Higgs as a Top-Mode Pseudo

Hidenori S. Fukano (KMI,Nagoya)

Based on

arXiv:1311.6629 [H.S.F, M.Kurachi, S.Matsuzaki and K.Yamawaki]

and

arXiv:1401.6292 [H.S.F, S.Matsuzaki]

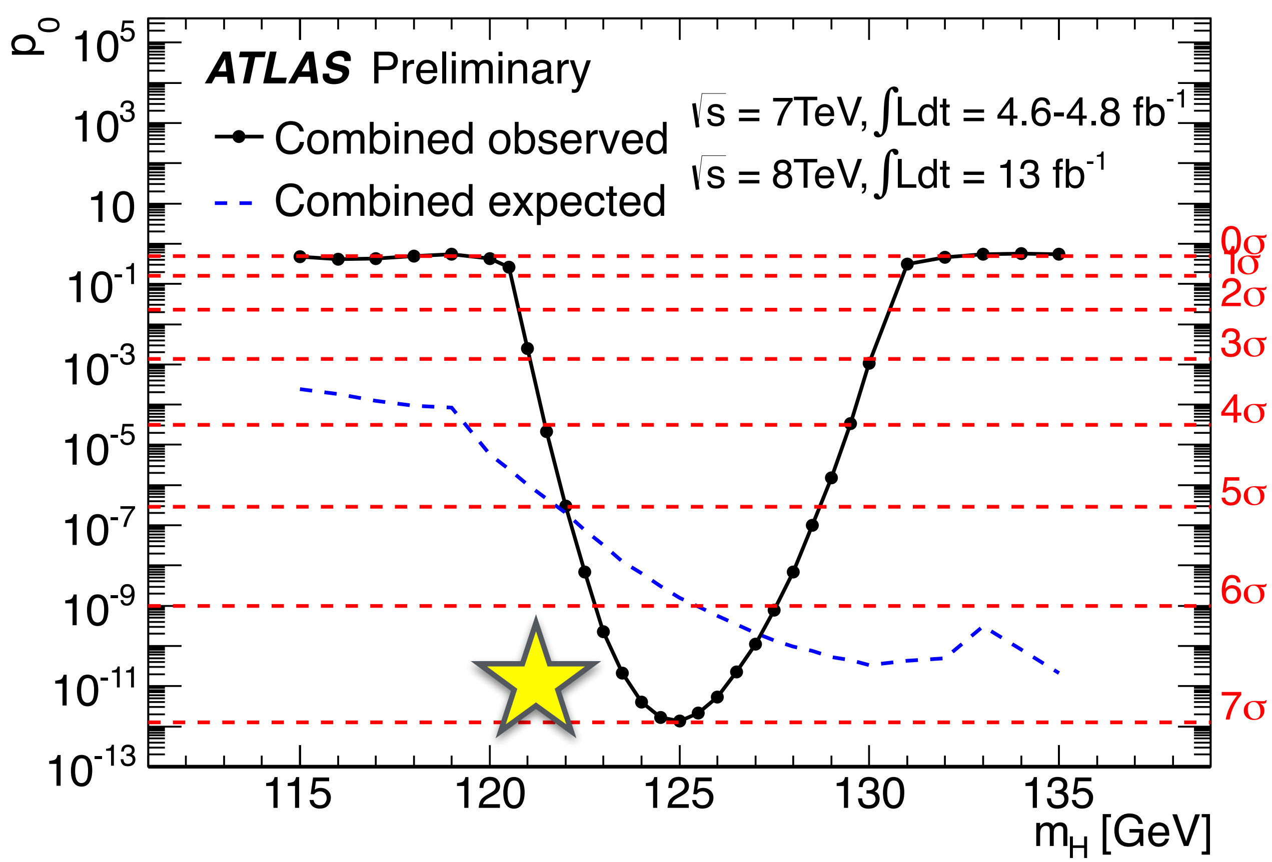
@SCGT14mini

07.Mar.2014

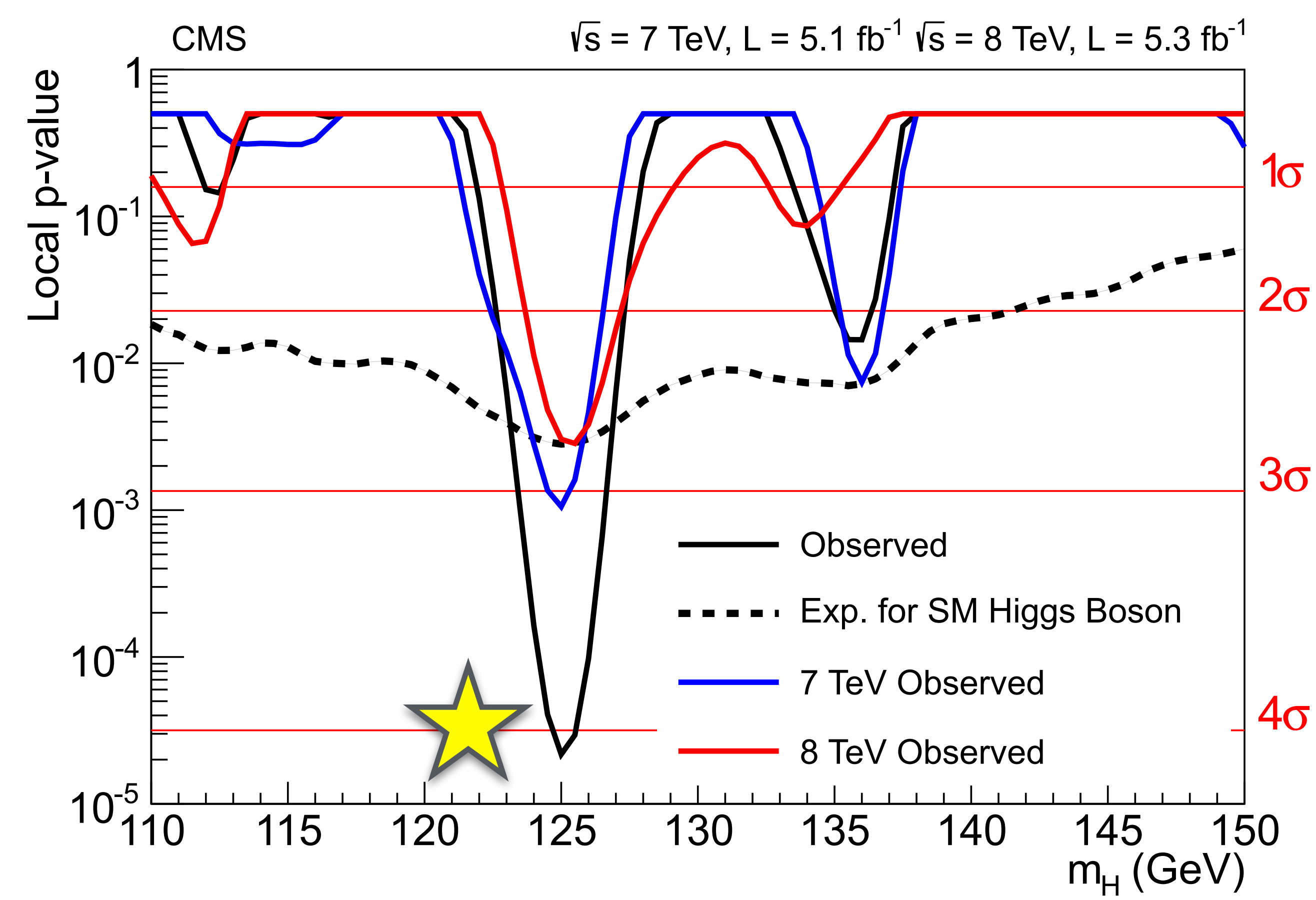
1. Background and Introduction (1/5) : Discovery of 126 GeV Higgs

As you already know,

A 126 GeV Higgs boson has been discovered at the LHC.



ATLAS-CONF-2012-170



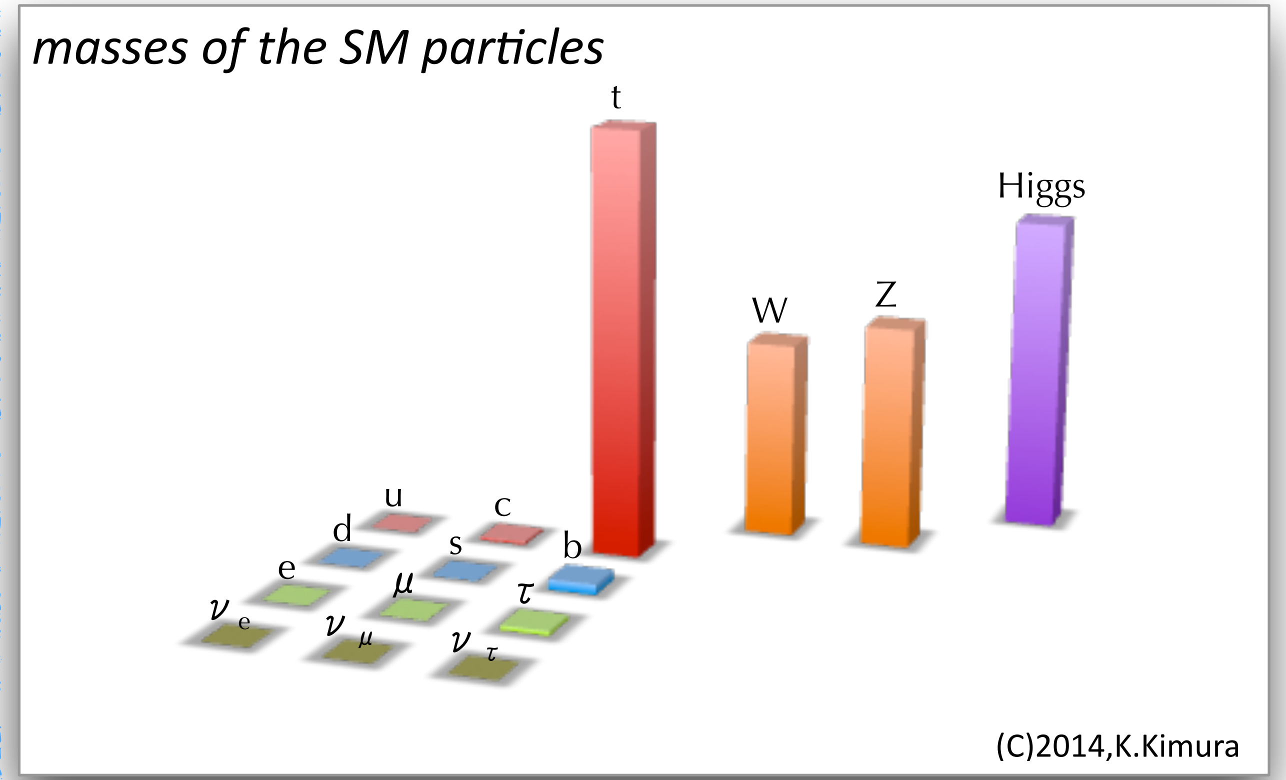
JHEP 1306 (2013) 081

1. Background and Introduction (2/5) : Next target

A primary target for future collider experiments (e.g. LHC Run-II) is to reveal ***the dynamical origin of Higgs boson.***

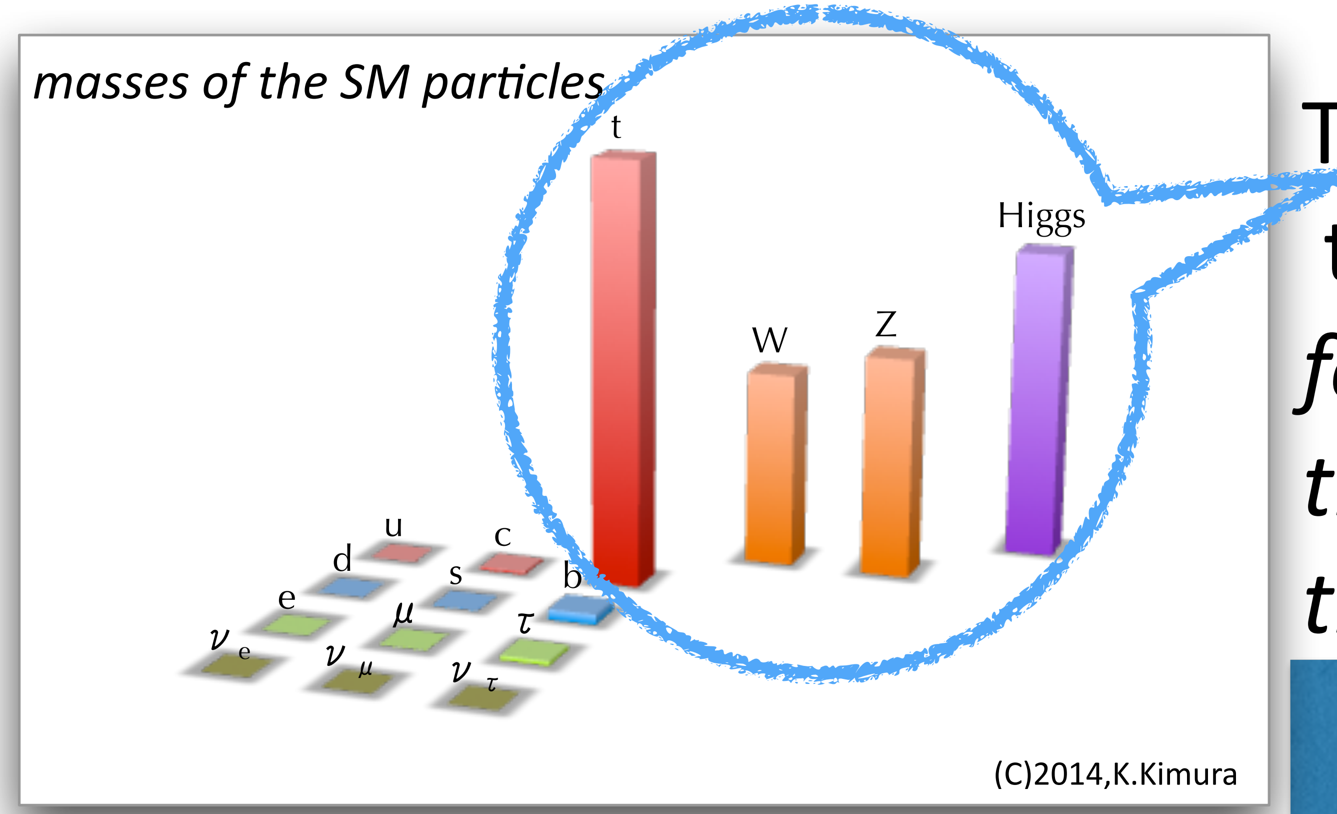
This is closely related to the origin of masses of the SM particles.

One Key Hint for revealing the origin of mass



Among masses of the SM particles, masses of the top quark, W/Z boson and Higgs boson are roughly the same order.

1. Background and Introduction (3/5) : Top quark condensation



This coincidence may imply that the *top quark plays a crucial role for the EWSB and the generation of the mass of the Higgs boson*.

Top quark condensation

Miransky,Tanabashi,Yamawaki(1989);Nambu(1989);Marciano(1989,1990);Bardeen,Hill,Lindner(1990)

Top quark condensation (Top-Mode SM; TMSM)

= A model constructed by NJL-like four-fermion interactions

1. Background and Introduction (4/5) : Sigma = 126 GeV Higgs ?

In general,

the *NJL model* predicts the existence of a *sigma-meson*

as a bound state of ***fermions*** with mass

$$m_\sigma = 2m$$

The *TMSM* predicts the existence of a *Higgs boson*

as a bound state of ***top quarks*** with mass

$$m_H = 2m_t$$

This relation generates a serious tension in the top quark condensation

after the discovery of 126 GeV Higgs boson.

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

In the spirit of the top quark condensation,

Q: Can we realize 126 GeV Higgs ?

in a model based on a four-fermion dynamics including the top quark

A: YES !!

H.S.F, M.Kurachi , S.Matsuzaki and K.Yamawaki; arXiv:1311.6629

126 GeV Higgs emerges as a pseudo Nambu-Goldstone boson

Not sigma-meson

2.Model (1/6) : symmetry breaking

arXiv:1311.6629

Model Lagrangian:

$$\psi_L = \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix}$$

$$\mathcal{L}_{\rm kin.} + \mathcal{L}^{4f}$$

$$= G(\bar{\psi}^i_L \chi_R)(\bar{\chi}_R \psi^i_L)$$

$$q_R = \begin{pmatrix} t_R \\ b_R \end{pmatrix} \quad \chi_R$$

Approximate global symmetry:

$$U(3)_L \times U(2)_R \times U(1)_R$$

SSB by $\mathcal{L}^{4f}$ $\quad G > G_{\rm crit} \equiv \frac{8\pi^2}{N_c \Lambda^2}$

$$U(2)_L \times U(2)_R \times U(1)'_V$$

8 - 3 = 5 NGBs emerge

2.Model (2/6) : Mass for NGBs arXiv:1311.6629

Model Lagrangian:

$$\mathcal{L}_{\rm kin.} + \mathcal{L}^{4f} + \mathcal{L}^{h} \qquad \Delta_{\chi\chi} \ll \Lambda \qquad G' \ll G$$

criticality

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

Approximate global symmetry:

$$U(3)_L \times U(2)_R \times U(1)_R$$

SSB by $\mathcal{L}^{4f}$ and explicitly broken by $\mathcal{L}^{h}$

$$U(2)_L \times U(2)_R \times U(1)'_V$$

NGB : (8 - 3 =) 5 = 3 + 2

2.Model (3/6) : full model

arXiv:1311.6629

Model Lagrangian:

top quark mass via
top-seesaw mechanism

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

$$\mathcal{L}_{\rm kin.} + \mathcal{L}^{4f} + \mathcal{L}^{h} + \mathcal{L}^{t} + \mathcal{L}^{\rm others}$$

criticality PNGB

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

Approximate global symmetry:

$$U(3)_L \times \cancel{U(2)_R} \times U(1)_R$$

SSB by $\mathcal{L}^{4f}$ and explicitly broken by $\mathcal{L}^{h}$ and $\mathcal{L}^{t}$

$$U(2)_L \times \cancel{U(2)_R} \times U(1)'_V$$

NGB : (8 - 3 =) 5 = 3 + 2

2.Model (4/6): 5 = 3 + 2 NGBs arXiv:1311.6629

Explicit breaking term

$\Delta_{\chi\chi} \ll \Lambda \qquad G' \ll G$

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

is invariant under the chiral transformation associated with

$$J_{3L}^{6,\mu} \pm iJ_{3L}^{7,\mu} \quad , \quad J_{3L}^{4,\mu}\cos\theta + J_{3L}^{A,\mu}\sin\theta$$

$w_t^+ \quad w_t^- \quad z_t^0$

$$\tan\theta \equiv \frac{m_{t\chi}}{m_{\chi\chi}}$$

but not for

$$J_{3L}^{5,\mu} \quad , \quad -J_{3L}^{4,\mu}\sin\theta + J_{3L}^{A,\mu}\cos\theta$$

partially conserved current

$h_t^0 \quad A_t^0$

Top-Mode Pseudos

2.Model (5/6): Mass of PNGBs arXiv:1311.6629

The Dashen's formula gives

2 NGBs = massive NGBs; Top-Mode Pseudos

A_t^0 $$m^2_{A_t^0} = \frac{2\langle\bar{\chi}_R\tilde{\chi}_L\rangle\langle\bar{\chi}_R\chi_L\rangle}{f^2\cos\theta} \simeq \frac{G'}{G^2} \times \frac{2(m^2_{t\chi}+m^2_{\chi\chi})}{f^2}$$

h_t^0 $$m^2_{h_t^0} = m^2_{A_t^0}\cdot\sin^2\theta$$

$$G' \ll G$$

$$\langle\bar{\chi}_R\tilde{\chi}_L\rangle = \langle\bar{\chi}_R t_L\rangle\sin\theta + \langle\bar{\chi}_R\chi_L\rangle\cos\theta$$

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

w_t^+ w_t^- z_t^0 $$m^2_{z_t^0} = m^2_{w_t^\pm} = 0$$

2.Model (6/6): Top-Mode Pseudos arXiv:1311.6629

"Meson" in the present model based on ***the four-fermion dynamics***

SSB

NGBs

massless: w_t^+ w_t^- z_t^0

massive; Top-Mode Pseudos: tHiggs h_t^0 A_t^0

addition

"sigma" mode in the usual NJL

H_t^0 with $m_{H_t^0}^2 = 4m_{\tilde{\chi}\chi}^2 = 4(m_{t\chi}^2 + m_{\chi\chi}^2)$

Higgs in the TMSM $m_{H_t^0} > m_{h_t^0}$ can be identified with 126 GeV Higgs

3. Phenomenologies (1/8): tHiggs in NLsM

arXiv:1311.6629 ,1401.6292

A low energy effective Lagrangian relevant to studying the LHC phenomenologies of the Top-Mode Pseudos

→ *A non-linear sigma model* based on $\dfrac{U(3)_{\psi_L} \times U(1)_{\chi_R}}{U(2)_{\psi_L} \times U(1)_{\psi_L+\chi_R}}$

tHiggs part

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

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

$\cos\theta \to 1$: SM limit

$$g_{h**} = g_{h**}(\cos\theta) \quad , \quad g_{ht't'} = \mathcal{O}\left(\frac{m_t^2}{m_{t'}^2}\right) \ll 1$$

$$\sin\theta = \frac{m_{h_t^0}}{m_{A_t^0}}$$

$$g_{hVV} = g_{hbb} = g_{h\tau\tau} = \cos\theta \quad , \quad g_{htt} = \left[\frac{1 + \cos^2\theta}{2} + \mathcal{O}\left(\frac{m_t^2}{m_{t'}^2}\right) \right]^{1/2} \quad , \quad g_{ht't'} = \mathcal{O}\left(\frac{m_t^2}{m_{t'}^2}\right) \ll 1$$

3. Phenomenologies (2/8): tHiggs @ the LHC

arXiv:1401.6292

We construct a simple chi^2 function:

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

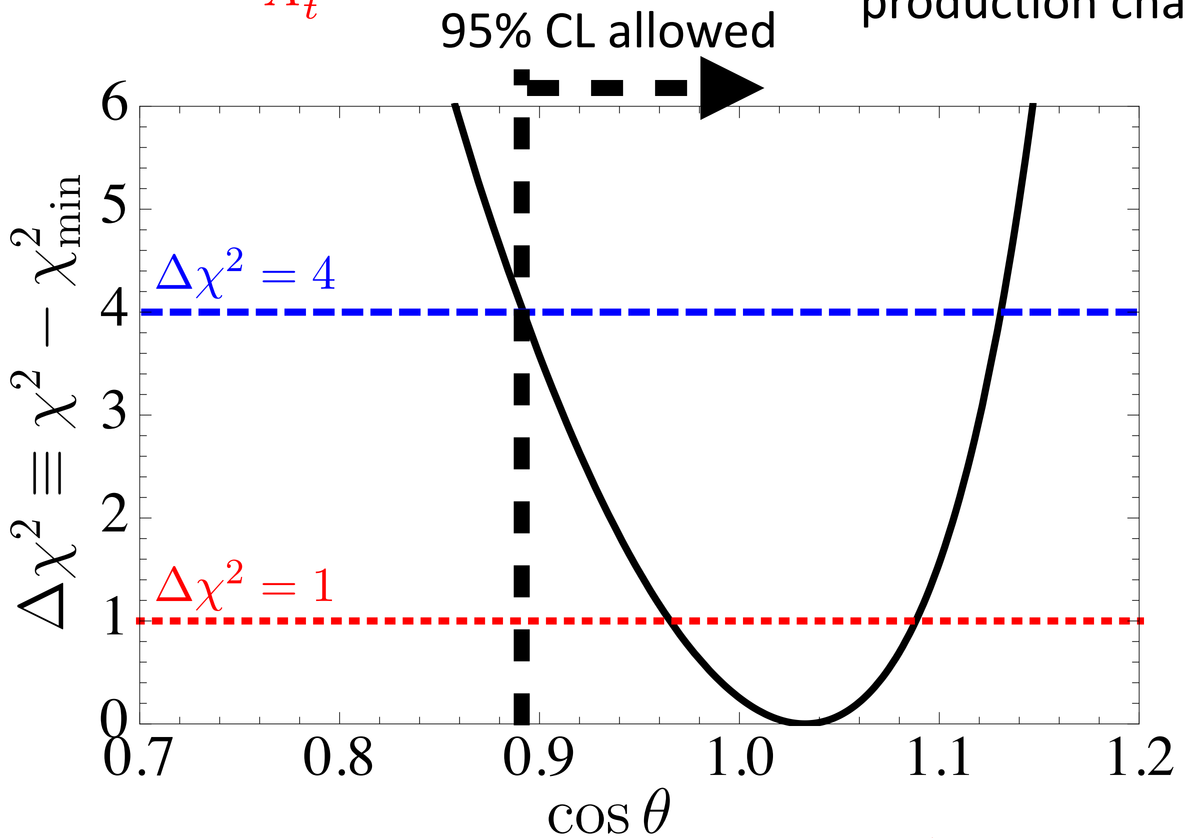
signal strength of tHiggs — signal strength (exp)

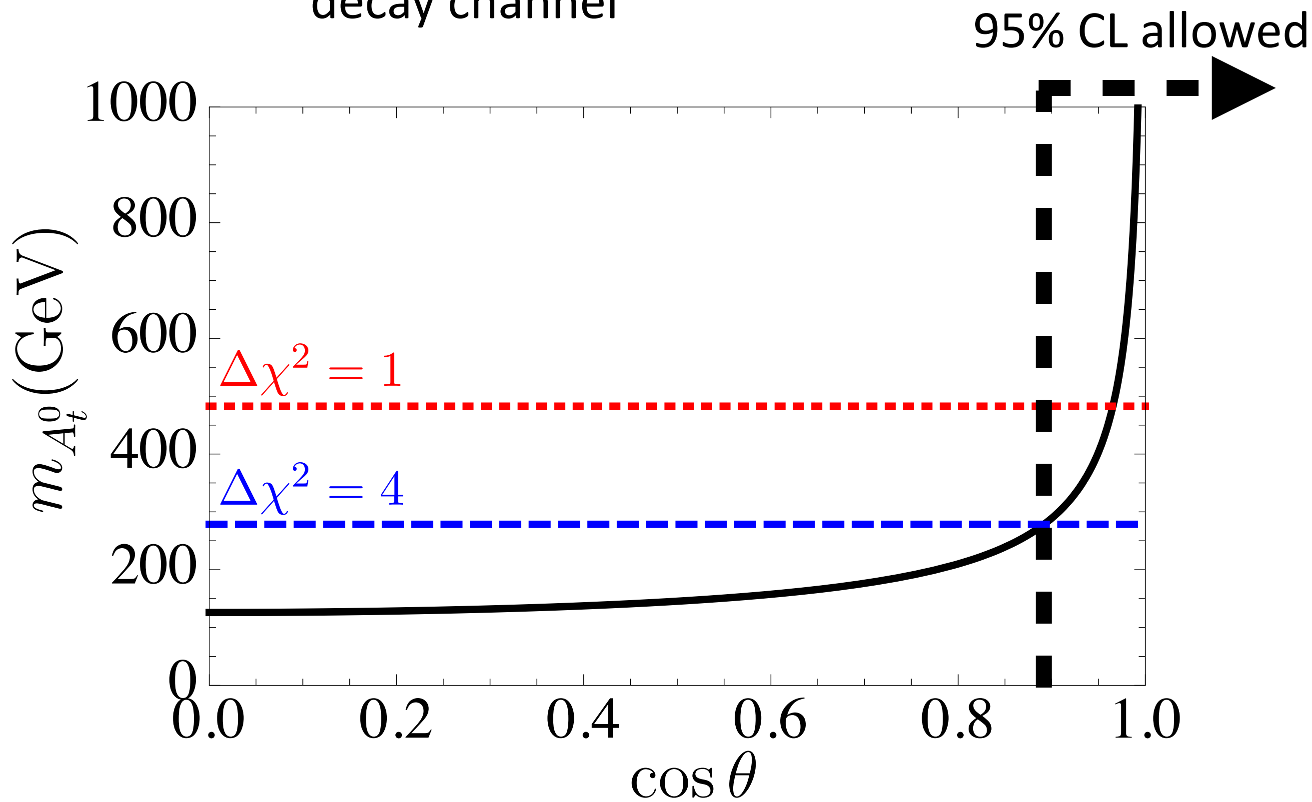
$$\chi^2(\cos\theta) \equiv \left[\sum_{i,j}\sum_X \left(\frac{\mu_i^X(\cos\theta) - \hat{\mu}_i^X}{\Delta\mu_i^X}\right)^2\right]_{\rm ATLAS} + \left[\sum_{i,j}\sum_X \left(\frac{\mu_i^X(\cos\theta) - \hat{\mu}_i^X}{\Delta\mu_i^X}\right)^2\right]_{\rm CMS}$$

1 sigma error

$$\sin\theta = \frac{m_{h_t^0}}{m_{A_t^0}} \qquad i,j \in \{{\rm ggF+t\bar{t}H, VBF+VH}\},\ X \in \{\gamma\gamma, ZZ^*, WW^*, \tau\tau, b\bar{b}\}$$

production channel — decay channel





95% CL allowed: $0.89 \leq \cos\theta \leq 1 \longleftrightarrow m_{A_t^0} \geq 278\,{\rm GeV}$

3. Phenomenologies (3/8): CP-odd Top-Mode Pseudo in NLsM

arXiv:1401.6292

CP-odd TMP part

$$\mathcal{L}_{A_t^0} = i\frac{m_t \sin\theta}{v_{\rm EW}} A_t^0 \bar{t}\gamma_5 t + i\frac{m_{t'} \sin\theta\cos\theta}{v_{\rm EW}} A_t^0 \bar{t}'\gamma_5 t'$$
$$-\frac{3\sin\theta\cos^2\theta}{4v_{\rm EW}}\left[z_t^0 \partial_\mu A_t^0 \partial^\mu h_t^0 - h_t^0 \partial_\mu A_t^0 \partial^\mu z_t^0 - 2m_{h_t^0}^2 A_t^0 h_t^0 z_t^0\right]$$
$$+\frac{3\sin^3\theta}{4v_{\rm EW}}\left[A_t^0 \partial_\mu z_t^0 \partial^\mu h_t^0 - h_t^0 \partial_\mu A_t^0 \partial^\mu z_t^0\right]$$

$$\sin\theta = \frac{m_{h_t^0}}{m_{A_t^0}}$$

CP-odd TMP does not couple to the W/Z bosons

due to the CP-symmetry

however

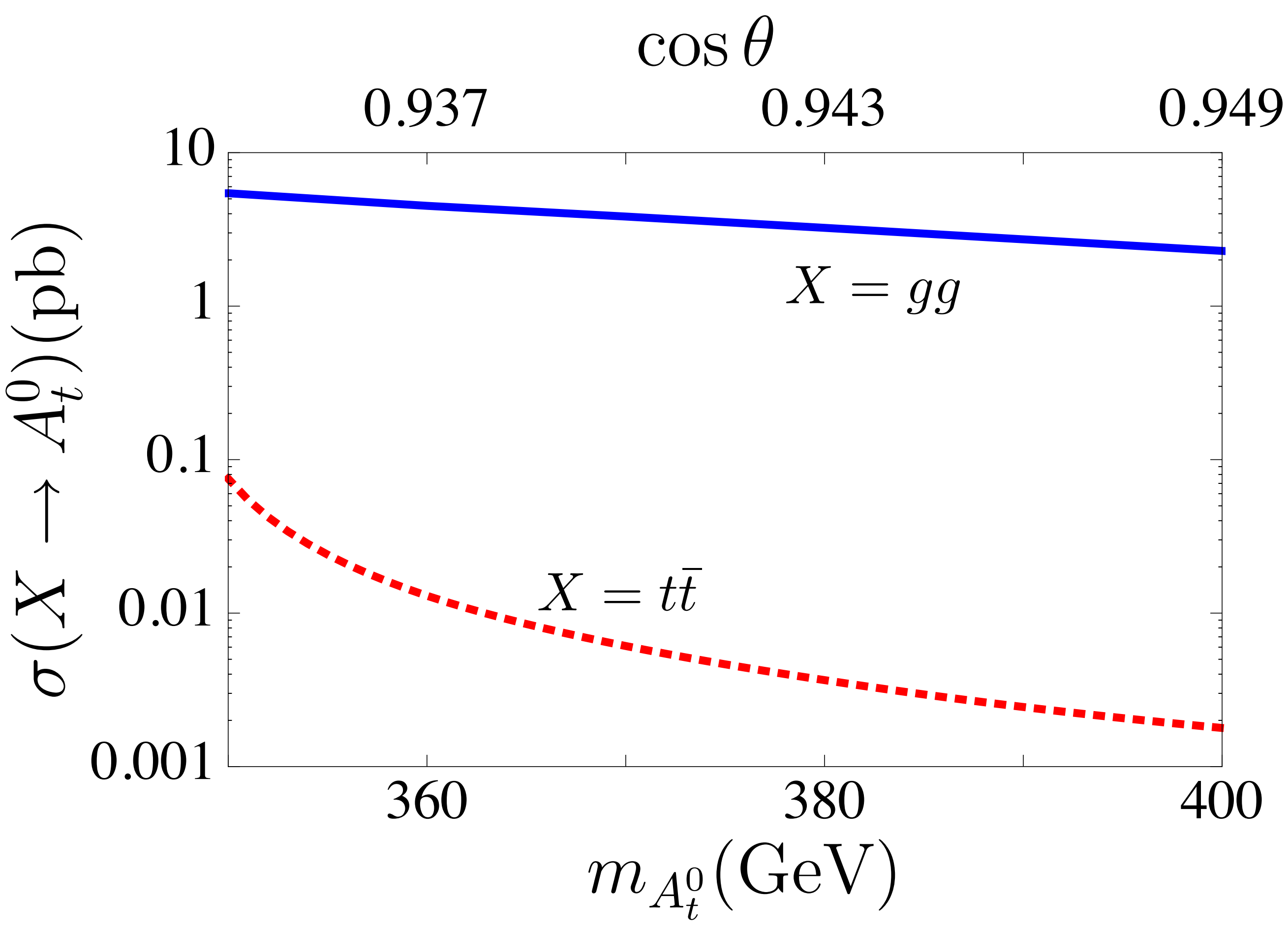
$Z_L^0 \equiv z_t^0$ contributes in the on-shell amplitude of CP-odd TMP.

$$A_t^0 \to Z_L^0 h_t^0$$

3. Phenomenologies (4/8): Production of CP-odd TMP

arXiv:1401.6292

The CP-odd TMP is mainly produced by
the gluon fusion (ggF) or top quark associate (ttA) process.

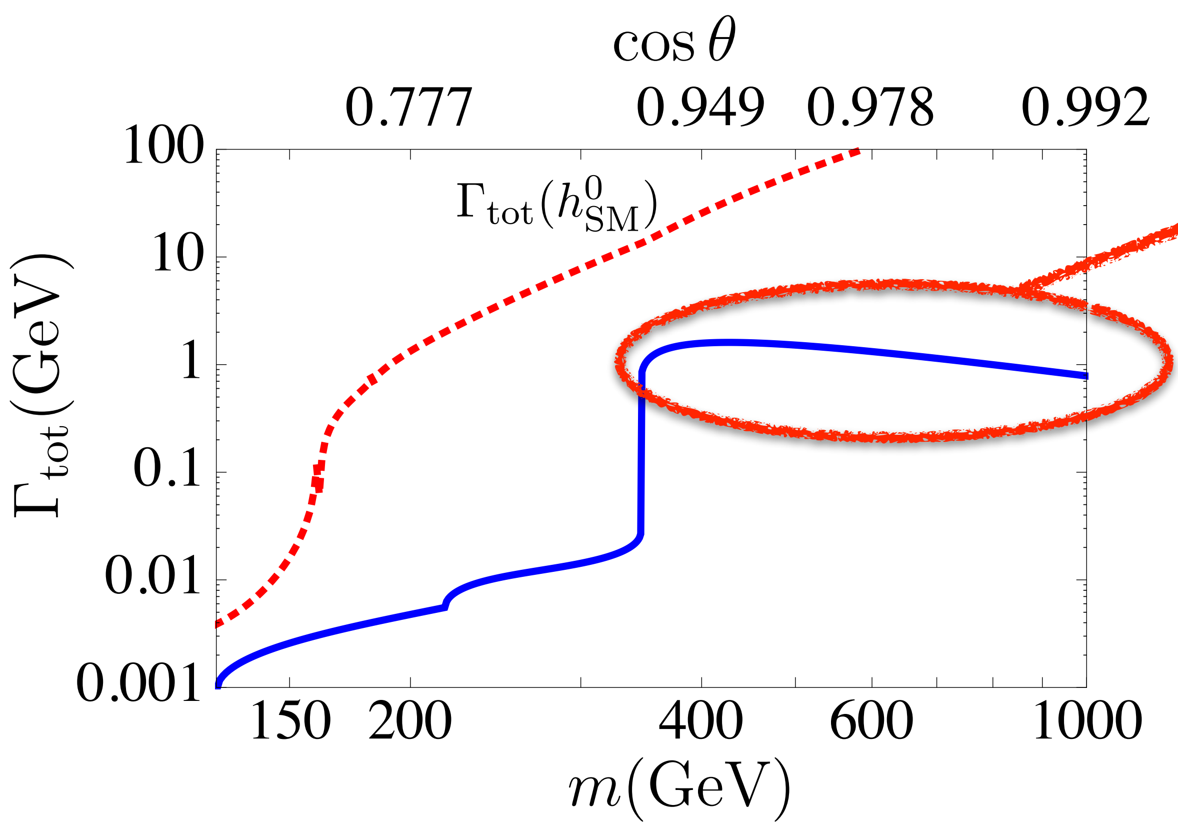


ggF production is highly dominant
enough to neglect the ttA production at the LHC.

3. Phenomenologies (5/8): Total decay width of CP-odd TMP

arXiv:1401.6292

The CP-odd TMP is a **narrower resonance** than the SM Higgs for the whole mass range.



As the mass gets larger, the total decay width decreases:

$$\Gamma_{tot}(A_t^0) \sim \Gamma(A_t^0 \to t\bar{t}) \sim \frac{1}{m_{A_t^0}}$$

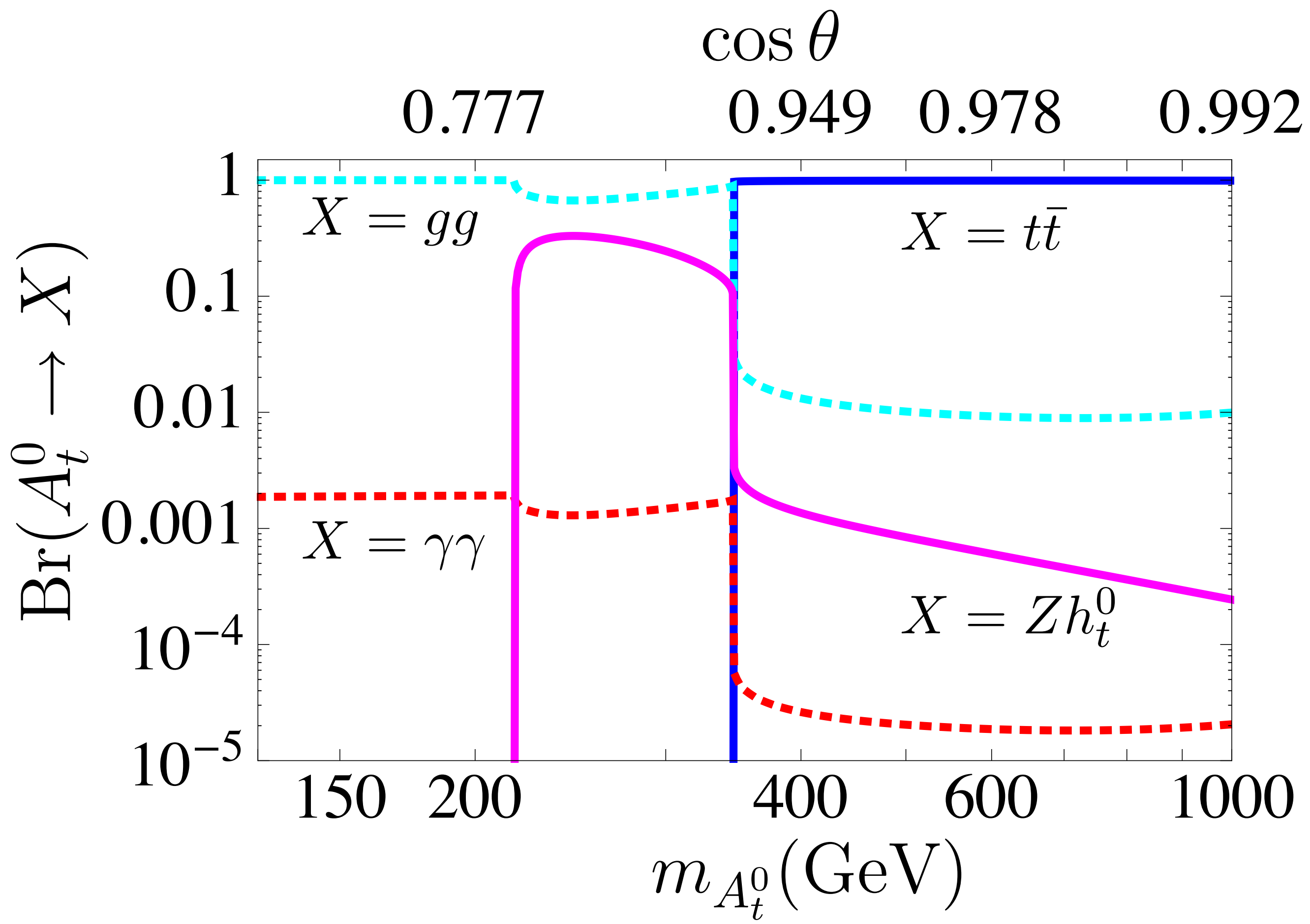
$$\Gamma(A_t^0 \to t\bar{t}) = \frac{\sqrt{2} G_F N_c m_t^2 m_{A_t^0}}{8\pi^2} \sin^2\theta \cdot \beta_A(m_t)$$

$$\sin\theta = \frac{m_{h_t^0}}{m_{A_t^0}}$$

This is the salient feature closely related to the fact that the CP-odd TMP is the partner of the tHiggs.

3. Phenomenologies (6/8): Branching ratio of CP-odd TMP

arXiv:1401.6292



The accessible decay channels of CP-odd TMP at the LHC:

$m_{h_t^0} + m_Z \leq m_{A_t^0} < 2m_t$ → $A_t^0 \to Zh_t^0$ mode

Low-mass

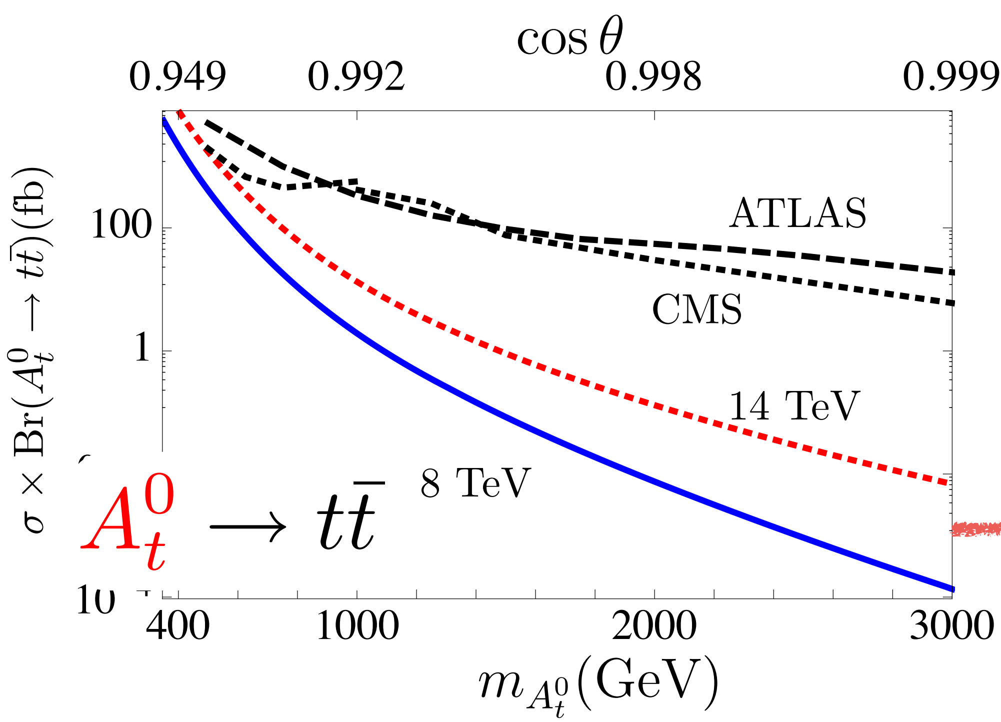
$m_{A_t^0} > 2m_t$ → $A_t^0 \to t\bar{t}$ mode

High-mass

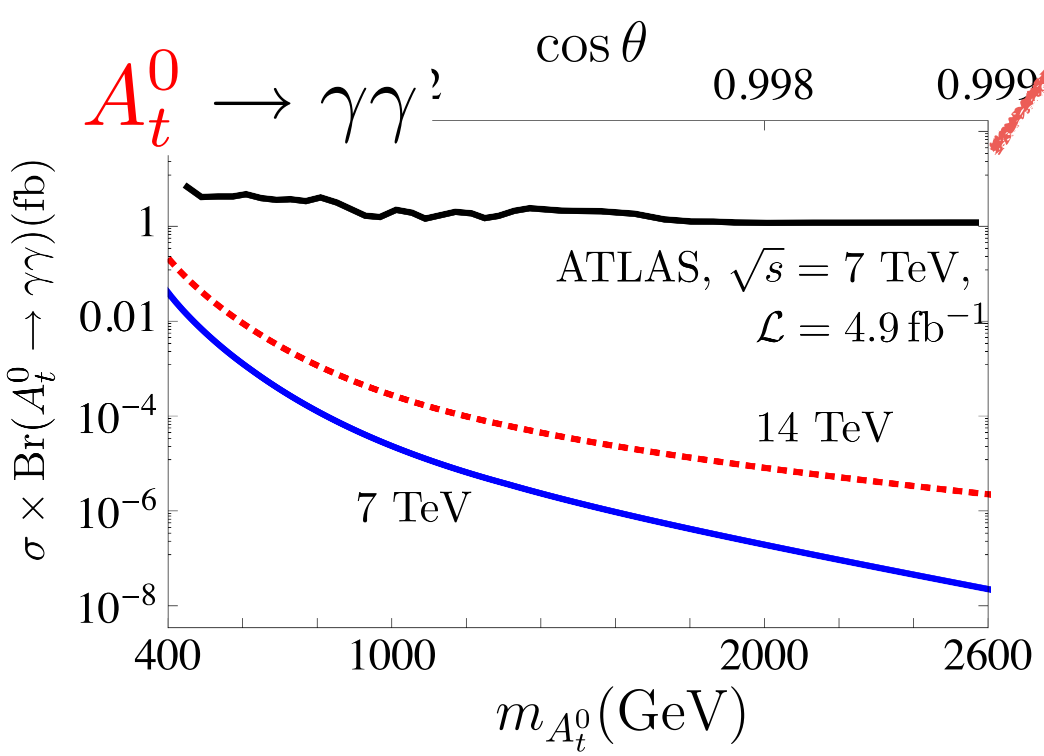
3. Phenomenologies (7/8): High-mass CP-odd TMP @ LHC

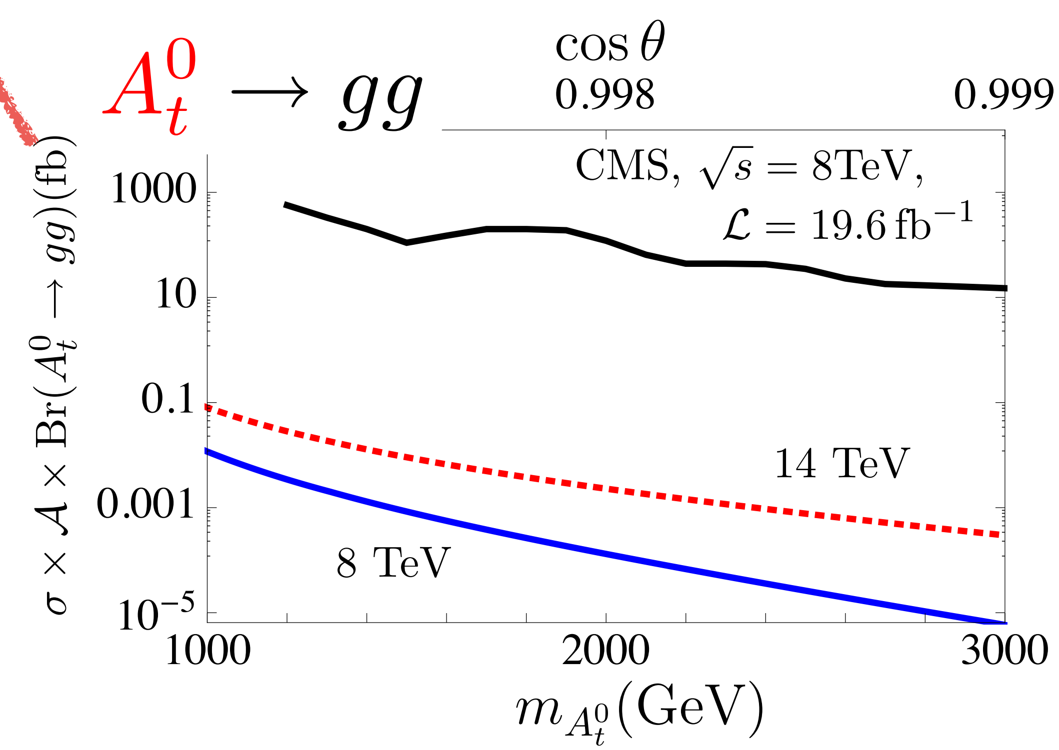
arXiv:1401.6292

tt : ATLAS-CONF-2013-052, PRL111,211804(2013)
diphoton: New J.Phys.15,043007(2013)
gg : CMS-PAS-EXO-12-059



High-mass CP-odd TMP ($m_{A_t^0} > 2m_t$) has not severely been constrained yet by the LHC Run-I data.

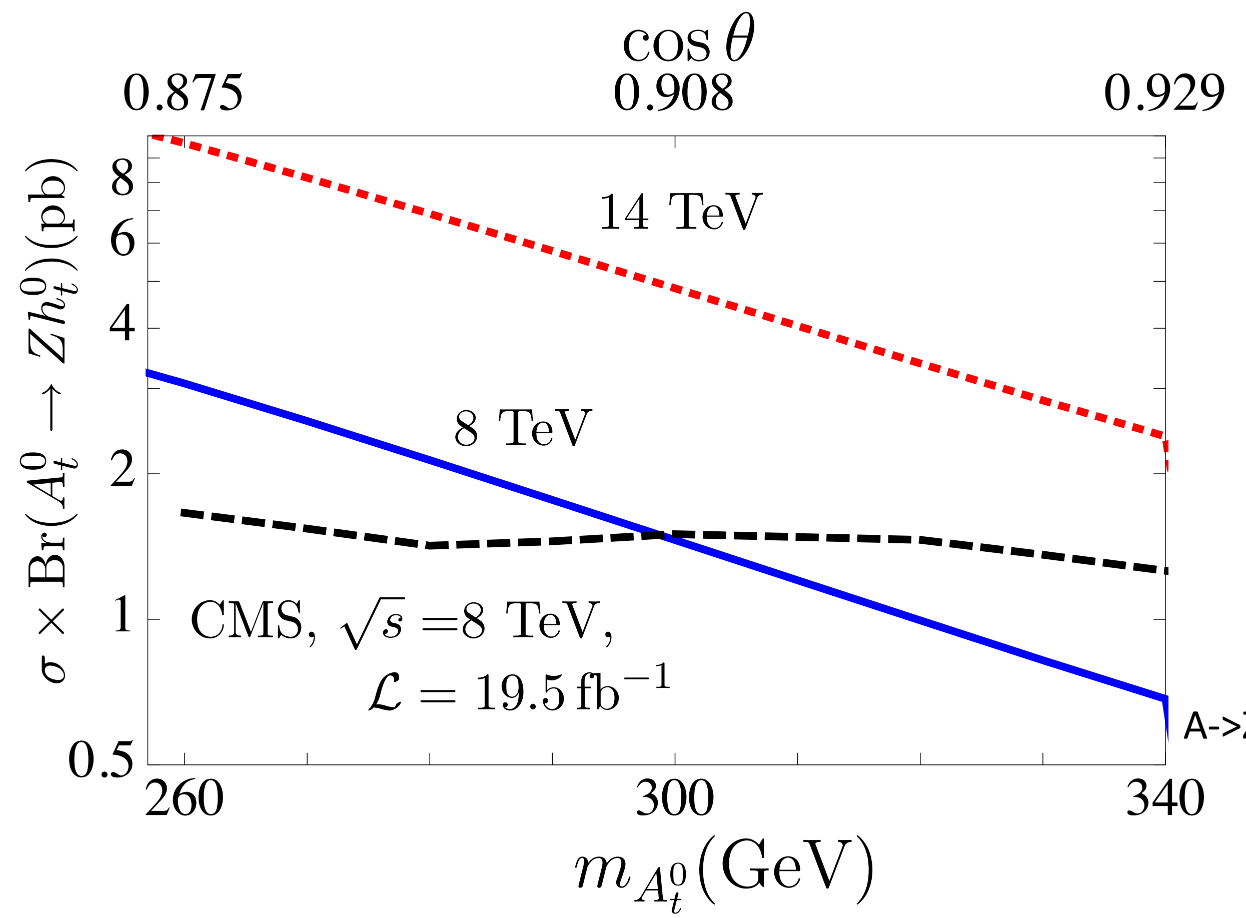




3. Phenomenologies (8/8): Low-mass CP-odd TMP @ LHC

arXiv:1401.6292

The limit for low-mass CP-odd TMP ($m_{h_t^0} + m_Z \leq m_{A_t^0} < 2m_t$)
can be read off from the data on searches for
extended Higgs sectors by the CMS experiments.



A->Zh: CMS-PAS-HIG-13-025

$$\sin\theta = \frac{m_{h_t^0}}{m_{A_t^0}}$$

The LHC Run-I data set 95%C.L. limits:

$$m_{A_t^0} \geq 299\,\mathrm{GeV} \longleftrightarrow 0.907 \leq \cos\theta (\leq 1)$$

4.Summary

- The spirit of the top quark condensation may provide a natural explanation for a dynamical origin of 126 GeV Higgs, **tHiggs**, **which emerges as a pseudo Nambu-Goldstone boson**.
- There is additional PNGB, ***CP-odd Top-Mode Pseudo***, other than the **tHiggs**.
- Mass relation between **two TMPs**:

$$m_{h_t^0} = m_{A_t^0} \sin\theta \iff m_{A_t^0} = \frac{m_{h_t^0}}{\sin\theta} \qquad g_{hVV} = \cos\theta$$

- Mass of **CP-odd TMP** is already constrained directly/indirectly:

$$m_{A_t^0} \geq 299\,\mathrm{GeV} \longleftrightarrow 0.907 \leq \cos\theta (\leq 1)$$

- *The discovery channel of **CP-odd TMP** in the LHC Run-II would be A-> Zh channel.*

Backup slides

Gap equations

We focus the system: $\mathcal{L}_{\text{kin.}} + \mathcal{L}^{4f} + \mathcal{L}^{h}$

The gap equations for dynamical masses:

$$m_{t\chi} = m_{t\chi} \cdot \frac{N_c G}{8\pi^2}\left[\Lambda^2 - m_{\tilde{\chi}\chi}^2 \ln \frac{\Lambda^2}{m_{\tilde{\chi}\chi}^2}\right]$$

$$m_{\chi\chi} = \Delta_{\chi\chi} + m_{\chi\chi} \cdot \frac{N_c (G - G')}{8\pi^2}\left[\Lambda^2 - m_{\tilde{\chi}\chi}^2 \ln \frac{\Lambda^2}{m_{\tilde{\chi}\chi}^2}\right]$$

$\Delta_{\chi\chi} \ll \Lambda \qquad G' \ll G$

$$m_{\tilde{\chi}\chi}^2 = m_{t\chi}^2 + m_{\chi\chi}^2$$

Both gap equations are separated by the *explicit breaking terms*.

There exist nontrivial solutions

$$\tan\theta \equiv \frac{m_{t\chi}}{m_{\chi\chi}}$$

$$G > G_{\text{crit}} \equiv \frac{8\pi^2}{N_c \Lambda^2} \Rightarrow m_{t\chi} \neq 0 \text{ and } m_{\chi\chi} \neq 0$$

$$U(3)_L \times U(2)_R \times U(1)_R \longrightarrow U(2)_L \times U(2)_R \times U(1)'_V$$

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
$J_{3L}^{4,\mu}$	$\pi_t^4 = z_t^0 \cos\theta - A_t^0 \sin\theta$	odd
$J_{3L}^{5,\mu}$	$\pi_t^5 = h_t^0$	even
$J_{3L}^{6,\mu} \pm i J_{3L}^{7,\mu}$	$\pi_t^6 \pm i\pi_t^7 = \sqrt{2} w_t^{\pm}$	–
J_A^{μ}	$\pi_t^A = z_t^0 \sin\theta + A_t^0 \cos\theta$	odd

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

5 NGBs emerge with the decay constant f as:

$$\langle 0 \left| J_{\mu}^a(x) \right| \pi_t^b(p) \rangle = -i f \delta^{ab} p_{\mu} e^{-ip\cdot x} \,, \qquad a, b = 4, 5, 6, 7, A$$

Broken currents

$$
\begin{aligned}
J^{4,\mu}_{3L} &= \bar{\tilde{\psi}}_L \gamma^\mu \lambda^4 \tilde{\psi}_L \\
&= \bar{\tilde{t}}_L \gamma^\mu \tilde{\chi}_L + \bar{\tilde{\chi}}_L \gamma^\mu \tilde{t}_L \\
&= (\bar{t}_L \gamma^\mu t_L + \bar{\chi}_L \gamma^\mu \chi_L) \sin 2\theta + (\bar{t}_L \gamma^\mu \chi_L + \bar{\chi}_L \gamma^\mu t_L) \cos 2\theta \,, \\
J^{5,\mu}_{3L} &= \bar{\tilde{\psi}}_L \gamma^\mu \lambda^5 \tilde{\psi}_L \\
&= i \left[-\bar{\tilde{t}}_L \gamma^\mu \tilde{\chi}_L + \bar{\tilde{\chi}}_L \gamma^\mu \tilde{t}_L \right] \\
&= -i \left(\bar{t}_L \gamma^\mu \chi_L - \bar{\chi}_L \gamma^\mu t_L \right) \,, \\
J^{6,\mu}_{3L} &= \bar{\tilde{\psi}}_L \gamma^\mu \lambda^6 \tilde{\psi}_L \\
&= \bar{\tilde{b}}_L \gamma^\mu \tilde{\chi}_L + \bar{\tilde{\chi}}_L \gamma^\mu \tilde{b}_L \\
&= \left(\bar{b}_L \gamma^\mu t_L + \bar{t}_L \gamma^\mu b_L \right) \sin\theta + \left(\bar{b}_L \gamma^\mu \chi_L + \bar{\chi}_L \gamma^\mu b_L \right) \cos\theta \,, \\
J^{7,\mu}_{3L} &= \bar{\tilde{\psi}}_L \gamma^\mu \lambda^7 \tilde{\psi}_L \\
&= i \left[-\bar{\tilde{b}}_L \gamma^\mu \tilde{\chi}_L + \bar{\tilde{\chi}}_L \gamma^\mu \tilde{b}_L \right] \\
&= -i \left(\bar{b}_L \gamma^\mu t_L - \bar{t}_L \gamma^\mu b_L \right) \sin\theta - i \left(\bar{b}_L \gamma^\mu \chi_L - \bar{\chi}_L \gamma^\mu b_L \right) \cos\theta \,,
\end{aligned}
$$

$$
\begin{aligned}
J^\mu_A &\equiv \frac{1}{4} \left(J^\mu_{1R} - \frac{1}{\sqrt{6}} J^{0,\mu}_{3L} + \frac{1}{\sqrt{3}} J^{8,\mu}_{3L} \right) \\
&= \frac{1}{4} \left(\bar{\chi}_R \gamma^\mu \chi_R - \bar{\tilde{\chi}}_L \gamma^\mu \tilde{\chi}_L \right) \\
&= \frac{1}{4} \left[\bar{\chi}_R \gamma^\mu \chi_R - \bar{t}_L \gamma^\mu t_L \sin^2\theta - \bar{\chi}_L \gamma^\mu \chi_L \cos^2\theta - (\bar{t}_L \gamma^\mu \chi_L + \bar{\chi}_L \gamma^\mu t_L) \sin\theta\cos\theta \right]
\end{aligned}
$$

NGBs as composite fields (current basis)

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

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

NGB as composite fields (mass basis)

$$
\begin{aligned}
z_t^0 &\equiv \pi_t^4 \cos\theta + \pi_t^A \sin\theta \\
&\sim \bar{\chi}_R t_L - \bar{t}_L \chi_R\,, \\
w_t^- &\equiv \frac{1}{\sqrt{2}}(\pi_t^6 + i\pi_t^7) \\
&\sim \sqrt{2}\bar{\chi}_R b_L\,, \\
w_t^+ &\equiv \frac{1}{\sqrt{2}}(\pi_t^6 - i\pi_t^7) \\
&\sim -\sqrt{2}\bar{b}_L \chi_R
\end{aligned}
$$

$$
\begin{aligned}
h_t^0 &\equiv \pi_t^5 \\
&\sim -i\left(\bar{\chi}_R \tilde{t}_L + \bar{\tilde{t}}_L \chi_R\right) \\
&= -i\,(\bar{\chi}_R t_L + \bar{t}_L \chi_R)\cos\theta + i\,(\bar{\chi}_R \chi_L + \bar{\chi}_L \chi_R)\sin\theta\,, \\
A_t^0 &\equiv -\pi_t^4 \sin\theta + \pi_t^A \cos\theta \\
&\sim \bar{\chi}_R \chi_L - \bar{\chi}_L \chi_R\,.
\end{aligned}
$$

Dashen's Formula

$$\Delta_{\chi\chi} \ll \Lambda$$

$$G' \ll G$$

Explicit breaking term

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

The masses of the 5NGBs can be estimated by the Dashen's formula:

Dashen (1969)

$$m_{ab}^2 = \frac{1}{f^2}\langle 0 | \left[iQ^a , \left[iQ^b , -\mathcal{L}^h \right]\right] | 0 \rangle$$

PNGB mass

Noether's charge with the broken currents

NLsM(I)

Below the mass of "sigma"-mode, the effective Lagrangian is described by a non-linear sigma model based on the coset space:

$$\frac{\mathcal{G}}{\mathcal{H}} = \frac{U(3)_L \times U(1)_R}{U(2)_L \times U(1)'_V}$$

We introduce representatives of this coset space:

$$\xi_L = \exp\left[-\frac{i}{f}\left(\sum_{a=4,5,6,7} \pi_t^a \lambda^a + \frac{\pi_t^A}{2\sqrt{2}}\lambda^A\right)\right] \quad , \quad \xi_R = \exp\left[\frac{i}{f}\frac{\pi_t^A}{2\sqrt{2}}\lambda^A\right]$$

where

$$\mathrm{tr}\left[\lambda^a \lambda^b\right] = 2\delta^{ab} \quad , \quad \lambda^A = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sqrt{2} \end{pmatrix}$$

NLsM(II)

We further introduce the "chiral" field:

$$U = \xi_L^\dagger \cdot \Sigma \cdot \xi_R \qquad \Sigma = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The transformation properties:

$$\xi_L \to h(\pi_t, \tilde{g}) \cdot \xi_L \cdot g^\dagger_{3\tilde{L}} \quad , \quad \xi_R \to h(\pi_t, \tilde{g}) \cdot \xi_R \cdot g^\dagger_{1R} \quad , \quad U \to g_{3\tilde{L}} \cdot U \cdot g^\dagger_{1R}$$

where

$$\tilde{g} = \{g_{3\tilde{L}}, g_{1R}\}\,,\ g_{3\tilde{L}} \in U(3)_L\,,\ g_{1R} \in U(1)_R \text{ and } h(\pi_t, \tilde{g}) \in \mathcal{H}$$

The covariant derivative:

$$D_\mu U \equiv R\left[\partial_\mu - ig\sum_{a=1}^{3} W^a_\mu \left(\begin{array}{cc|c} \multicolumn{2}{c|}{\tau^a/2} & 0 \\ & & 0 \\ \hline 0 & 0 & 0 \end{array}\right) + ig' B_\mu \begin{pmatrix} 1/2 & 0 & 0 \\ 0 & 1/2 & 0 \\ 0 & 0 & 0 \end{pmatrix}\right] R^T \cdot U$$

$$R = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix}$$

NLsM(III)

Lagrangian for NGB sector:

explicit breaking term

$$\mathcal{L}_{\mathrm{NL}\sigma\mathrm{M}} = \frac{f^2}{2}\mathrm{tr}\left[D_\mu U^\dagger D^\mu U\right] + \frac{f^2}{2}\mathrm{tr}\left[\cos\theta\left(\chi_1^\dagger U + U^\dagger \chi_1\right) - U^\dagger \chi_2 U\right]$$

$$\frac{\mathcal{G}}{\mathcal{H}} = \frac{U(3)_L \times U(1)_R}{U(2)_L \times U(1)'_V} \qquad \frac{\mathcal{G}}{\mathcal{H}} = \frac{\cancel{U(3)_L \times U(1)_R}}{U(2)_L \times U(1)'_V}$$

where

$$\chi_1 \equiv m^2_{A_t^0}\left(R\cdot\Sigma\right) \quad , \quad \chi_2 \equiv m^2_{A_t^0}\left(R\cdot\Sigma\cdot R^T\right)$$

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

The realistic W/Z boson masses require $v_{\mathrm{EW}} = f\sin\theta$

NLsM(IV)

Interaction between NGBs and top quark:

$$R = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix}$$

$$\mathcal{L}^{t,t'}_{\text{yuk.}} = -\frac{yf}{\sqrt{2}} \cdot \bar{\psi}_L (R^T U) \begin{pmatrix} t_R \\ b_R \\ \chi_R \end{pmatrix} + \text{h.c.}$$

where

$$y^2 = \frac{2(m^2_{t\chi} + m^2_{\chi\chi})}{f^2}$$

$$v_{\text{EW}} = f \sin\theta$$

Interaction between h^0_t and SM fermions other than top quark:

$$\mathcal{L}^{\text{others}}_{\text{yuk.}}\Big|_{h^0_t} = -\cos\theta \left[\sum_{\alpha=1,2} \frac{m_{u^\alpha}}{v_{\text{EW}}} h^0_t \bar{u}^\alpha u^\alpha + \sum_{\alpha=1,2,3} \frac{m_{d^\alpha}}{v_{\text{EW}}} h^0_t \bar{d}^\alpha d^\alpha + \sum_{\alpha=1,2,3} \frac{m_{e^\alpha}}{v_{\text{EW}}} h^0_t \bar{e}^\alpha e^\alpha \right]$$

t-t' mixing angle

$$\begin{pmatrix} t_{L(R)} \\ t'_{L(R)} \end{pmatrix}_m = \begin{pmatrix} c^t_{L(R)} & -s^t_{L(R)} \\ s^t_{L(R)} & c^t_{L(R)} \end{pmatrix} \begin{pmatrix} t_{L(R)} \\ \chi_{L(R)} \end{pmatrix}_g$$

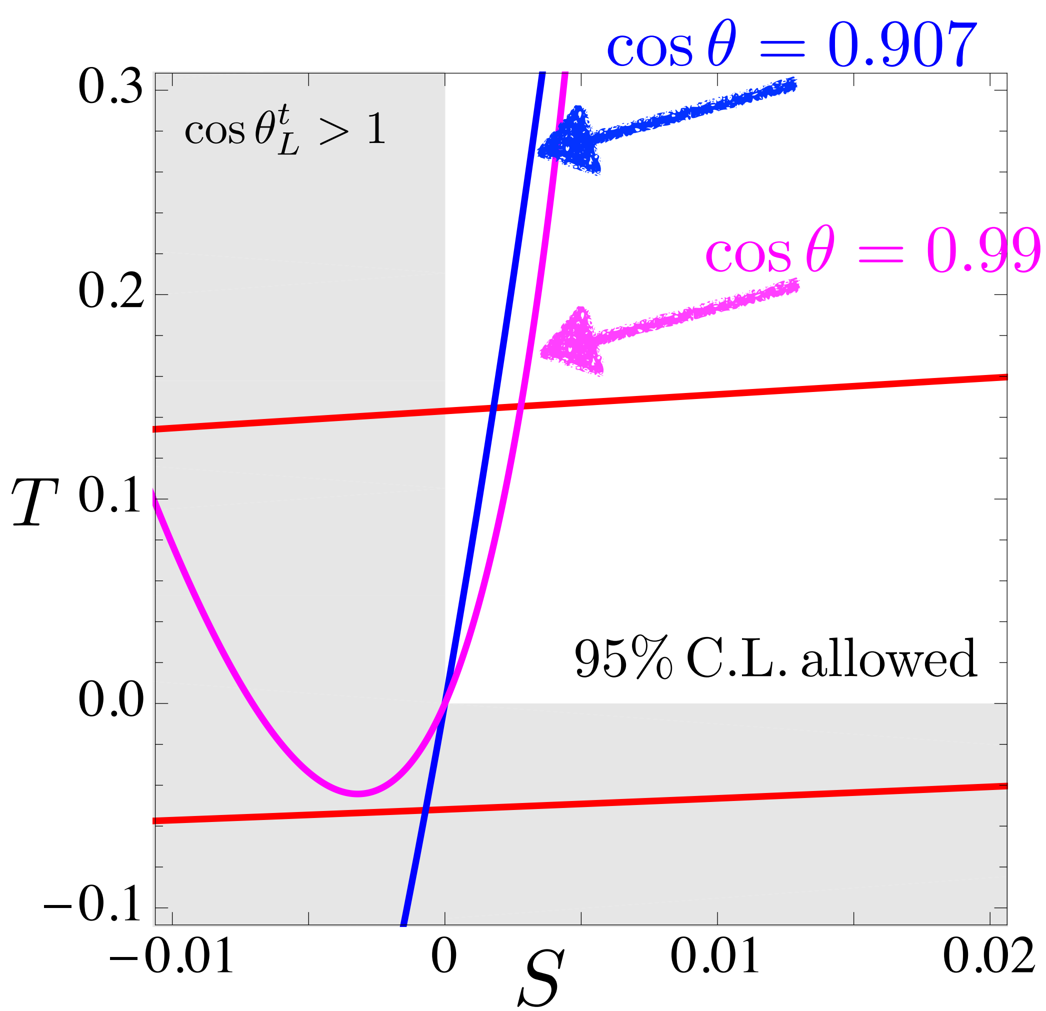
$$\begin{aligned}
c^t_L &= \frac{1}{\sqrt{2}} \left[1 + \frac{m^2_{\chi\chi} - m^2_{t\chi} + \mu^2_{\chi t}}{m^2_{t'} - m^2_t} \right]^{1/2} \simeq \cos\theta \left[1 + \left(\frac{G''}{G} \right)^2 \cos^2\theta \sin^2\theta \right]^{1/2} , \\
s^t_L &= \frac{1}{\sqrt{2}} \left[1 - \frac{m^2_{\chi\chi}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

The Peskin-Takeuchi S,T-paramters

Peskin,Takeuchi (1990,1992)

The CP-odd TMP is not constrained from the S,T due to the CP-symmetry.
However, t'-quark mass can be constrained from the S,T.

t'-quark direct search would also provide another constraint for the mass of CP-odd TMP.



$$S = 0.08 \pm 0.10$$
$$T = 0.10 \pm 0.08$$
$$\rho_{ST} = 0.85$$

Ciuchini,Franco,Mishima, Silvestrini (2013)

$$754\,\text{GeV} \leq m_{t'} \leq 809\,\text{GeV} \qquad \text{for } \cos\theta = 0.907$$

$$6255\,\text{GeV} \leq m_{t'} \leq 7308\,\text{GeV} \qquad \text{for } \cos\theta = 0.99$$

S,T-parameters

For $m_{t'} \gg m_t \gg m_b$

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

where

$$x_a \equiv m_a^2/m_Z^2\,, (a = t, t')$$

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

Higgs search data on 2D plane

decay channel	$\hat{\mu}$(ggF+$\mathrm{t\bar{t}H}$)	$\hat{\mu}$(VBF+VH)	$\Delta\mu$(ggF+$\mathrm{t\bar{t}H}$)	$\Delta\mu$(VBF+VH)
$\gamma\gamma$ (ATLAS)	1.6	1.7	0.25	0.63
ZZ^* (ATLAS)	1.8	1.2	0.35	1.30
WW^* (ATLAS)	0.82	1.66	0.36	0.79
$\tau\tau$ (ATLAS)	1.1	1.6	1.16	0.75
$b\bar{b}$ (ATLAS)	–	0.2	–	0.64
$\gamma\gamma$ (CMS)	0.52	1.48	0.60	1.33
ZZ^* (CMS)	0.9	1.0	0.45	2.35
WW^* (CMS)	0.72	0.62	0.37	0.53
$\tau\tau$ (CMS)	1.07	0.94	0.46	0.41
$b\bar{b}$ (CMS)	–	1.0	–	0.5

Partial decay widths of CP-odd TMP

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

$$\Gamma(A_t^0 \to gg) = \frac{\sqrt{2} G_F \alpha_s^2 m_{A_t^0}^3}{128\pi^3} \sin^2\theta \cdot \left| A_{1/2}^A(\tau_t) + \cos\theta A_{1/2}^A(\tau_{t'}) \right|^2 ,$$

$$\Gamma(A_t^0 \to \gamma\gamma) = \frac{\sqrt{2} G_F \alpha^2 m_{A_t^0}^3}{256\pi^3} \sin^2\theta \cdot \left| N_c Q_t^2 A_{1/2}^A(\tau_t) + \cos\theta N_c Q_{t'}^2 A_{1/2}^A(\tau_{t'}) \right|^2 ,$$

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

$$\beta_A(m_t) \equiv \sqrt{1 - \frac{4m_t^2}{m_{A_t^0}^2}}\,,$$

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