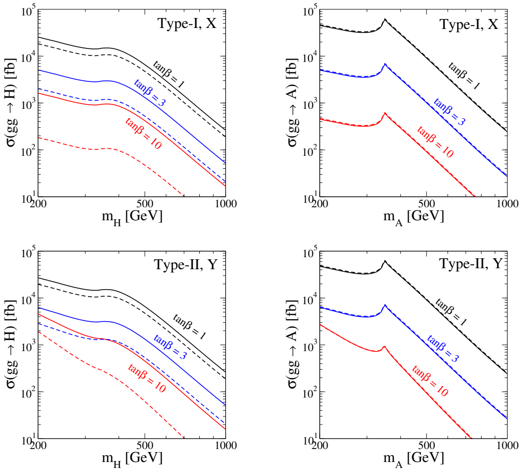


Figure : Gluon fusion production cross section as a function of the mass of the neutral Higgs boson at $\sqrt{s} = 13$ TeV. We take $\tan\beta = 1$ (black), 3 (blue) and 10 (red). The solid (dashed) curves show the results in the E2HDM with $s_\theta = -0.2$ and $\xi = 0$ (C2HDM with $s_\theta = 0$ and $\xi = 0.04$).

Conclusion

- We have explicitly shown that the amplitude grows with $\sqrt{s}$ in scattering processes, so that unitarity is broken at a certain energy scale depending on the scale f.
- We have discovered significant differences of the allowed parameter space in E2HDM and C2HDM from unitarity.
- The differences between types of Yukawas affect the BRs and production cross section at the LHC.
- We can distinguish decays and productions of the extra Higgs bosons in the C2HDM from that of E2HDM.

Thank You!

Backup Slides

the SM quarks and leptons can be embedded into into the **6**-plet representation Ψ_X as follows:

$$
\begin{aligned}
(\Psi_{2/3})_L &\equiv Q_L^u = (-id_L, -d_L, -iu_L, u_L, 0, 0)^T, \\
(\Psi_{-1/3})_L &\equiv Q_L^d = (-iu_L, u_L, id_L, d_L, 0, 0)^T, \\
(\Psi_{2/3})_R &\equiv U_R = (0, 0, 0, 0, 0, u_R)^T, \\
(\Psi_{-1/3})_R &\equiv D_R = (0, 0, 0, 0, 0, d_R)^T, \\
(\Psi_{-1})_L &\equiv L_L = (-i\nu_L, \nu_L, ie_L, e_L, 0, 0)^T, \\
(\Psi_{-1})_R &\equiv E_R = (0, 0, 0, 0, 0, e_R)^T.
\end{aligned}
$$

$$\Sigma = U \Sigma_0 U^T,$$

where Σ_0 is the $SO(4) \times SO(2)$ invariant VEV parameterized as

$$\Sigma_0 = \begin{pmatrix} 0_{4\times 4} & 0_{4\times 2} \\ 0_{2\times 4} & i\sigma_2 \end{pmatrix}.$$

Now, the field Σ is transformed linearly under $SO(6)$, i.e., $\Sigma \to g \Sigma g^T$.