Current status of Top quark condensation

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Based on PRD85,095025(2012), arXiv:1210.6756, work in progress
(wtih K.Tuominen)

Outline

1. Introduction (12-pages)

2. Models with 126 GeV Higgs (6-pages)

3. In light of LHC (9-pages)

4. Summary (1-page)

BSM Market

- Representative scenarios in BSM market
  - Supersymmetry
  - Extra dimension
  - Strong dynamics
    - Walking technicolor
    - Top quark condensation

Why top quark condensation ?

The origin of fermion mass

Well-known approach is
extended technicolor w/ walking dynamics.

BUT

It is very hard to build an ETC model
to realize the large top-bottom mass splitting.

as discussed @ EHQG-seminar by Matsuzaki

Top quark condensation can realize the large top-bottom mass splitting.

Higgs(-like) boson

“Higgs” boson = composite object

- Top quark condensation

Nambu 1988; Miransky et.al. 1988; Bardeen et.al. 1989

$$\text{EW doublet scalar field : } \Phi = \begin{pmatrix} \bar{t}_L t_R \\ \bar{b}_L t_R \end{pmatrix} \sim h^0$$

c.f. walking TC : techni-dilaton (can be 126 GeV) Matsuzaki et.al. 2012

talked by Matsuzaki @ EHQG-seminar

TD : Pseudo Nambu-Goldstone boson associated with the spontaneous breakdown of the approximate scale symmetry

Yamawaki et.al. 1986

What is top quark condensation ?

- Based on

SM gauge + Nambu-Jona-Lashinio(NJL) model

Nambu et.al. 1961

Top-Mode Lagrangian

$$\mathcal{L} = \bar{q}_L i\gamma_\mu D_\mu q_L + \bar{t}_R i\gamma_\mu D_\mu t_R + G_t \left(\bar{q}_L t_R\right)\left(\bar{t}_R q_L\right)$$

Nambu 1988; Miransky et.al. 1988; Bardeen et.al. 1989

$$q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

- Four fermion coupling G_t

depends on a concrete UV model

Higgs boson from TM ?

Q : Higgs in the top quark condensation model ?

A : Top-Mode Lagrangian derives the SM Lagrangian.

Top-Mode Lagrangian

$$\mathcal{L} = \bar{q}_L i\gamma_\mu D_\mu q_L + \bar{t}_R i\gamma_\mu D_\mu t_R + G_t \left(\bar{q}_L t_R\right)\left(\bar{t}_R q_L\right)$$

Nambu 1988; Miransky et.al. 1988; Bardeen et.al. 1989

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin}(\Phi) - y_t\left[\bar{q}_L \Phi t_R + \text{h.c.}\right] - m^2|\Phi|^2 - \frac{\lambda}{2}\left(\Phi^\dagger\Phi\right)^2$$

with $m^2 < 0$

How ?

SM from NJL (step.1)

Top-Mode Lagrangian

$$\mathcal{L} = \bar{q}_L i\gamma_\mu D_\mu q_L + \bar{t}_R i\gamma_\mu D_\mu t_R + G_t \left(\bar{q}_L t_R\right)\left(\bar{t}_R q_L\right)$$

Introduce an auxiliary field : $\Phi^{(0)} \sim G_t[\bar{t}_R q_L]$

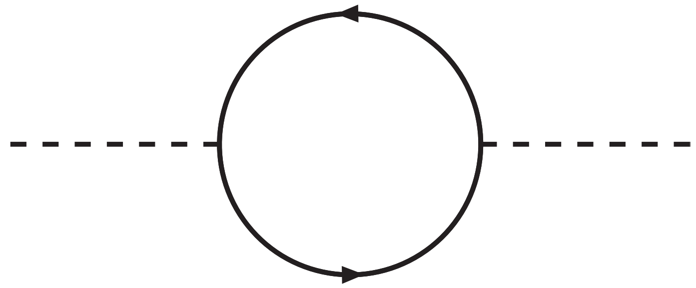
The Top-Mode Lagrangian is rewritten by

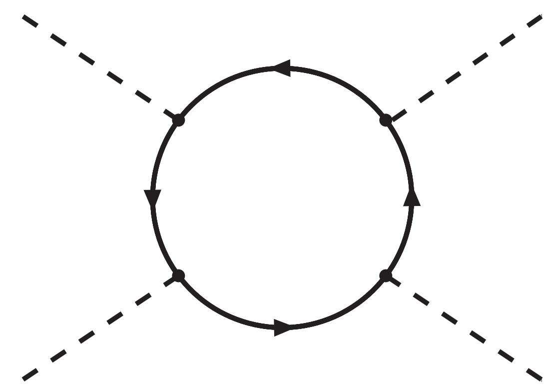
$$\mathcal{L}_\Lambda = \mathcal{L}_{\text{kin.}}(q_L, t_R) - \frac{1}{G_t}|\Phi^{(0)}|^2 - \left[\bar{q}_L \Phi^{(0)} t_R + \text{h.c.}\right]$$

SM from NJL (step.2)

$$\mathcal{L}_\Lambda = \mathcal{L}_{\text{kin.}}(q_L, t_R) - \frac{1}{G_t}|\Phi^{(0)}|^2 - \left[\bar{q}_L \Phi^{(0)} t_R + \text{h.c.}\right]$$

Integrate out the fermion fields on scale $[\mu\,,\,\Lambda]$





$$\mathcal{L}_{\mu<\Lambda} = \mathcal{L}_{\text{kin}}(Z_\Phi \Phi^{(0)}, q, t) - \left[\bar{q}_L \Phi^{(0)} t_R + \text{h.c.}\right] - \left(\frac{1}{G_t} - \frac{N_c \Lambda^2}{8\pi^2}\right)|\Phi^{(0)}|^2 - \frac{\lambda_0}{2}\left(\Phi^{(0)\dagger}\Phi^{(0)}\right)^2$$

EWSB

$$G_t > \frac{8\pi^2}{N_c \Lambda^2} \quad , \quad Z_\Phi = \frac{N_c}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2} \quad , \quad \lambda_0 = \frac{N_c}{8\pi^2} \ln \frac{\Lambda^2}{\mu^2}$$

SM from NJL (step.3)

$$\mathcal{L}_{\mu<\Lambda} = \mathcal{L}_{\rm kin}(Z_\Phi \Phi^{(0)}, q, t) - \left[\bar{q}_L \Phi^{(0)} t_R + \text{h.c.}\right] - \left(\frac{1}{G_t} - \frac{N_c \Lambda^2}{8\pi^2}\right)|\Phi^{(0)}|^2 - \frac{\lambda_0}{2}\left(\Phi^{(0)\dagger}\Phi^{(0)}\right)^2$$

Rescale : $\sqrt{Z_\Phi}\Phi^{(0)} \to \Phi$

$$y_t = \frac{1}{\sqrt{Z_\Phi}} \quad , \quad \lambda = \frac{\lambda_0}{Z_\Phi^2}$$

Top-Mode SM

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin}(\Phi, q, t) - y_t \left[\bar{q}_L \Phi t_R + \text{h.c.}\right] - m^2 |\Phi|^2 - \frac{\lambda}{2}\left(\Phi^\dagger \Phi\right)^2$$

with $\lambda = 2 \times y_t^2$ and $m^2 < 0$

SM from NJL (summary)

Top-Mode Lagrangian

$$\mathcal{L} = \bar{q}_L i\gamma_\mu D_\mu q_L + \bar{t}_R i\gamma_\mu D_\mu t_R + G_t \left(\bar{q}_L t_R\right)\left(\bar{t}_R q_L\right)$$

with $G_t > \dfrac{8\pi^2}{N_c\Lambda^2}$

Top-Mode SM = SM w/ constraint

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin}(\Phi, q, t) - y_t\left[\bar{q}_L \Phi t_R + \text{h.c.}\right] - m^2|\Phi|^2 - \frac{\lambda}{2}\left(\Phi^\dagger\Phi\right)^2$$

with $\lambda = 2 \times y_t^2$ and $m^2 < 0$

VEV, top mass and Higgs mass

Top-Mode SM = SM w/ constraint

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin}(\Phi, q, t) - y_t \left[\bar{q}_L \Phi t_R + \text{h.c.}\right] - m^2|\Phi|^2 - \frac{\lambda}{2}\left(\Phi^\dagger \Phi\right)^2$$

with $\lambda = 2 \times y_t^2$ and $m^2 < 0$

- VEV for EWSB : Pagels-Stokar formula

Pagels et.al. 1979

$$v_t^2 = m_t^2 \frac{N_c}{8\pi^2} \ln \frac{\Lambda^2}{m_t^2}$$

- Top quark mass :

$$m_t = y_t \frac{v_t}{\sqrt{2}}$$

- Higgs boson mass :

$$m_h = \sqrt{\lambda} v_t$$

TMSM prediction

TMSM prediction

$$m_h = (\sqrt{2} \sim 2) \times m_t$$

2 : pure NJL

$\sqrt{2}$: gauge + NJL

Higgs boson mass [TMSM v.s. LHC]

TMSM prediction

$$m_h = (\sqrt{2} \sim 2) \times m_t$$

- Too large to explain the LHC "Higgs" boson mass

$$m_h \text{@LHC} \simeq 126\text{GeV}$$

As solutions.....

1. Top quark mass might be shared by other sector

$$174\text{GeV} = m_t[\text{TM}] + m_t[\text{other}]$$

2. TMSM prediction might be modified

$$m_h = 2 \times C \times m_t$$

C : additional dynamical effect

Model.1 [Particle contents] H.S.F and Tuominen (2012)

1. Top quark mass is shared by ETC sector

$$174\text{GeV} = m_t[\text{TM}] + m_t[\text{ETC}]$$

2. TMSM prediction might be modified

field	TC	$SU(3)_1$	$SU(3)_2$	$SU(2)_L$	$U(1)_Y$
$q_L^{(3)}$	1	3	1	2	1/6
$t_R^{(3)}, b_R^{(3)}$	1	1	3	1	(2/3, -1/3)
$t_L^{(4)}, b_L^{(4)}$	1	1	3	1	(2/3, -1/3)
$t_R^{(4)}, b_R^{(4)}$	1	3	1	1	(2/3, -1/3)
$q^{(1,2)}$	1	1	3	SM	SM
Q_{TC}	R	-	-	-	-

$$\text{EWSB} : v_{\text{EW}}^2 = v_{\text{TC}}^2 + v_t^2 + v_b^2 \quad , \quad \frac{v_t}{v_{\text{EW}}} \leq 1$$

Model.1 [Scenario]

- $SU(3)_1 \times SU(3)_2 \to SU(3)_c$ derives

$$\mathcal{L}_{\rm model.1} = G_t \left(\bar{q}_L^{(3)} t_R^{(4)} \right) \left(\bar{t}_R^{(4)} q_L^{(3)} \right)$$

- Top quark($t^{(3)}$) and vector-like top quark($t^{(4)}$)

- Seesaw mechanism

$$\Sigma_t \neq 0 (\rm EWSB)$$

$$\begin{pmatrix} \bar{t}_L^{(3)} & \bar{t}_L^{(4)} \end{pmatrix} \begin{pmatrix} 0 & \Sigma_t \\ m & M \end{pmatrix} \begin{pmatrix} t_R^{(3)} \\ t_R^{(4)} \end{pmatrix} \Rightarrow m_t[\rm TM]\bar{t}t + m_T T\bar{T}$$

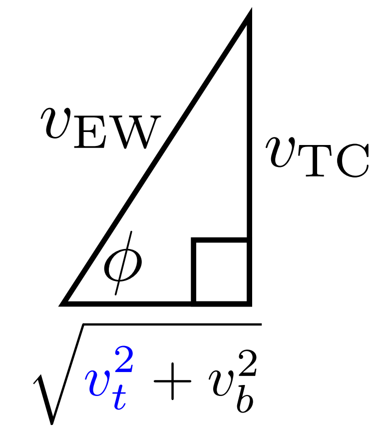
$$m_t^2[\rm TM] \simeq \frac{m^2}{M^2}\Sigma_t^2 , \quad m_T^2 \simeq M^2$$

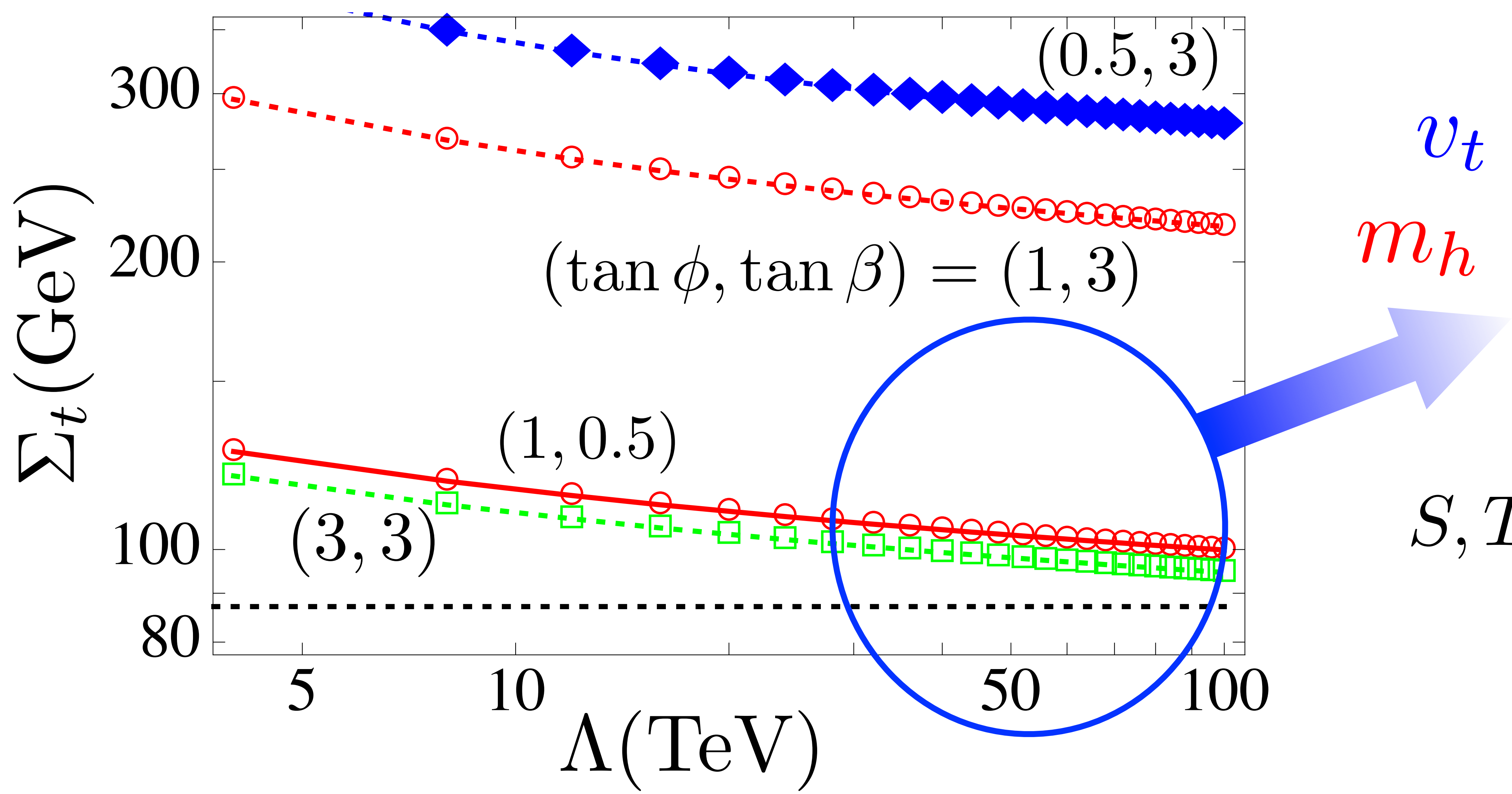
Model.1 [Result]

TMSM prediction

$$m_h = (\sqrt{2} \sim 2) \times \Sigma_t$$

$$\tan\beta \equiv \frac{v_t}{v_b},$$





$v_t \simeq 70\mathrm{GeV}$

$m_h \simeq 126\mathrm{GeV}$

S, T, R_b : O.K.

Model.2

Dobrescuet.al.(1998); Chivukula et.al.(1998); H.S.F and Tuominen(2013)

1. Top quark mass might be shared by other sector

2. TMSM prediction might be modified

$$m_h = 2 \times C \times m_t$$

field	TC	$\mathrm{SU}(3)_1$	$\mathrm{SU}(3)_2$	$\mathrm{SU}(2)_L$	$U(1)_Y$
$q_L^{(3)}$	1	3	1	2	1/6
$t_R^{(3)}$	1	3	1	1	2/3
$t_L^{(4)}$	1	3	1	1	2/3
$t_R^{(4)}$	1	3	1	1	2/3
$q^{(1,2)}$	1	1	3	SM	SM
Q_{TC}	R	-	-	-	-

$$\mathrm{EWSB} : v_{\mathrm{EW}}^2 = v_{\mathrm{TC}}^2 + v_t^2 \quad , \quad \frac{v_t}{v_{\mathrm{EW}}} \lesssim 1$$

Model.2 [Scenario & Result]

- Vector-like partner and seesaw mechanism

almost the same as Model.1

- $SU(3)_1 \times SU(3)_2 \to SU(3)_c$ derives

$$\mathcal{L}_{\text{model.2}} = G_t \left(\bar{q}_L^{(3)} t_R^{(4)}\right)\left(\bar{t}_R^{(4)} q_L^{(3)}\right) + G_{43}\left(\bar{t}_L^{(4)} t_R^{(3)}\right)\left(\bar{t}_R^{(3)} t_L^{(4)}\right) + G_{44}\left(\bar{t}_L^{(4)} t_R^{(4)}\right)\left(\bar{t}_R^{(4)} t_L^{(4)}\right)$$

$$G_t, G_{43}, G_{44} > \frac{8\pi^2}{N_c \Lambda^2}$$

$$G_t \to \text{EWSB}$$

$$G_{43}, G_{44} \to \text{Not EWSB}$$

$$g_A \equiv \frac{N_c \Lambda^2}{8\pi^2} G_A$$

Modified TMSM prediction

$$m_h = 2 \times \Sigma_t \times \left[\frac{g_t - g_{44}}{g_t - g_{44} + 2 g_t g_{44}}\right]^{1/2}$$

Summary of Model.1&2

1. Top quark mass is shared by ETC sector

$$m_h = (\sqrt{2} \sim 2) \times \Sigma_t \simeq 126\text{GeV}$$

$$v_t^2 = \Sigma_t^2 \frac{N_c}{8\pi^2} \ln \frac{\Lambda^2}{\Sigma_t^2} \simeq (70\text{GeV})^2$$

for $\Sigma_t \simeq \frac{174\text{GeV}}{2}$

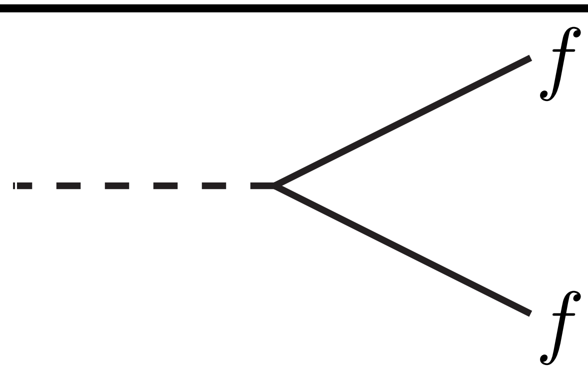
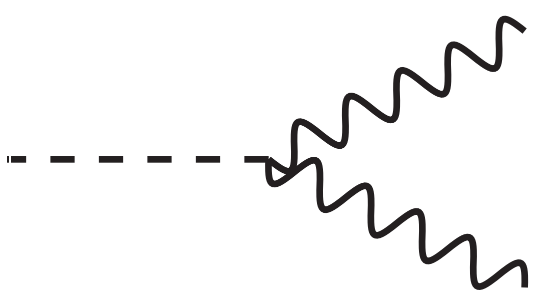
2. TMSM prediction is modified

$$m_h = 2 \times \Sigma_t \times \left[\frac{g_t - g_{44}}{g_t - g_{44} + 2 g_t g_{44}} \right]^{1/2} \simeq 126\text{GeV}$$

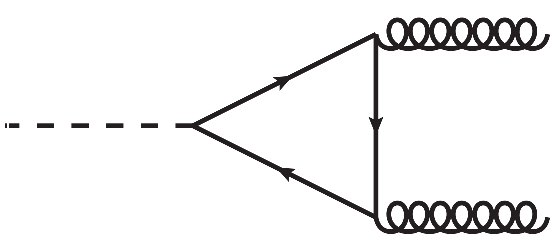
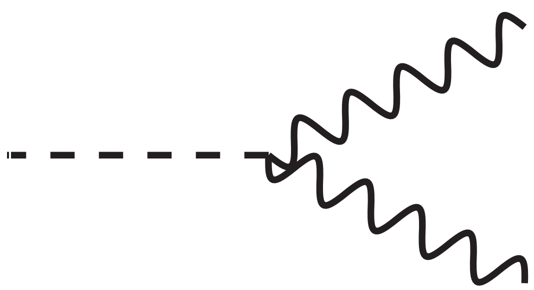
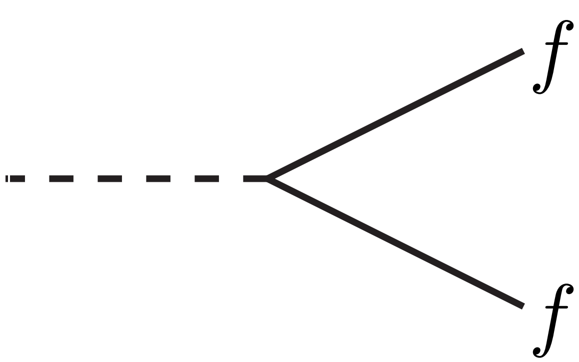
$$v_t^2 = \Sigma_t^2 \frac{N_c}{8\pi^2} \ln \frac{\Lambda^2}{\Sigma_t^2} \simeq (246\text{GeV})^2$$

TM Higgs boson coupling

- Both models CAN give 126 GeV Higgs boson.
- How are Higgs boson couplings ?

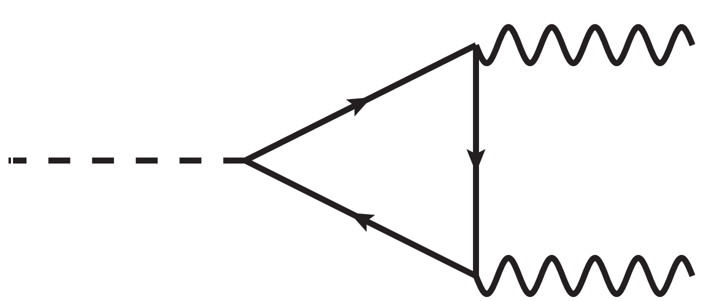
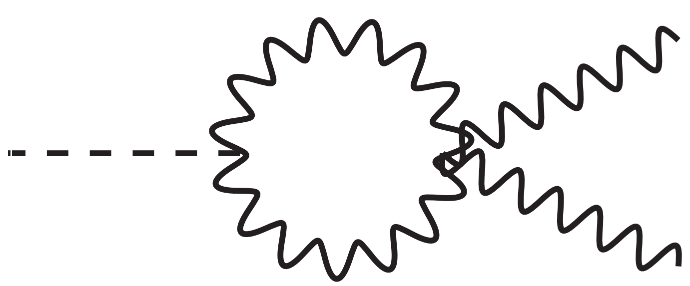
	TM-Higgs	
	Model.1	Model.2
	$f = t$ almost SM	$f = t$ almost SM
	$f = b, \tau$ parametrical	$f = b, \tau$ parametrical
	Suppressed $\frac{v_t}{v_{\rm EW}} \simeq 0.3$	almost SM

TM Higgs boson decay (w/o diphoton channel)

	TM-Higgs	
	Model.1	Model.2
	almost SM	almost SM
	Suppressed $\frac{v_t}{v_{\rm EW}} \simeq 0.3$	almost SM
 $f = b, \tau$	can be the same as the SM	can be the same as the SM

TM Higgs boson decay (diphoton channel.I)

$$\Gamma(h \to \gamma\gamma) \propto \left| C_{hWW} A_1 \left(\frac{4M_W^2}{m_h^2} \right) + \sum_f C_{hff} N_c Q_f^2 A_{1/2} \left(\frac{4m_f^2}{m_h^2} \right) \right|^2$$

	TM-Higgs	
	Model.1	Model.2
	$f = t$ almost SM	$f = t$ almost SM
	$f = T$ $\frac{v_{\rm EW}}{m_T} \simeq \frac{246\text{GeV}}{5\text{TeV}}$ tiny	$f = T$ $\frac{v_{\rm EW}}{m_T} \simeq \frac{246\text{GeV}}{5\text{TeV}}$ tiny
	Suppressed $\frac{v_t}{v_{\rm EW}} \simeq 0.3$	almost SM

TM Higgs boson decay (diphoton channel.II)

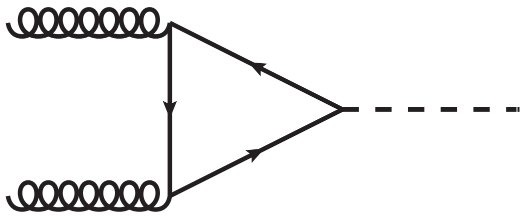
	TM-Higgs	
	Model.1	Model.2
C_{hff}	$C_{htt} \simeq 1$	$C_{htt} \simeq 1$
	$C_{hTT} \simeq 0$	$C_{hTT} \simeq 0$
C_{hWW}	$C_{hWW} = \frac{v_t}{v_{\rm EW}} \simeq 0.3$	$C_{hWW} = \frac{v_t}{v_{\rm EW}} \simeq 1$
$\Gamma(h \to \gamma\gamma)$	<< SM	~ SM

$$\Gamma(h \to \gamma\gamma) \propto \left| C_{hWW} A_1 \left(\frac{4M_W^2}{m_h^2} \right) + \sum_f C_{hff} N_c Q_f^2 A_{1/2} \left(\frac{4m_f^2}{m_h^2} \right) \right|^2$$

$$A_1 \simeq -7 \quad , \quad A_{1/2} \simeq 4/3$$

TM Higgs boson signal strength [ggF]

- Signal strength via ggF = difference of Br

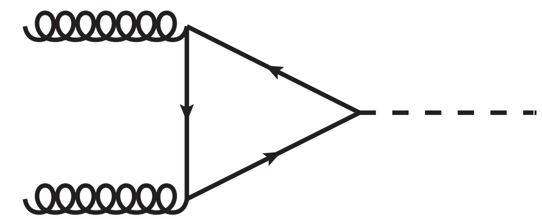
$\because$  ~ SM

- Model.1 : $\dfrac{\mathrm{Br}(h \to VV)}{\mathrm{Br}(h_{\mathrm{SM}} \to VV)} \ll 1, \quad (V = \gamma, W, Z)$

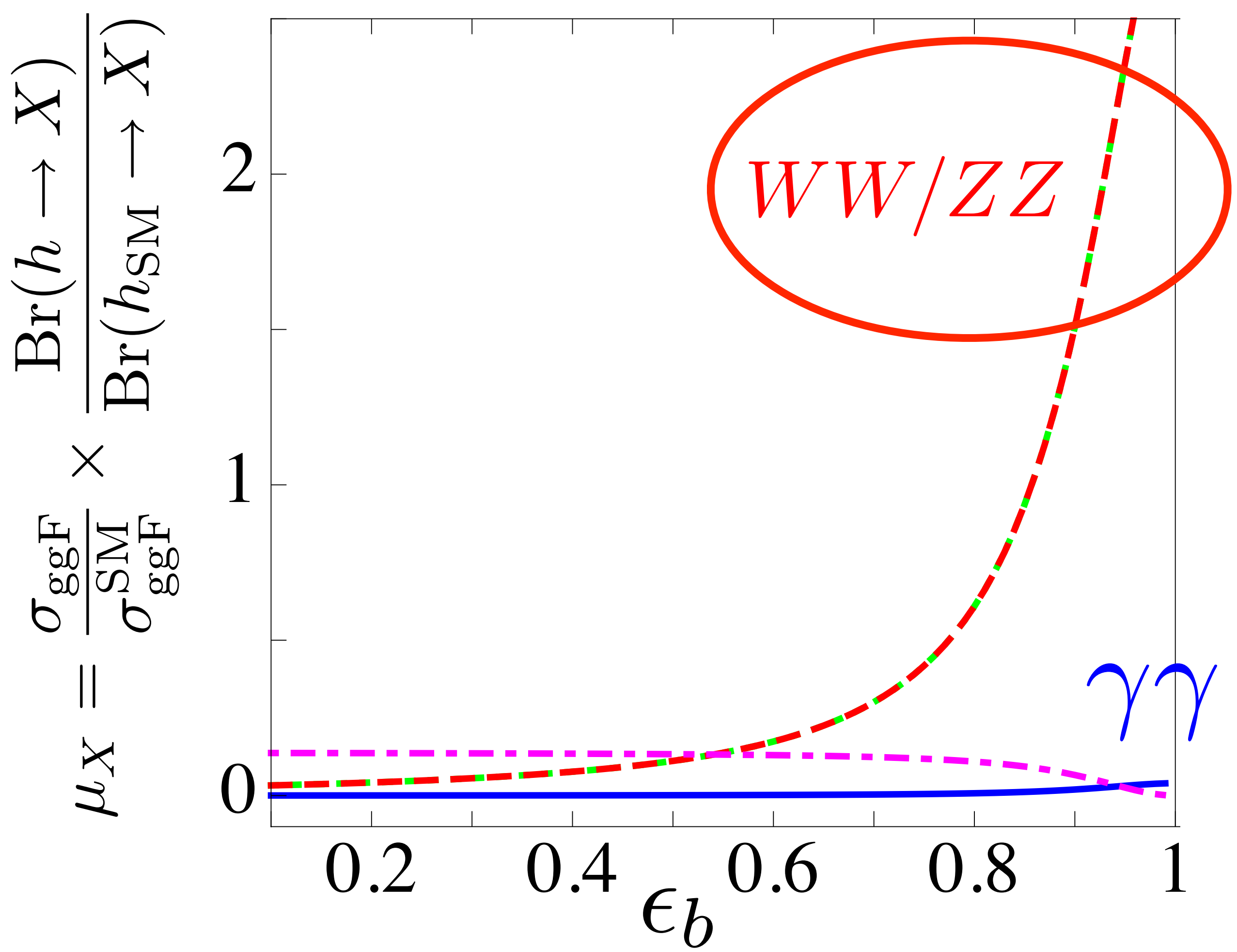
	TM-Higgs	
	Model.1	Model.2
$gg \to h \to WW/ZZ$	<< SM	~ SM
$gg \to h \to \gamma\gamma$	<< SM	~ SM

TM Higgs boson signal strength [WW/ZZ]

- Signal strength via ggF = difference of Br

$\because$  ~ SM

- Model.1 : $\frac{\mathrm{Br}(h \to VV)}{\mathrm{Br}(h_{\mathrm{SM}} \to VV)} \ll 1, \quad (V = \gamma, W, Z)$



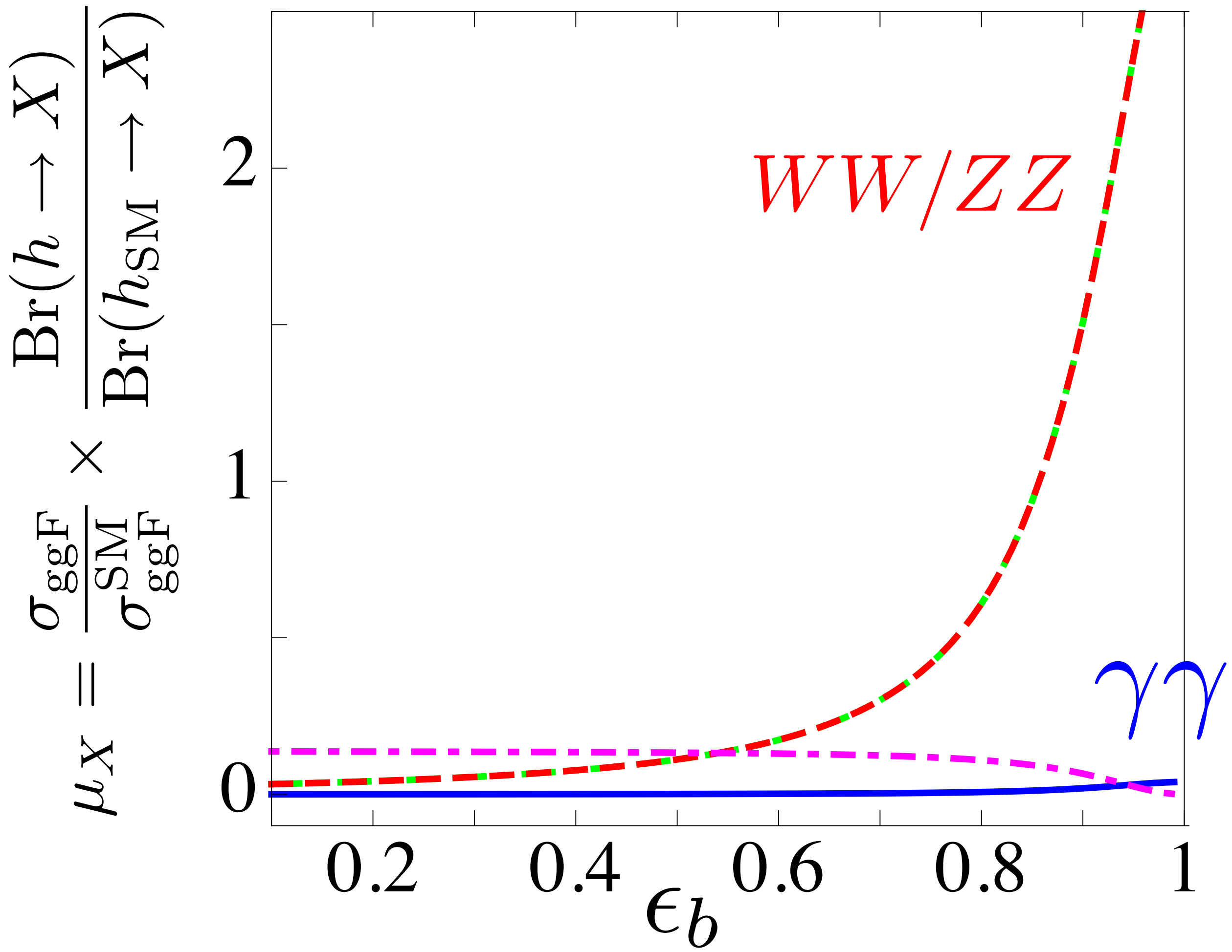
$\frac{\mathrm{Br}(h \to WW/ZZ)}{\mathrm{Br}(h_{\mathrm{SM}} \to WW/ZZ)} : \nearrow$

$\because \frac{\mathrm{Br}(h \to b\bar{b})}{\mathrm{Br}(h_{\mathrm{SM}} \to b\bar{b})} \propto 1 - \epsilon_b$

$\mathcal{L} \supset (1 - \epsilon_b) h \bar{b} b$

remains small...

TM Higgs boson signal strength [diphoton]

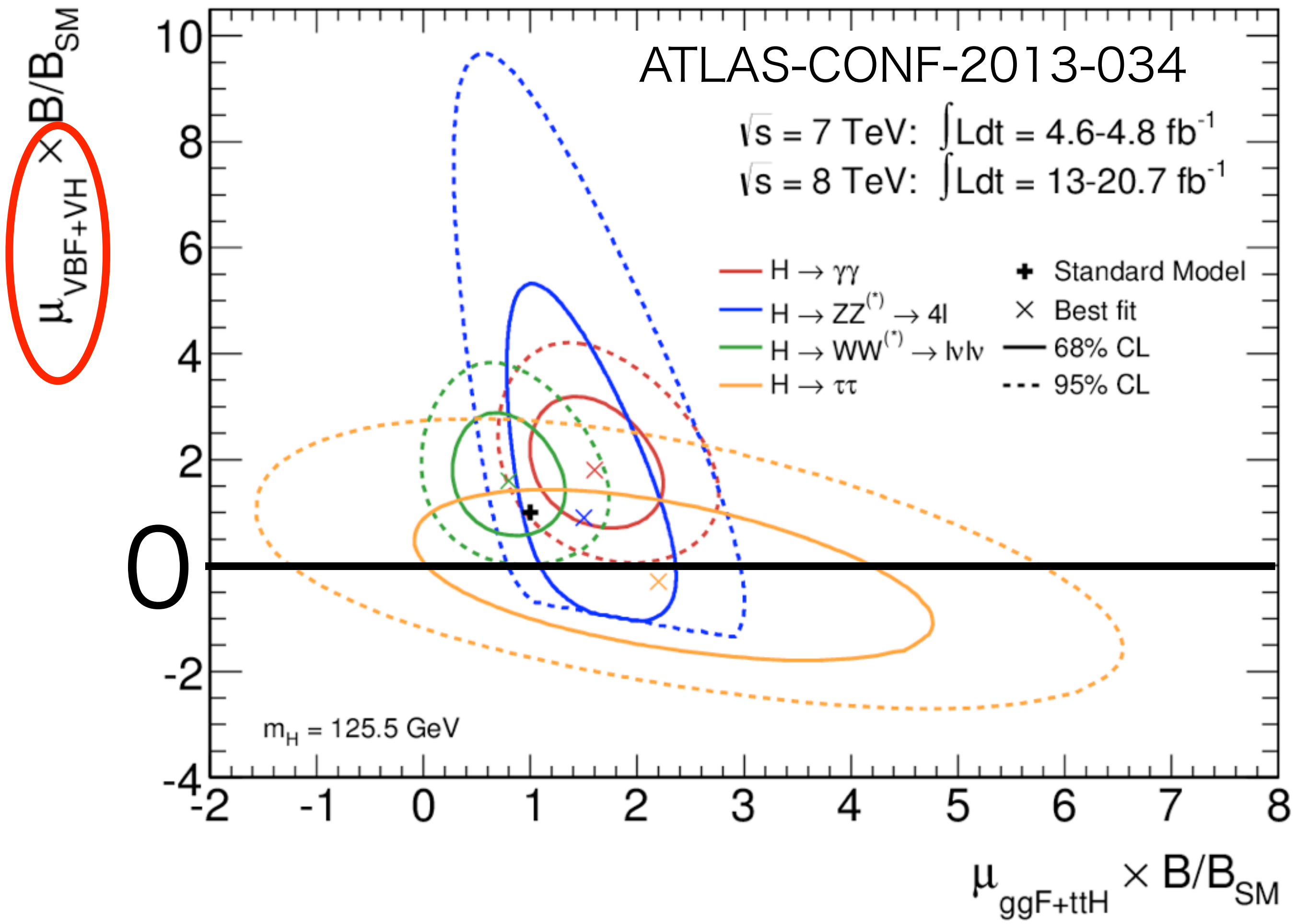


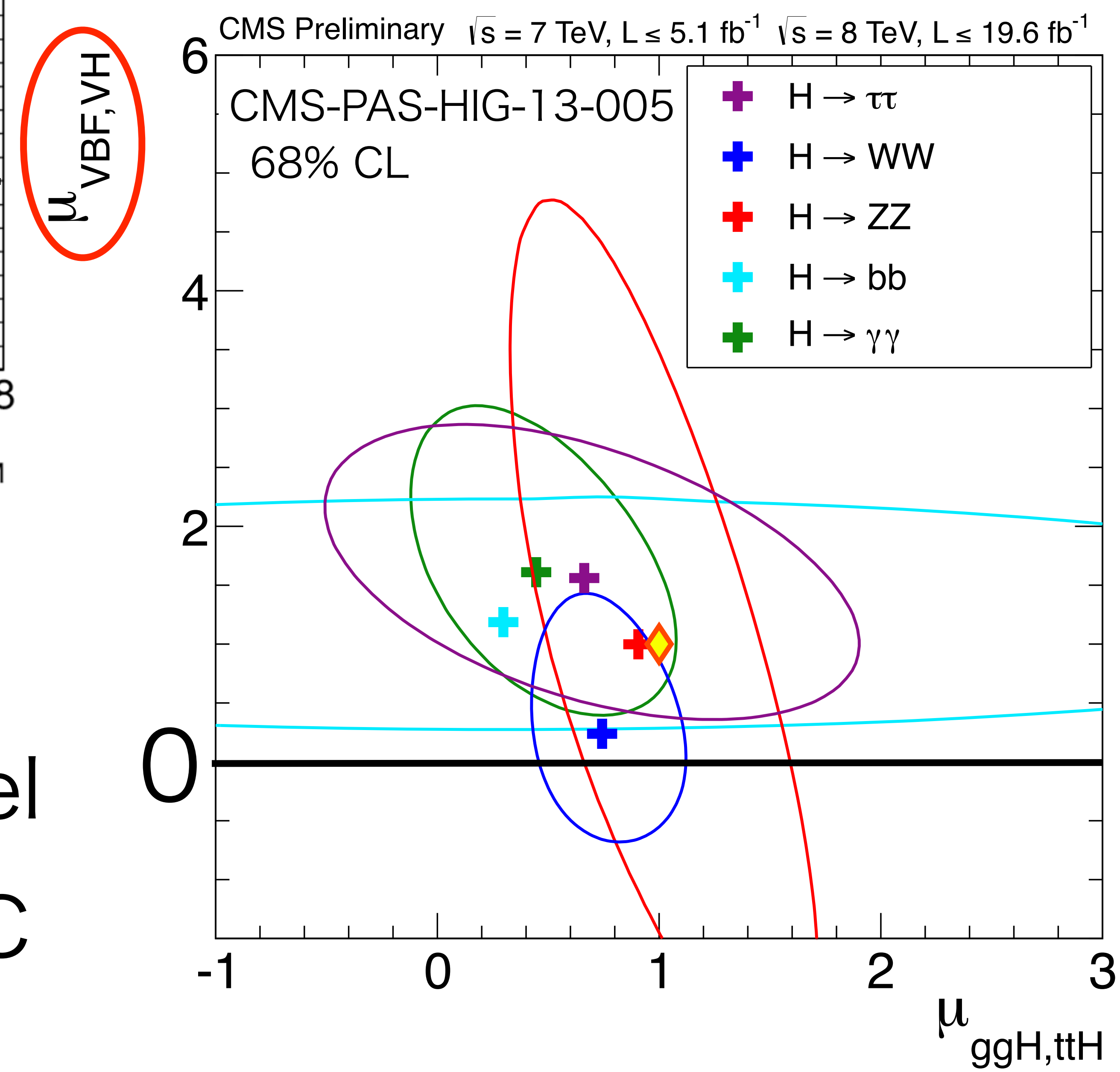
- We can improve $\frac{{\rm Br}(h \to \gamma\gamma)}{{\rm Br}(h_{\rm SM} \to \gamma\gamma)}$

by introducing new vector bosons ....

HOWEVER.....

Current LHC results (ggF VS VBF)





- Model.1 is ruled out by WW/ZZ-decay channel and/or VBF+VH @ LHC

TM Higgs boson status

	TM-Higgs	
	Model.1 X	Model.2
$gg \to h \to \gamma\gamma$	<< SM X	~ SM
$gg \to h \to WW/ZZ$	<< SM X	~ SM
VBF, VH	<< SM X	~ SM
$\mathrm{VBF,VH} \to b\bar{b}, \tau^- \tau^+$	<< SM X	depend on $h\bar{f}f$-couplings

- ☑ Top quark condensation is an alternative scenario to ETC w/ walking dynamics.
- ☑ Top quark condensation gives

$$m_h = (\sqrt{2} \sim 2) \times m_t$$

- ☑ There are several scenarios to realize 126 GeV Higgs boson.
- ☑ Model.1[top mass shared by ETC] is already ruled out by LHC data.
- ☑ Model.2[modified TMSM prediction] is a viable TMSM.

Thank you very much !!

Model.2 [Effective potential]

$$\Phi \quad : \text{EW doublet}$$

$$\phi \quad : \text{EW singlet}$$

$$\begin{aligned}
V(\Phi,\phi) \quad = \quad & \left[M_t^2 \left|\Phi_t\right|^2 + M_\chi^2 \left|\Phi_\chi\right|^2 + \sum_{f=t,b,\chi} M_{\chi f}^2 \left|\phi_{\chi f}\right|^2 \right] \\
& + C_{\chi t}\left[\phi_{\chi t} + \phi_{\chi t}^\dagger\right] + C_{\chi\chi}\left[\phi_{\chi\chi} + \phi_{\chi\chi}^\dagger\right] \\
& + \frac{\lambda}{2} \left[\left(\Phi_t^\dagger \Phi_t + \phi_{\chi t}^\dagger \phi_{\chi t}\right)^2 \right. \\
& + \left(\Phi_\chi^\dagger \Phi_\chi + \phi_{\chi b}^\dagger \phi_{\chi b}\right)^2 + \left(\Phi_\chi^\dagger \Phi_\chi + \phi_{\chi\chi}^\dagger \phi_{\chi\chi}\right)^2 \\
& + 2\left|\Phi_t^\dagger \tilde{\Phi}_\chi + \phi_{\chi t}^\dagger \phi_{\chi b}\right|^2 + 2\left|\Phi_\chi^\dagger \Phi_t + \phi_{\chi\chi}^\dagger \phi_{\chi t}\right|^2 \\
& \left. + 2\left|\tilde{\Phi}_\chi^\dagger \Phi_\chi + \phi_{\chi b}^\dagger \phi_{\chi\chi}\right|^2 \right]
\end{aligned}$$

htt and hTT coupling

$$\mathcal{L} \supset -c_{htt} \frac{m_t}{v_{\rm EW}} \bar{t} t h^0 - c_{hTT} \frac{m_T}{v_{\rm EW}} \bar{T} T h^0$$

where

$$c_{htt} \simeq \frac{v_{\rm EW}}{m_t} \frac{y}{\sqrt{2}} c_L^t c_R^t \quad , \quad c_{hTT} \simeq \frac{v_{\rm EW}}{m_T} \frac{y}{\sqrt{2}} s_L^t s_R^t$$

and

$$m_t \simeq \frac{y v_t}{\sqrt{2}} \times c_L^t c_R^t \quad , \quad v_{\rm EW} \simeq v_t \quad , \quad s_L^t \simeq \frac{m_t}{m_T}$$

EWPT constraints imply $c_L^t \simeq 1$

$$c_{htt} \simeq 1 \quad , \quad c_{hTT} \ll 1$$