Top-Mode pseudo Nambu-Goldstone boson Higgs model

Hidenori S. Fukano (KMI,Nagoya)

Based on

PRD90,055009(2014) [arXiv:1311.6629, H.S.F, M.Kurachi, S.Matsuzaki and K.Yamawaki]
PRD90,015005(2014) [arXiv:1401.6292, H.S.F and S.Matsuzaki]
arXiv:1411.1199 [H.S.F, M.Kurachi and S.Matsuzaki]

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

@SCGT 2015
04.Mar.2015

SCGT15

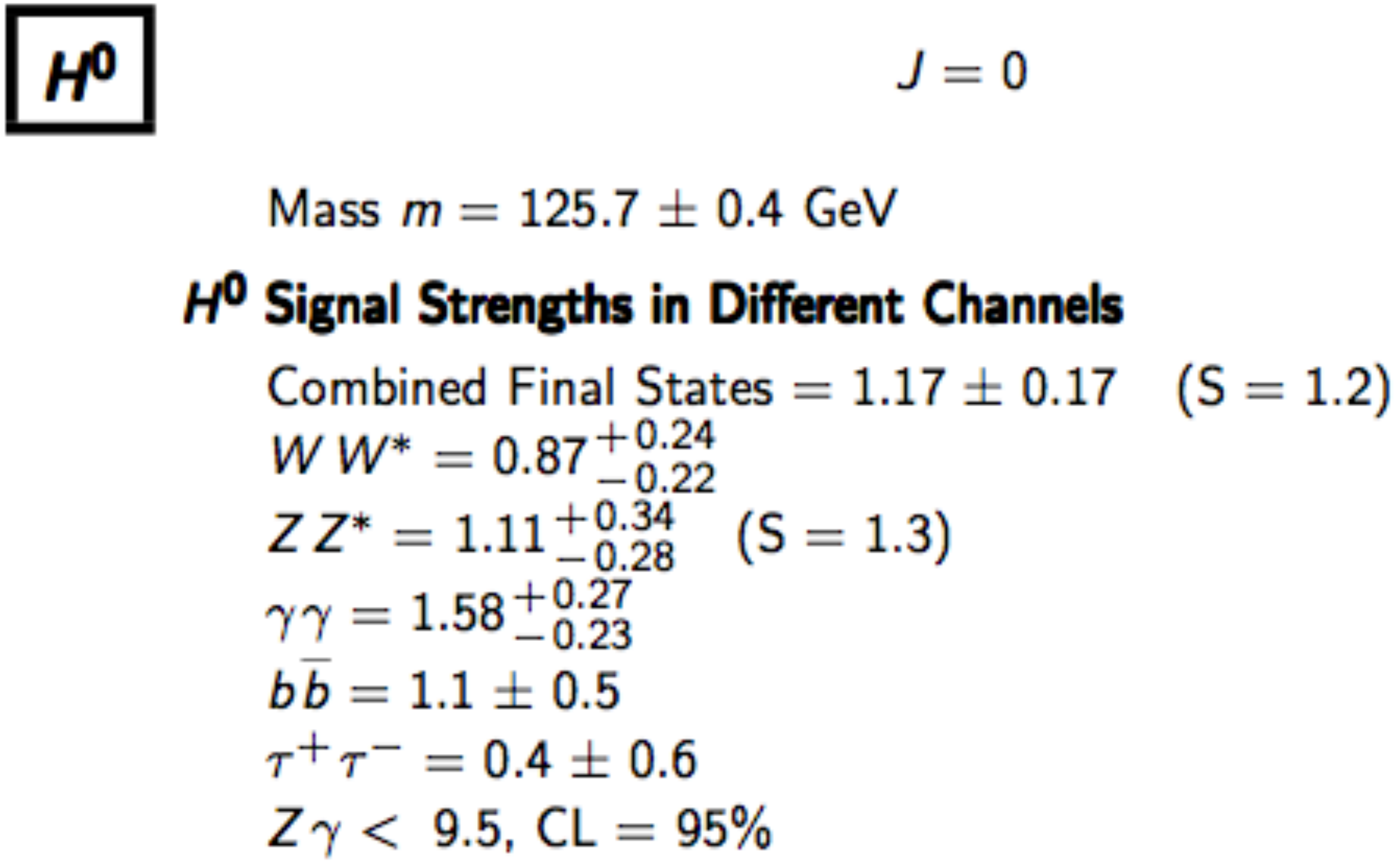
1. Background and Introduction 5-pages

2.Model 18-pages

3.Phenomenologies 6-pages

4. Summary 1-page

1. Background and Introduction (1/5) : 126 GeV Higgs



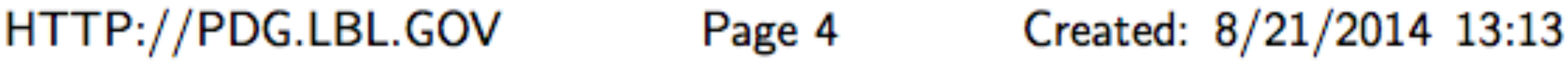
H^0 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States = 1.17 ± 0.17 (S = 1.2)
$W W^* = 0.87^{+0.24}_{-0.22}$
$Z Z^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$
$b\overline{b} = 1.1 \pm 0.5$
$\tau^+\tau^- = 0.4 \pm 0.6$
$Z\gamma <$ 9.5, CL = 95%

Higgs boson has been discovered!!



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1. Background and Introduction (2/5) : The origin of Higgs ?

BUT

We do not yet know anything

about the **origin of Higgs** boson

This is one of primary targets

@ LHC Run-II or ILC.

I would like to talk about it from the viewpoint of

126 GeV Higgs

= “composite” Higgs

1. Background and Introduction (3/5) : "composite" Higgs models

In the market, the traditional "composite" Higgs models are

I) based on the gauge theory

e.g. walking technicolor

"Higgs" = Techni-Dilaton

Yamawaki,Bando,Matumoto (1986)
Bando,Morozumi,So,Yamawaki (1987)
Bando,Matumoto,Yamawaki (1986)

SCGT2015 Talks given by many Lattice people, Kurachi, Matsuzaki, Shrock

II) based on the Nambu-Jona-Lasinio model

e.g. Top quark condensation

Miransky,Tanabashi,Yamawaki (1989)
Bardeen,Hill,Lindner (1990)

"Higgs" = Sigma meson-like particle

III) Higgs = pseudo Nambu-Goldstone boson

"Higgs" = CP-even pion -like particle

Kaplan and Georgi (1984);
Little Higgs model;
Minimal Composite Higgs Model

1. Background and Introduction (4/5) : Higgs in my talk

"Higgs" in my talk

H.S.F, Kurachi,Matsuzaki,Yamawaki (2013)
Cheng,Dobrescu,Gu (2013)

= not Sigma but a **pNGB**

in a **top quark condensate** model

II) based on the Nambu-Jona-Lasinio model

e.g. Top quark condensation

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"Higgs" = Sigma meson-like particle

III) Higgs = pseudo Nambu-Goldstone boson

"Higgs" = CP-even pion -like particle

Kaplan and Georgi (1984);
Little Higgs model;
Minimal Composite Higgs Model

1. Background and Introduction (5/5) : TMpNGBH model

"Higgs" in my talk

H.S.F, Kurachi,Matsuzaki,Yamawaki (2013)
Cheng,Dobrescu,Gu (2013)

= not Sigma but a **pNGB**

in a **top quark condensate** model

We call such model

Top-Mode
pseudo Nambu-Goldstone boson Higgs
(TMpNGBH) Model

2.Model (1/18) : Summary of Model

Main particle contents in the model

Step.1

$$\psi_L = \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix} \qquad \begin{matrix} t_R \\ b_R \\ \chi_R \end{matrix}$$

$\mathcal{L}_{4f}$ = NJL : $U(3)_L \times U(1)_{\chi_R} \rightarrow U(2)_L \times U(1)_V$

Step.2

5 NGBs emerge

$\mathcal{L}_h$ $\mathcal{L}_{\rm EW}$ $\mathcal{L}_t$ vacuum alignment $0 \neq \cos\theta = \dfrac{C_2}{C_1} < 1$

Step.3

EWSB

5 NGBs = 2 pNGBs + 3 would-be NGBs

h_t^0 A_t^0

2.Model (2/18) : Step.1 -particle contents

arXiv:1311.6629

Step.1: Particle Contents

Main particle contents in the model

$$\psi_L = \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix} \qquad\qquad \begin{matrix} t_R \\ b_R \\ \chi_R \end{matrix}$$

SM 3rd gen. quarks

$$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \qquad t_R \qquad b_R$$

Vector-like quark (= color triplet, SU(2)-singlet, Y=2/3)

$$\chi_L \qquad \chi_R$$

2.Model (3/18) : Step.1 -Model Lagrangian

Step.1: Lagrangian

Lagrangian: $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{4f} + \mathcal{L}_{h} + \mathcal{L}_{\text{EW}} + \mathcal{L}_{t}$

$$\mathcal{L}_{4f} = G_{4f}(\bar{\psi}^i_L \chi_R)(\bar{\chi}_R \psi^i_L)$$

$$\mathcal{L}_{h} = -\left[\Delta_{\chi\chi}\bar{\chi}_R\chi_L + \text{h.c.}\right] - G'\left(\bar{\chi}_L\chi_R\right)\left(\bar{\chi}_R\chi_L\right)$$

$$\begin{aligned}\mathcal{L}_{\text{EW}} &= -\frac{1}{4}W^{\hat{a}\mu\nu}W^{\hat{a}}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\ &\quad +\bar{\psi}_L\gamma^\mu L_\mu\psi_L + \bar{\psi}_R\gamma^\mu R_\mu\psi_R\end{aligned}$$

$$\mathcal{L}_{t} = G''\left(\bar{\chi}_L\chi_R\right)\left(\bar{t}_R\chi_L\right) + \text{h.c.}$$

2.Model (4/18) : Question to Step.2

arXiv:1311.6629, 1411.1199

Main particle contents in the model

✓ **Step.1**

$$\psi_L = \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix} \qquad \begin{matrix} t_R \\ b_R \\ \chi_R \end{matrix}$$

Step.2

Q: Global symmetry breaking ?

Step.3

Q: EWSB ? Higgs boson mass ?

2.Model (5/18) : Step.2 -Global symmetry in NJL

arXiv:1311.6629

In Step.2, we turn off $\mathcal{L}_h$ $\mathcal{L}_{\rm EW}$ $\mathcal{L}_t$

Lagrangian: $\mathcal{L} = \mathcal{L}_{\rm kin.} + \mathcal{L}_{4f}$

Step.2 $\mathcal{L}_{4f} = G_{4f}(\bar{\psi}^i_L \chi_R)(\bar{\chi}_R \psi^i_L)$

@ Λ

Global symmetry:

$U(3)_L \times U(1)_{\chi_R}$

Introduce auxiliary field

$$\Phi = \frac{1}{\sqrt{2}} U \cdot \vec{\phi}$$

3-component real vector

3 x 3 unitary matrix

Integrate out fermion fields on scale $\Lambda_\chi \leq p \leq \Lambda$

$$Z = \frac{1}{y^2} = \frac{1}{\lambda} = \frac{N_c}{16\pi^2} \ln \frac{\Lambda^2}{\Lambda_\chi^2}$$

@ $\Lambda_\chi (< \Lambda)$

Effective Lagrangian by NJL:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm kin.} + \partial^\mu \Phi^\dagger \partial_\mu \Phi - y\left[\bar{\psi}_L \Phi \chi_R + {\rm h.c.}\right] - \left[\frac{1}{Z}\left(\frac{1}{G_{4f}} - \frac{N_c}{8\pi^2}\Lambda^2\right)(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2\right]$$

2.Model (6/18) : Step.2 -Global Symmetry breaking

Lagrangian: $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{4f}$

Step.2

$$\mathcal{L}_{4f} = G_{4f}(\bar{\psi}^i_L \chi_R)(\bar{\chi}_R \psi^i_L)$$

$$Z = \frac{1}{y^2} = \frac{1}{\lambda} = \frac{N_c}{16\pi^2} \ln \frac{\Lambda^2}{\Lambda_\chi^2}$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{kin.}} + \partial^\mu \Phi^\dagger \partial_\mu \Phi - y\left[\bar{\psi}_L \Phi \chi_R + \text{h.c.}\right] - \left[\frac{1}{Z}\left(\frac{1}{G_{4f}} - \frac{N_c}{8\pi^2}\Lambda^2\right)(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2\right]$$

$$\frac{1}{G_{4f}} < \frac{1}{G_{\text{crit}}} = \frac{N_c \Lambda^2}{8\pi^2} \Longrightarrow U(3)_L \times U(1)_{\chi_R} \to U(2)_L \times U(1)_V$$

$$\Phi = \frac{1}{\sqrt{2}} U \cdot \vec{\phi}$$

5 NGBs emerge

$$\langle \vec{\phi} \rangle = f \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

2.Model (7/18) : Question to Step.3

arXiv:1311.6629, 1411.1199

Main particle contents in the model

✓ **Step.1**

$$\psi_L = \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix} \qquad \begin{matrix} t_R \\ b_R \\ \chi_R \end{matrix}$$

$\mathcal{L}_{4f}$ = NJL : $U(3)_L \times U(1)_{\chi_R} \to U(2)_L \times U(1)_V$

✓ **Step.2**

5 NGBs emerge

Step.3

Q: EWSB ? Higgs boson mass ?

2.Model (8/18) : To Step.3

arXiv:1311.6629, 1411.1199

Q: EWSB ? Higgs boson mass?

A: Vacuum alignment

by explicit breaking terms

$\mathcal{L}_h$ $\mathcal{L}_{\rm EW}$ $\mathcal{L}_t$

2.Model (9/18) : Step.3 -Electroweak Interactions

Lagrangian: $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{4f} + \mathcal{L}_{\text{EW}}$

EW-NGB interaction term

$$\mathcal{L}_{\text{eff}}(U) = \frac{f^2}{2}\text{tr}\left[D_\mu U^\dagger D^\mu U \Sigma_0\right]$$

EW interactions

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$D_\mu U = \left(\partial_\mu - ig\hat{W}_\mu + ig'\hat{B}_\mu\right) U$$

$$\hat{W}_\mu = \sum_{\hat{a}=1}^{3} W_\mu^{\hat{a}} \frac{\lambda^{\hat{a}}}{2}, \quad \hat{B}_\mu = B_\mu \begin{pmatrix} 1/2 & 0 & 0 \\ 0 & 1/2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

2.Model (10/18) : Step.3 -NGB-top interaction

Lagrangian: $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{4f} + \qquad \mathcal{L}_t$

top-NGB interaction term

$$\mathcal{L}_{\text{eff}}(U) = \qquad - \tilde{m}_\chi \left[\bar{\psi}_L \mathcal{M}_f(U) \psi_R + \text{h.c.} \right]$$

$$m_{\tilde{\chi}} = \frac{yf}{\sqrt{2}}$$

$$\mathcal{L}_t = G'' \left(\bar{\chi}_L \chi_R \right) \left(\bar{t}_R \chi_L \right) + \text{h.c.}$$

$$\mathcal{M}_f(U) = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \frac{G''}{G_{4f}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

2.Model (11/18) : Step.3 -small NGB-NGB interaction

Lagrangian: $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{4f} + \mathcal{L}_h$

NGB-NGB interaction term

$$\mathcal{L}_{\text{eff}}(U) =$$

$$-c_1 f^2 \text{tr}\left[U^\dagger \Sigma_0 U \Sigma_0\right] + c_2 f^2 \text{tr}\left[U\Sigma_0 + \Sigma_0 U^\dagger\right]$$

$$\mathcal{L}_h = -\left[\Delta_{\chi\chi}\bar{\chi}_R \chi_L + \text{h.c.}\right] - G'\left(\bar{\chi}_L \chi_R\right)\left(\bar{\chi}_R \chi_L\right)$$

$$c_1 = \frac{y^2}{2}\frac{G'}{G_{4f}^2}\,, \qquad c_2 = \frac{y}{\sqrt{2}f}\frac{\Delta_{\chi\chi}}{G_{4f}}$$

2.Model (12/18) : Step.3 -All explicit breaking terms

Lagrangian: $\mathcal{L} = \mathcal{L}_{\rm kin.} + \mathcal{L}_{4f} + \mathcal{L}_h + \mathcal{L}_{\rm EW} + \mathcal{L}_t$

NGB interaction term

$$\mathcal{L}_{\rm eff}(U) = \frac{f^2}{2}{\rm tr}\left[D_\mu U^\dagger D^\mu U \Sigma_0\right] - \tilde{m}_\chi \left[\bar{\psi}_L \mathcal{M}_f(U)\psi_R + {\rm h.c.}\right]$$
$$-c_1 f^2 {\rm tr}\left[U^\dagger \Sigma_0 U \Sigma_0\right] + c_2 f^2 {\rm tr}\left[U\Sigma_0 + \Sigma_0 U^\dagger\right]$$

To see vacuum alignment,

we need the effective potential for NGBs

taking into account all explicit breaking terms

$\mathcal{L}_h$ $\mathcal{L}_{\rm EW}$ $\mathcal{L}_t$

2.Model (13/18) : Step.3 -Effective Lagrangian for NGBs

$$\mathcal{L}_{\mathrm{eff}}(U) = \frac{f^2}{2}\mathrm{tr}\left[D_\mu U^\dagger D^\mu U \Sigma_0\right] - \tilde{m}_\chi\left[\bar{\psi}_L \mathcal{M}_f(U)\psi_R + \mathrm{h.c.}\right]$$
$$-c_1 f^2 \mathrm{tr}\left[U^\dagger \Sigma_0 U \Sigma_0\right] + c_2 f^2 \mathrm{tr}\left[U\Sigma_0 + \Sigma_0 U^\dagger\right]$$

Effective Lagrangian for NGBs

1-loop correction

$$\mathcal{L}^{\text{1-loop}}_{\mathrm{eff}}(U) = \underbrace{\boxed{\frac{f^2}{2}\left(1-\frac{\Lambda_\chi^2}{4\pi^2 f^2}\right)}}_{F^2}\mathrm{tr}\left[\bar{D}_\mu U^\dagger \bar{D}^\mu U \Sigma_0\right] - \tilde{m}_\chi\left[\bar{\psi}_L \mathcal{M}_f(U)\psi_R + \mathrm{h.c.}\right]$$
$$-\underbrace{\boxed{\left[c_1 f^2\left(1-\frac{3\Lambda_\chi^2}{8\pi^2 f^2}\right) - \frac{f^2\Lambda_\chi^2}{32\pi^2}\left(\frac{9}{4}g^2 + \frac{3}{4}g'^2 + 2N_c y^2\left(\frac{G''}{G_{4f}}\right)^2\right)\right]}}_{C_1F^2}\mathrm{tr}\left[U^\dagger\Sigma_0 U\Sigma_0\right]$$
$$+\underbrace{\boxed{c_2 f^2\left(1-\frac{5\Lambda_\chi^2}{32\pi^2 f^2}\right)}}_{C_2F^2}\mathrm{tr}\left[U\Sigma_0 + \Sigma_0 U^\dagger\right]$$

re-definition

re-definition

2.Model (14/18) : Step.3 -Effective potential for NGBs

Effective potential for NGBs:

$$V_{\rm eff}(U) = \boxed{C_1 F^2}\,{\rm tr}\left[U^\dagger \Sigma_0 U \Sigma_0\right] - \boxed{C_2 F^2}\,{\rm tr}\left[U\Sigma_0 + \Sigma_0 U^\dagger\right]$$

The vev of U is parametrized by $\langle U \rangle = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}$

$$V_{\rm eff}(U = \langle U \rangle) = \boxed{F^2}\left[\boxed{C_1}\cos^2\theta - 2\boxed{C_2}\cos\theta\right]$$

If $\boxed{C_1} > 0\,, \boxed{C_2} \neq 0$ with $\boxed{\dfrac{C_2}{C_1}} < 1,$

$V_{\rm eff}(U = \langle U \rangle)$ is minimized at $\boxed{\cos\theta = \dfrac{C_2}{C_1}} \neq 0$

2.Model (15/18) : Step.3 -Realization of EWSB

Effective potential for NGBs:

$$V_{\text{eff}}(U) = \boxed{C_1 F^2} \text{tr}\left[U^\dagger \Sigma_0 U \Sigma_0\right] - \boxed{C_2 F^2} \text{tr}\left[U\Sigma_0 + \Sigma_0 U^\dagger\right]$$

The vev of U is parametrized by $\langle U \rangle = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}$

$$\Phi \sim \bar{\chi}_R \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix}$$

$\langle \bar{\chi}_R \chi_L \rangle \neq 0$ $\langle \bar{\chi}_R t_L \rangle \neq 0$

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \cdot \langle U \rangle \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \frac{f}{\sqrt{2}} \left[\cos\theta \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + \boxed{\sin\theta} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \right]$$

$$0 \neq \boxed{\cos\theta = \frac{C_2}{C_1}} < 1 \Longrightarrow$$

EWSB

✓ **Step.3**

2.Model (16/18) : Step.3 -Realization of Higgs mass

Effective potential for NGBs:

$$V_{\text{eff}}(U) = \boxed{C_1 F^2} \text{tr}\left[U^\dagger \Sigma_0 U \Sigma_0\right] - \boxed{C_2 F^2} \text{tr}\left[U \Sigma_0 + \Sigma_0 U^\dagger\right]$$

$\text{At } 0 \neq \boxed{\cos\theta = \frac{C_2}{C_1}} < 1,$ **EWSB** and

5 NGBs

3 NGBs = would-be NGBs eaten by W/Z bosons

2 NGBs = massive NGBs; **Pseudo-NGBs**

$$A_t^0 \qquad m_{A_t^0}^2 = 2C_1$$

$$h_t^0 \qquad m_{h_t^0}^2 = 2C_1 \sin^2\theta = m_{A_t^0}^2 \sin^2\theta$$

✓ **Step.3**

2.Model (17/18) : Summary of the model

Main particle contents in the TMpNGBH model

✓ **Step.1**

$$\psi_L = \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix} \qquad \begin{matrix} t_R \\ b_R \\ \chi_R \end{matrix}$$

$\mathcal{L}_{4f}$ = NJL : $U(3)_L \times U(1)_{\chi_R} \to U(2)_L \times U(1)_V$

✓ **Step.2** 5 NGBs emerge

$\mathcal{L}_h$ $\mathcal{L}_{\rm EW}$ $\mathcal{L}_t$ vacuum alignment $0 \neq \cos\theta = \dfrac{C_2}{C_1} < 1$

✓ **Step.3** EWSB

5 NGBs = 2 pNGBs + 3 would-be NGBs

h_t^0 A_t^0

2.Model (18/18) : Top quark mass in TMpNGBH model

TMpNGBH - top quark interaction: $-\tilde{m}_\chi \left[\bar{\psi}_L \mathcal{M}_f(U)\psi_R + \text{h.c.}\right]$

$$\mathcal{M}_f(U) = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \frac{G''}{G_{4f}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \qquad m_{\tilde{\chi}} = \frac{yf}{\sqrt{2}}$$

After the vacuum misalignment, mass matrix is given by

$$\tilde{m}_\chi \mathcal{M}_f(\langle U \rangle) = \tilde{m}_\chi \begin{pmatrix} 0 & 0 & \sin\theta \\ 0 & 0 & 0 \\ \left(\frac{G''}{G_{4f}}\right)\cos\theta & 0 & \cos\theta \end{pmatrix}$$

Thus

$$m_{t'} \simeq \tilde{m}_\chi \quad , \quad m_t \simeq m_{t'} \sin\theta\cos\theta \left(\frac{G''}{G_{4f}}\right)\left[1 - \cos^4\theta \left(\frac{G''}{G_{4f}}\right)^2\right]$$

Top SeeSaw mechanism

Dobrescu,Hill(1998);Chivukula,Dobrescu,Georgi, Hill (1999)

3. Phenomenologies (1/6)

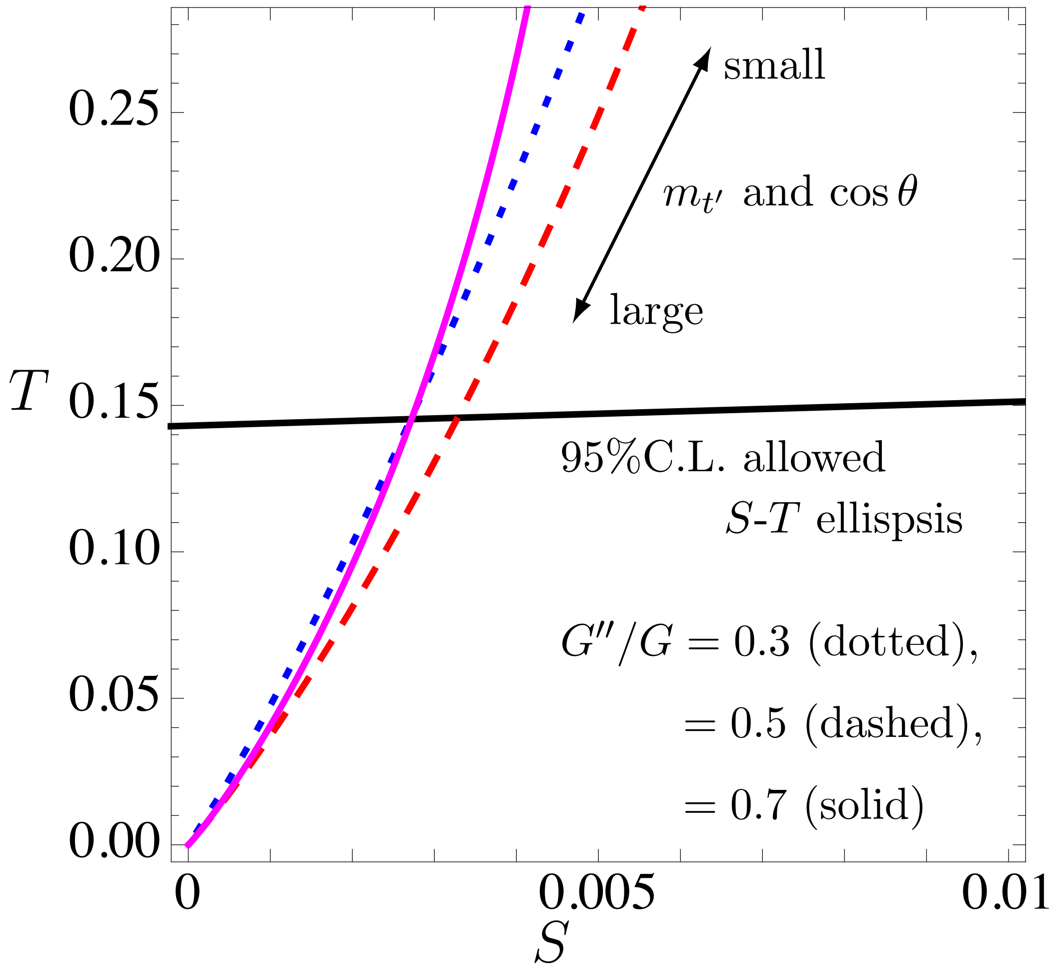
phenomenological aspects of TMpNGBH model:

- Electroweak precision tests (EWPTs),
- Higgs signal strength@LHC,
- Direct search of CP-odd TMpNGB, t' quark

3. Phenomenologies (2/6): TMpNGBH V.S. EWPT

arXiv:1311.6629

$\cos\theta$, $m_{t'}$ are constrained from EWPTs.



$$S = 0.08 \pm 0.10$$
$$T = 0.10 \pm 0.08$$

Ciuchini,Franco,Mishima,Silvestrini (2013)

EWPTs place constraints on s_L^t and $m_{t'}$

$$s_L^t \simeq \sin\theta \left[1 - \left(\frac{G''}{G_{4f}}\right)^2 \cos^4\theta\right]$$

$$m_{t'} \simeq \frac{m_t}{\sin\theta\cos\theta\,(G''/G_{4f})}\left[1 - \cos^4\theta\left(\frac{G''}{G_{4f}}\right)^2\right]^{-1}$$

95 % C.L. allowed region: $$m_{t'} \geq \begin{cases} 8.11\,\text{TeV}, & \cos\theta \geq 0.997 \quad \text{for } \dfrac{G''}{G_{4f}} = 0.3\,, \\ 3.23\,\text{TeV}, & \cos\theta \geq 0.991 \quad \text{for } \dfrac{G''}{G_{4f}} = 0.5\,, \\ 1.19\,\text{TeV}, & \cos\theta \geq 0.952 \quad \text{for } \dfrac{G''}{G_{4f}} = 0.7\,, \end{cases}$$

3. Phenomenologies (3/6): Higgs in TMpNGBH model

After adding $\mathcal{L}_{b,\tau} = G_{tb}(\bar{q}_L^i \chi_R)(i\tau^2)^{ij}(\bar{q}_L^j b_R) + G_{t\tau}(\bar{q}_L^i \chi_R)(i\tau^2)^{ij}(\bar{l}_L^j \tau_R) + \text{h.c}$

Higgs sector in TMpNGBH model:

$$\mathcal{L}_{h_t^0} = g_{hVV}\frac{v_{\rm EW}}{2}\left(g^2 h_t^0 W_\mu^+ W^{-\mu} + \frac{g^2+g'^2}{2} h_t^0 Z_\mu Z^\mu\right)$$

$$-g_{h\tau\tau}\frac{m_\tau}{v_{\rm EW}} h_t^0 \bar{\tau}\tau - g_{hbb}\frac{m_b}{v_{\rm EW}} h_t^0 \bar{b}b - g_{htt}\frac{m_t}{v_{\rm EW}} h_t^0 \bar{t}t - g_{ht't'}\frac{m_t'}{v_{\rm EW}} h_t^0 \bar{t}'t'$$

where

$$g_{hVV} = g_{hbb} = g_{h\tau\tau} = \cos\theta$$

$$g_{htt} = \frac{2\cos^2\theta - 1}{\cos\theta} + \mathcal{O}\left(\frac{m_t^2}{m_{t'}^2}\right)$$

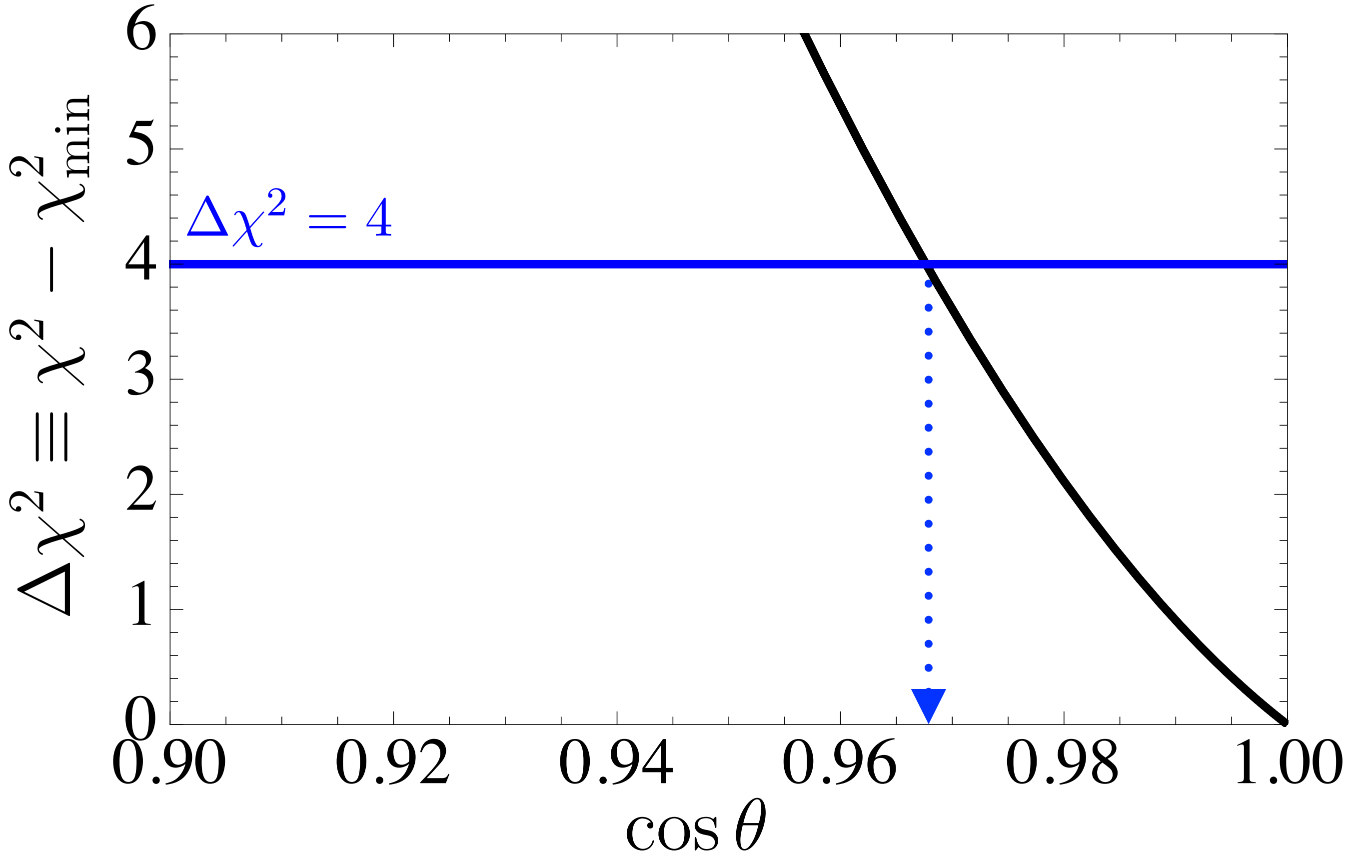
$$g_{ht't'} = \mathcal{O}\left(\frac{m_t^2}{m_{t'}^2}\right) \ll 1$$

3. Phenomenologies (4/6): Higgs signal strength

arXiv:1401.6292

chi^2 function for **Higgs signal strengths**

= a function of $\cos\theta$



95 % C.L. allowed region is given by

$$\boxed{0.97 \leq \cos\theta \leq 1}$$

diphoton: ATLAS-CONF-2013-012, CMS-PAS-HIG-13-001
ZZ : PLB726,88(2013), CMS-PAS-HIG-13-002
WW : ATLAS-CONF-2013-030, CMS-PAS-HIG-13-022
tau : ATLAS-CONF-2013-108, arXiv:1401.5041
bottom : ATLAS-CONF-2013-079, arXiv:1310.3687

independent of $\dfrac{G''}{G_{4f}}$

3. Phenomenologies (5/6): EWPT & LHC constraints

arXiv:1401.6292

EWPT

$$m_{t'} \geq \begin{cases} 8.11\,\mathrm{TeV}, & \cos\theta \geq 0.997 \quad \text{for } \frac{G''}{G} = 0.3\,, \\ 3.23\,\mathrm{TeV}, & \cos\theta \geq 0.991 \quad \text{for } \frac{G''}{G} = 0.5\,, \\ 1.19\,\mathrm{TeV}, & \cos\theta \geq 0.952 \quad \text{for } \frac{G''}{G} = 0.7\,, \end{cases}$$

signal strength

$$0.97 \leq \cos\theta \leq 1$$

We take a benchmark point which allows light t'-quark and light CP-odd TMpNGB:

$$m_{t'} \gtrsim 1800\,\mathrm{GeV} \quad , \quad m_{A_t^0} \gtrsim 500\,\mathrm{GeV}$$

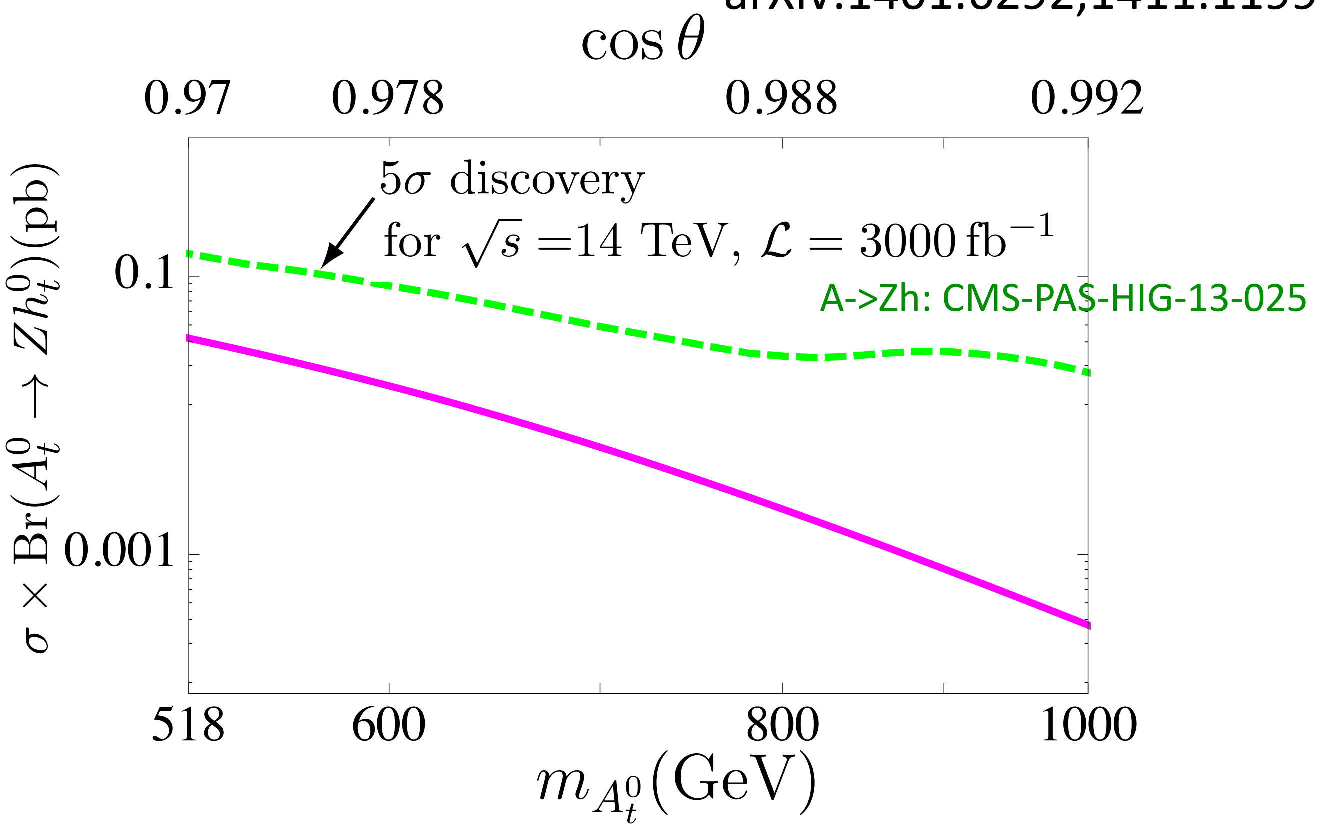
3. Phenomenologies (6/6): CP-odd TMpNGB and t'-quark

arXiv:1401.6292,1411.1199

CP-odd TMpNGB

Characteristic channel of CP-odd TMpNGB:

$$gg \longrightarrow A_t^0 \longrightarrow Z_L^0 h_t^0$$



t' quark

characteristic channel of t':

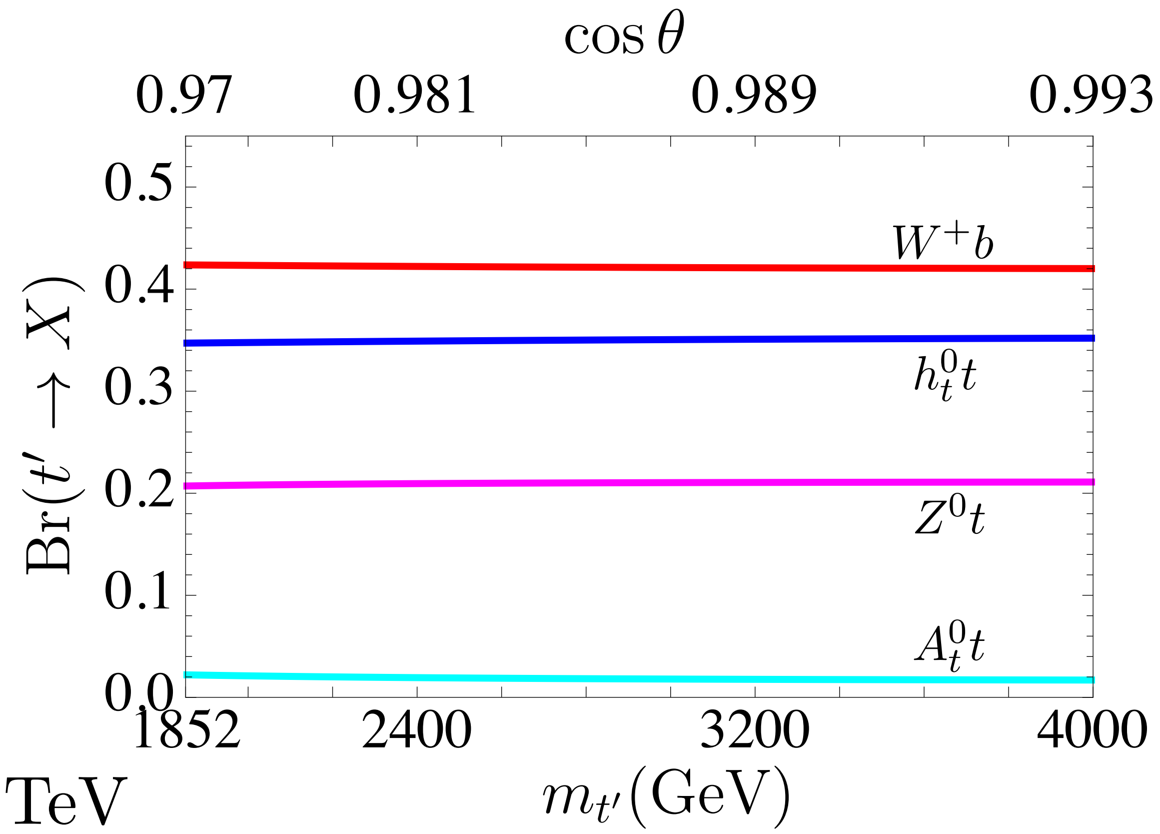
$$t' \longrightarrow h_t^0 t$$

In a vector-like model:

$\mathrm{Br}(t' \to W^+ b)$:	$\mathrm{Br}(t' \to Zt)$:	$\mathrm{Br}(t' \to ht)$
0.5	0.25	0.25

Aguilar-Saavedra et.al. (2013)

for $m_{t'} \simeq 2\,\mathrm{TeV}$



4.Summary

- 126 GeV Higgs (CP-even TMpNGB)
  = **a pseudo Nambu-Goldstone boson**
  based on the **Top quark condensation**.
- EWSB & pNGB masses = **the vacuum misalignment**
- Top quark mass = **the top seesaw mechanism**
- EWPT, LHC Higgs measurements : O.K.
- Signal candidates: CP-odd TMpNGB & t' quark

$$500\,\mathrm{GeV} \lesssim m_{A_t^0} \qquad 1800\,\mathrm{GeV} \lesssim m_{t'}$$

Thank you very much

Backup slides

Broken currents and NGBs

The broken currents and corresponding NGBs:

$$\bar{\psi}_{1L}\gamma^{\mu}\psi_{2L} \xrightarrow{CP} -\bar{\psi}_{2L}\gamma^{\mu}\psi_{1L}$$

Broken current	corresponding NGB	CP-property
$J^{4,\mu}_{3L}$	$\pi^4_t = z^0_t \cos\theta - A^0_t \sin\theta$	odd
$J^{5,\mu}_{3L}$	$\pi^5_t = h^0_t$	even
$J^{6,\mu}_{3L} \pm iJ^{7,\mu}_{3L}$	$\pi^6_t \pm i\pi^7_t = \sqrt{2}w^{\pm}_t$	–
J^{μ}_{A}	$\pi^A_t = z^0_t \sin\theta + A^0_t \cos\theta$	odd

$$J^{a,\mu}_{3L} = \bar{\tilde{\psi}}_L\gamma^{\mu}\lambda^a\tilde{\psi}_L \qquad J^{\mu}_{A} = \frac{1}{4}\left(J^{\mu}_{1R} - \frac{1}{\sqrt{6}}J^{0,\mu}_{3L} + \frac{1}{\sqrt{3}}J^{8,\mu}_{3L}\right) \qquad J^{a,\mu}_{1R} = \bar{\chi}_R\gamma^{\mu}\chi_R$$

5 NGBs emerge with the decay constant f as:

$$\langle 0 \left| J^a_{\mu}(x) \right| \pi^b_t(p) \rangle = -if\delta^{ab}p_{\mu}e^{-ip\cdot x}\,, \qquad a, b = 4, 5, 6, 7, A$$

NGBs as composite fields

$$
\begin{aligned}
\pi_t^4 &\sim \bar{\chi}_R\tilde{t}_L - \bar{\tilde{t}}_L\chi_R \\
&= (\bar{\chi}_R t_L - \bar{t}_L\chi_R)\cos\theta - (\bar{\chi}_R\chi_L - \bar{\chi}_L\chi_R)\sin\theta\,, \\
\pi_t^5 &\sim -i\left(\bar{\chi}_R\tilde{t}_L + \bar{\tilde{t}}_L\chi_R\right) \\
&= -i\,(\bar{\chi}_R t_L + \bar{t}_L\chi_R)\cos\theta + i\,(\bar{\chi}_R\chi_L + \bar{\chi}_L\chi_R)\sin\theta\,, \\
\pi_t^6 + i\pi_t^7 &\sim \left(\bar{\chi}_R\tilde{b}_L - \bar{\tilde{b}}_L\chi_R\right) + \left(\bar{\chi}_R\tilde{b}_L + \bar{\tilde{b}}_L\chi_R\right) \\
&= 2\bar{\chi}_R b_L\,, \\
\pi_t^6 - i\pi_t^7 &\sim \left(\bar{\chi}_R\tilde{b}_L - \bar{\tilde{b}}_L\chi_R\right) - \left(\bar{\chi}_R\tilde{b}_L + \bar{\tilde{b}}_L\chi_R\right) \\
&= -2\bar{b}_L\chi_R\,, \\
\pi_t^A &\sim \bar{\chi}_R\tilde{\chi}_L - \bar{\tilde{\chi}}_L\chi_R \\
&= (\bar{\chi}_R t_L - \bar{t}_L\chi_R)\sin\theta + (\bar{\chi}_R\chi_L - \bar{\chi}_L\chi_R)\cos\theta\,.
\end{aligned}
$$

$$\bar{\psi}_{1L}\psi_{2R} \xrightarrow{CP} \bar{\psi}_{2R}\psi_{1L}$$

t-t' mixing angle

$$\begin{pmatrix} t_L \\ t'_L \end{pmatrix}_m = \begin{pmatrix} c^t_L & -s^t_L \\ s^t_L & c^t_L \end{pmatrix} \begin{pmatrix} t_L \\ \chi_L \end{pmatrix}_g \quad , \quad \begin{pmatrix} t_R \\ t'_R \end{pmatrix}_m = \begin{pmatrix} -c^t_R & s^t_R \\ s^t_R & c^t_R \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix}_g$$

$$\begin{aligned}
c^t_L &= \frac{1}{\sqrt{2}} \left[1 + \frac{m^2_{\chi\chi} - m^2_{t\chi} + \mu^2_{\chi t}}{m^2_{t'} - m^2_t} \right]^{1/2} \simeq \cos\theta \left[1 + \left(\frac{G''}{G} \right)^2 \cos^2\theta \sin^2\theta \right] , \\
s^t_L &= \frac{1}{\sqrt{2}} \left[1 - \frac{m^2_{\chi\chi} - m^2_{t\chi} + \mu^2_{\chi t}}{m^2_{t'} - m^2_t} \right]^{1/2} \simeq \sin\theta \left[1 - \left(\frac{G''}{G} \right)^2 \cos^4\theta \right] , \\
c^t_R &= \frac{1}{\sqrt{2}} \left[1 + \frac{m^2_{\chi\chi} + m^2_{t\chi} - \mu^2_{\chi t}}{m^2_{t'} - m^2_t} \right]^{1/2} \simeq 1 - \frac{1}{2} \left(\frac{G''}{G} \right)^2 \cos^4\theta \, , \\
s^t_R &= \frac{1}{\sqrt{2}} \left[1 - \frac{m^2_{\chi\chi} + m^2_{t\chi} - \mu^2_{\chi t}}{m^2_{t'} - m^2_t} \right]^{1/2} \simeq \frac{G''}{G} \cos^2\theta
\end{aligned}$$

S & T parameters

$$
\begin{aligned}
S &= \frac{3}{2\pi}(s_L^t)^2\left[-\frac{1}{9}\ln\frac{x_{t'}}{x_t} - (c_L^t)^2 F(x_t, x_{t'})\right] , \\
T &= \frac{3}{16\pi s_W^2 c_W^2}(s_L^t)^2\left[(s_L^t)^2 x_{t'} - \left(1+(c_L^t)^2\right)x_t + (c_L^t)^2\frac{2x_{t'}x_t}{x_{t'}-x_t}\ln\frac{x_{t'}}{x_t}\right] ,
\end{aligned}
$$

$$x_a \equiv \frac{m_a^2}{m_Z^2}\,, (a = t, t')$$

$$F(x,y) = \frac{5(x^2+y^2)-22xy}{9(x-y)^2} + \frac{3xy(x+y)-x^3-y^3}{3(x-y)^3}\ln\frac{x}{y}$$

Branching ratio of CP-odd Higgs

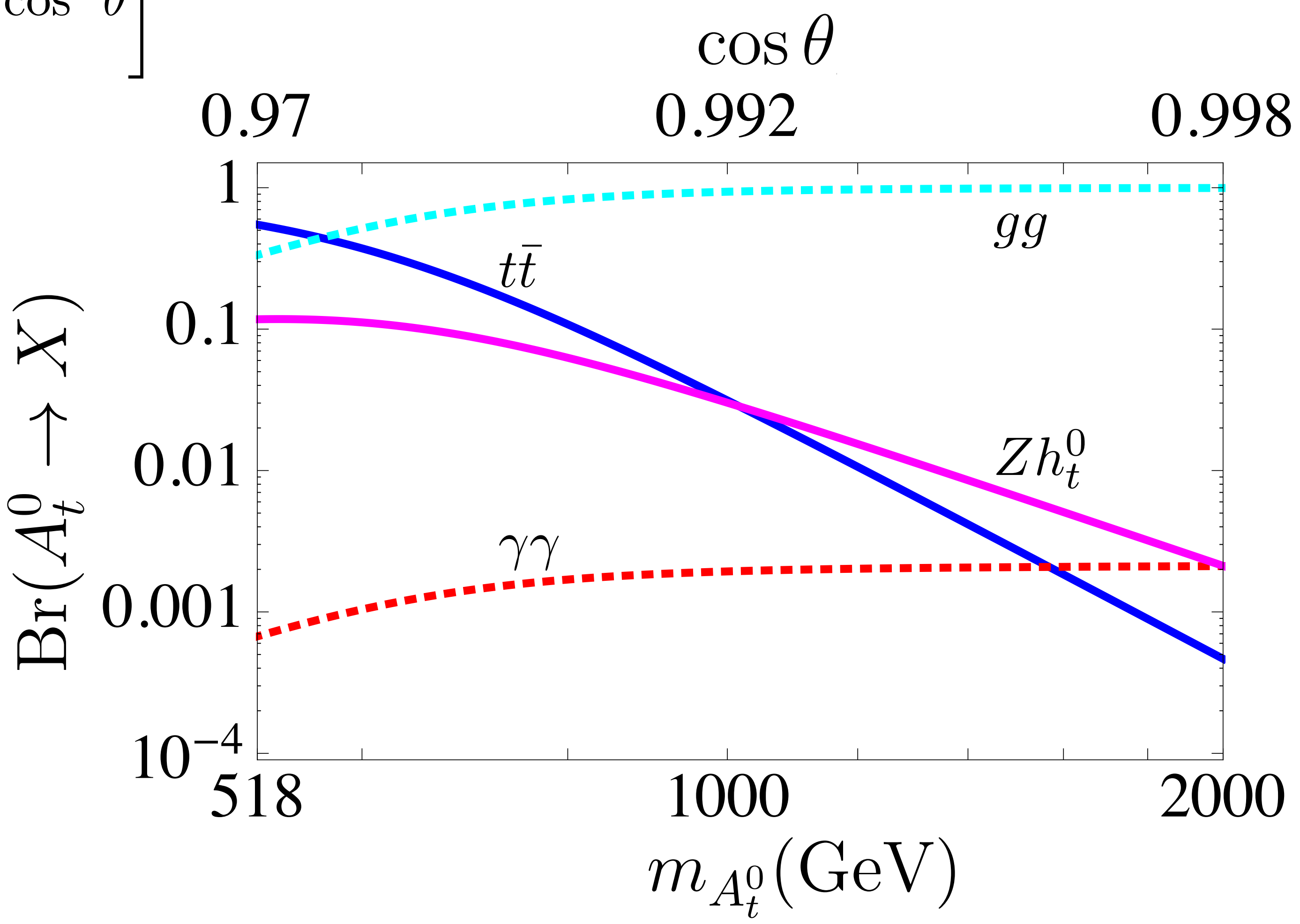
$$\beta_A(m_t) \equiv \sqrt{1 - \frac{4m_t^2}{m_{A_t^0}^2}}\,, \quad \beta_A(m_{h_t^0}) \equiv \sqrt{\left[1 - \frac{\left(m_{h_t^0} - m_Z\right)^2}{m_{A_t^0}^2}\right]\left[1 - \frac{\left(m_{h_t^0} + m_Z\right)^2}{m_{A_t^0}^2}\right]}\,.$$

$$\Gamma(A_t^0 \to t\bar{t}) = \frac{\sqrt{2}G_F N_c m_t^2 m_{A_t^0}}{8\pi^2}\left(\frac{\sin^3\theta}{\cos\theta}\right)^2 \cdot \beta_A(m_t)\,,$$

$$\Gamma(A_t^0 \to gg) = \frac{\sqrt{2}G_F \alpha_s^2 m_{A_t^0}^3}{128\pi^3} \cdot \left|\left(\frac{\sin^3\theta}{\cos\theta}\right) A_{1/2}^A(\tau_t) + 2(\sin\theta\cos\theta)\right|^2\,,$$

$$\Gamma(A_t^0 \to \gamma\gamma) = \frac{\sqrt{2}G_F \alpha^2 m_{A_t^0}^3}{256\pi^3} \cdot \left|\left(\frac{\sin^3\theta}{\cos\theta}\right) N_c Q_t^2 A_{1/2}^A(\tau_t) + \frac{8N_c}{9}(\sin\theta\cos\theta)\right|^2\,,$$

$$\Gamma(A_t^0 \to Z_L h_t^0) = \frac{9\sqrt{2}G_F m_{A_t^0}^3}{256\pi}\sin^2\theta \cdot \beta_A(m_{h_t^0})\left[\frac{m_Z^2}{m_{A_t^0}^2}\cos^2\theta\right]^2$$



Partial decay widths of t' quark

$$\begin{aligned}
\Gamma(t' \to W^+ b) &= \frac{g^2}{64\pi}(s_L^t)^2 \frac{m_{t'}^3}{M_W^2}\left(1-\frac{M_W^2}{m_{t'}^2}\right)^2\left(1+2\frac{M_W^2}{m_{t'}^2}\right) ,\\
\Gamma(t' \to Zt) &= \frac{g^2}{64\pi c_W^2}(c_L^t s_L^t)^2 \frac{m_{t'}^3}{2M_Z^2}\beta\left(\frac{m_t^2}{m_{t'}^2},\frac{M_Z^2}{m_{t'}^2}\right)\left(1-\frac{2m_t^2-M_Z^2}{m_{t'}^2}+\frac{m_t^4-2M_Z^4+m_t^2M_Z^2}{m_{t'}^4}\right) ,\\
\Gamma(t' \to h_t^0 t) &= \frac{y^2}{32\pi}m_{t'}\beta\left(\frac{m_t^2}{m_{t'}^2},\frac{m_{h_t^0}^2}{m_{t'}^2}\right)\left[(C_{hL}^2+C_{hR}^2)\left(1+\frac{m_t^2+m_{h_t^0}^2}{m_{t'}^2}\right)+4C_{hL}C_{hR}\frac{m_t}{m_{t'}}\right] ,\\
\Gamma(t' \to A_t^0 t) &= \frac{y^2}{32\pi}m_{t'}\beta\left(\frac{m_t^2}{m_{t'}^2},\frac{m_{A_t^0}^2}{m_{t'}^2}\right)\left[(C_{AL}^2+C_{AR}^2)\left(1+\frac{m_t^2+m_{A_t^0}^2}{m_{t'}^2}\right)-4C_{AL}C_{AR}\frac{m_t}{m_{t'}}\right]
\end{aligned}$$

$$\beta(x,y) = \sqrt{(1-x-y)^2-4xy}$$