Scenarios with Composite Higgs Bosons

Michio Hashimoto

(Chubu U.)

§1 Introduction

Let us consider scenarios that

Some strong dynamics generate

Composite particles, vectors, ρ_T

Pseudo-scalars, π_T

Scalars (composite Higgs boson)

→ **Is there still a room for "composite" ?**

Yes

But, the situation is NOT so nice for these scenarios…

July, 4, 2012

CERN experiments have observed particle consistent with long-sought Higgs boson!

This news was widely broadcasted on TV, newspapers, etc.

Mass of the new particle

$$M_h = 125\ \mathrm{GeV}$$

If this is the SM Higgs boson and the SM were ultimate,

New ··· **elementary scalar**

New ··· **fundamental interactions**

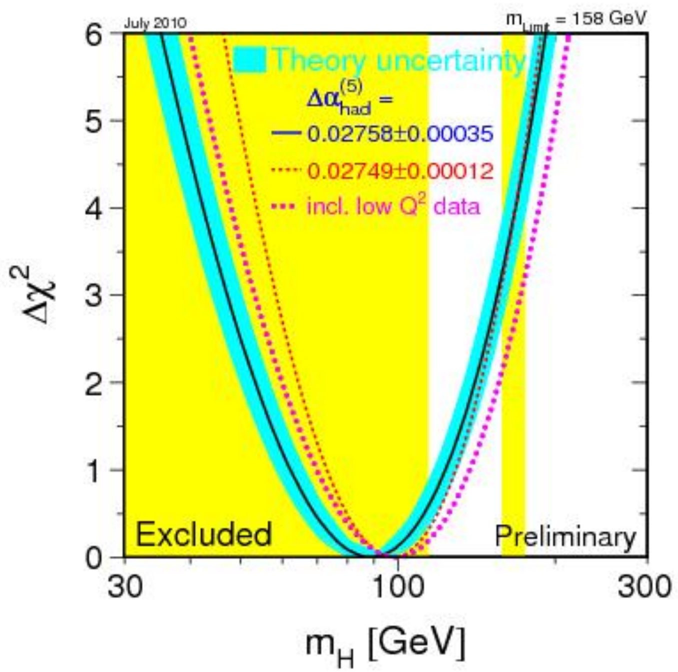
Yukawa int. and Higgs quartic coupling

But, the Yukawa int. don't look like fundamental for me,

So complicated and No principle...

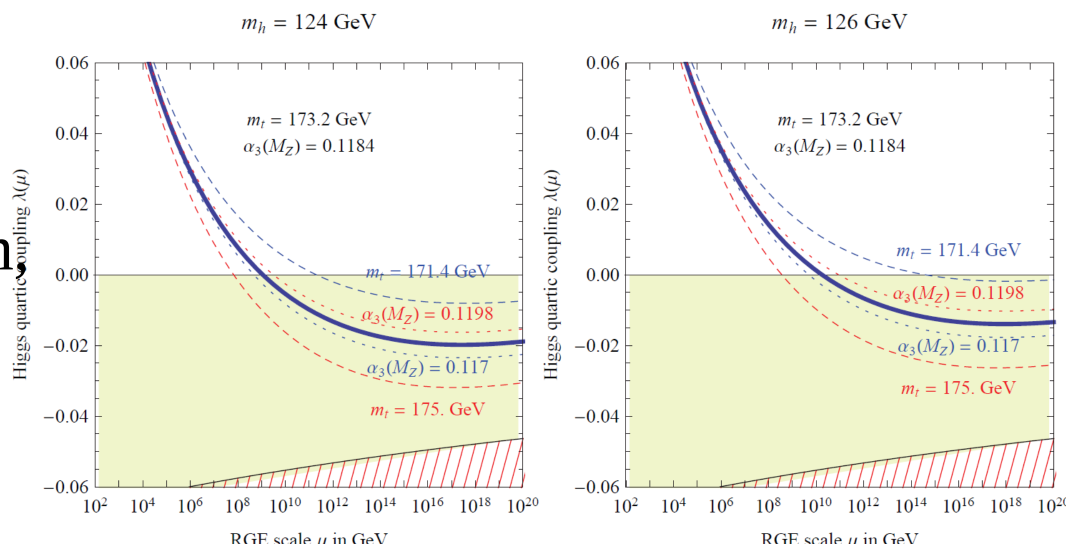
DM, ν

This mass as the SM Higgs
perfectly agrees with
the indirect bound
from the precision measurements…



Remember success for the top quark mass…

In the framework of the SM,
allowing meta-stable vacuum,
the perturbation works up to
very high energy scale…



(PDG2012)

Constraints for the contact interactions (compositeness):

$$\boxed{\mathrm{p} + \mathrm{p} \rightarrow \mathrm{jet} + X}$$

(CMS, arXiv: 1301.5023)

$$L = \zeta \frac{2\pi}{\Lambda^2} (\overline{\mathrm{q}}_L \gamma^\mu \mathrm{q}_L)(\overline{\mathrm{q}}_L \gamma_\mu \mathrm{q}_L),$$

$\zeta = +1$ or -1 (destructive or constructive)

$\Lambda > 9.9$ TeV for $\zeta = +1$

$\Lambda > 14.3$ TeV for $\zeta = -1$

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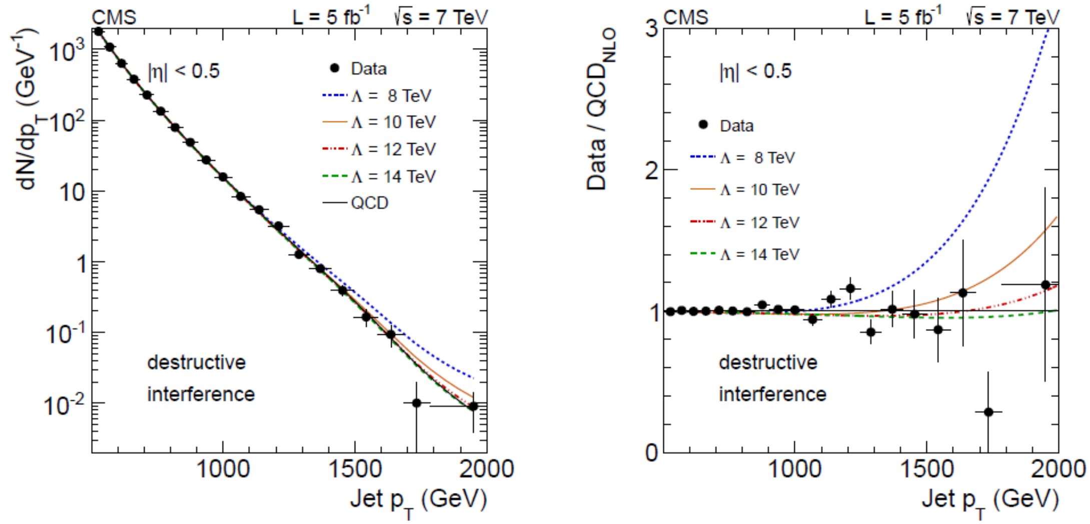


Figure 5: The data compared with model spectra for different values of Λ for models with destructive interference (left). The ratio of these spectra to the NLO QCD jet p_T spectrum (right).

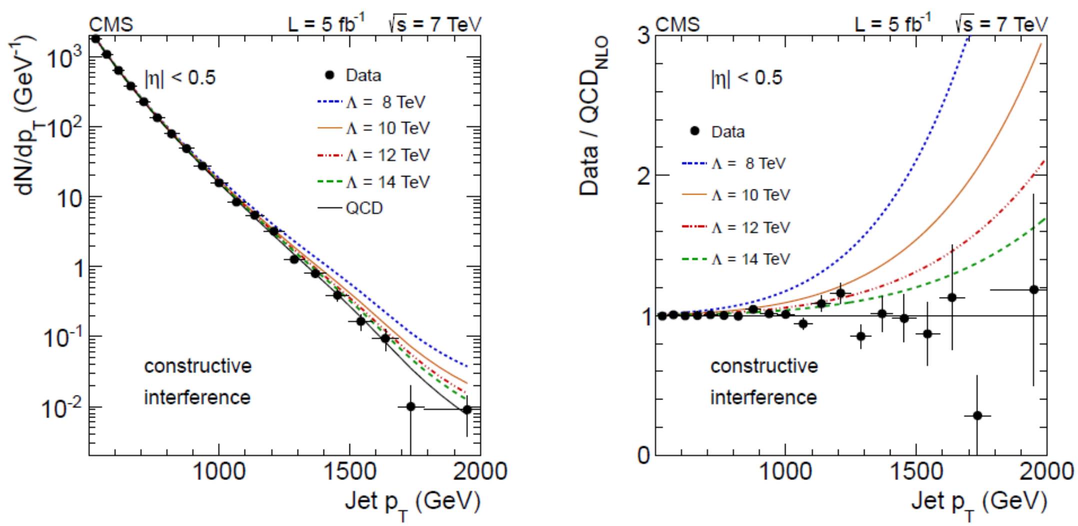


Figure 6: The data compared to model spectra for different values of Λ for models with constructive interference (left). The ratio of these spectra to the NLO QCD jet p_T spectrum (right).

$$\boxed{q\bar{q} \to \ell^+\ell^-}$$

(ATLAS, arXiv: 1211.1150)

$$\mathcal{L} = \frac{g^2}{2\Lambda^2}[\eta_{\mathrm{LL}}\bar{\psi}_{\mathrm{L}}\gamma_\mu\psi_{\mathrm{L}}\bar{\psi}_{\mathrm{L}}\gamma^\mu\psi_{\mathrm{L}} + \eta_{\mathrm{RR}}\bar{\psi}_{\mathrm{R}}\gamma_\mu\psi_{\mathrm{R}}\bar{\psi}_{\mathrm{R}}\gamma^\mu\psi_{\mathrm{R}} + 2\eta_{\mathrm{LR}}\bar{\psi}_{\mathrm{L}}\gamma_\mu\psi_{\mathrm{L}}\bar{\psi}_{\mathrm{R}}\gamma^\mu\psi_{\mathrm{R}}],$$

$\Lambda^- >$ 12.1 TeV ($\Lambda^+ > 9.5$ TeV) in the dielectron channel

$\Lambda^- > 12.9$ TeV ($\Lambda^+ > 9.6$ TeV) in the dimuon channel

for constructive (destructive) interference

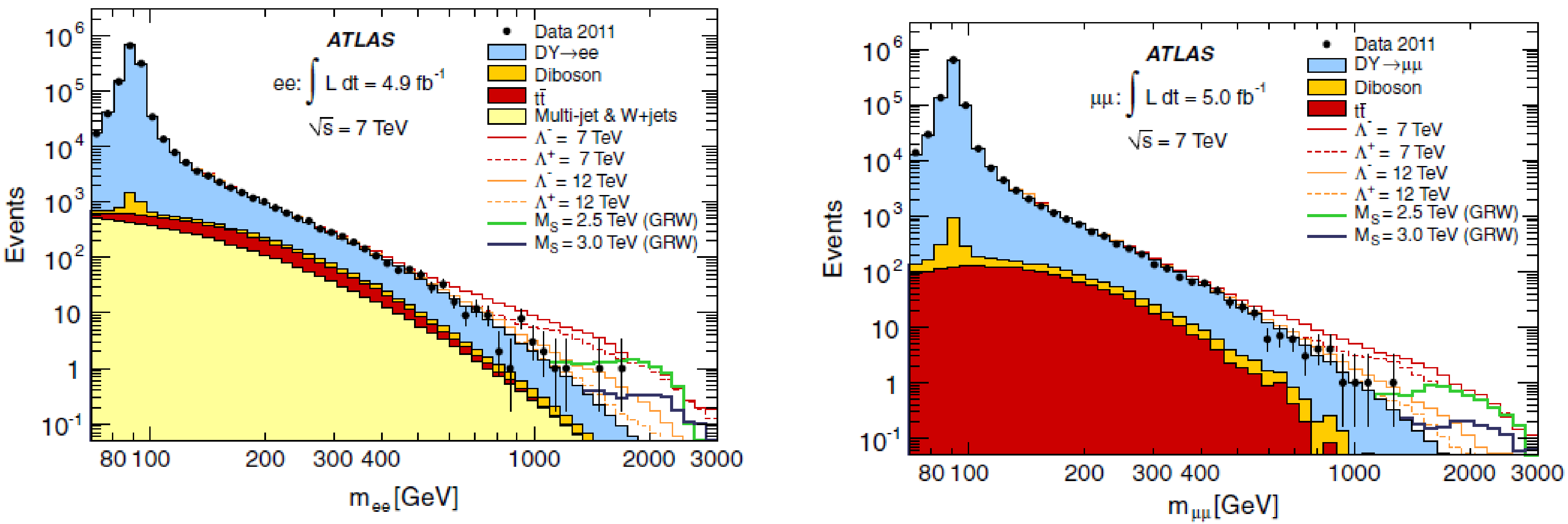


FIG. 2 (color online). Dielectron (top panel) and dimuon (bottom panel) invariant mass distributions for data (points) and Monte Carlo simulation (filled histograms). The open histograms correspond to the distributions expected in the presence of contact interactions or large extra dimensions for several model parameters. The bin width is constant in $\log(m_{\ell\ell})$.

The constraints for the contact interactions of the Lepton pair are also roughly

$$\ell^+\ell^- \to \ell^+\ell^-$$

$$\Lambda > 10\ \mathrm{TeV}$$

(PDG2012)

But,

some strong dynamics might be hidden
in the Higgs sector and/or the top sector…

⇒ §3

§2 Typical scenarios with composite Higgs bosons

Models with the composite Higgs bosons

Technicolor (TC)

walking TC

Topcolor models

Composite Higgs as Pseudo-Nambu-Goldstone Boson

→ **Moretti**

…

In the SM Higgs sector, the global symmetry breaks down,

$$SU(2)_L \times SU(2)_{cust} \to SU(2)$$

Three NG bosons supply the weak boson masses,

$$\pi^{\pm},\ \pi^{0} \quad \rightarrow \quad M_W,\ M_Z$$

$$F_\pi = v$$

This dynamically occurs in the low-energy QCD !

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

NGB: $\pi^{\pm},\ \pi^0$

It is triggered by $\langle \bar{q}_L q_R \rangle = -\Lambda_{QCD}^3 \neq 0$

$$\Lambda_{QCD} \sim 300 \text{ MeV}$$

The EWSB might be just 1000 times scaled up.

Technicolor (TC)

S. Weinberg, PRD13, 974 (1976); PRD19, 1277 (1979);
L. Susskind, PRD20, 2619 (1979).

Scalar particles in QCD (Higgs boson in the EW theory)

(PDG)

IV. The I = 0 States: The $I = 0\ J^{PC} = 0^{++}$ sector is the most complex one, both experimentally and theoretically.

$f_0(600)$, $f_0(980)$, $f_0(1370)$

phase shift in ππ scatt.

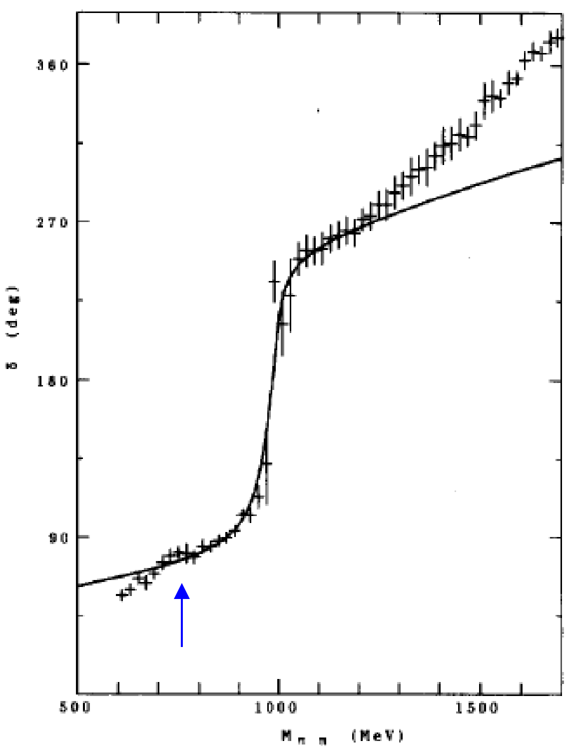
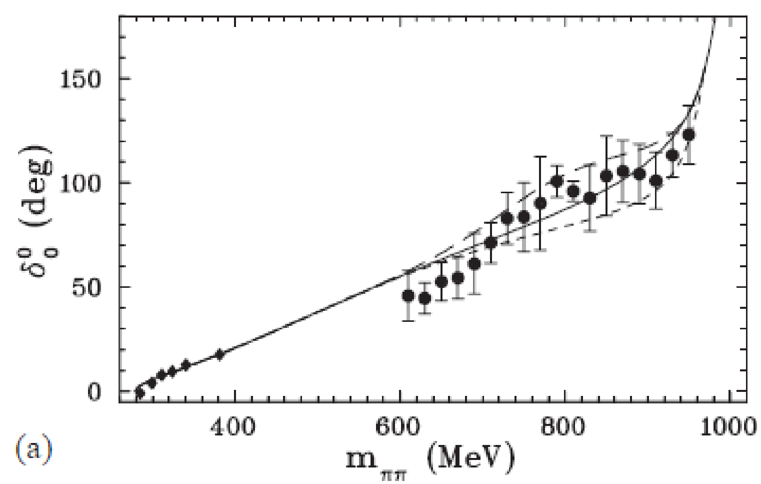


Fig. 1. $\pi\pi$ scattering phase shift. The fitting by the conventional interpretation with $f_0(980)$ and $f_0(1300)$ is also shown.

(Ishida, et. al.)

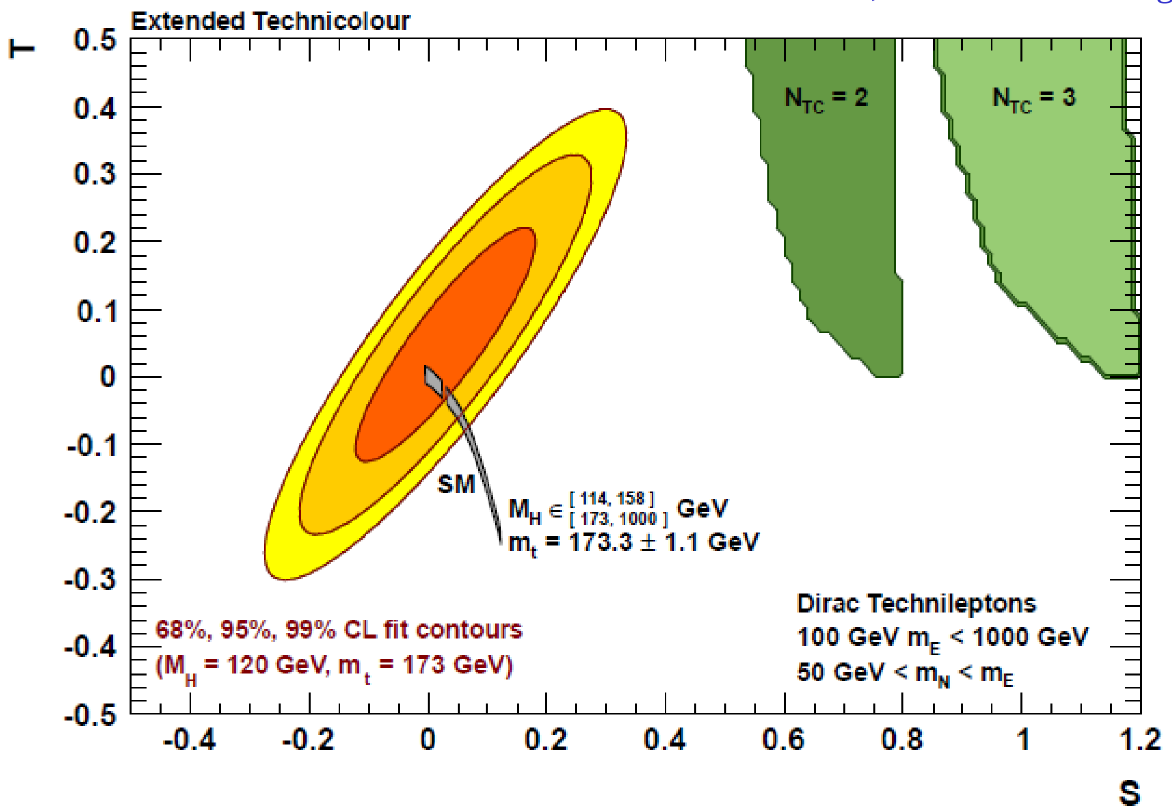


Amsler & Tornqvist, Phys.Rep.389(2004)61.

Naïve QCD-like TC has been faced by several difficulties:

QCD-like TC (1 Family type = 4 weak doublets)

Peskin & Takeuchi; Holdom & Terning, Gorden & Landall



The Gfitter Group arXiv:1107.0975

Walking Technicolor

Holdom

Yamawaki, Bando, Matsumoto

Appelquist, Karabali, Wijewardhana

Akiba, Yanagida

It resolves three problems in QCD-like TC;

(1) strange quark mass, (2) FCNC in K-system, (3) too light NGB.

In QCD-like TC,

$$< \bar{T}T > \sim -v^3$$

With anomalous dimension, generally, γ_m : anomalous dim.

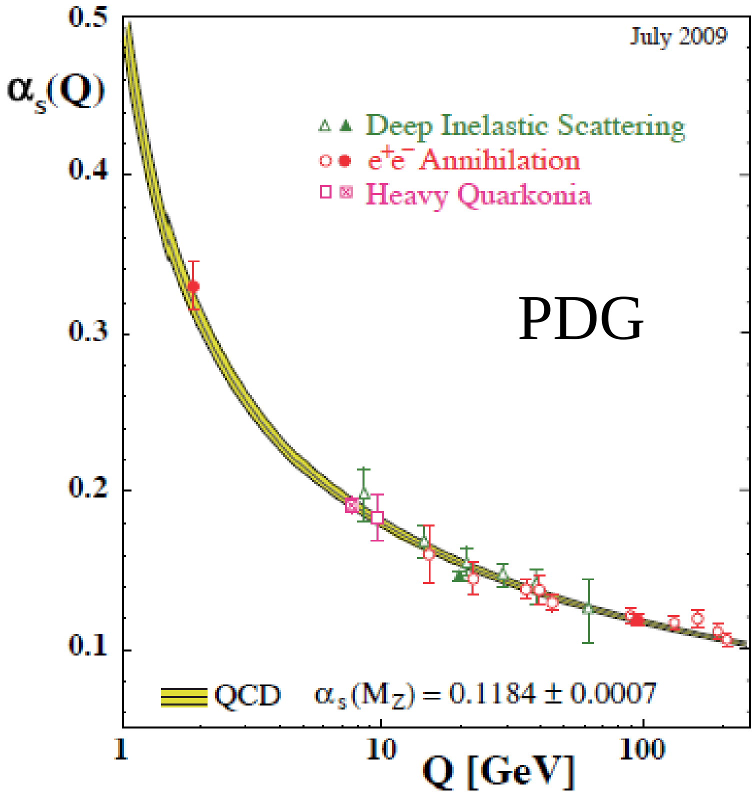
$$\langle \bar{T}T \rangle_{ETC} \sim -\left(\frac{\Lambda_{\mathrm{ETC}}}{v}\right)^{\gamma_m} v^3$$

In QCD $\gamma_m \sim 0$, but, $\gamma_m \sim 1$ in walking TC

$$m_f \sim \frac{-<\bar{T}T>_{ETC}}{\Lambda_{\mathrm{ETC}}^2} \sim \frac{v^2}{\Lambda_{\mathrm{ETC}}} \qquad M_P^2 \sim \frac{-<\bar{T}T>_{ETC}^2}{F_P^2 \Lambda_{\mathrm{ETC}}^2} \sim v^2$$

$\Lambda_{ETC} \sim 1000$ TeV is now OK.

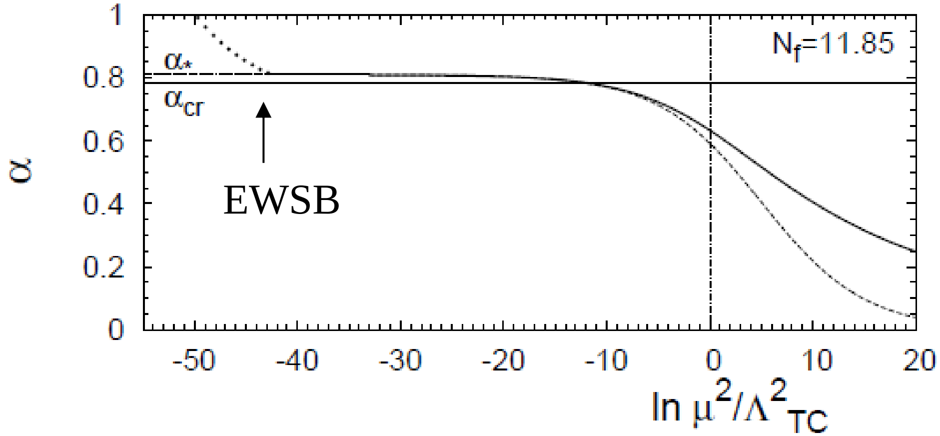
running effects in QCD



$$\gamma_m \sim 0$$

Walking gauge theory

slowly running



Schematic running behavior in WTC

$$\gamma_m \sim 1$$

How large S in walking TC?

The S-parameter constraint in QCD-like TC is NOT applicable to WTC.

Lattice simulation will give a definite answer…

$$\alpha S \equiv 4e^2[\Pi'_{33}(0) - \Pi'_{3Q}(0)] \ ,$$

Peskin and Takeuchi, PRD46('92)381.

$$\longrightarrow \quad \Pi_{33} = \tfrac{1}{4}(\Pi_{VV} + \Pi_{AA}), \quad \Pi_{3Q} = \tfrac{1}{2}\Pi_{VV}$$

$$\longrightarrow \quad S = -4\pi[\Pi'_{VV}(0) - \Pi'_{AA}(0)]$$

Assuming ρ dominance,

$$S = 4\pi \frac{f_\rho^2}{M_\rho^2}$$

$$f_\rho \sim v \quad \rightarrow \quad \boxed{M_\rho > \text{few TeV}}$$

for S < 0.1

Estimate of the mass of the composite Higgs boson in Walking TC

Simple formula M.H, PLB441('98)389.

$$M_S \simeq \sqrt{2}m$$

(m: dynamical mass of the techni-fermions)

More complicated calculation gives

$$\Sigma^2(m^2) : M_S^2 : M_V^2 : M_A^2 \;=\; 1 \;:\; 2.4 \;:\; 17.0 \;:\; 18.5$$

Harada, et al., PRD68('03)076001.

$$\Rightarrow \quad M_S \simeq \sqrt{\frac{2.4}{17}} M_V = 0.38 M_V$$

$\boxed{M_V \sim \text{few TeV}}$ $\Leftrightarrow$ $\boxed{M_S = 125 \text{ GeV}}$

Can the mass of the composite Higgs boson in walking TC be 125 GeV?

(On the other hand, the techni-rho mass should be larger than few TeV.)

- If we identify the dilaton to the Higgs boson in question and this techni-dilaton decay constant is much larger than the weak scale, a light Higgs is possible.

$$M_{TD} = \frac{m^2}{F_{TD}}$$

- Multiple scalars and their mixings might be helpful to get a light scalar.

- others…

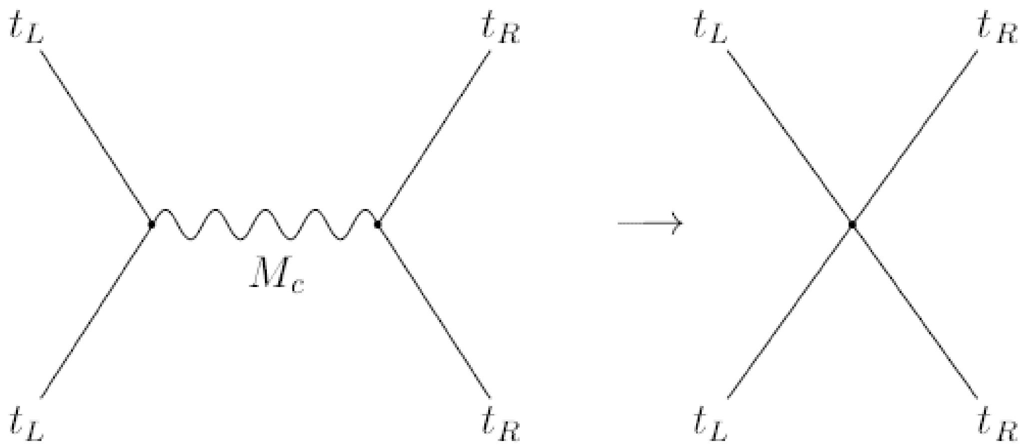
Topcolor models

C.T.Hill, PLB266('91)419; PLB345('95)483.

Why is only the top quark so heavy?

→ The top quark has a strong topcolor charge.

The top mass is dynamically generated and causes the EWSB. Thus it is so heavy.



Topcolor exchange **NJL int.**

RGE Approach

Bardeen, Hill, Lindner, PRD41('90)1647.

NJL model is equivalent to a linear sigma model with the compositeness conditions:

Miransky, Tanabashi, Yamawaki, PLB221('89)177;MPLA4('89)1043.
Y.Nambu,EFI89-08,'89

$$\mathcal{L} = \bar{q}_L i D q_L + \bar{t}_R i D t_R + G_t (\bar{q}_L t_R)(\bar{t}_R q_L)$$

$$\Downarrow \qquad \text{at } \Lambda$$

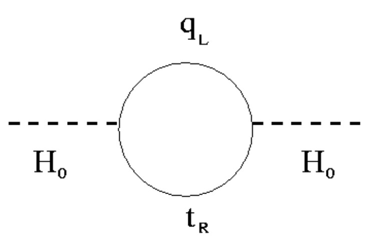
(composite scale)

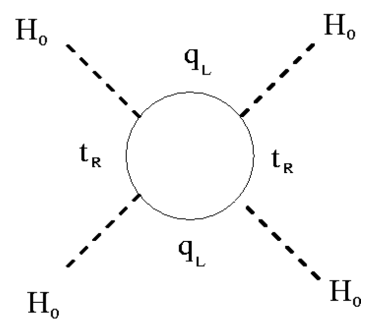
$$\mathcal{L}^{\text{eff}} = Z_H |\partial_\mu H_0|^2 + \bar{q}_L t_R H_0 + M^2 |H_0|^2 + \lambda |H_0|^4,$$
$$\to |\partial_\mu H|^2 + y_t \bar{q}_L t_R H + M_H^2 |H|^2 + \lambda_H |H|^4$$

at μ

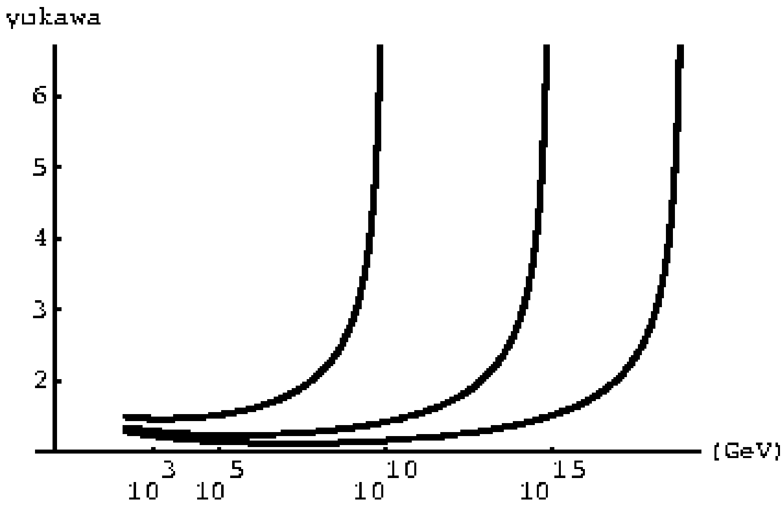
Compositeness conditions

- $\dfrac{1}{y_t^2(\Lambda)} = Z_H(\Lambda) = 0$
- $\dfrac{\lambda_H(\Lambda)}{y_t^4(\Lambda)} = \lambda(\Lambda) = 0$





RG flow



$$16\pi^2 \frac{\partial y_t}{\partial \ln \mu} = \frac{9}{2} y_t^3 - \left(8 g_3^2 + \frac{9}{4} g_2^2 + \frac{17}{12} g_Y^2\right) y_t$$

Λ (GeV)	10^3	10^4	10^5	$\cdots$	10^{15}	10^{19}
m_t (GeV)	600–700	500	400	$\cdots$	230	220

The simplest 4D top-condensate model predicts
Too large top-quark mass!

We can modify this in several ways.

§3. Isospin symmetric Higgs model

M.H, Miransky, PRD80, 013004 (2009); PRD81, 055014 (2010); PRD86, 095018 (2012).

To resolve quark mass hierarchy, we proposed the following scenario:

★ The dynamics triggering the strong isospin violation in 3rd and 2nd families in quark sector may be different from the EWSB dynamics.

★ We assume that the dynamics responsible for the EWSB is almost isospin symmetric and the down-type quark mass is correct.

★ The heavy top-Higgs boson provides the top mass with a strong isospin violation. (**Topcolor model**)

★ Horizontal flavor-changing-neutral int. **equally** between t and c, and b and s produce correct masses.

Isospin symmetric Higgs (h)

$$m_t = m_0^{(3)}$$

$$m_b = m_0^{(3)}$$

$$m_c = m_0^{(2)}$$

$$m_s = m_0^{(2)}$$

$$m_u = m_0^{(1)}$$

$$m_d = m_0^{(1)}$$

h

$m_0^{(3)} \sim O(1\mathrm{GeV})$

$m_0^{(2)} \sim O(100\mathrm{MeV})$

$m_0^{(1)} \sim O(1\mathrm{MeV})$

Down-type quarks masses are correct!

★ Model contains

(by hand)

$\boxed{\text{Isospin symmetric Higgs boson}}$ $m_h = 125\ \text{GeV}$

$$h \sim \bar{T}T$$ (composite scalar ? elementary scalar ?)

$$< h > \sim v$$ **EWSB**

$$y_t \simeq y_b \sim 10^{-2}$$ **Isospin sym.**

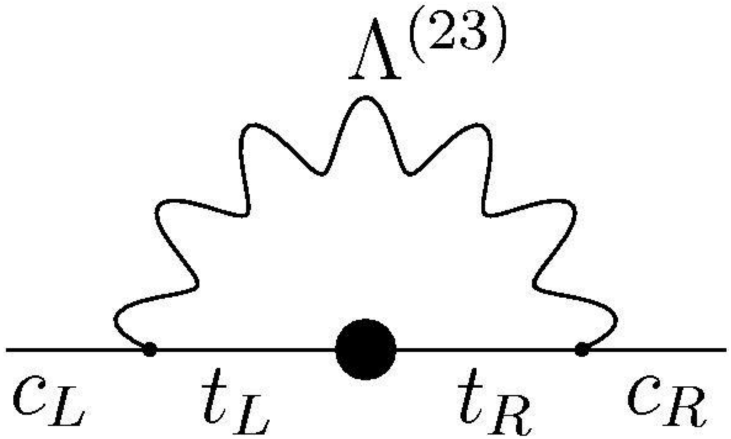
$\boxed{\text{Top-Higgs boson}}$ Mass of the top-Higgs～1 TeV

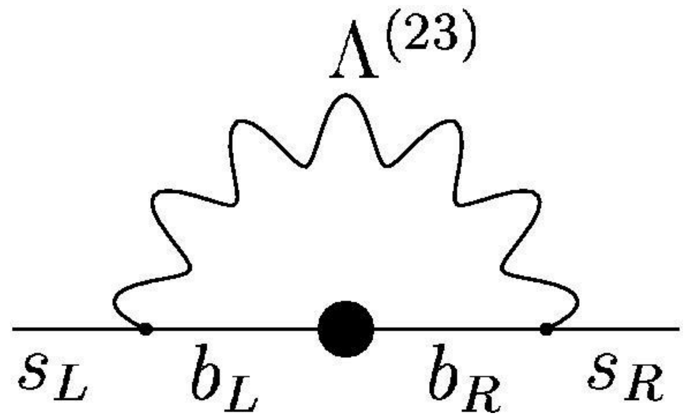
$$h_t \sim \bar{t}t$$

$$< h_t > \sim 50\ \text{GeV} \longrightarrow m_t$$

$$y_{h_t} \sim 3$$ **Strong !**

◎charm and strange mass hierarchy → mt/mb and loop factor





$$m_c = m_0^{(2)} + \eta^{(23)} m_t$$

~ 1 GeV

$$m_s = m_0^{(2)} + \eta^{(23)} m_b$$

~ 0.1 GeV

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

$\Lambda^{(23)} \sim$ several hundred TeV

Yukawa structure in the TeV scale

$$-\mathcal{L}_Y = \sum_{i,j} \bar{\psi}_L^{(i)} Y_D^{ij} d_R^{(j)} \Phi_h + \sum_{i,j} \bar{\psi}_L^{(i)} Y_U^{ij} u_R^{(j)} \tilde{\Phi}_h$$

$$+ y_{h_t} \bar{\psi}_L^{(3)} t_R \tilde{\Phi}_{h_t},$$

$$\tilde{\Phi}_h \equiv i\tau_2 \Phi_h^*, \qquad \tilde{\Phi}_{h_t} \equiv i\tau_2 \Phi_{h_t}^*,$$

$$\Phi_{h_t} = \begin{pmatrix} \omega_t^+ \\ \frac{1}{\sqrt{2}}(v_t + h_t + iz_t) \end{pmatrix}, \qquad \Phi_h = \begin{pmatrix} \omega^+ \\ \frac{1}{\sqrt{2}}(v_h + h + iz_0) \end{pmatrix},$$

$$\langle \Phi_h \rangle = \begin{pmatrix} 0 \\ \frac{v_h}{\sqrt{2}} \end{pmatrix}, \qquad \langle \Phi_{h_t} \rangle = \begin{pmatrix} 0 \\ \frac{v_t}{\sqrt{2}} \end{pmatrix},$$

$$Y_D \equiv \frac{\sqrt{2}}{v_h} M_D, \qquad Y_U \equiv \frac{\sqrt{2}}{v_h} M_U$$

$$M_D = \begin{pmatrix} m_0^{(1)} & \xi_{12} m_0^{(1)} & \xi_{13} m_0^{(1)} \\ \xi_{21} m_0^{(1)} & m_0^{(2)} + \delta \cdot m_b & \xi_{23} m_0^{(2)} \\ \xi_{31} m_0^{(1)} & \xi_{32} m_0^{(2)} & m_0^{(3)} \end{pmatrix},$$

$$M_U = \begin{pmatrix} \eta_{11} m_0^{(1)} & \eta_{12} m_0^{(1)} & \eta_{13} m_0^{(1)} \\ \eta_{21} m_0^{(1)} & m_0^{(2)} + \delta \cdot m_t & \eta_{23} m_0^{(2)} \\ \eta_{31} m_0^{(1)} & \eta_{32} m_0^{(2)} & m_0^{(3)} \end{pmatrix},$$

$m_0^{(3)} \sim 1$ GeV

$m_0^{(2)} \sim 100$ MeV

$m_0^{(1)} \sim 1$ MeV

$\delta \sim 1/100$

$\xi_{ij}, \eta_{ij} \sim \mathcal{O}(1)$

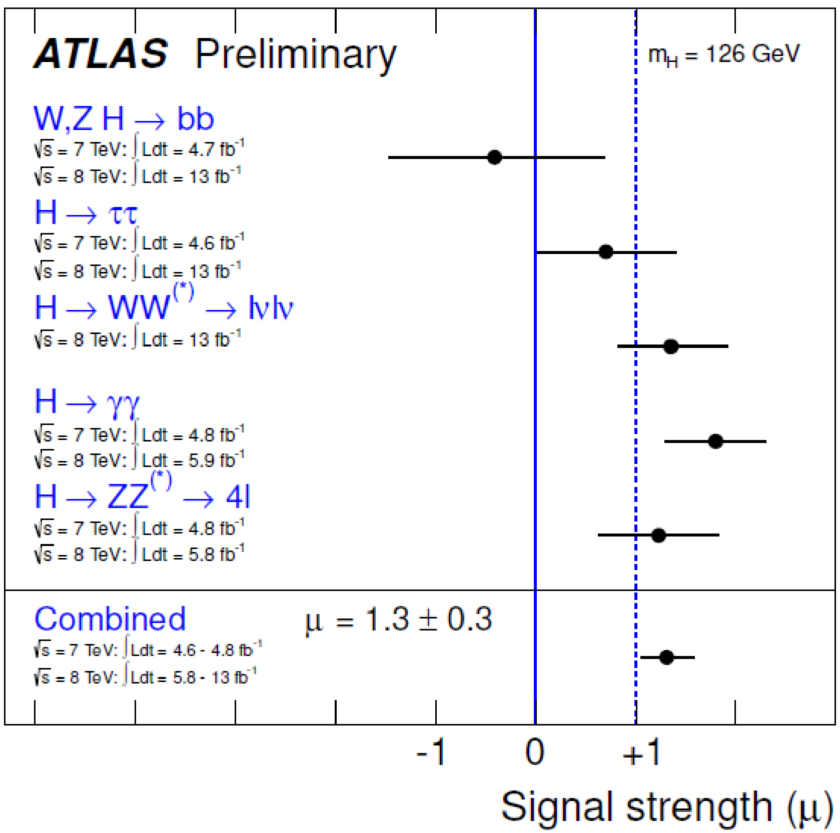
$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1 - \frac{|\xi_{12}|^2}{2}\left(\frac{m_0^{(1)}}{m_0^{(2)}}\right)^2 & \xi_{12}\frac{m_0^{(1)}}{m_0^{(2)}} & \xi_{13}\frac{m_0^{(1)}}{m_0^{(3)}} \\ -\xi_{12}^*\frac{m_0^{(1)}}{m_0^{(2)}} & 1 - \frac{|\xi_{12}|^2}{2}\left(\frac{m_0^{(1)}}{m_0^{(2)}}\right)^2 & \xi_{23}\frac{m_0^{(2)}}{m_0^{(3)}} \\ -(\xi_{13}^* - \xi_{12}^*\xi_{23}^*)\frac{m_0^{(1)}}{m_0^{(3)}} & -\xi_{23}^*\frac{m_0^{(2)}}{m_0^{(3)}} & 1 \end{pmatrix}.$$

We can get easily PDG values!

Is this a signal of NEW PHYSICS beyond the SM?

ATLAS CONF-2012-162

2012/11/14



CMS PAS-HIG-12-045

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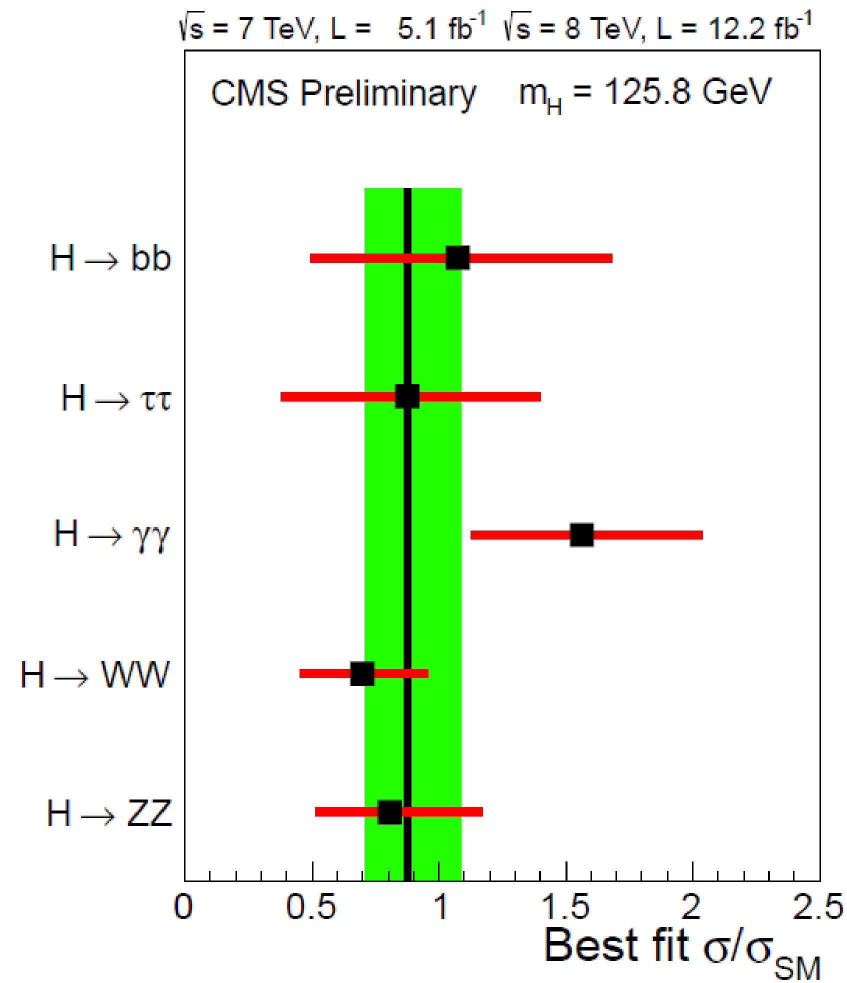


$H \to \gamma\gamma$ in the SM

$$\Gamma(H \to \gamma\gamma) = \frac{\sqrt{2} G_F \alpha^2 m_H^3}{256\pi^3} \left| A_1(\tau_W) + N_c Q_t^2 A_{\frac{1}{2}}(\tau_t) \right|^2$$

$$\tau_W \equiv \frac{m_H^2}{4m_W^2} \qquad \tau_t \equiv \frac{m_H^2}{4m_t^2}$$

$$A_1(\tau_W) = -8.32 \qquad \cancel{A_{\frac{1}{2}}(\tau_t) = 1.38}$$

$$y_t \simeq y_b \sim 10^{-2}$$

$$\frac{(-8.32)^2}{(-8.32 + 3 \cdot (\frac{2}{3})^2 \cdot 1.38)^2} \sim 1.6$$

(our model)

To enhance the Higgs production via the gluon fusion, we may introduce colored scalars.

$$\mathcal{L} \supset \mathcal{L}_S = \frac{1}{2}(D_\mu S)^2 - \frac{1}{2} m_{0,S}^2 S^2 - \frac{\lambda_S}{4} S^4 - \frac{\lambda_{hS}}{2} S^2 \Phi_h^\dagger \Phi_h,$$

$$M_S^2 = m_{0,S}^2 + \frac{\lambda_{hS}}{2} v_h^2, \qquad \Phi_h = \begin{pmatrix} \omega^+ \\ \frac{1}{\sqrt{2}}(v_h + h + i z_0) \end{pmatrix},$$

$\lambda_{hS} > 0$ gives an amplitude with the same sign as the fermion one.

Typically, $\lambda_{hS} \sim \mathcal{O}(1)$

$$\frac{\sigma(gg \to h)}{\sigma^{\rm SM}(gg \to H)} \sim \frac{\Gamma(h \to gg)}{\Gamma^{\rm SM}(H \to gg)}$$

$$= \left| \frac{C_A \lambda_{hS} \frac{v v_h}{2M_S^2} A_0(\tau_S)}{A_{\frac{1}{2}}(\tau_t)} \right|^2,$$

$$\tau_S \equiv m_h^2/(4M_S^2)$$

$$\tau_t \equiv \frac{m_H^2}{4m_t^2}$$

S: adjoint rep. $C_A = 3$

The same production rate as the SM requires

$$\lambda_{hS} \simeq 2.5\text{–}2.7 \times \frac{M_S^2}{v v_h}$$

Typically,

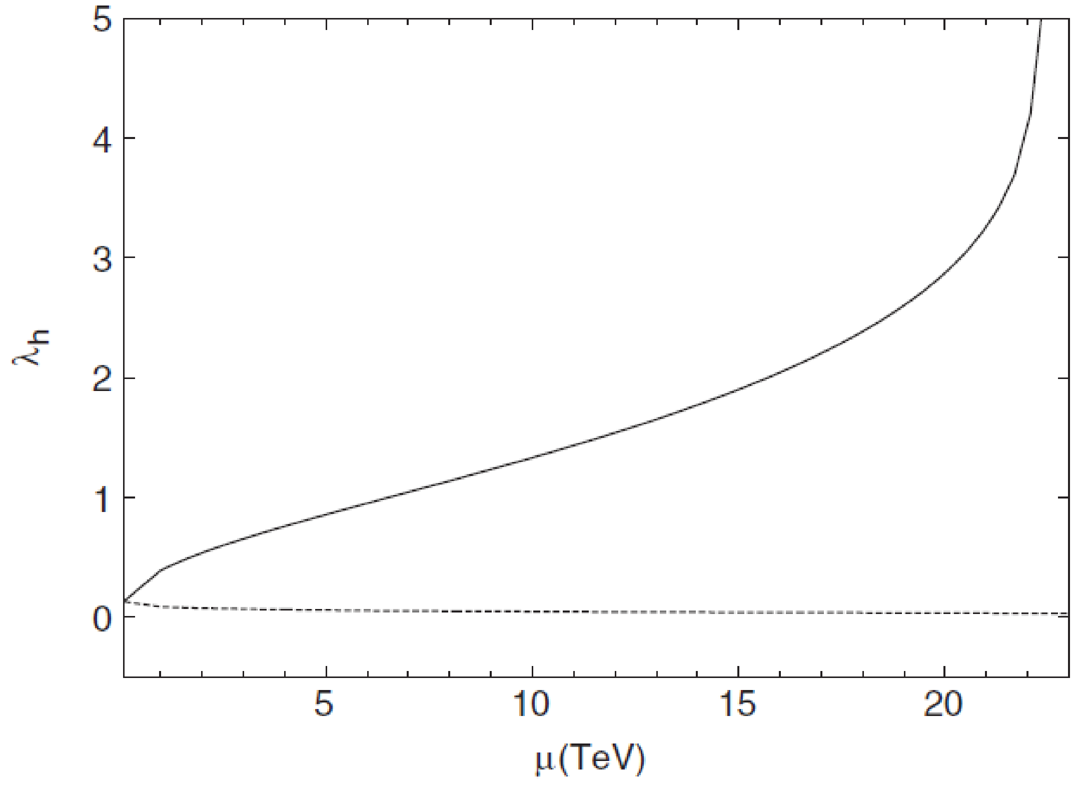
$\lambda_{hS} = 1.8$ $M_S = 200$ GeV $v_t = 50$ GeV $v_h = 240$ GeV

$$v^2 = v_h^2 + v_t^2$$

comment

$m_h = 125\ \text{GeV}$ suggests perturbative nature in the SM

In this case, $\lambda_{hS} \sim \mathcal{O}(1)$ allows strong dynamics…



§4. Summary

● I briefly reviewed typical composite Higgs scenarios.

★ **I also introduced our recent work, isospin symmetric Higgs model.**

Predictions by IS Higgs model

$$\frac{\Gamma^{\mathrm{IS}}(h \to \gamma\gamma)}{\Gamma^{\mathrm{SM}}(H \to \gamma\gamma)} \simeq 1.56,$$

$$\frac{\Gamma^{\mathrm{IS}}(h \to WW^*)}{\Gamma^{\mathrm{SM}}(H \to WW^*)} = \frac{\Gamma^{\mathrm{IS}}(h \to ZZ^*)}{\Gamma^{\mathrm{SM}}(H \to ZZ^*)} = \left(\frac{v_h}{v}\right)^2 \simeq 0.96$$

$$\frac{\Gamma^{\mathrm{IS}}(h \to Z\gamma)}{\Gamma^{\mathrm{SM}}(H \to Z\gamma)} \simeq 1.07$$

Isospin symmetric top and bottom yukawa couplings

$$y_t \simeq y_b \sim 10^{-2}$$

If lucky, the top-Higgs might be discovered at the LHC.