DEWSB, quark mass hierarchy, and Fourth Family

Mt. Tsukuba

2nd Workshop on Beyond 3 generation

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(KEK)

M.H., Miransky, PRD80(2009)013004.

M.H., Miransky, 0912.4453.

M.H., in preparation.

§1 Introduction

◎ No theoretical reason to reject the 4th generation

★If the 4th generation exists, what is it for?

Holdom, PRL57(1986)2496.

$\Rightarrow$ $\boxed{\textbf{Dynamical Electroweak Symmetry Breaking}}$

We don't need to introduce an elementary Higgs. $\langle \overline{t'} t' \rangle \neq 0$

⋮

★The LHC has a discovery potential for the chiral 4th family at early stage.

urgent problem!

◎ If the 4th family quarks are discovered,
the next target is the Higgs sector.

$\Rightarrow$ $\boxed{\text{multiple Higgs bosons}}$

bound states of $\bar{t}'t'$, $\bar{b}'b'$, and also $\bar{t}t$, or more.

M.H., Miransky, 0912.4453.

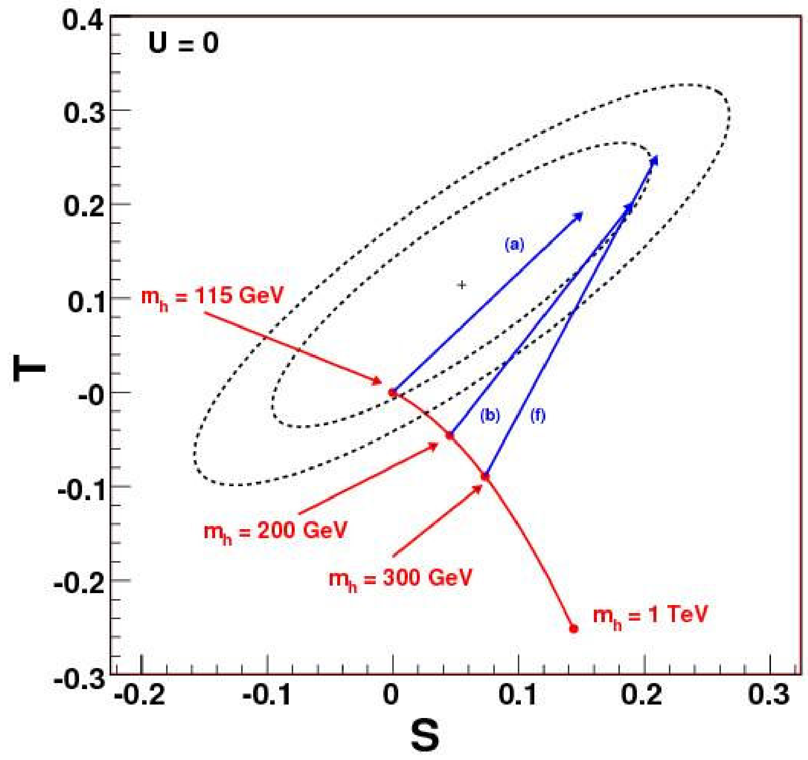
2,3,4,5 composite Higgs doublets

depending on scenarios

contents

Constraints on the mass spectrum of the 4th generation fermions and Higgs bosons

◎ Severe constraints arise from the oblique corrections



LEP EWWG 68% and 95% C.L. constraints

★ For the degenerate masses,

$$m_{t'} = m_{b'} \quad m_{\nu'} = m_{\tau'}$$

$$S_f = \frac{3+1}{6\pi} = 0.21$$

$\boxed{\text{viable parameter region}}$

1 Higgs + 4th family

$$m_{\tau'} - m_{\nu'} \simeq 30\text{–}60\,\mathrm{GeV}$$

$$m_{t'} - m_{b'} \simeq \left(1 + \frac{1}{5}\log\frac{m_H}{115\mathrm{GeV}}\right) \times 50\mathrm{GeV}$$

G.D.Kribs, T.Plehn, M.Spannowsky, T.M.P.Tait, PRD76('07)075016.

- LEPWG, $S = 0.07 \qquad T = 0.13$
- PDG2009, $S = -0.04 \pm 0.09 \quad T = 0.02 \pm 0.09$

★ Very recently, I reanalyzed the (S,T) constraints.
I also studied the effects of the RGE's;

- Instability bound for the Higgs potential

(If the Higgs mass is so small, the Higgs potential is unstable at some scale.)

- Perturbarive unitarity bounds
for the yukawa and Higgs quartic couplings

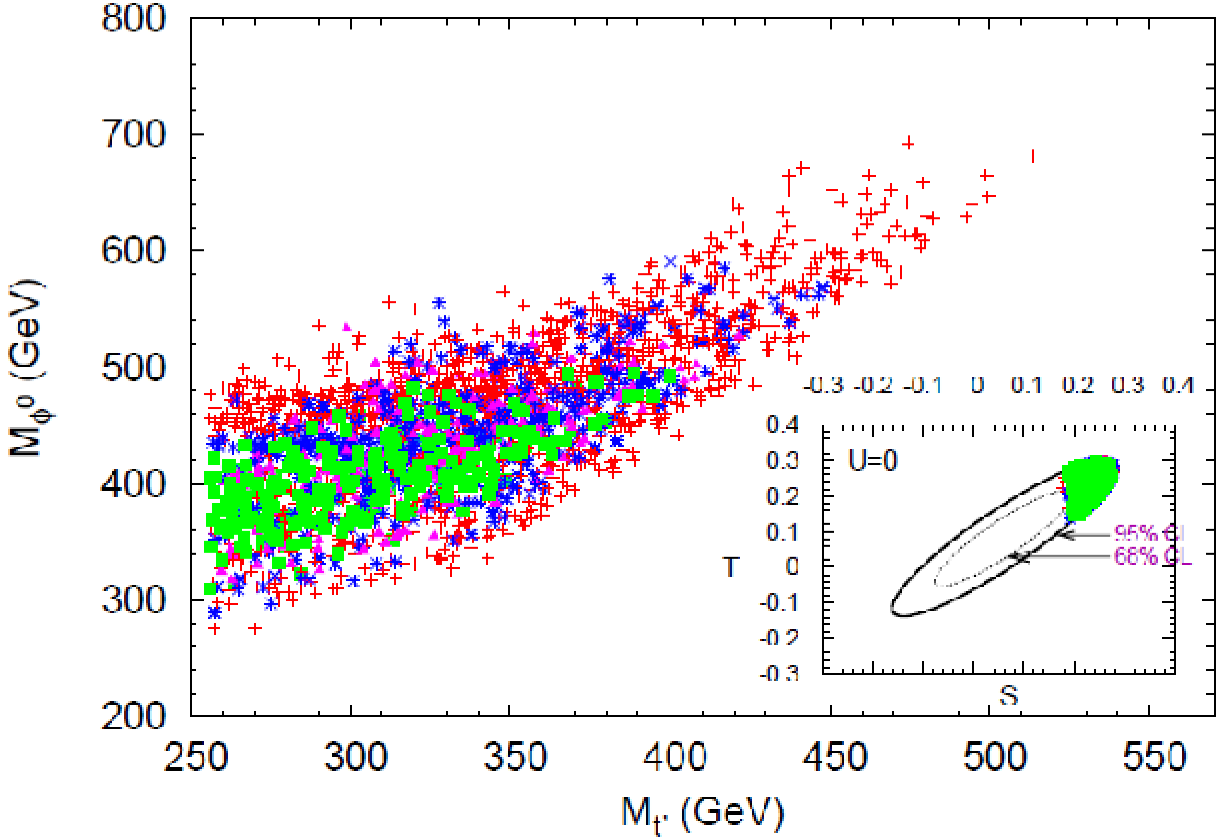
(If the couplings are so large, they diverge at some scale.)

$\Rightarrow$ Theoretical cutoff Λ

Inside of the cutoff, the theory is perturbative and also the Higgs potential is stable.

The cutoff should not be so small. Otherwise,
the effective theory @ TeV should contain something else…

$M_{t'}$ v.s. M_{ϕ^0} (SM4) (M.H., in preparation)



$$M_{\phi^0} \gtrsim M_{t'}$$

when $\Lambda \geq 2$ TeV

$$M_{\phi^0} \gtrsim M_{t'} - 50 \text{ GeV}$$

for $\Lambda \geq 1$ TeV

Red $2 \text{ TeV} \leq \Lambda < 3 \text{ TeV}$

Blue $3 \text{ TeV} \leq \Lambda < 4 \text{ TeV}$

Violet $4 \text{ TeV} \leq \Lambda < 5 \text{ TeV}$

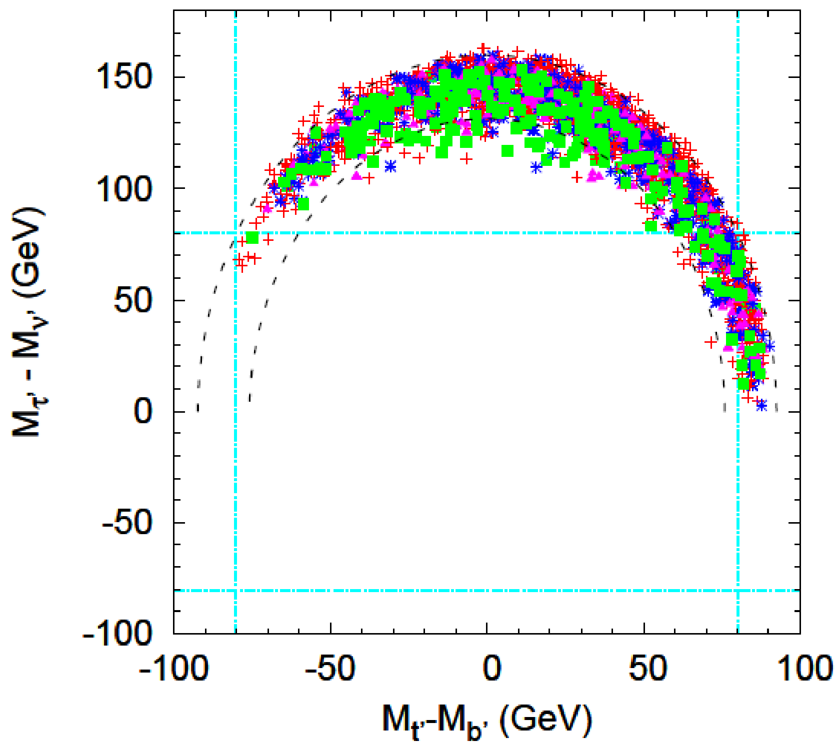
Green $\Lambda \geq 5 \text{ TeV}$

We varied

$$256 \text{ GeV} < M_{t'} < 552 \text{ GeV}$$
$$255 \text{ GeV} < M_{b'} < 552 \text{ GeV}$$
$$100.8 \text{ GeV} < M_{\tau'} < 1.23 \text{ TeV}$$
$$90.3 \text{ GeV} < M_{\nu'} < 1.23 \text{ TeV}$$
$$114 \text{ GeV} < M_{\phi^0} < \sqrt{4\pi} v$$

Dirac-type neutrnos are assumed.
The 1-loop RGE's are employed.

The mass difference of the fermions (Preliminary)



Favorable parameter region:

$$M_{t'} > M_{b'}$$

$$M_{\tau'} > M_{\nu'}$$

$$\frac{3(M_{t'}-M_{b'})^2}{M_W^2} + \frac{(M_{\tau'}-M_{\nu'})^2}{M_W^2} \approx (1.4\text{–}2.0) + 1.4 \ln \frac{M_{\phi^0}}{M_{\phi^0,ref}} .$$

(I took $M_{\phi^0,ref} = 117$ GeV)

$\tau' \to \nu' + W^-$ is allowed in a wide parameter space!!

$t' \to b' + W^{(*)}$ is also possible.

Notice that the Higgs is not so light, $M_{\phi^0} \gtrsim M_{t'}$

(Preliminary)

	M_{ϕ^0}	$M_{t'}$	$M_{b'}$	$M_{\nu'}$	$M_{\tau'}$	Λ	S	T
(a1)	0.47	0.36	0.34	0.092	0.23	3.5	0.20	0.22
(a2)	0.59	0.45	0.42	0.092	0.24	2.3	0.21	0.22
(b1)	0.45	0.32	0.36	0.098	0.23	8.0	0.23	0.27
(b2)	0.55	0.40	0.41	0.13	0.23	3.4	0.24	0.22
(c1)	0.39	0.32	0.34	0.093	0.23	2.4	0.21	0.23
(c2)	0.55	0.43	0.41	0.13	0.28	2.1	0.24	0.23
(d1)	0.49	0.36	0.34	0.26	0.40	2.1	0.26	0.24

TABLE I: Sample data for several scenarios. The mass unit is TeV. For (a1), (b1), (c1) and (d1), we took the mass bounds $M_{t'} > 311$ GeV and $M_{b'} > 338$ GeV [38], whereas we did $M_{t',b'} > 400$ GeV for (a2), (b2) and (c2). For all samples, we took $\Lambda \geq 2$ TeV. The criterion for (a1) and (a2) is the χ^2-minimum. Similarly, (b1) and (b2) have the largest Λ within the 95% C.L. limit of the (S,T)-constraints. The samples (c1) and (c2) are most favorable data for $M_{\phi^0} < 2M_{\tau'}$, while (d1) is for $M_{\phi^0} < 2M_{\nu'}$. We do not have the data sample with $M_{t',b'} > 400$ GeV and $M_{\phi^0} < 2M_{\nu'}$.

Several decay channels are possible

$$\phi^0 \rightarrow \bar{\nu}'\nu'$$
$$\phi^0 \rightarrow \bar{\tau}'\tau'$$

etc…

★ Let us take into account the effects of the mixing between the 3rd and 4th family quarks.
(I didn't consider the mixing in the lepton sector.)

$$\left|V_{t'b}\right| = \left|V_{tb'}\right| = s_{34}$$

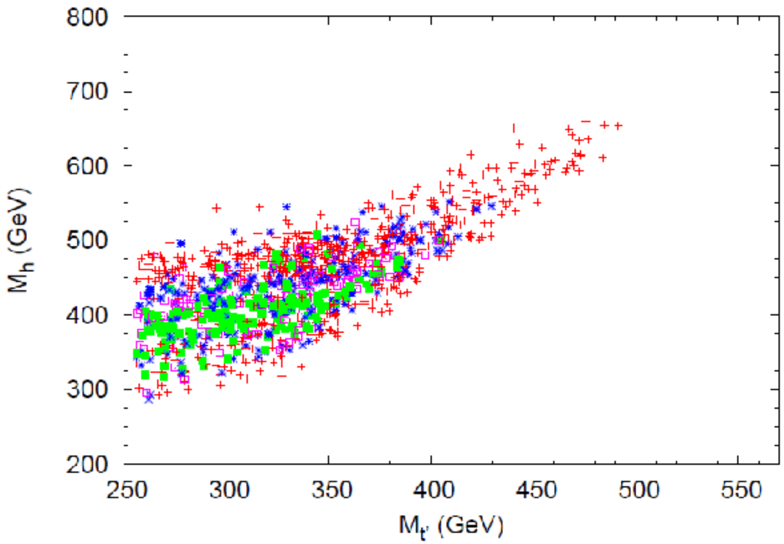
◎ It contributes to the T-parameter (and also the RGE's).

$$T_4 = \frac{1}{8\pi x_W(1-x_W)}\left\{3\left[F_{t'b'} + s_{34}^2(F_{t'b} + F_{tb'} - F_{tb} - F_{t'b'})\right] + F_{l_4\nu_4}\right\}.$$

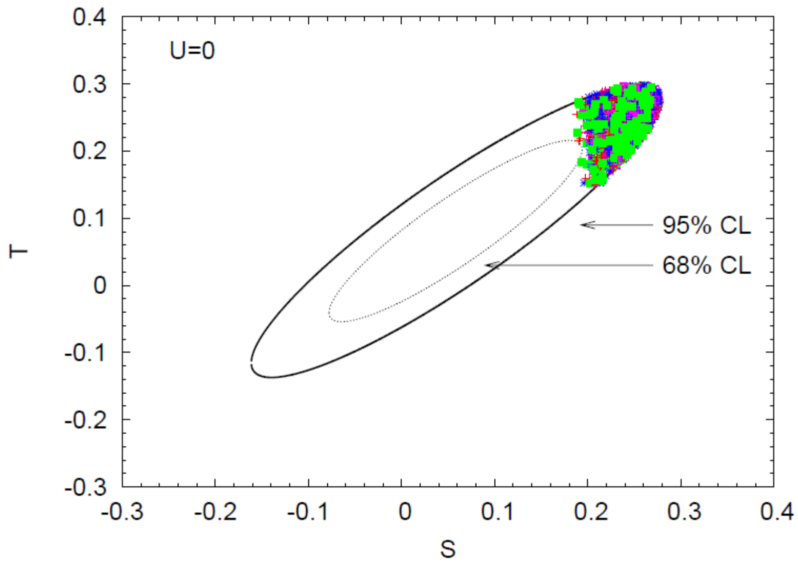
M. S. Chanowitz, Phys. Rev. D79, 113008 (2009) .

$s_{34} = 0.10$

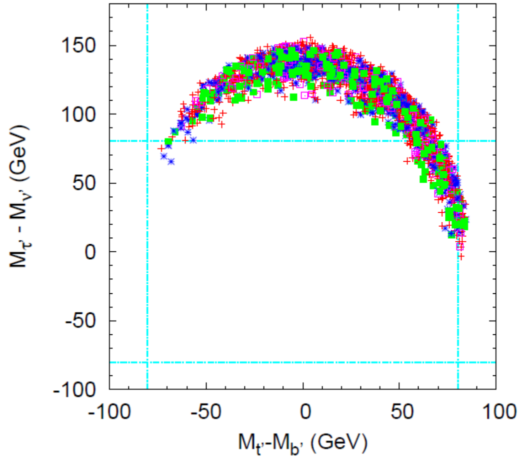
$M_{t'}$ v.s. M_{ϕ^0}



Data samples and (S,T)-contour



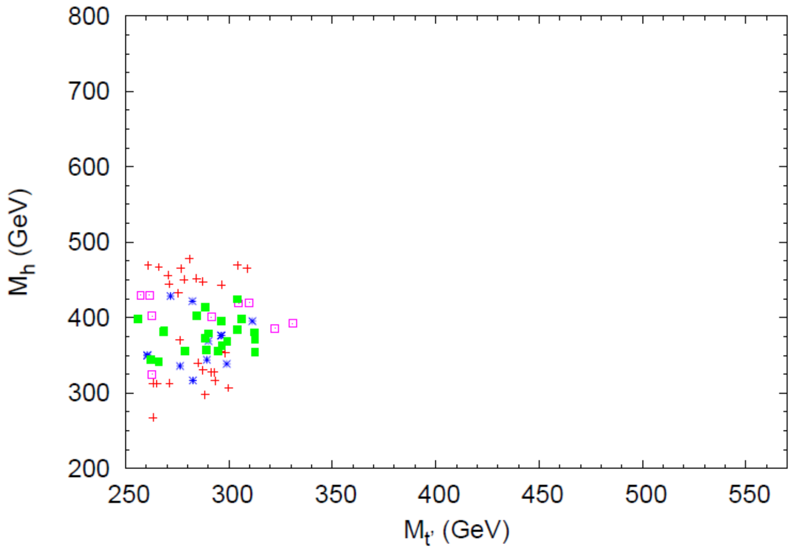
(Preliminary)



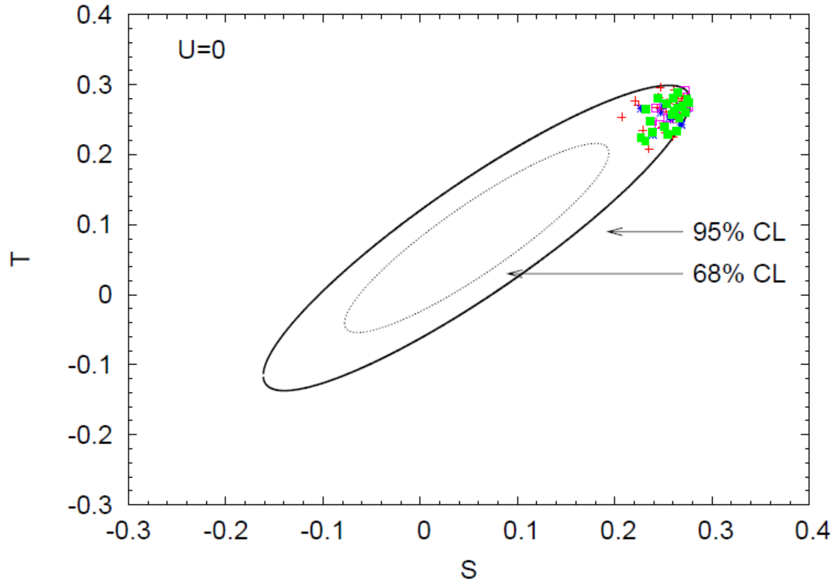
Mass diff.

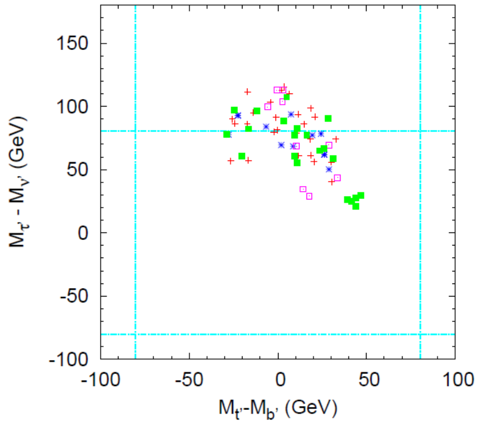
$s_{34} = 0.30$

$M_{t'}$ v.s. M_{ϕ^0}



Data samples and (S,T)-contour





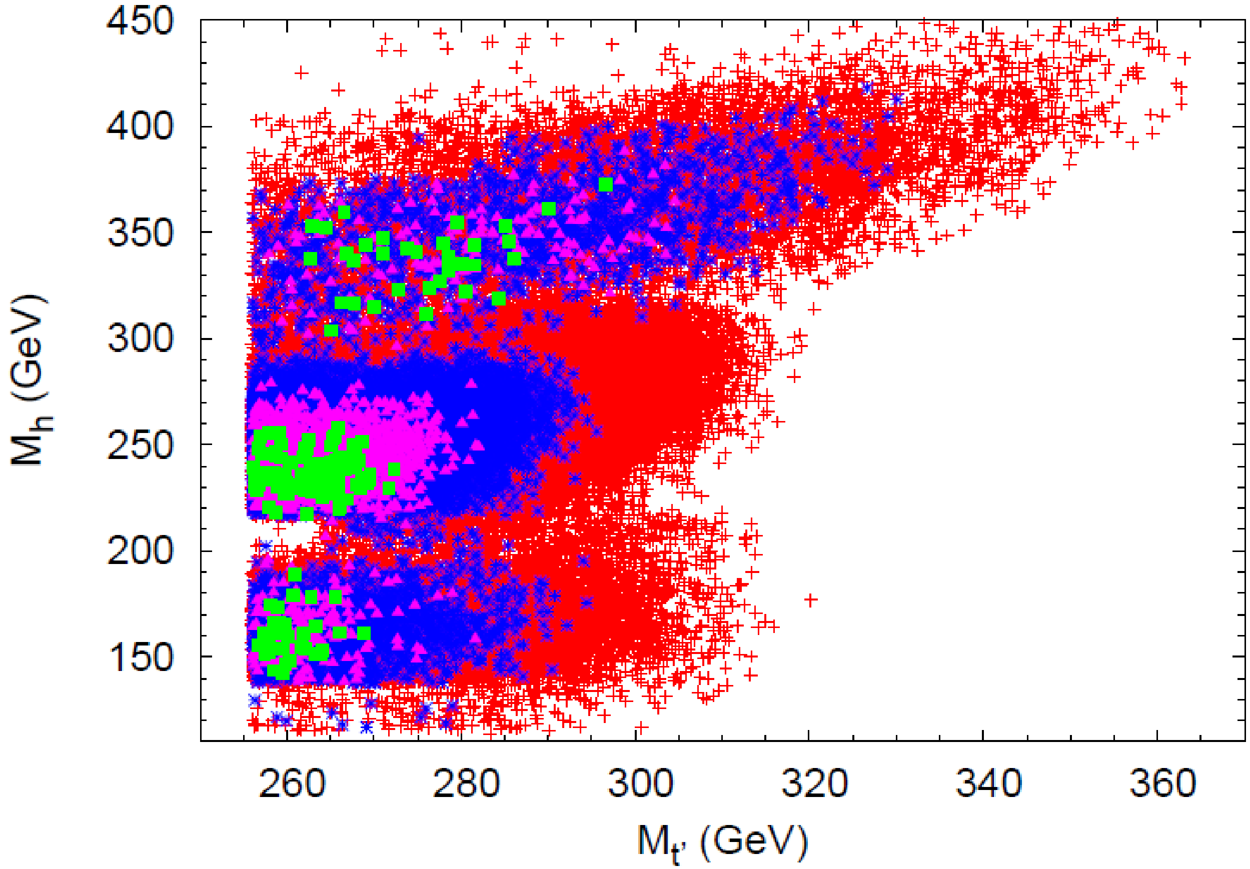
Mass diff.

(Preliminary)

Two Higgs doublet model of type II

$$\sin(\beta - \alpha) = 1$$

The light CP even Higgs h is completely SM-like.



Schematically speaking,

$M_h \gtrsim 300$ GeV

corresponds to

the heavy Higgs decoupling regime.

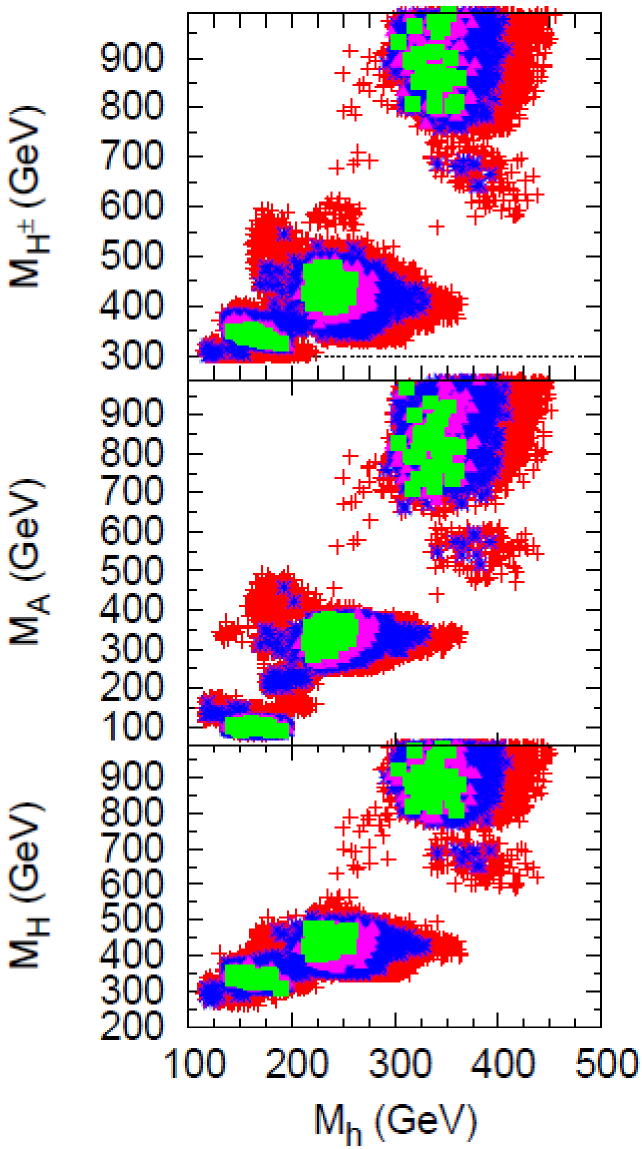
The low mass region

$M_h \lesssim 300$ GeV,

is exotic!

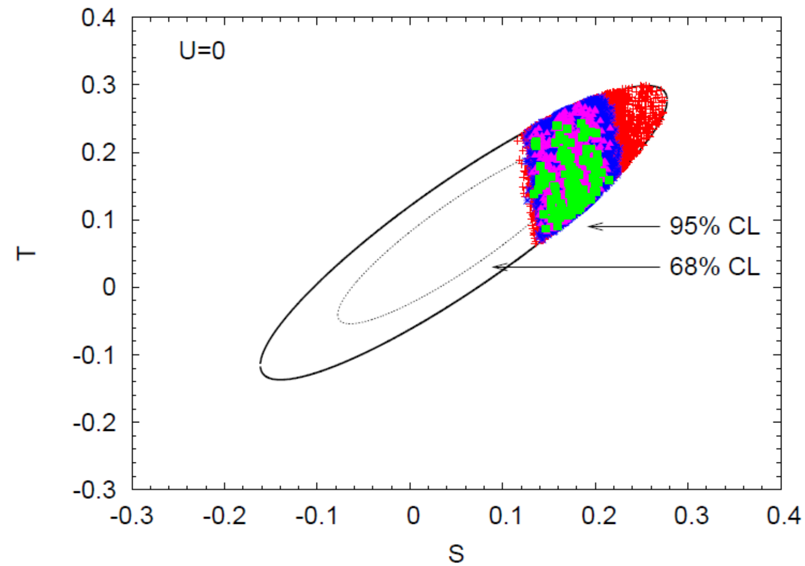
$M_h \sim 100$ GeV is possible due to **dynamics of quartic couplgs.**

Heavy Higgs masses



(Preliminary)

Data samples and (S,T)-contour



The 2HDM is better than the SM4!

Detailed studies are needed.

$\sin(\beta-\alpha) \neq 1$, Type I, type X, etc.

The RGE's for the quartic couplings in the 2HDM II

$$
\begin{aligned}
(16\pi^2)\mu\frac{\partial}{\partial\mu}\lambda_1 = \quad & 24\lambda_1^2 + 2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_5^2 - 3\lambda_1(3g_2^2 + g_1^2) + \frac{3}{8}\left[2g_2^4 + (g_2^2 + g_1^2)^2\right] \\
& +4\lambda_1\left[3y_{b'}^2 + 3y_b^2 + y_{\tau'}^2 + y_\tau^2\right] - 2\left[3y_{b'}^4 + 3y_b^4 + y_{\tau'}^4 + y_\tau^4\right], \\
(16\pi^2)\mu\frac{\partial}{\partial\mu}\lambda_2 = \quad & 24\lambda_2^2 + 2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_5^2 - 3\lambda_2(3g_2^2 + g_1^2) + \frac{3}{8}\left[2g_2^4 + (g_2^2 + g_1^2)^2\right] \\
& +4\lambda_2\left[3y_{t'}^2 + 3y_t^2 + y_{\nu'}^2\right] - 2\left[3y_{t'}^4 + 3y_t^4 + y_{\nu'}^4\right], \\
(16\pi^2)\mu\frac{\partial}{\partial\mu}\lambda_3 = \quad & 2(\lambda_1 + \lambda_2)(6\lambda_3 + 2\lambda_4) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 - 3\lambda_3(3g_2^2 + g_1^2) + \frac{3}{4}\left[2g_2^4 + (g_2^2 - g_1^2)^2\right] \\
& +2\lambda_3\left[3(y_t^2 + y_b^2 + y_{t'}^2 + y_{b'}^2) + y_{\nu'}^2 + y_{\tau'}^2 + y_\tau^2\right] - 4\left[3y_{t'}^2 y_{b'}^2 + 3y_t^2 y_b^2 + y_{\nu'}^2 y_{\tau'}^2\right], \\
(16\pi^2)\mu\frac{\partial}{\partial\mu}\lambda_4 = \quad & 4(\lambda_1 + \lambda_2 + 2\lambda_3 + \lambda_4)\lambda_4 + 8\lambda_5^2 - 3\lambda_4(3g_2^2 + g_1^2) + 3g_1^2 g_2^2 \\
& +2\lambda_4\left[3(y_t^2 + y_b^2 + y_{t'}^2 + y_{b'}^2) + y_{\nu'}^2 + y_{\tau'}^2 + y_\tau^2\right] + 4\left[3y_{t'}^2 y_{b'}^2 + 3y_t^2 y_b^2 + y_{\nu'}^2 y_{\tau'}^2\right], \\
(16\pi^2)\mu\frac{\partial}{\partial\mu}\lambda_5 = \quad & \lambda_5\left[4(\lambda_1 + \lambda_2) + 8\lambda_3 + 12\lambda_4 - 3(3g_2^2 + g_1^2) + 2\left\{3(y_t^2 + y_b^2 + y_{t'}^2 + y_{b'}^2) + y_{\nu'}^2 + y_{\tau'}^2 + y_\tau^2\right\}\right]
\end{aligned}
$$

The chiral 4th generation has not yet been excluded by experiments.

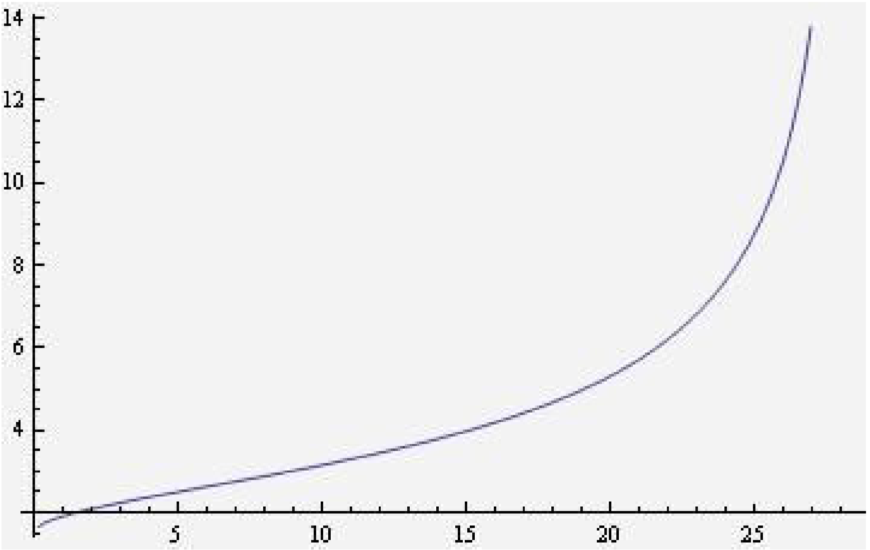
◎ **A multiple Higgs scenario seems to be more natural and favorable than the SM4.**

Probably, the LHC will answer the question.

$\Longrightarrow$ If the 4th family may exist, what is interesting?

Dynamical Electroweak Symmetry Breaking

The 4th generation quarks can be closely connected with the DEWSB through their condensations.



$y_{t'}$

μ (TeV)

The yukawa coupling runs very quickly and reaches the Landau pole at most several tens TeV.

This is a signal for the DEWSB!!

§.3 Superheavy quarks and multi-Higgs doublets

M.H., Miransky, PRD80(2009)013004; 0912.4453.

◎ The yukawa couplings have the Landau pole,
so that the theory is effective only up to this scale < O(10TeV).

★The Nambu-Jona-Lasinio description is applicable in low energy.

○ The point is that the masses of t', b' and t are O(v=246GeV).

$$m_{t'}, m_{b'} \gtrsim 300\text{GeV} \quad m_t = 175\text{GeV}$$

$$\Downarrow$$

★ The t' and b' condensations can dynamically trigger the EWSB and also the top may contribute somewhat.

$$\boxed{\text{Multiple Higgs doublet model}}$$

2,3,4,5 Higgs doublets

§. 3-1 Three Higgs doublet model

M.H., Miransky, 0912.4453.

Model low energy effective theory @ composite scale

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_g + \mathcal{L}_{\mathrm{NJL}}$$

$\mathcal{L}_f$: kinetic term for the fermions

We consider only t', b' and t.

$\mathcal{L}_g$: kinetic term for the gauge bosons

$\mathcal{L}_{\mathrm{NJL}}$: Nambu-Jona-Lasinio couplings effectively induced in low energy

$$\mathcal{L}_{\mathsf{NJL}} = G_{t'}(\bar{\psi}_L^{(4)} t'_R)^2 + G_{b'}(\bar{\psi}_L^{(4)} b'_R)^2 + G_t(\bar{\psi}_L^{(3)} t_R)^2$$
$$+ G_{t'b'}(\bar{\psi}_L^{(4)} t'_R)(\bar{b}'_R{}^c i\tau_2 (\psi_L^{(4)})^c) + (h.c.)$$
$$+ G_{t't}(\bar{\psi}_L^{(4)} t'_R)(\bar{t}_R \psi_L^{(3)}) + (h.c.)$$
$$+ G_{b't}(\bar{\psi}_L^{(3)} t_R)(\bar{b}'_R{}^c i\tau_2 (\psi_L^{(4)})^c) + (h.c.)$$

How to get them:

$G_{t'}, G_{b'}, G_t$: Topcolor gauge boson exchange

$G_{t'b'}$: topcolor instanton

$G_{t't}$: flavor changing neutral interaction between t'-t

$G_{b't}$: We don't know a natural candidate of the origin.

$$G_{b't} = 0$$

Auxiliary Field Method

Let us introduce the auxiliary field,

$$\Phi_{t0} = \frac{1}{G_t}(\bar{t}_R \psi_L^{(3)}) \quad \text{etc.}$$

yukawa int.

$$\mathcal{L}_{\mathrm{NJL}} \to (\bar{\psi}_L^{(4)} t'_R)\Phi_{t'0} + (\bar{\psi}_L^{(4)} b'_R)\tilde{\Phi}_{b'0} + (\bar{\psi}_L^{(3)} t_R)\Phi_{t0}$$

$$+ M^2_{\Phi_{t'0}} \Phi^\dagger_{t'0}\Phi_{t'0} + M^2_{\Phi_{b'0}} \Phi^\dagger_{b'0}\Phi_{b'0} + M^2_{\Phi_{t0}} \Phi^\dagger_{t0}\Phi_{t0}$$

$$+ M^2_{\Phi_{t'0}\Phi_{b'0}} \Phi^\dagger_{t'0}\Phi_{b'0} + (h.c.)$$

$$+ M^2_{\Phi_{t'0}\Phi_{t0}} \Phi^\dagger_{t'0}\Phi_{t0} + (h.c.)$$

Higgs mass terms

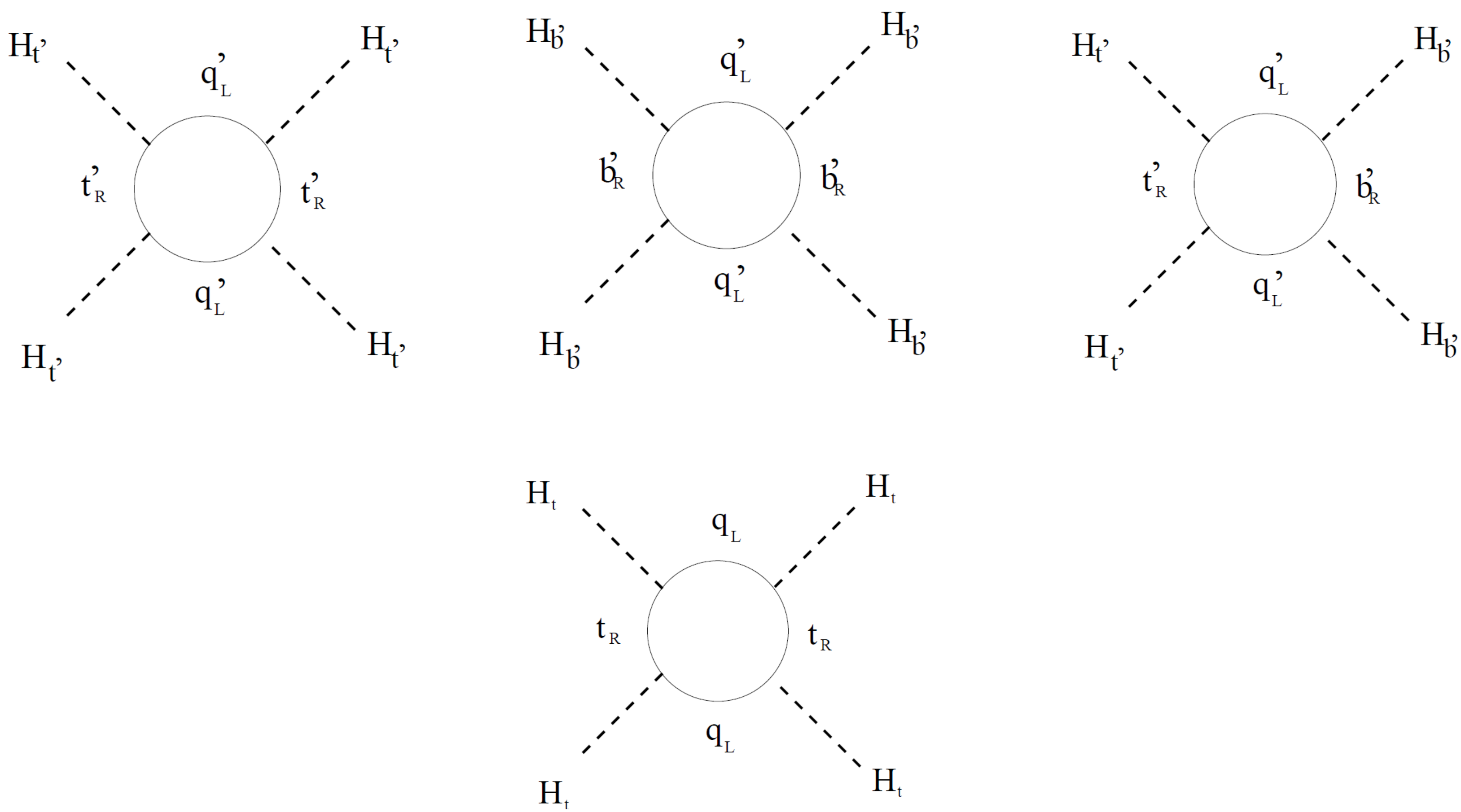
$$+ M^2_{\Phi_{b'0}\Phi_{t0}} \Phi^\dagger_{b'0}\Phi_{t0} + (h.c.)$$

$$\tilde{\Phi}_{b'0} \equiv -i\tau_2 \Phi^*_{b'0}$$

If $G_{b't} = 0 \ \Rightarrow \ M^2_{\Phi_{b'0}\Phi_{t0}} \approx 0$

◎The low energy effective theory @ EWSB scale

Higgs quartic couplings @ 1/Nc leading approximation



◎ When we ignore the EW 1-loop effect,
the (2+1)-Higgs structure is safely kept.
The quartic term is then written as

$$
\begin{aligned}
V^{(4)}_{2+1} = \lambda_1(\Phi^\dagger_{b'}\Phi_{b'})^2 &+ \lambda_2(\Phi^\dagger_{t'}\Phi_{t'})^2 \\
&+ \lambda_3|\Phi_{t'}|^2|\Phi_{b'}|^2 + \lambda_4|\Phi^\dagger_{t'}\Phi_{b'}|^2 \\
&+ \lambda_t(\Phi^\dagger_t\Phi_t)^2
\end{aligned}
$$

Higgs quartic coupling --- 2 Higgs part + 1 Higgs part

(2+1)-Higgs doublet model

(The mass terms are general one.)

Cf) $|\Phi_{t'}|^2|\Phi_t|^2$ is absent.

§. 3-2 Numerical Analysis

- We have 8 theoretical parameters;

$$G_{t'} \quad G_{b'} \quad G_t \quad G_{t'b'} \quad G_{t't} \quad G_{b't} \quad \Lambda_4 \quad \Lambda_3$$

Λ_4 : composite scale (Landau pole) of t' and b'

Λ_3 : composite scale (Landau pole) of the top

The physical quantities are

3 Higgs doublets:	CP even Higgs -- 3	H_1, H_2, H_3
	CP odd Higgs -- 2	A_1, A_2
	charged Higgs -- 2+2	$H_1^{\pm}, H_2^{\pm}$
$M_{H_1} < M_{H_2} < M_{H_3}$ $M_{A_1} < M_{A_2}$	VEV -- 3	$v_{b'}, v_{t'}, v_t$
	etc.	

◎It is convenient to take the following parameters:

$$v(= 246\mathrm{GeV}) \qquad m_t(= 171.2\mathrm{GeV})$$

$$\tan\beta_4(\simeq 1) \qquad M_{A_1} \quad M_{A_2} \quad \Lambda_4 \quad \Lambda_3$$

$$M^2_{\Phi_{b'}\Phi_t} \approx 0$$

★ The outputs are

$$m_{t'} \quad m_{b'} \quad M_{H_1} \quad M_{H_2} \quad M_{H_3} \quad M_{H_1^\pm} \quad M_{H_2^\pm} \quad \tan\beta_{34}$$

decay widths of $H_{1,2,3} \to WW, ZZ$ etc.

yukawa couplings between the fermions and the Higgs bosons

◎ Definition of the angles of the VEVs

$$v_{b'} \equiv < \Phi_{b'} > = v \cos\beta_4 \cos\beta_{34}$$

$$v_{t'} \equiv < \Phi_{t'} > = v \sin\beta_4 \cos\beta_{34}$$

$$v_t \equiv < \Phi_t > = v \sin\beta_{34}$$

$$v = 246\text{GeV}$$

◎ It is natural to take similar composite scales.

$$\Lambda_4 \simeq \Lambda_3 \qquad \Lambda_4 \leftarrow y_{t'}, y_{b'} \qquad \Lambda_3 \leftarrow y_t$$

◎ Owing to yt' = yb', the T parameter constraint implies

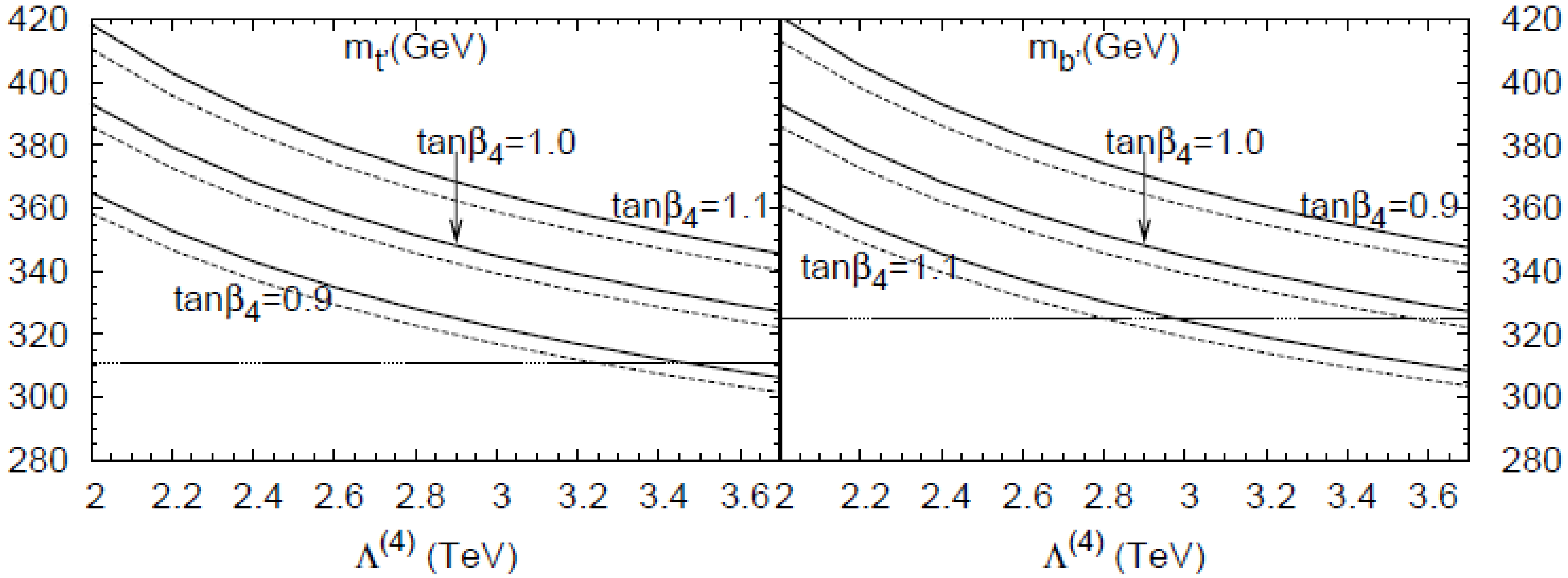
$$m_{t'} \simeq m_{b'} \Rightarrow v_{t'} \simeq v_{b'} \qquad \tan\beta_4 \simeq 1$$

Also, $\tan^2\beta_{34} \simeq \dfrac{m_t^2}{m_{t'}^2 + m_{b'}^2} \sim 0.1 - 0.2 \ll 1$

We calculate the mass spectrum by using the RGE:

RGE for the (2+1)-Higgs doublets + compositeness conditions

(Bardeen – Hill – Lindner approach)

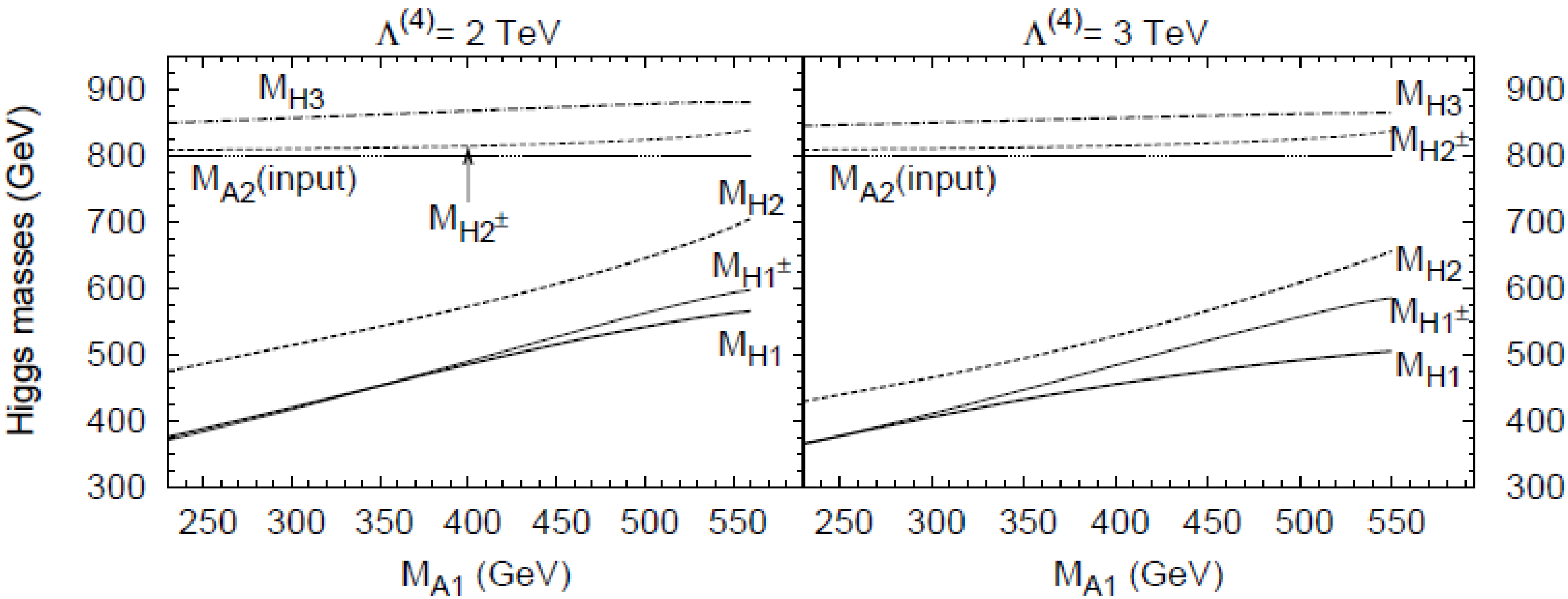


$m_{t'}$ and $m_{b'}$ for various Λ_4

The bold curves are for $\Lambda_3/\Lambda_4 = 1$

The dashed curves are for $\Lambda_3/\Lambda_4 = 2$

The mass spectrum of the Higgs bosons for various M_{A_1}



We also used $\tan\beta_4 = 1$ and $\Lambda_3/\Lambda_4 = 1.5$

$M_{A_2} \sim M_{H_3} \sim M_{H_2^{\pm}} \gg M_{H_1,H_2,H_1^{\pm}}$ → (2+1) Higgs structure

How about the Higgs contributions to the S,T-parameter

$$S_H = 0 \sim 0.04, \; T_H = -0.02 \sim -0.1$$

$\Lambda_4 = 2 - 10$ TeV $\quad \Lambda_3/\Lambda_4 = 1 - 2$

$0.2\text{TeV} < M_{A_1} < 0.6\text{TeV} \quad 0.5\text{TeV} < M_{A_2} < 0.8\text{TeV}$

→ If $M_{\tau'} - M_{\nu'} \sim 150$ GeV the model is within 95%CL limit of S,T.

★ R_b constraint is potentially dangerous.

$$R_b^{\text{obs}} = 0.21629 \pm 0.00066 \qquad R_b^{\text{SM}} = 0.21584$$

2σ bounds yield the constraint to $M_{H_2^\pm}$ and it corresponds to

$$M_{A_2} = 0.70, 0.58, 0.50 \;\text{ TeV}$$

for $\Lambda_4 = 2, 5, 10$ TeV

The sensitivity of M_{A_1} and Λ_3/Λ_4 is small.

★ CKM structure

M.H., Miransky, PRD80(2009)013004.

To obtain the diagonal part, the current mass enhancement mechanism may be useful:

Supposing the down-type quark masses are “correct”,

$$m_0^{(3)} \sim 1 \text{ GeV},\ m_0^{(2)} \sim 100 \text{ MeV},\ m_0^{(1)} \sim 1 \text{ MeV}$$

the top mass can be obtained through

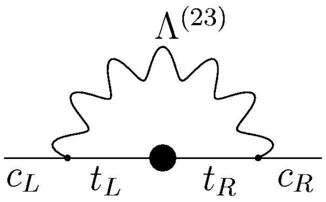
$$m_t \simeq \frac{m_0^{(3)}}{1 - G_t/G_{crit}} \to O(100\text{GeV})$$

$1 - G_t/G_{crit} \sim 10^{-2}$

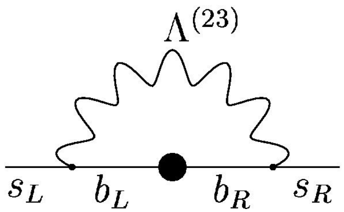
Mendel, Miransky, PLB268(1991)384;
Miransky, PRL69(1992)1022.

★ Once we get correctly $m_t = 170\text{GeV}$, $m_b = 4\text{GeV}$
the 2nd family quark masses can be generated by

$$m_c = m_0^{(2)} + \eta^{(2)} m_t \sim 1\text{GeV},$$



$$m_s = m_0^{(2)} + \eta^{(2)} m_b \sim 100\text{MeV},$$

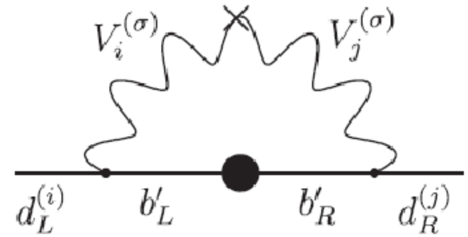


with $\eta^{(2)} \equiv \frac{C_F g_{23}^2}{4\pi^2} \frac{\Lambda_t^2}{(\Lambda^{(23)})^2} \to \frac{1}{100}$

◎ The existence of the current mass term is crucial to get

$$\frac{m_t}{m_b} \neq \frac{m_c}{m_d}$$

★ Mixing terms and CKM structure



$$-\mathcal{L}_Y = \sum_{i,j} \bar{\psi}_L^{(i)} Y_D^{ij} d_R^{(j)} \tilde{\Phi}_{b'} + \sum_{i,j} \bar{\psi}_L^{(i)} Y_U^{ij} u_R^{(j)} \Phi_{t'} + y_t \bar{\psi}_L^{(3)} t_R \Phi_t,$$

$$Y_D \equiv \frac{\sqrt{2}}{v_{b'}} M_D, \quad Y_U \equiv \frac{\sqrt{2}}{v_{t'}} M_U,$$

$$M_D = \begin{pmatrix} m_d & \xi_1 m_d & \xi_1 m_d & \xi_1 m_d \\ \xi_1 m_d & m_s & \xi_2 m_s & \xi_2 m_s \\ \xi_1 m_d & \xi_2 m_s & m_b & \xi_2 m_s \\ \xi_1 m_d & \xi_2 m_s & \xi_2 m_s & m_{b'} \end{pmatrix}.$$

← Let us consider only two parameters.

CKM matrix elements

$$|V_{ud}| \simeq |V_{cs}| \simeq 1 - \frac{\xi_1^2}{2}\left(\frac{m_d}{m_s}\right)^2, \qquad |V_{us}| \simeq |V_{cd}| \simeq \xi_1 \frac{m_d}{m_s},$$

$$|V_{ub}| \simeq |V_{td}| \simeq \xi_1 \frac{m_d}{m_b}, \qquad |V_{cb}| \simeq |V_{ts}| \simeq \xi_2 \frac{m_s}{m_b}.$$

$$|V_{tb}| \simeq 1,$$

$$|V_{t'd}| \simeq \xi_1 \frac{m_d}{m_s} \cdot \xi_2 \frac{m_c}{m_{t'}} \sim 0.23 \times \xi_2 \frac{m_c}{m_{t'}} \sim \mathcal{O}(10^{-3}),$$

$$|V_{t's}| \simeq |V_{t'b}| \simeq \xi_2 \frac{m_c}{m_{t'}} \sim \mathcal{O}(10^{-2}).$$

sample data for CKM

$$V_{\rm CKM}^{4\times 4} = \begin{pmatrix} 0.97 & 0.23 & -0.006 & 0.00009 \\ -0.23 & 0.97 & -0.04 & -0.008 \\ -0.003 & 0.04 & 1.0 & 0.02 \\ -0.002 & 0.007 & -0.02 & 1.0 \end{pmatrix},$$

What is the signature?

◎ An example data for the scenario with $M_{H_1} > 2m_t$

Inputs:

$$\Lambda_4 = 3 \text{ TeV}, \quad \Lambda_3/\Lambda_4 = 1.5, \quad \tan\beta_4 = 1$$

$$M_{A_1} = 0.40 \text{ TeV}, \quad M_{A_2} = 0.80 \text{ TeV},$$

Outputs:

$$m_{t'} = m_{b'} = 0.33 \text{ TeV},$$

$$M_{H_1^\pm} = 0.48 \text{ TeV},$$

$$M_{H_2^\pm} = 0.82 \text{ TeV},$$

$$M_{H_1} = 0.45 \text{ TeV},$$

$$M_{H_2} = 0.53 \text{ TeV},$$

$$M_{H_3} = 0.86 \text{ TeV},$$

yukawa couplings

$$\bar{t}tH_1 = \frac{m_t}{v}\cdot 1.73, \qquad \bar{t}tH_2 = \frac{m_t}{v}\cdot 0.243, \qquad \bar{t}tH_3 = \frac{m_t}{v}\cdot 2.11,$$

$$\bar{t}'t'H_1 = \frac{m_{t'}}{v}\cdot 1.16, \qquad \bar{t}'t'H_2 = \frac{m_{t'}}{v}\cdot 0.127, \qquad \bar{t}'t'H_3 = \frac{m_{t'}}{v}\cdot 0.967,$$

$$\bar{b}'b'H_1 = \frac{m_{b'}}{v}\cdot 0.183, \qquad \bar{b}'b'H_2 = \frac{m_{b'}}{v}\cdot 1.51, \qquad \bar{b}'b'H_3 = \frac{m_{b'}}{v}\cdot 0.024,$$

Decay width into WW, ZZ

$$\Gamma(H_1 \to WW/ZZ) = 0.66\,\Gamma_{SM},$$

$$\Gamma(H_2 \to WW/ZZ) = 0.32\,\Gamma_{SM},$$

$$\Gamma(H_3 \to WW/ZZ) = 0.02\,\Gamma_{SM},$$

Enhancement of Higgs production of H1

$$\Gamma(H_1 \to gg) = 7.4\,\Gamma_{SM},$$

$$\Gamma_{ZZ}/(\Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{tt}) = 0.51 \times \mathrm{SM}.$$

- We may have a ttbar resonance of H1
- The heavier Higgs H2 resonance may exist in the ZZ mode.
- Also, in the ttbar channel, there may appear a scalar resonance H3.

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Higgs Phenomenology is quite rich!

§.4 Summary and discussions

- There exists an allowed parameter region for the 4th generation model. I reanalyzed it under the consideration of the RGE's.
- If the 4th generation exist, the t' and b' will be closely connected with the EWSB. The top quark also contributes to the EWSB by a small amount.
- The dynamical model with the 4th generation naturally yields multi-Higgs doublets.
  We analyzed the (2+1)-Higgs model.

In Progress:

Decay mode of the Higgs bosons

Branching ratio of the Higgs

etc.

Under construction:

Lepton sector

Majorana neutrinos

etc.

Thank you,

Backup Slides

★ A natural expectation is that the top quark plays a minor role for the EWSB and this also suggests the sub-criticality;

(Pagels-Stokar formula)

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

<u>*Input:*</u>

$$\Lambda_t = 10 \text{ TeV} \qquad m_t = 171.3\text{GeV}$$

$$\Rightarrow \quad \frac{v_t^2}{v^2} = 0.15 \qquad v = 246\text{GeV}$$

The top mass is big, but insufficient for the EWSB!!

More general case:

$$M_U = \begin{pmatrix} m_u & \eta_{12} m_u & \eta_{13} m_u & \eta_{14} m_u \\ \eta_{21} m_u & m_c & \eta_{23} m_c & \eta_{24} m_c \\ \eta_{31} m_u & \eta_{32} m_c & \eta_{33} m_c & \eta_{34} m_c \\ \eta_{41} m_u & \eta_{42} m_c & \eta_{43} m_c & m_{t'} \end{pmatrix} \qquad M_D = \begin{pmatrix} m_d & \xi_{12} m_d & \xi_{13} m_d & \xi_{14} m_d \\ \xi_{21} m_d & m_s & \xi_{23} m_s & \xi_{24} m_s \\ \xi_{31} m_d & \xi_{32} m_s & m_b & \xi_{34} m_s \\ \xi_{41} m_d & \xi_{42} m_s & \xi_{43} m_s & m_{b'} \end{pmatrix}$$

$$V_{CKM}^{4\times 4} \simeq \begin{pmatrix} 1 - \frac{|\xi_{12}|^2}{2}\left(\frac{m_d}{m_s}\right)^2 & \xi_{12}\frac{m_d}{m_s} & \xi_{13}\frac{m_d}{m_b} & -(\eta_{14} - \eta_{12}\eta_{24})\frac{m_u}{m_{t'}} + \xi_{14}\frac{m_d}{m_{b'}} \\ -\xi_{12}^*\frac{m_d}{m_s} & 1 - \frac{|\xi_{12}|^2}{2}\left(\frac{m_d}{m_s}\right)^2 & \xi_{23}\frac{m_s}{m_b} - \eta_{23}\frac{m_c}{m_t} & -\eta_{24}\frac{m_c}{m_{t'}} \\ -\eta_{23}^*\frac{m_c}{m_t}\cdot\xi_{12}^*\frac{m_d}{m_s} - (\xi_{13}^* - \xi_{12}^*\xi_{23}^*)\frac{m_d}{m_b} & -\xi_{23}^*\frac{m_s}{m_b} + \eta_{23}^*\frac{m_c}{m_t} & 1 & -\eta_{34}\frac{m_c}{m_{t'}} \\ -\eta_{24}^*\frac{m_c}{m_{t'}}\cdot\xi_{12}^*\frac{m_d}{m_s} & \eta_{24}^*\frac{m_c}{m_{t'}} & \eta_{34}^*\frac{m_c}{m_{t'}} & 1 \end{pmatrix}$$

FCNC

D0-D0bar mixing

$$Y_{u-c-h_{t',t}} \simeq \frac{m_t}{v_{t',t}} \frac{m_u}{m_t} \frac{m_c}{m_t}$$

$$\frac{Y^2_{u-c-h_{t',t}}}{M^2_{H_{2,3}}} f_D^2 B_D \sim \frac{f_D^2 B_D}{M^2_{H_{2,3}}} \times O(10^{-14})$$

The contribution is tiny!