Phenomenology of Composite 2-Higgs Doublet Models

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Outline

1. Motivation
   - Generalities on Composite two Higgs Doublet Models (C2HDMs)
   - Deviations of the Higgs boson couplings in a C2HDM
2. Perturbative unitarity and vacuum stability constraints of a C2HDM
3. Phenomenology @ the LHC of C2HDMs and comparison with Elementary 2HDM (E2HDM) predictions
   - Constraints from collider experiments for a C2HDM
   - Decays of the extra-Higgs bosons
   - Production of the extra-Higgs bosons at the LHC
4. Phenomenology @ future e^+e^- colliders
5. Conclusion

Georgi-Kaplan '84

- Higgs boson emerges as a pseudo-Nambu-Goldstone Boson (pNGB) from a new strong dynamics at the compositeness scale f without problem with naturalness
- C2HDMs 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

The model - 2 Higgs Doublets as pNGBs

Analogue of the construction in non-linear sigma models developed by Callan-Coleman-Wess-Zumino (CCWZ)

The kinetic Lagrangian invariant under the SO(6) is:

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

are the 8 broken SO(6) generators

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

GB matrix

covariant derivative: $D_{\mu} = \partial_{\mu} - i g T^a_L W^a_{\mu} - i g' Y B_{\mu}$, $\boxed{h^4_{\alpha} = \tilde{h}_{\alpha} = h_{\alpha} + \upsilon_{\alpha}}$

$$\boxed{\upsilon^2 \equiv \upsilon_1^2 + \upsilon_2^2},\ m_w^2 = \frac{g^2}{4} \boxed{f^2 \sin^2 \frac{\upsilon}{f}},\ f > \upsilon_{SM},\ \xi = \frac{v_{SM}^2}{f^2}, \tan\beta = \frac{v_2}{v_1}$$

the gauge boson mass

υ^2_{SM}

Five physical Higgs bosons: $h, H, A, H^{\pm}$

Higgs potential in C2HDM

* The Higgs potential generated at loop level studied by J.Mrazek et al. 1105.5403 in the $SO(6)/SO(4) \times SO(2)$ model for several reps. of fermion fields

To study a phenomenology of a C2HDM in a rather model independent way, we consider the most general CP − conserving E2HDM form for the potential

7 free parameters in total:

$$m_H, m_A, m_{H^\pm}, \sin\theta, \tan\beta, M, \xi$$

$\theta \to$ mixing in CP-even neutral sectors

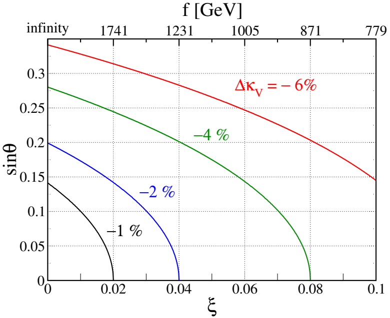
$$\text{Soft symmetry breaking scale} : M^2 = \frac{m_3^2}{s_\beta c_\beta}$$

$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 +$$
$$\frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}]$$

$\Rightarrow$ Extract the mass spectrum and express the λ_i parameters in terms of the masses of the physical Higgs bosons

Deviations of the Higgs boson couplings in the C2HDM

- Even without introducing fermions, the pattern of deviations from the SM-like properties can be different between C2HDMs and E2HDMs
- Introduce a scaling factor $\kappa_X = g_{hXX}^{NP}/g_{hXX}^{SM}$ $\Delta\kappa_X = \kappa_X - 1$
- In the C2HDM, $\kappa_V = (1-\xi/2)c_\theta$, $V = W, Z$. Limit $\xi \to 0$ E2HDM, while $\kappa_V \to 1$ SM limit
- In C2HDMs, non zero value of ξ and θ gives $\kappa_x \neq 1$, contrary to E2HDMs where only $\theta \neq 0$ gives $\kappa_x \neq 1$



- Even in the case of no-mixing between h and H, a non-zero deviation in hVV coupling is present in a C2HDM

Perturbative unitarity and vacuum stability constraints of the C2HDM

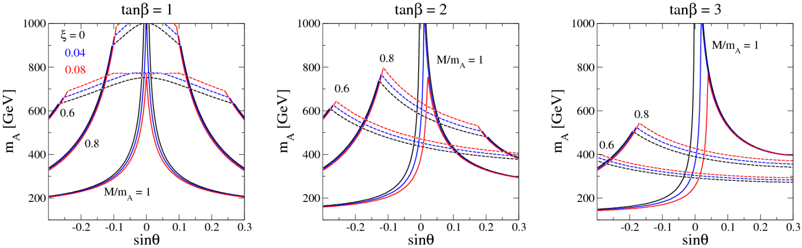


Figure : C2HDM bounds are for $\sqrt{s}$=1000 GeV and f =1250(850) GeV corresponding to ξ=0.04(0.08), E2HDM corresponds to $f \to \infty$ $(\xi = 0)$. $m_\phi = m_{H^\pm} = m_A = m_H$ and $M/m_A = 1, 0.8, 0.6$

below solid (dashed) lines : allowed by vacuum stability (unitarity)

$$\textit{for}\ m_\phi = 500\ GeV,\ \ M = 0.8 m_A, \tan\beta = 1, 2$$
$$-0.2 < \sin\theta < 0.2\ \textit{is allowed}$$
larger $\tan\beta$ *values require lower* m_ϕ

Effective Yukawa Lagrangian for C2HDMs

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

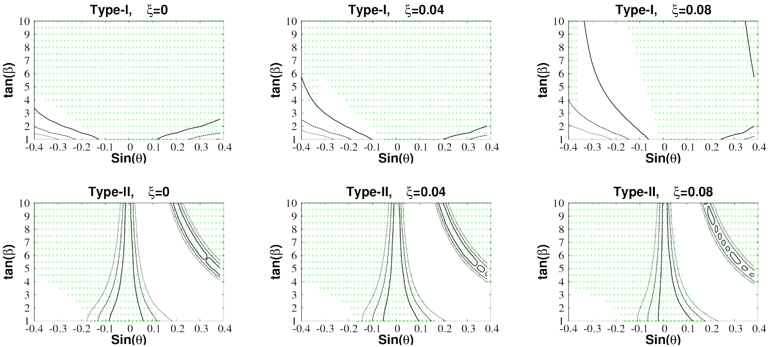
where Σ $SO(6)$ adjoint representation **15**-plet under $SO(4)\times SO(2)$

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

	$\bar{X}_u^h$	$\bar{X}_d^h$	$\bar{X}_e^h$	$\bar{X}_u^H$	$\bar{X}_d^H$	$\bar{X}_e^H$	$\bar{X}_u^A$	$\bar{X}_d^A$	$\bar{X}_e^A$
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

Present collider bounds for the C2HDM Type-I and II

$m_H = m_{H^+} = m_A = 500$ GeV $M = 0.8 m_A$ $m_h = 125$ GeV



- Green shaded region 95% CL allowed by LEP, Tevatron and LHC data by using HiggsBounds package
- The solid, dashed and dotted lines corresponds to $\Delta\chi^2$-contours @ the 68%, 95% and 99% CL respectively by using HiggsSignal package
- Type-I reveals a better compliance with the LHC data
- Type-II disfavoured for $\sin\theta > 0.2$
- ξ dependence is only marginally evident for Type-I

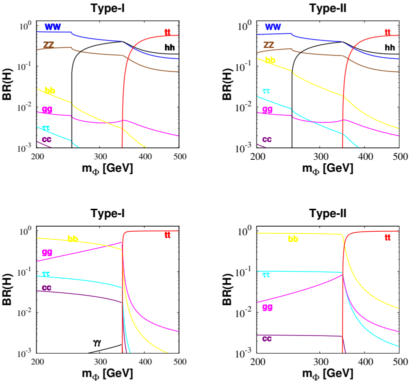


Figure : $m_h = 125$ GeV, $m_H = m_{H^+} = m_A = 500$ GeV and $M = 0.8 m_A$ and $\tan\beta = 2$

$$\Delta\kappa_V = -2\%$$

upper plots

E2HDM $(\sin\theta = -0.2, \xi = 0)$

lower plots

C2HDM $(\sin\theta = 0, \xi = 0.04)$

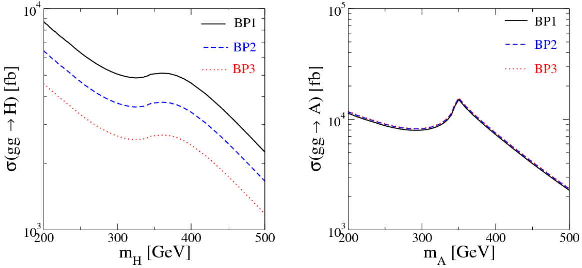
Below the $t\bar{t}$ threshold, $H \to hh, WW, ZZ$ are the dominant channels in E2HDM while they are absent in the C2HDM with $\sin\theta = 0$ (in all 4 Yukawa Types)

Production of the extra-Higgs bosons at the LHC $\sigma(gg \to H/A)$

E2HDM: BP1 $(\sin\theta = -0.2, \xi = 0)$, C2HDM: BP2 $(\sin\theta = -0.1, \xi = 0.03)$

C2HDM: BP3 $(\sin\theta = 0, \xi = 0.04)$

$$\sqrt{s} = 13 \text{ TeV}, \quad \tan\beta = 2, \quad \Delta\kappa_V = -2\%$$



⇒ Same for all Types   only top Yukawa is relevant

⇒ Sizeable differences between E2HDM and C2HDM in gluon fusion H production. For the A production the differences are marginal due to the $\sin\theta$ dependence in the top Yukawa couplings

Present and future LHC bounds for the C2HDM Type-I

$m_h = 125$ GeV, $m_H = m_{H^+} = m_A = 500$ GeV and $M = 0.8 m_A$

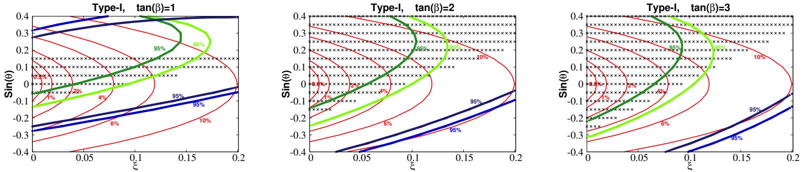
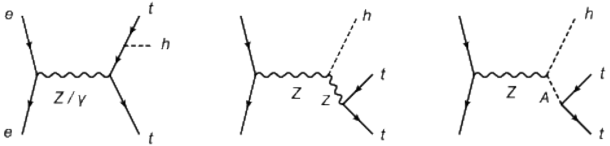


Figure : Regions marked by $\times$ allowed by current collider data (HiggsBounds tool) @ 95%CL. Compatibility with the observed Higgs signals (SM) extrapolated at 3000 fb^{-1} (3000 fb^{-1}), 300 fb^{-1} (300 fb^{-1}) @ 95% CL. Red contours are $|\Delta\kappa_V| = g_{hVV}^{C2HDM}/g_{hVV}^{SM} - 1$

After HL-LHC (High Luminosity LHC) there remains scope to distinguish C2HDMs from E2HDMs ($\xi = 0$) at future e^+e^- colliders

Associated Higgs Boson production with top quarks $e^+e^- \to t\bar{t}h$



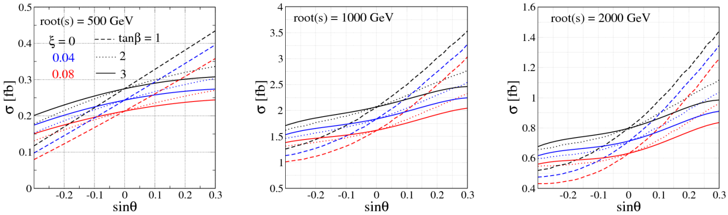
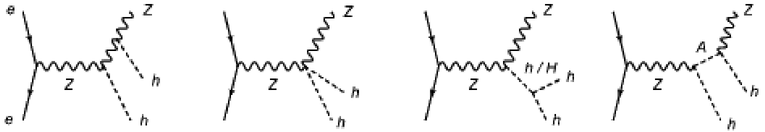


Figure : $m_H = m_A$ is taken to be 400, 500 and 500 GeV for the left, center and right panels, respectively. $M = 0.8 m_A$, $\tan\beta = 2$

At $\sqrt{s} = 1, 2$ TeV the on-shell production of A is realised and the cross section get enhanced. The ξ dependence acts like an overall rescaling with negative deviations $> 20\%$ for $\xi = 0.08$



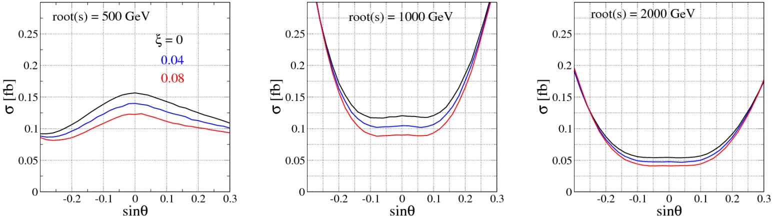


Figure : $m_H = m_A$ is taken to be 400, 500 and 500 in GeV unit for the left, center and right panels, respectively. $M = 0.8 m_A$, $\tan\beta = 2$

At $\sqrt{s} = 1, 2$ TeV the on-shell production of H, A is realised, followed by $H \to hh$ and $A \to Zh$ respectively, both proportional to $\sin\theta$

The ξ dependence remains comparable at all energies being in the 20-30% range

Conclusion

- In presence of a deviation in hVV couplings from SM prediction, E2HDMs would require non-zero mixing case while C2HDMs could obtain this with zero mixing case
- If such deviations will be established by the LHC (or by a future e^+e^- collider) in the couplings of the discovered SM like h, this will be an indirect evidence for a non-minimal Higgs sector possible belonging to a E2HDM or C2HDM
- Differences in the decay BR's and production cross sections for the extra Higgs bosons could enable us to distinguish a C2HDM from E2HDM at both hadron and lepton colliders

Thank You

BACK UP 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., $\Sigma \to g\Sigma g^T$.

$$\zeta_h = \left(1 - \frac{3}{2}\xi\right) c_\theta + s_\theta \cot\beta, \ \xi_h = \left(1 - \frac{\xi}{2}\right) c_\theta - s_\theta \tan\beta,$$

$$\zeta_H = -\left(1 - \frac{3}{2}\xi\right) s_\theta + c_\theta \cot\beta, \ \xi_H = -\left(1 - \frac{\xi}{2}\right) s_\theta - c_\theta \tan\beta,$$

$$\zeta_A = \left(1 + \frac{\xi}{2}\right) \cot\beta, \ \xi_A = -\left(1 - \frac{\xi}{2}\right) \tan\beta.$$

Differences in $e^+e^- \to t\bar{t}h$ cross-section for fixed $\kappa_V^2 = 0.99$, 0.98

$$\Delta\sigma = (\sigma_{C2HDM}/\sigma_{E2HDM} - 1) \quad \kappa_V = g_{hVV}/g_{hVV}^{SM}$$

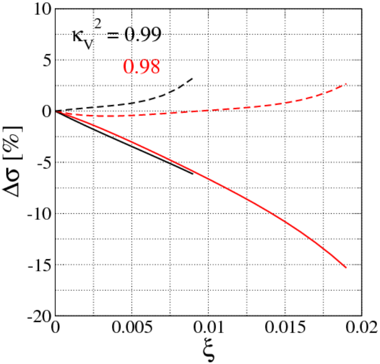


Figure : $\sqrt{s} = 1000$ GeV, $m_H = m_{H^+} = m_A = 500$ GeV $m_h = 125$ GeV, $M = 0.8 m_A$, $\tan\beta = 2$

Dashed lines: $\sin\theta < 0$
Solid lines: $\sin\theta > 0$

$\Delta\kappa_V = -0.5\%$ $\Delta\kappa_V = -1\%$

- The lines correspond to values of Type-I C2HDM parameters allowed by unitarity and stability bounds and after 3000 fb $^{-1}$ at the LHC
- Even with very small deviations in κ_V precisely determined via HS and VBF, the differences between E2HDM and C2HDM in $e^+e^- \to t\bar{t}h$ cross section can be $\sim -15\%$

Differences in $e^+e^- \to Zhh$ cross-section for fixed $\kappa_V^2 = 0.99$, 0.98

$$\Delta\sigma = (\sigma_{C2HDM}/\sigma_{E2HDM} - 1) \quad \kappa_V = g_{hVV}/g_{hVV}^{SM}$$

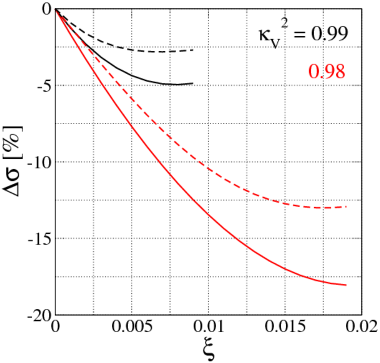


Figure : $\sqrt{s} = 1000$ GeV, $m_H = m_{H^+} = m_A = 500$ GeV $m_h = 125$ GeV $M = 0.8 m_A$, $\tan\beta = 2$

Dashed lines: $\sin\theta < 0$
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$\Delta\kappa_V = -0.5\%$ $\Delta\kappa_V = -1\%$

- The lines correspond to values of Type-I C2HDM parameters allowed by unitarity and stability bounds and after 3000 fb $^{-1}$ at the LHC
- Large negative differences between C2HDM and E2HDM are predicted also for $\leq 1\%$ deviations in the hVV coupling