

New resonance scale and fingerprint identification in composite Higgs models



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[arXiv:1410.xxxx](https://arxiv.org/abs/1410.xxxx)

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Introduction

- The Higgs boson has been discovered.

However, a big question still remains.

Is the Higgs boson **Elementary scalar** or **Composite state**?

Elementary scalar

SUSY? GUT over the grand desert?

Composite state

Technicolor

Little Higgs

(Minimal) Composite Higgs Model

Minimal Composite Higgs Model

The Higgs boson = pseudo Nambu-Goldstone boson

Minimal set up : $G/H = SO(5)/SO(4)$

Agashe, Contino, Pamarol, Nucl.Phys.B719
Contino, arXiv.1005.4269

- # of NGB = $\dim(G) - \dim(H)$ (H contains the SM gauge group)
- The breaking scale is higher than 246 GeV by a certain strong dynamics.

➤ $G/H = SO(5)/SO(4)$ (# of NGB = $10 - 6 = 4$)

f : decay constant

A : $SO(5)$ gauge

X : $U(1)_X$ gauge

Higgs fields : $\Sigma = \frac{\sin(h/f)}{h} (h^1, h^2, h^3, h^4, h \cot(h/f))$

Gauge fields : $\mathcal{L} = \frac{1}{2} P_{\mu\nu} [\Pi_0^X(p) X^\mu X^\nu + \Pi_0(p) \text{Tr}[A^\mu A^\nu] + \Pi_1(p) \Sigma A^\mu A^\nu \Sigma^T]$

➤ Higgs potential : Coleman-Weinberg mechanism

$$V(h) = \text{[diagram: wavy line with a vertex]} + \text{[diagram: circle with a vertex]} + \dots$$

The explicit form of the Higgs potential and matter Lagrangian depend on matter representation.

1-, 4-, 5-, 10-, 14-dimensional rep. of $SO(5)$. We study **fourteen** models.

Minimal Composite Higgs Model

The Higgs boson = pseudo Nambu-Goldstone boson

Minimal set up : $G/H = SO(5)/SO(4)$

Agashe, Contino, Pamarol, Nucl.Phys.B719
Contino, arXiv.1005.4269

- # of NGB = $\dim(G) - \dim(H)$
- The breaking scale is higher than 246 GeV by a certain strong dynamics.

➤ $G/H = SO(5)/SO(4)$ (# of NGB = $10 - 6 = 4$) Compositeness parameter :
 $\xi = v^2/f^2$ (< 1 , $\xi = 0$ is SM limit)

$$\mathcal{L}_{\text{eff}}^{\text{gauge}} = \frac{g^2 v^2}{4} W_\mu^+ W^{-\mu} + \frac{g^2 v}{2} \sqrt{1 - \xi} \hat{h} W_\mu^+ W^{-\mu} + \frac{g^2 (1 - 2\xi)}{4} \hat{h}^2 W_\mu^+ W^{-\mu} \\ + \frac{g_Z^2 v^2}{4} Z_\mu Z^\mu + \frac{g_Z^2 v}{2} \sqrt{1 - \xi} \hat{h} Z_\mu Z^\mu + \frac{g_Z^2 (1 - 2\xi)}{4} \hat{h}^2 Z_\mu Z^\mu ,$$

These deviations don't depend on matter rep.

➤ Higgs potential : Coleman-Weinberg mechanism

$$\left\langle \frac{\partial V_h}{\partial h} \right\rangle = 0 ,$$

$$\left\langle \frac{\partial^2 V_h}{\partial h^2} \right\rangle = m_h^2 > 0 ,$$

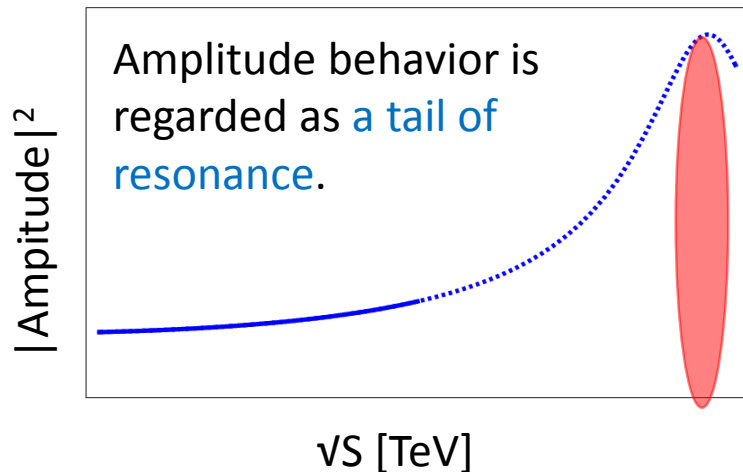
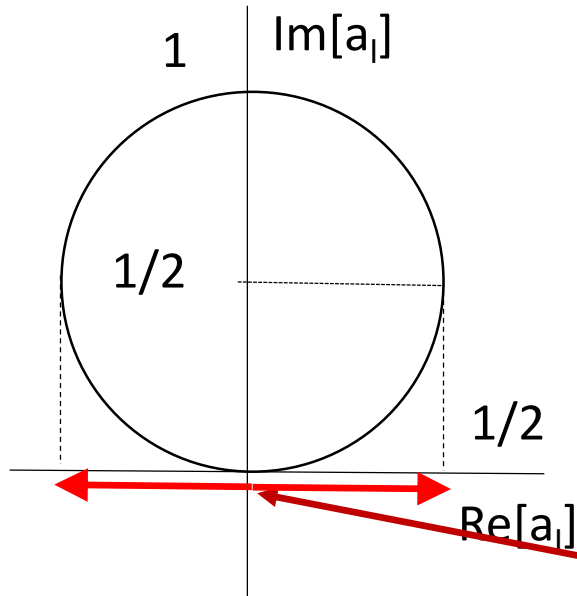
$$\left\langle \frac{\partial^3 V_h}{\partial h^3} \right\rangle = \frac{3m_h^2}{v} \sqrt{1 - \xi} \equiv \lambda_{hhh}$$

In the case of MCHM₄ (4-dim. rep.)

These terms are deviations from the SM predictions. Especially, the gauge coupling deviation violates perturbative unitarity.

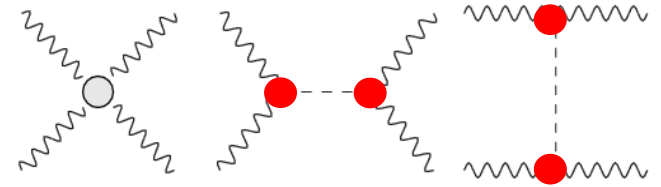
Perturbative unitarity

$$\text{Re}[a_l]^2 + (\text{Im}[a_l] - 1/2)^2 \leq (1/2)^2$$



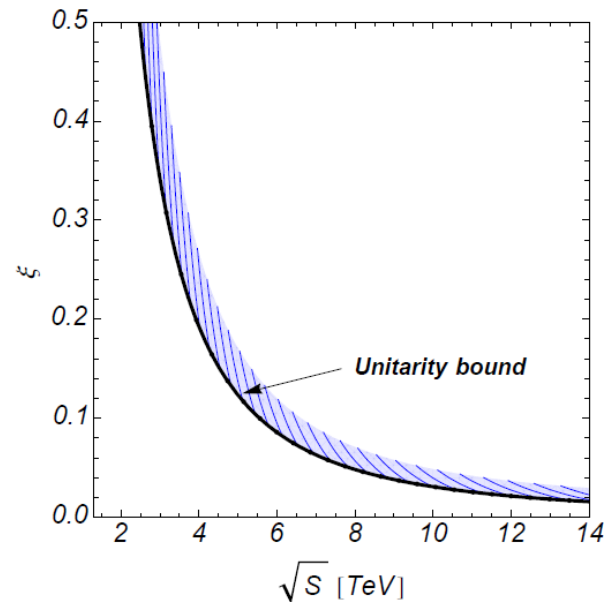
WW scattering

$$g_{hVV} = g_{hVV}^{\text{SM}} \sqrt{1 - \xi}$$



$$\left| \frac{G_F \xi S}{(16\sqrt{2}\pi)} + G_F(m_h^2 - M_W^2)(1 - \xi)/(4\sqrt{2}\pi) \right| \leq 1/2$$

Energy dependence remains.

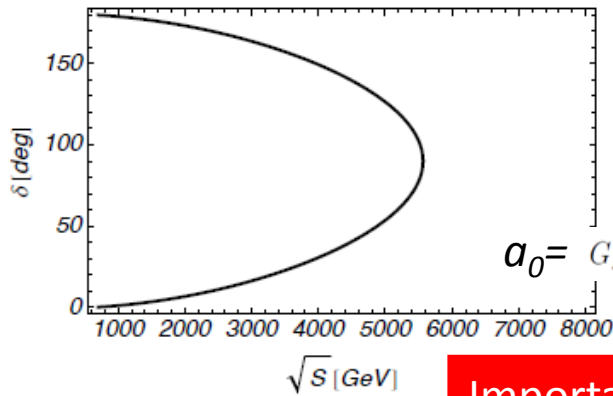


Kanemura, Kaneta,
Machida, Shindou,
arXiv:1410.xxxx

The unitarity violation indicates
a new resonance scale.

New resonance scale

In previous calculation, we didn't discuss **Im. part of Amp.**

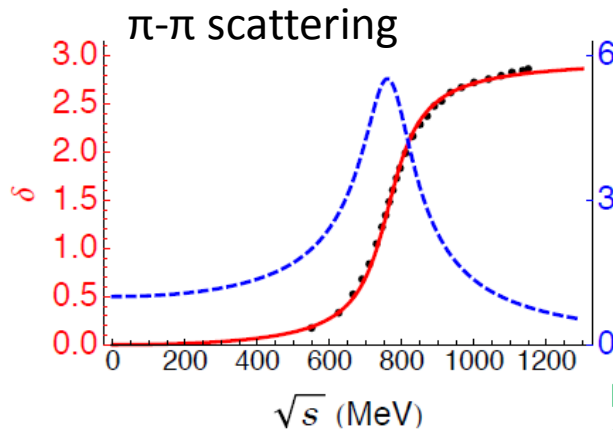


Important Assumption

$$\delta = \tan^{-1} \left[\frac{1}{2\text{Re}[a_0]} \pm \sqrt{1/(4\text{Re}[a_0]^2) - 1} \right]$$

II

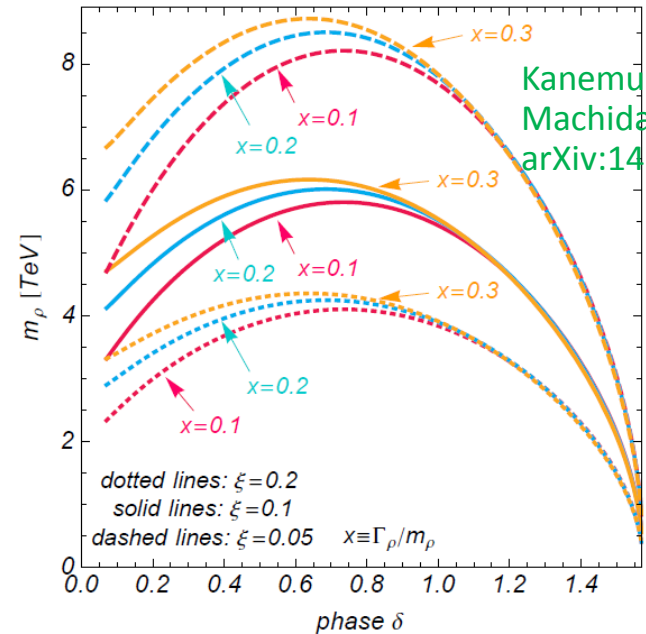
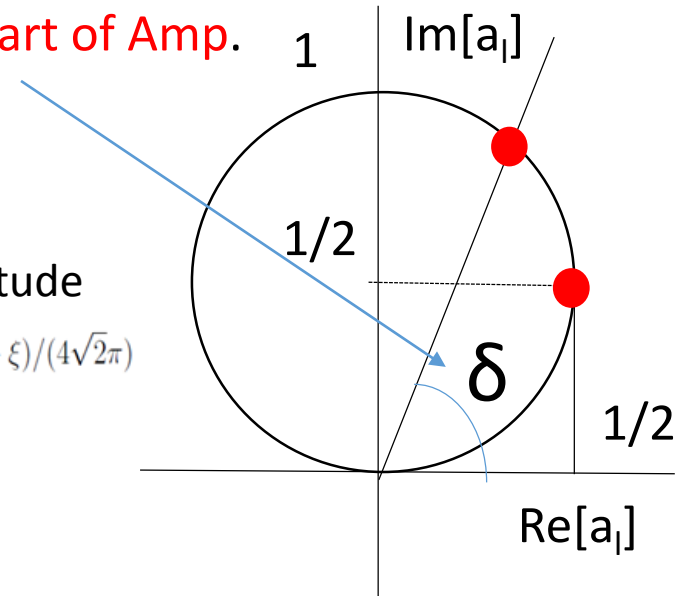
$$\delta = \begin{cases} \tan^{-1}[(\Gamma/m)S/(m^2 + \Gamma^2 - S)] & \text{for } \sqrt{S} < \sqrt{m^2 + \Gamma^2} \\ \tan^{-1}[(\Gamma/m)S/(m^2 + \Gamma^2 - S)] + \pi & \text{for } \sqrt{S} \geq \sqrt{m^2 + \Gamma^2} \end{cases}$$



Black dot :
experimental value

Red curve : Fitting
function

Murayama, et al.
arXiv :1401. 3761



Kanemura, Kaneta,
Machida, Shindou,
arXiv:1410.xxxx

How to measure a phase δ ?

Measurement at LHC and Higher-energy Collider

Murayama et al
arXiv: 1401. 3761

$$u\bar{d} \rightarrow W^+ Z \rightarrow \ell^+ \nu \ell^+ \ell^-$$

λ_W and λ_Z are W and Z helicity eigenvalues.
0 means longitudinal mode.

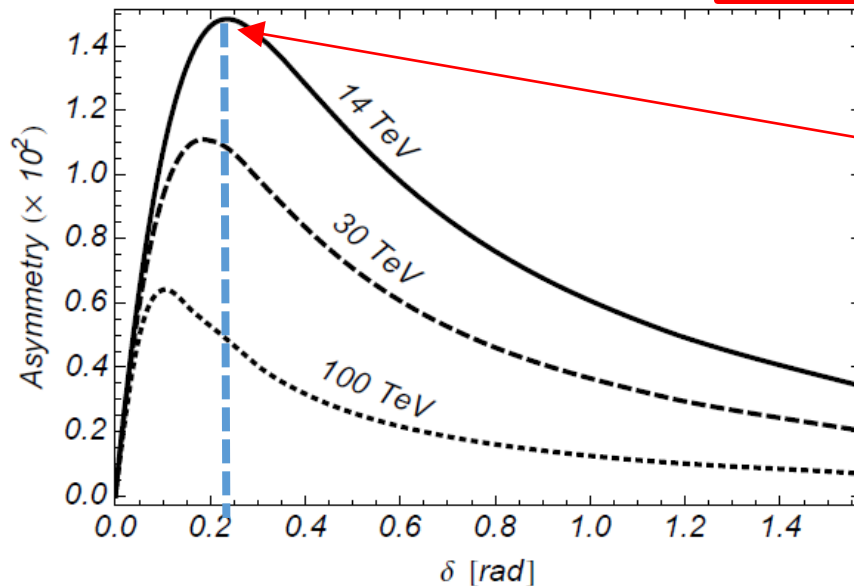
$$\mathcal{M}_{\text{Prod}}(\Theta, \lambda_W, \lambda_Z)$$

$$\mathcal{M}_{\text{Prod}}(\Theta, 0, 0) \rightarrow \mathcal{M}_{\text{Prod}}(\Theta, 0, 0)e^{i\delta}$$

The phase δ is extracted by

$$|\text{amplitude}|^2 \supset \sin(\lambda_W \phi_1 - \lambda_Z \phi_2) \sin \delta$$

$$A_{\pm} \equiv |\sigma_+ - \sigma_-|/(\sigma_+ + \sigma_-), \quad \sigma_{\pm} \equiv \sigma(\sin \phi_1 \gtrless 0)$$



+ : Above production plane
-- : Below production plane

The **maximum asymmetry** and cross section at $\delta = 0.24$ with 14 TeV are

$$A_{\pm} \simeq 0.015$$

$$\sigma \simeq 0.037 \text{ pb}$$

This asymmetry can be observed if we accumulate 3000 fb^{-1} with HL-LHC.

Coupling deviation from the SM

$$\kappa_{h\phi\phi} = g_{h\phi\phi}^{\text{MCHM}} / g_{h\phi\phi}^{\text{SM}}$$

Carena et al. JHEP 1406 (2014)

Kanemura, Kaneta, Machida, Shindou, arXiv:1410.xxxx

The Higgs-gauge couplings are **universal**.
They do not depend on matter representation.

The Higgs-fermion and Higgs-self couplings are **not universal**. They depend on matter representation. We can distinguish models by **correlations among several coupling deviations**.

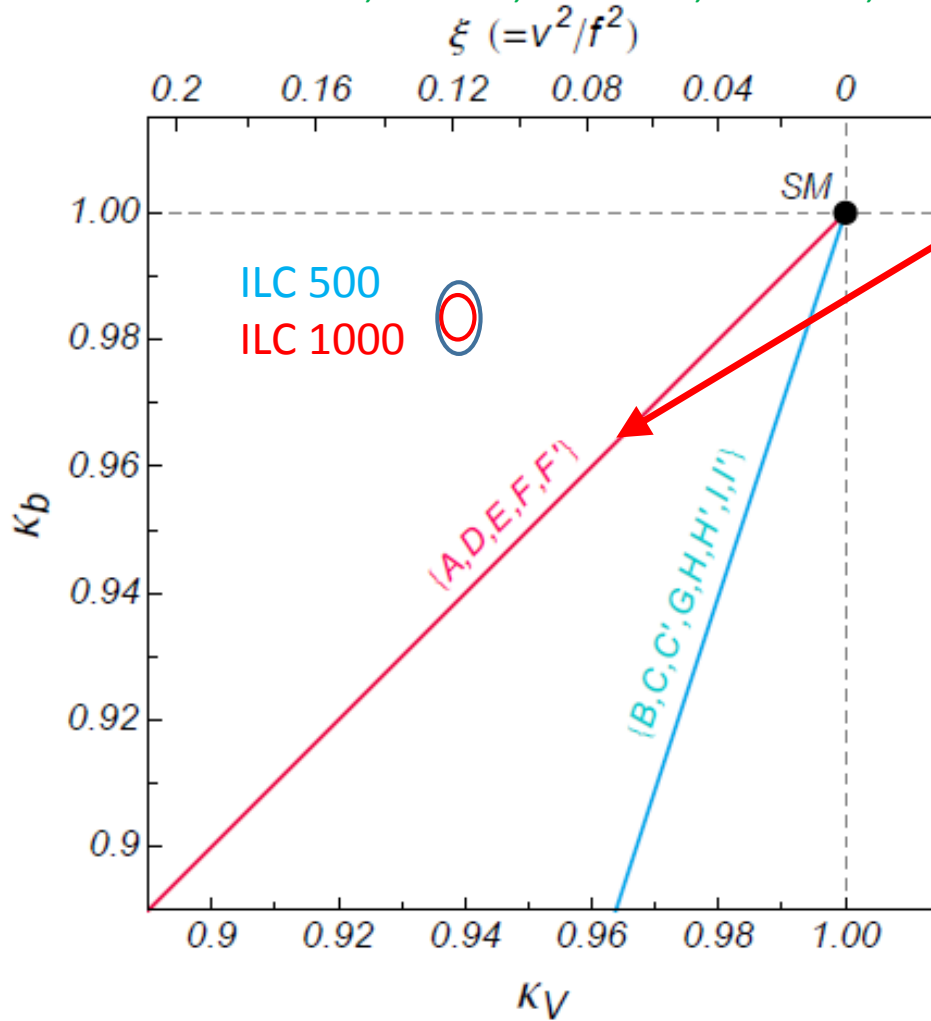
Depends on G/H

Depends on Matter representation

Label	Model	κ_V	κ_{hhVV}	κ_{hhh}	κ_{hhhh}	κ_t	κ_b	$\kappa_{hh\bar{t}t}$	$\kappa_{hh\bar{b}b}$
A	MCHM ₄	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
B	MCHM ₅	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
B	MCHM ₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
C, C'	MCHM ₁₄	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ
D	MCHM ₅₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\sqrt{1-\xi}$	-4ξ	$-\xi$
E	MCHM ₅₋₁₀₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
F, F'	MCHM ₅₋₁₄₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\sqrt{1-\xi}$	F_8	$-\xi$
G	MCHM ₁₀₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-\xi$	-4ξ
B	MCHM ₁₀₋₁₄₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
B	MCHM ₁₄₋₁₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
H, H'	MCHM ₁₄₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_4	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_7	-4ξ
B	MCHM ₁₄₋₁₀₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
I, I'	MCHM ₁₄₋₁₄₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ

Fingerprint identification of MCHMs : K_V VS. K_b

Kanemura, Kaneta, Machida, Shindou, arXiv:x1410.xxxx



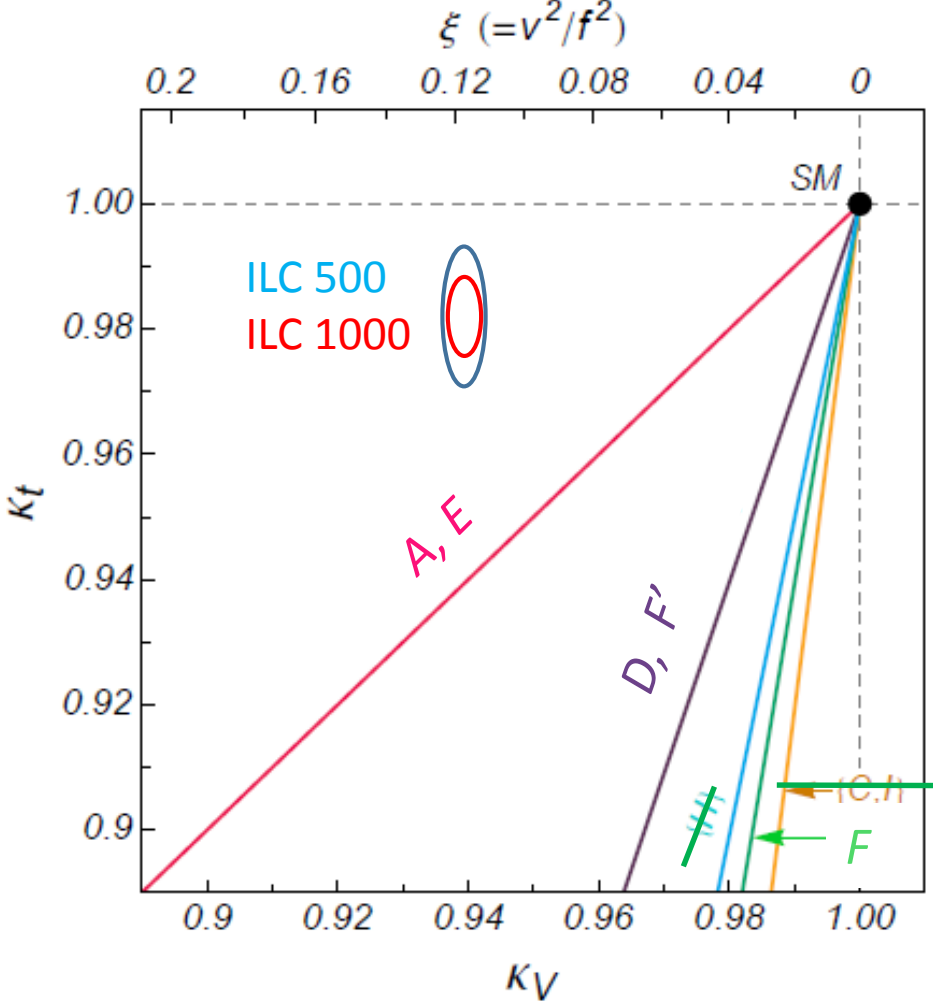
If measured value is on this line, (A, D, E, F, F') are still degenerate.

Label	Model
A	MCHM ₄
B	MCHM₅
B	MCHM₁₀
C, C'	MCHM₁₄
D	MCHM ₅₋₅₋₁₀
E	MCHM ₅₋₁₀₋₁₀
F, F'	MCHM ₅₋₁₄₋₁₀
C	MCHM₁₀₋₅₋₁₀
B	MCHM₁₀₋₁₄₋₁₀
B	MCHM₁₄₋₁₋₁₀
H, H'	MCHM₁₄₋₅₋₁₀
B	MCHM₁₄₋₁₀₋₁₀
I, I'	MCHM₁₄₋₁₄₋₁₀

	ILC(500)	ILC(1000)
\sqrt{s} (GeV)	250+500	250+500+1000
L (fb ⁻¹)	250+500	250+500+1000
$\gamma\gamma$	8.3 %	3.8 %
gg	2.0 %	1.1 %
WW	0.4 %	0.3 %
ZZ	0.5 %	0.5 %
$t\bar{t}$	2.5 %	1.3 %
$b\bar{b}$	1.0 %	0.6 %
$\tau^+\tau^-$	1.9 %	1.3 %
$\Gamma_T(h)$	1.7 %	1.1 %
$\mu^+\mu^-$	91 %	16 %
hhh	83 %	21 %
BR(invis.)	< 0.9 %	< 0.9 %
$c\bar{c}$	2.8 %	1.8 %

Fingerprint identification of MCHMs : K_V VS. K_t

Kanemura, Kaneta, Machida, Shindou, arXiv:1410.xxxx



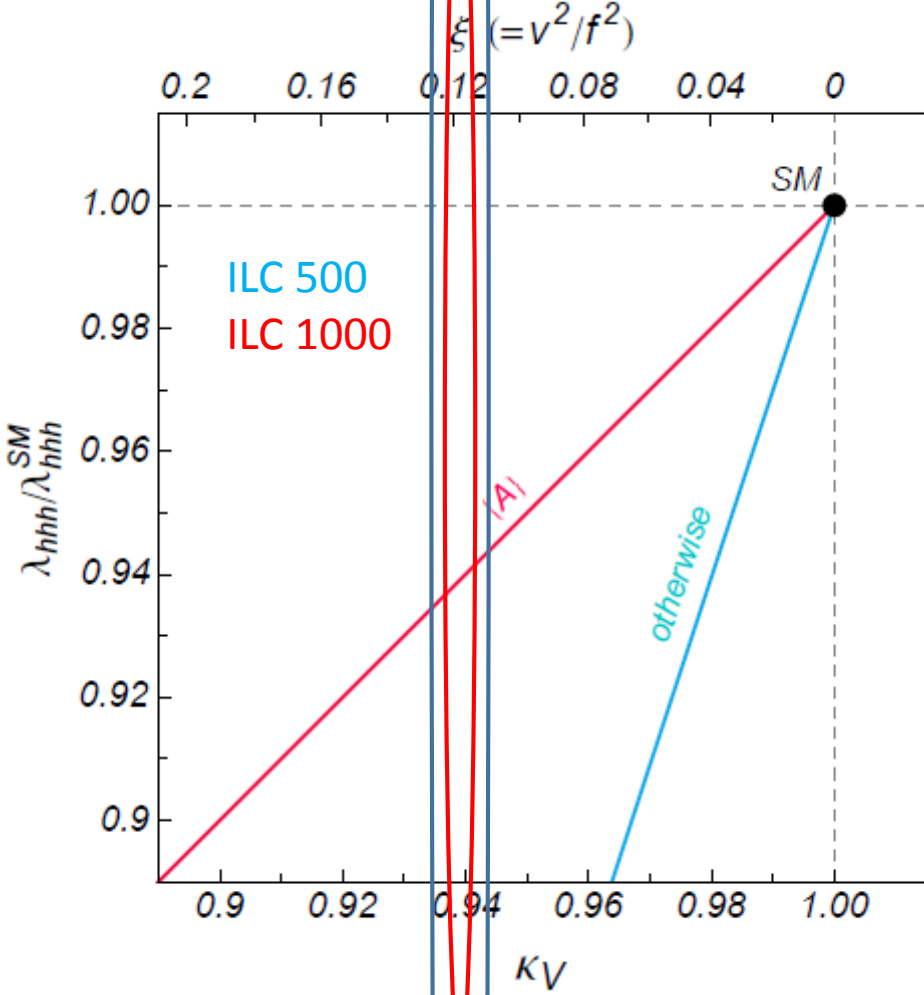
(A, E)
or
(D, F')
or
F

	ILC(500)	ILC(1000)
\sqrt{s} (GeV)	250+500	250+500+1000
L (fb ⁻¹)	250+500	250+500+1000
$\gamma\gamma$	8.3 %	3.8 %
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Label	Model
A	MCHM ₄
B	MCHM ₅
B	MCHM ₁₀
C, C'	MCHM ₁₄
D	MCHM ₅₋₅₋₁₀
E	MCHM ₅₋₁₀₋₁₀
F, F'	MCHM ₅₋₁₄₋₁₀
C	MCHM ₁₀₋₅₋₁₀
B	MCHM ₁₀₋₁₄₋₁₀
B	MCHM ₁₄₋₁₋₁₀
H, H'	MCHM ₁₄₋₅₋₁₀
B	MCHM ₁₄₋₁₀₋₁₀
I, I'	MCHM ₁₄₋₁₄₋₁₀

Fingerprint identification of MCHMs : K_V vs. $\lambda_{hhh}/\lambda_{hhh}^{SM}$

Kanemura, Kaneta, Machida, Shindou, arXiv:1410.xxxx



We may distinguish
A, E, (D, F') and F.

We may distinguish
A
and
E.

Label	Model
A	MCHM ₄
B	MCHM₅
B	MCHM₁₀
C, C'	MCHM₁₄
D	MCHM ₅₋₅₋₁₀
E	MCHM ₅₋₁₀₋₁₀
F, F'	MCHM ₅₋₁₄₋₁₀
G	MCHM₁₀₋₅₋₁₀
B	MCHM₁₀₋₁₄₋₁₀
B	MCHM₁₄₋₁₋₁₀
H, H'	MCHM₁₄₋₅₋₁₀
B	MCHM₁₄₋₁₀₋₁₀
I, I'	MCHM₁₄₋₁₄₋₁₀

	ILC(500)	ILC(1000)
\sqrt{s} (GeV)	250+500	250+500+1000
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$\gamma\gamma$	8.3 %	3.8 %
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$\mu^+\mu^-$	91 %	16 %
hhh	83 %	21 %
BR(invis.)	< 0.9 %	< 0.9 %
$c\bar{c}$	2.8 %	1.8 %

Summary

The **Composite Higgs model** is one of the promising candidates of the essence of the Higgs sector.

By using **phase shift information**, we can explore new resonance scale above the LHC direct reach .

We have discussed how to distinguish various models of MCHM **by using the precise measurement of Higgs boson couplings**.

Back up slides

Coupling deviation from the SM

Kanemura, Kaneta, Machida, Shindou, arXiv:1410.xxxx

$$\kappa_{h\phi\phi} = g_{h\phi\phi}^{\text{MCHM}} / g_{h\phi\phi}^{\text{SM}}$$

Label	Model	κ_V	κ_{hhVV}	κ_{hhh}	κ_{hhhh}	κ_t	κ_b	κ_{hhtt}	κ_{hhbb}
A	MCHM ₄	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
B	MCHM ₅	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
B	MCHM ₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
C, C'	MCHM ₁₄	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ
D	MCHM ₅₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\sqrt{1-\xi}$	-4ξ	$-\xi$
E	MCHM ₅₋₁₀₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
F, F'	MCHM ₅₋₁₄₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\sqrt{1-\xi}$	F_8	$-\xi$
G	MCHM ₁₀₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-\xi$	-4ξ
B	MCHM ₁₀₋₁₄₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
B	MCHM ₁₄₋₁₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
H, H'	MCHM ₁₄₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_4	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_7	-4ξ
B	MCHM ₁₄₋₁₀₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
I, I'	MCHM ₁₄₋₁₄₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ

Coupling deviation from the SM

$$\kappa_{h\phi\phi} = g_{h\phi\phi}^{\text{MCHM}} / g_{h\phi\phi}^{\text{SM}}$$

$$F_3 = \frac{1}{\sqrt{1-\xi}} \frac{3(1-2\xi)M_1^t + 2(4-23\xi+20\xi^2)M_2^t}{3M_1^t + 2(4-5\xi)M_2^t},$$

$$F_4 = \sqrt{1-\xi} \frac{M_1^t + 2(1-3\xi)M_2^t}{M_1^t + 2(1-\xi)M_2^t}, \quad F_5 = \sqrt{1-\xi} \frac{M_1^t - (4-15\xi)M_2^t}{M_1^t - (4-5\xi)M_2^t},$$

$$F_6 = -4\xi \frac{3M_1^t + (23-40\xi)M_2^t}{3M_1^t + 2(4-5\xi)M_2^t}, \quad F_7 = -\xi \frac{M_1^t + 2(7-9\xi)M_2^t}{M_1^t + 2(1-\xi)M_2^t},$$

$$F_8 = -\xi \frac{M_1^t - (34-45\xi)M_2^t}{M_1^t - (4-5\xi)M_2^t},$$

$$H_1 = 1 - \frac{3\xi}{2} - \frac{5\xi^2}{8} + \frac{\xi^3}{3m_h^2} \left[-\frac{21m_h^2}{16} + \frac{48\gamma}{v^2} \right],$$

$$H_2 = 1 - \frac{25\xi}{2} + \xi^2 + \frac{\xi^3}{3m_h^2} \left[3m_h^2 + \frac{288\gamma}{v^2} \right],$$

SO(5) generators & eigenvectors

- 5-representation

$$(T^{a_{L,R}})_{ij} = -\frac{i}{2} \left[\frac{1}{2} \epsilon^{abc} \left(\delta_i^b \delta_j^c - \delta_j^b \delta_i^c \right) \pm \left(\delta_i^a \delta_j^4 - \delta_j^a \delta_i^4 \right) \right]$$
$$T_{ij}^{\hat{a}} = -\frac{i}{\sqrt{2}} \left(\delta_i^{\hat{a}} \delta_j^5 - \delta_j^{\hat{a}} \delta_i^5 \right).$$

$$v_{(-,-)} = \frac{1}{\sqrt{2}} \begin{pmatrix} i \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad v_{(-,+)} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ i \\ 1 \\ 0 \end{pmatrix},$$
$$v_{(+,-)} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ -i \\ 1 \\ 0 \end{pmatrix}, \quad v_{(+,+)} = \frac{1}{\sqrt{2}} \begin{pmatrix} -i \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad v_{(0,0)} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

SO(5) generators & eigenvectors

- 10-representation

$$(\mathbf{3}, \mathbf{1}) : v_{(\pm 1, 0)} = \frac{1}{\sqrt{2}}(T_L^1 \pm iT_L^2), \quad v_{(0, 0)} = T_L^3,$$

$$(\mathbf{1}, \mathbf{3}) : v_{(0, \pm 1)} = \frac{1}{\sqrt{2}}(T_R^1 \pm iT_R^2), \quad v_{(0, 0)} = T_R^3,$$

$$(\mathbf{2}, \mathbf{2}) : v_{(-1/2, -1/2)} = \frac{1}{\sqrt{2}}(T^{\hat{1}} - iT^{\hat{2}}), \quad v_{(+1/2, +1/2)} = \frac{1}{\sqrt{2}}(T^{\hat{1}} + iT^{\hat{2}}),$$

$$v_{(-1/2, +1/2)} = \frac{1}{\sqrt{2}}(T^{\hat{3}} - iT^{\hat{4}}), \quad v_{(+1/2, -1/2)} = \frac{1}{\sqrt{2}}(T^{\hat{3}} + iT^{\hat{4}}).$$

$$v_{(0,0)} = \frac{1}{2} \begin{pmatrix} & -i & & & \\ +i & & & & \\ & & & -i & \\ & & +i & & \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Anti-symmetric

$$\Sigma^T \bar{\Psi} \Sigma \rightarrow 0$$

SO(5) generators & eigenvectors

- 1 4-representation

$$(\mathbf{3}, \bar{\mathbf{3}}) : T_{ij}^{ab} = \frac{1}{\sqrt{2}}(\delta_i^a \delta_j^b + \delta_j^a \delta_i^b), \quad a < b, \ a, \ b = 1, \dots, 4$$

$$T_{ij}^{aa} = \frac{1}{\sqrt{2}}(\delta_i^a \delta_j^a - \delta_i^{a+1} \delta_j^{a+1}), \quad a = 1, 2, 3$$

$$(\mathbf{2}, \bar{\mathbf{2}}) : T_{ij}^{\hat{a}} = \frac{1}{\sqrt{2}}(\delta_i^a \delta_j^5 + \delta_j^a \delta_i^5), \quad a = 1, \dots, 4$$

$$(\mathbf{1}, \bar{\mathbf{1}}) : T_{ij}^0 = \frac{1}{2\sqrt{5}} \text{diag}(1, 1, 1, 1, -4).$$

$$v_{(+1,+1)} = \frac{1}{4} \begin{pmatrix} 1 & 2i & & & 0 \\ 2i & -2 & & & 0 \\ & & 1 & & 0 \\ & & & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Symmetric

$$\Sigma^T \bar{\Psi} \Sigma \neq 0$$

Matter sector of MCHM

Many **variations** depending on matter representations

1, 4, 5, 10, 14 representations

ex) MCHM₄

$$\Psi_q^{(4)} = \begin{pmatrix} \textcircled{q_L} \\ Q_L \end{pmatrix}, \quad \Psi_u^{(4)} = \begin{pmatrix} q_R^u \\ \textcircled{u_R} \\ d_R' \end{pmatrix}, \quad \Psi_d^{(4)} = \begin{pmatrix} q_R^d \\ u_R' \\ \textcircled{d_R} \end{pmatrix}$$

SM quarks
(other fields
are non-
dynamical)

$$\mathcal{L}_{\text{eff}}^{\text{matter}} = \sum_{r=q,u,d} \bar{\Psi}_r^{(4)} \not{p} [\Pi_0^r(p) + \Pi_1^r(p) \Gamma^i \Sigma_i] \Psi_r^{(4)} + \sum_{r=u,d} \bar{\Psi}_q^{(4)} [M_0^r(p) + M_1^r(p) \Gamma^i \Sigma_i] \Psi_r^{(4)}$$

MCHM **variations** (Introducing q_L, u_R, d_R)

MCHM₅ (q_L, u_R, d_R)=5 rep.

MCHM₁₄₋₅₋₁₀ (q_L, u_R, d_R)=(14,5,10) rep.

We discuss 14 variation models of MCHMs.

Matter sector

● MCHM₄

$$\mathcal{L}_{\text{eff}}^{\text{matter}} = \sum_{r=q,u,d} \bar{\Psi}_r^{(4)} \not{p} [\Pi_0^r(p) + \Pi_1^r(p) \Gamma^i \Sigma_i] \Psi_r^{(4)} + \sum_{r=u,d} \bar{\Psi}_q^{(4)} [M_0^r(p) + M_1^r(p) \Gamma^i \Sigma_i] \Psi_r^{(4)} ,$$

● MCHM₅

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{\text{matter}} = & \sum_{r=t_L, t_R, b_L, b_R} \bar{\Psi}_r^{(5)} [\not{p} \Pi_0^r + \Sigma^\dagger \not{p} \Pi_1^r \Sigma] \Psi_r^{(5)} \\ & + \bar{\Psi}_{t_L}^{(5)} [M_0^t + \Sigma^\dagger M_1^t \Sigma] \Psi_{t_R}^{(5)} + \bar{\Psi}_{b_L}^{(5)} [M_0^b + \Sigma^\dagger M_1^b \Sigma] \Psi_{b_R}^{(5)} + \text{h.c.} . \end{aligned}$$

Matter sector

● MCHM₁₀

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{\text{matter}} = & \sum_{r=q_L, t_R, b_R} \left[\bar{\Psi}_r^{(10)} \not{p} \Pi_0^r \Psi_r^{(10)} + (\Sigma \bar{\Psi}_r^{(10)}) \not{p} \Pi_1^r (\Psi_r^{(10)} \Sigma^\dagger) \right] \\ & + \bar{\Psi}_{q_L}^{(10)} M_0^t \Psi_{t_R}^{(10)} + (\Sigma \bar{\Psi}_{q_L}^{(10)}) M_1^t (\Psi_{t_R}^{(10)} \Sigma^\dagger) \\ & + \bar{\Psi}_{q_L}^{(10)} M_0^b \Psi_{b_R}^{(10)} + (\Sigma \bar{\Psi}_{q_L}^{(10)}) M_1^b (\Psi_{b_R}^{(10)} \Sigma^\dagger) + \text{h.c.} .\end{aligned}$$

● MCHM₁₄

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{\text{matter}} = & \sum_{r=q_L, t_R, b_R} \left[\bar{\Psi}_r^{(14)} \not{p} \Pi_0^r \Psi_r^{(14)} + (\Sigma \bar{\Psi}_r^{(14)}) \not{p} \Pi_1^r (\Psi_r^{(14)} \Sigma^\dagger) + (\Sigma \bar{\Psi}_r^{(14)} \Sigma^\dagger) \not{p} \Pi_2^r (\Sigma \Psi_r^{(14)} \Sigma^\dagger) \right] \\ & + \bar{\Psi}_{q_L}^{(14)} M_0^t \Psi_{t_R}^{(14)} + (\Sigma \bar{\Psi}_{q_L}^{(14)}) M_1^t (\Psi_{t_R}^{(14)} \Sigma^\dagger) + (\Sigma \bar{\Psi}_{q_L}^{(14)} \Sigma^\dagger) M_2^t (\Sigma \Psi_{t_R}^{(14)} \Sigma^\dagger) \\ & + \bar{\Psi}_{q_L}^{(14)} M_0^b \Psi_{b_R}^{(14)} + (\Sigma \bar{\Psi}_{q_L}^{(14)}) M_1^b (\Psi_{b_R}^{(14)} \Sigma^\dagger) + (\Sigma \bar{\Psi}_{q_L}^{(14)} \Sigma^\dagger) M_2^b (\Sigma \Psi_{b_R}^{(14)} \Sigma^\dagger) + \text{h.c.} .\end{aligned}$$