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- Introduction
- Walking technicolor and TD
- 125 GeV TD signal at LHC
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Based on
S.M. and K. Yamawaki (KMI, Nagoya U.),
PRD85 (2012);
PRD86 (2012)
1207.5911 (to appear in PLB)
1209.2017 (to appear in PRD)

@SCGT12 12/4 – 12/7
Introduction

This year is exciting!!

A new boson at around 125 GeV was observed at LHC
**The signal strengths** \((\mu = \sigma/\sigma_{SM})\)

Somewhat large diphoton event rate:

\[\mu (\text{diphoton}) \sim 2\] implies a “new Higgs boson” (impostor) beyond the SM!
Is it Techni-dilaton (TD)?

* TD: composite scalar;

predicted in walking technicolor,

arising as a pNGB for (approximate) scale symmetry

spontaneously broken by techni-fermion condensate;

its lightness is protected by the scale symmetry,

and hence can be, say, ~ 125 GeV.

* 125 GeV TD signatures at LHC are consistent with current data!!

S.M. and K. Yamawaki, PRD85 (2012); PRD86 (2012); 1207.5911; 1209.2017

Yamawaki et al (1986); Bando et al (1986)
Walking technicolor and TD
A schematic view of walking TC

Chiral/EW sym. breaking by dynamical generation of TF mass @μcr

\[ m_F \sim \Lambda_{TC} e^{-\frac{\pi}{\sqrt{\alpha/\alpha_{cr}}-1}} \quad \text{for} \quad \alpha > \alpha_{cr} \]

\[ \langle \bar{F}F \rangle_{\Lambda_{TC}} \sim \frac{N_{TC}}{4\pi^2} m_F^2 \Lambda_{TC} \]

\[ \gamma_m \approx 1 \quad \text{(solve FCNC problem)} \]

wide range walking \( m_F < \mu < \Lambda_{TC} \) (approx. scale invariance)

(naturalness)

Miransky (1985)

"Miransky scaling"
**Walking TC and techni-dilaton**

*Techni-dilaton (TD) emerges as (p)NGB for approx. scale symmetry*

\[
m_F \sim \Lambda_{TC} e^{-\frac{\pi}{\sqrt{\alpha/\alpha_{cr} - 1}}} \quad \text{for} \quad \alpha > \alpha_{cr}
\]

**SSB of (approximate) scale sym.**

- \(\alpha\) starts **“running”** (walking) up to \(m_F\)
- Nonpert. scale anomaly induced by \(m_F\) itself

\[
\beta(\alpha) = \Lambda_{TC} \frac{\partial \alpha}{\partial \Lambda_{TC}} = -\frac{2\alpha_{cr}}{\pi} \left( \frac{\alpha}{\alpha_{cr}} - 1 \right)^{3/2}
\]

\[
\partial_{\mu} D^{\mu} = \frac{\beta(\alpha)}{4\alpha^2} \left( \alpha G_{\mu\nu}^2 \right) \neq 0
\]

TD gets massive
Ladder estimate of TD mass

* LSD + BS in large Nf QCD

* LSD via gauged NJL

A composite Higgs mass
\[ M_\phi \sim 4 F_\pi \]
\[ \sim 500 \text{ GeV} \]
for one-family model (1FM) still larger than \( \sim 125 \text{ GeV} \)

* This is reflected in PCDC (partially conserved dilatation current)

\[ F_\phi^2 M_\phi^2 = -4 \langle \theta^\mu_\mu \rangle = \frac{\beta(\alpha)}{\alpha} \langle G_{\mu\nu}^2 \rangle \sim 3 \eta m_F^4 \]

where \( \eta \sim \frac{N_{TC}N_{TF}}{2\pi^2} = \mathcal{O}(1) \)

\[ \frac{F_\phi^2}{m_F^2} \cdot \frac{M_\phi^2}{m_F^2} = \text{finite} \]

No massless NGB limit:
\[ M_\phi / m_F \to 0, \quad \text{only} \quad \text{when} \quad F_\phi / \tilde{m}_F \to \infty, \text{i.e., a decoupled limit.} \]
Holographic estimate w/ techni-gluonic effects

K. Haba et al PRD82 (2010); S.M. and K.Yamawaki, 1209.2017

* Ladder approximation: gluonic dynamics is neglected

* Deformation of successful AdS/QCD model (Bottom-up approach)

Da Rold and Pomarol (2005); Erlich, Katz, Son and Stephanov (2005)

incorporates nonperturbative gluonic effects

\[ S_5 = \int d^4x \int_{\epsilon}^{z_m} dz \sqrt{-g} \frac{1}{g_5^2} e^{cg_5^2\Phi_X(z)} \left( -\frac{1}{4} \text{Tr} \left[ L_{MN}L^{MN} + R_{MN}R^{MN} \right] + \text{Tr} \left[ D_M \Phi^\dagger D^M \Phi - m_\Phi^2 \Phi^\dagger \Phi \right] + \frac{1}{2} \partial_M \Phi_X \partial^M \Phi_X \right) \]

\[ m_\Phi^2 = -\left(3 - \gamma_m\right)\left(1 + \gamma_m\right)/L^2 \]

QCD \quad \gamma_m = 0

WTC \quad \gamma_m = 1
* QCD-fit w/ $\gamma_m = 0$

**Input**

<table>
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<th>Parameter</th>
<th>Value</th>
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<td>$M_\rho$</td>
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<td>$&lt;\alpha G\mu^2&gt;/\pi$</td>
<td>0.012 GeV$^4$</td>
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**Fix**

<table>
<thead>
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<th>Value</th>
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<td>$\xi$</td>
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</tr>
<tr>
<td>$G$</td>
<td>0.25</td>
</tr>
<tr>
<td>$z m^{-1}$</td>
<td>347 MeV</td>
</tr>
</tbody>
</table>

**Model Parameters**

- Measured values:
  - $M_a1$ [a1 meson]: 1.2 GeV, 1.1 GeV, 1.3 GeV
  - $M_{f_0(1370)}$ [qqbar bound state]: 1.2 GeV, 1.1 GeV, 1.2 GeV
  - $M_{G}$ [glueball]: 1.3 GeV, 1.4 GeV, 1.7 GeV (lat.)
  - $S = -16 \pi L_{10}$ [S parameter]: 0.31, 0.29, 0.37
  - $[ - <q\bar{q}> ]^{(1/3)}$ [chiral condensate]: 277 MeV, 200 MeV

**Model Predictions**

- $M_a1$ [a1 meson]: 1.3 GeV
- $M_{f_0(1370)}$ [qqbar bound state]: 1.2 GeV
- $M_{G}$ [glueball]: 1.3 GeV
- $S = -16 \pi L_{10}$ [S parameter]: 0.31
- $[ - <q\bar{q}> ]^{(1/3)}$ [chiral condensate]: 277 MeV

**Monitoring QCD works well!**
*WTC-case with \( \gamma_m = 1 \)

--- TD mass (lowest pole of dilatation current correlator)

\[
\frac{M_\phi}{4\pi F_\pi} \simeq \sqrt{\frac{3}{N_{TC}}} \frac{\sqrt{3/2}}{1 + G} \quad \frac{M_\phi}{F_\pi} \to 0 \quad \text{as} \quad G \to \infty.
\]

125 GeV TD is realized by a large gluonic effect: \( G \sim 10 \)
for one-family model w/ \( F_\pi = 123 \) GeV  (c.f. QCD case, \( G \sim 0.25 \))

--- TD decay constant (pole residue)

\[
\frac{F_\phi}{F_\pi} \simeq \sqrt{2N_{TF}} \cdot \left[ \sqrt{J_0^2(x) + J_1^2(x)} \right]_{x = (M_\phi z_m) \ll 1} \approx \sqrt{2N_{TF}}. \quad \text{free from model-parameters!!}
\]

Massless NGB limit (“conformal limit”) is realized:

\[
\frac{M_\phi}{F_\pi} \to 0 \quad \text{and} \quad \frac{F_\phi}{F_\pi} \to \text{finite}, \quad \text{as} \quad G \to \infty.
\]

in contrast to ladder approximation

\[
G \sim \frac{\langle \alpha G^2_{\mu\nu} \rangle}{F_\pi^4}
\]

\[
\beta(\alpha) \sim \frac{1}{G(1+G)^2} \to 0
\]
* More on the “conformal limit” $G \to \infty$

$$G \sim \frac{\langle \alpha G_{\mu \nu}^2 \rangle}{F_π^4} \quad \beta(\alpha) \sim \frac{1}{G(1+G)^2} \to 0$$

Ratios of masses of FFbar boundstates to Techni-glueball mass $M_G$ (lowest pole of $G_{\mu \nu}^2$ correlator)

TD mass/TG mass:
$$\frac{M_\phi}{M_G} \sim \frac{1}{1+G} \to 0$$

rho mass/TG mass:
$$\frac{M_\rho}{M_G} \to 0$$

Note: $\frac{M_\phi}{M_\rho} \to 0$

Hence
$$\frac{M_\phi}{M_G} \ll \frac{M_\rho}{M_G} \to 0$$

Interesting to check in lattice simulations!!
A low-energy theory below $m_F$

* effective theory below $m_F$
after TF decoupled/integrated out & confinement:

governed by $TD$ and other light TC hadrons

-- $TD (\Phi)$, techni-pions ($\pi$),
techni-vector/axial-vector mesons ($\rho_t, a_{1t}$) ...

$N_{TC} = 3, 4, 5$ & $N_{TF} = 8$ (one-family) (+ EW-singlets)

$\rho_t, a_{1t} \sim 3 -- 4$ TeV

$\pi \sim 300 -- 500$ GeV

$\Phi \sim 125$ GeV

* $S = 0.1, T = 0$: keeps consistency w/ EWPT

J.Jia, S.M. & K.Yamawaki, 1207.0735
S.M. & K.Yamawaki, 1209.2017
TD Lagrangian below $m_F$


* effective theory below $m_F$
  after TF decoupled/integrated out & confinement:
  governed by TD and other light TC hadrons

* Nonlinear realization of scale and chiral symmetries

Nonlinear base $\chi$ for scale sym. w/ TD field $\Phi$

$$\chi = e^{\phi/F_\phi}, \quad \delta \chi = (1 + x^\nu \partial_\nu)\chi$$

TD decay constant $F_\phi$

$$\delta \phi = F_\phi + x^\nu \partial_\nu \phi$$

Nonlinear base $U$ for chiral sym. w/ TC pion field $\pi$

$$U = e^{2i\pi/F_\pi}, \quad \delta U = x^\nu \partial_\nu U$$
eff. TD Lagrangian \[ \mathcal{L} = \mathcal{L}_{\text{inv}} + \mathcal{L}_S - V_\chi \]

i) The scale anomaly-free part:
\[ \mathcal{L}_{\text{inv}} = \frac{F_\pi^2}{4} \chi^2 \text{Tr}[D_\mu U^\dagger D_\mu U] + \frac{F_\phi^2}{2} \partial_\mu \chi \partial^\mu \chi \]

ii) The anomalous part (made invariant by including spurion field “S”):
\[ \mathcal{L}_S = -m_f \left( \left( \frac{\chi}{S} \right)^{2-\gamma_m} \cdot \chi \right) \bar{f} f \]
\[ + \log \left( \frac{\chi}{S} \right) \left\{ \frac{\beta_F(g_s)}{2g_s} G_{\mu\nu}^2 + \frac{\beta_F(e)}{2e} F_{\mu\nu}^2 \right\} + \ldots \]

iii) The scale anomaly part:
\[ V_\chi = \frac{F_\phi^2 M_\phi^2}{4} \chi^4 \left( \log \chi - \frac{1}{4} \right) \]

which correctly reproduces the PCDC relation:
\[ \langle \theta_\mu^\mu \rangle = -\delta_D V_\chi \bigg|_{\text{vacuum}} = -\frac{F_\phi^2 M_\phi^2}{4} \langle \chi^4 \rangle \bigg|_{\text{vacuum}} = -\frac{F_\phi^2 M_\phi^2}{4} \]
TD couplings to the SM particles

* TD couplings to W/Z boson (from $L_{\text{inv}}$)

\[ g_{\phi WW/ZZ} = \frac{2m_{W/Z}}{F_{\phi}} \]

* TD couplings to $\gamma\gamma$ and $gg$ (from $L_{\text{S}}$)

\[ g_{\phi \gamma\gamma} = \frac{\beta_F (e)}{e} \frac{1}{F_{\phi}} \]

\[ g_{\phi gg} = \frac{\beta_F (g_s)}{g_s} \frac{1}{F'_{\phi}} \]

$\beta_F$: TF-loop contribution to beta function
**TD couplings to the SM particles**

* TD couplings to W/Z boson (from L_inv)

\[ g_{\phi WW/ZZ} = \frac{2m_{W/Z}}{F_\phi} \]

* TD couplings to γγ and gg (from L_S)

\[ g_{\phi \gamma \gamma} = \frac{\beta_{F}(e)}{e} \frac{1}{F_\phi} \]

\[ g_{\phi gg} = \frac{\beta_{F}(g_s)}{g_s} \frac{1}{F_\phi} \]

\( \beta_{F} \): TF-loop contribution to beta function

The same form as SM Higgs couplings except \( F_\phi \) and betas
* TD couplings to SM fermions

\[ -(3 - \gamma_m) m_f \frac{\phi f f}{F_\phi} \]

* \( \gamma_m \simeq 1 \)

in WTC to get realistic masses w/o FCNC concerning 1\textsuperscript{st} and 2\textsuperscript{nd} generations

\[ \frac{g_{\phi ff}}{g_{h_{SM ff}}} = 2 \frac{v_{EW}}{F_\phi} \]


* \( \gamma_m \simeq \frac{1}{2} \),

in Strong ETC to accommodate masses of the 3\textsuperscript{rd} generations (t, b, tau)

\[ \frac{g_{\phi ff}}{g_{h_{SM ff}}} = \frac{1}{2} \frac{v_{EW}}{F_\phi} \]
Thus, the TD couplings to SM particles essentially take the same form as those of the SM Higgs:

Just a simple scaling from the SM Higgs:

\[
\frac{g_{\phi WW/ZZ}}{g_{h_{\text{SM}} WW/ZZ}} = \frac{v_{\text{EW}}}{F_\phi},
\]

\[
\frac{g_{\phi ff}}{g_{h_{\text{SM}} ff}} = \frac{v_{\text{EW}}}{F_\phi}, \quad \text{for } f = t, b, \tau.
\]

But, note \(\phi\)-gg, \(\phi\)-\(\gamma\gamma\) depending highly on particle contents of WTC models.

\[
\mathcal{L}_{\phi\gamma\gamma, gg} = \frac{\phi}{F_\phi} \left[ \frac{\beta_F(e)}{2e^3} F^2_{\mu\nu} + \frac{\beta_F(g_s)}{2g^3_s} G^2_{\mu\nu} \right]
\]

To be concrete, we consider the one-family model (1FM)
★ Estimate of $\frac{v_{\text{EW}}}{F_\phi}$ : #1 – Ladder approximation

* PCDC (partially conserved dilatation current)

$$F_\phi^2 M_\phi^2 = -4\langle \theta_\mu^\mu \rangle$$
$$\langle \theta_\mu^\mu \rangle = 4\mathcal{E}_{\text{vac}} = -\kappa_V \left( \frac{N_{\text{TC}} N_{\text{TF}}}{2\pi^2} \right) m_F^4$$

* criticality condition  Appelequist et al (1996)

$$N_{\text{TF}} \simeq 4N_{\text{TC}}$$

* Pagels-Stokar formula

$$F_\pi^2 = \kappa_F^2 \frac{N_{\text{TC}}}{4\pi^2} m_F^2$$

$$F_\pi = \frac{v_{\text{EW}}}{\sqrt{N_D}}$$  

# of EW doublets

$$\frac{v_{\text{EW}}}{F_\phi} \simeq \frac{1}{8\sqrt{2}\pi} \sqrt{\frac{\kappa_F^4}{\kappa_V} N_D \frac{M_\phi}{v_{\text{EW}}}}$$

* Recent ladder SD analysis (large Nf QCD)

$$\kappa_V \simeq 0.7, \quad \kappa_F \simeq 1.4$$

Hashimoto et al (2011)
* Inclusion of theoretical uncertainties

Ladder approximation is subject to **about 30% uncertainty** for estimate of critical coupling and QCD hadron spectrum

- Critical coupling: T. Appelquist et al (1988);

\[
\frac{N_{TF}}{4N_{TC}} \approx 1 \pm 0.3
\]

\[
\langle \theta^{\mu}_{\mu} \rangle = 4E_{\text{vac}} = -\kappa V \left( \frac{N_{TC}N_{TF}}{2\pi^2} \right) m_F^4
\]

\[
F_\pi^2 = \kappa_F^2 \frac{N_{TC}}{4\pi^2} m_F^2
\]

**Estimate w/ uncertainty included**

- \[ \frac{v_{\text{EW}}}{iF_\phi} \approx (0.1 - 0.3) \times \left( \frac{N_D}{4} \right) \left( \frac{M_\phi}{125 \text{ GeV}} \right) \]
* TD decay constant for the light TD case w/ G ~ 10:

\[
\frac{F_\phi}{F_\pi} \approx \sqrt{2N_{TF}} \cdot \sqrt{|J_0^2(x) + J_1^2(x)|}
\]

\[
\approx \sqrt{2N_{TF}}. \quad \text{free from model-parameters !!}
\]

Inclusion of typical size of 1/NTC (20% ~ 30%) corrections:

This is consistent with ladder estimate:

\[
\left. \frac{u_{EW}}{F_\phi} \right|_{\text{holo}} \sim 0.2 - 0.4
\]

\[
\left. \frac{u_{EW}}{iF_\phi} \right|_{\text{ladder}} \approx (0.1 - 0.3) \times \left( \frac{N_D}{4} \right) \left( \frac{M_\phi}{125 \text{ GeV}} \right)
\]
**Calculation of beta functions**

\[
\mathcal{L}_{\phi\gamma\gamma,gg} = \frac{\phi}{F_\phi} \left[ \frac{\beta_F(e)}{2e^3} F_{\mu\nu}^2 + \frac{\beta_F(g_s)}{2g_s^3} G_{\mu\nu}^2 \right]
\]

The loop is dominated at IR \((\gamma_m = 2)\)

(well approximated by constant mass)

Yukawa vertex

\[
\chi_{\phi FF}(p, q = 0) = \frac{1}{F_\phi}\delta_D S_F^{-1}(p) = \frac{1}{F_\phi} \left( 1 - p_\mu \frac{\partial}{\partial p_\mu} \right) S_F^{-1}(p)
\]

The resultant betas coincide just one-loop perturbative expressions:

\[
\beta_F(g_s) = \frac{g_s^3}{(4\pi)^2} \frac{4}{3} N_{TC}
\]

\[
\beta_F(e) = \frac{e^3}{(4\pi)^2} \frac{16}{9} N_{TC}
\]
Can TD mass be as small as 125GeV below $m_F$?

Walking regime = scale symm well protected (natural enough)

$\alpha_{TC}$

$\mu$

$m_F$

~1TeV

$\Lambda_{TC}$

~$10^3$TeV
**TD mass stability below $m_F$**


$\alpha_{TC}$

**walking regime** = scale symm well protected
(natural enough)

Can TD mass be as small as 125GeV below $m_F$?

→ YES!!!

Work on the eff. TD Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{inv}} + \mathcal{L}_S - V_\chi$$

Dominant corrections come from top-loop (quadratic div.)

cutoff by $m_F \sim 4\pi F\pi \sim 1\text{TeV} (~ F\Phi)$:

$$\delta M^2_\phi \approx -\frac{3}{4\pi^2} \frac{m_t^2}{F^2_\phi} \cdot m_F^2$$

w/ $m_t \approx 2M^2_\phi$

$$\frac{\delta M_\phi}{M_\phi(125\text{GeV})} \approx -\frac{3}{4\pi^2} \frac{m_F^2}{F^2_\phi} \approx O(10^{-2} - 10^{-1})$$

naturally light thanks to large $F\Phi$
125 GeV TD signal at the LHC

S.M. and K. Yamawaki

PRD85 (2012);
PRD86 (2012);
arXiv:1207.5911;
arXiv:1209.2017
Characteristic features of $125$ GeV TD in 1FM (w/ $N_{TC}=4,5$) at LHC

**di-weak bosons**

$W, Z$  

$W^*, Z^*$

$g_\phi = (v_{EW}/F_\phi) \ g_\phi = (0.1-0.3) \ g_\phi$

v.s. SM Higgs

**suppressed**

**quark, lepton pairs**

$b, \tau$

$g_\phi$

**suppressed**

**digluon**

$g$

$F, t$

$\beta_F(g_s)$

enhanced

QCD-colored TF contributions

**diphoton**

$\gamma$

$F, t$

$\beta_F(e)$

enhanced

$\gg$ W-loops

EM-charged TF contributions
The 125 GeV TD signal fitting to the current Higgs search data

*TD* can be better than the SM Higgs ($\chi^2$/d.o.f= 33/20=1.6), due to the enhanced diphoton rate, by extra BSM (TF) contributions!

---

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<tr>
<th>N_{TC}</th>
<th>[v_{EW}/F_{\Phi}]_{\text{best}}</th>
<th>$\chi^2$/min /d.o.f.</th>
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<td>0.22</td>
<td>18/19 = 0.95</td>
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<tr>
<td>5</td>
<td>0.17</td>
<td>18/19 = 0.95</td>
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*updated from “1207.5911” after HCP2012*
* The TD characteristic signal strengths for each category

<table>
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<tr>
<th>Category</th>
<th>Signal Strengths</th>
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<tr>
<td>$\mu_{zz}$</td>
<td>$0.7 , -- , 1.0$ (inclusive)</td>
</tr>
<tr>
<td>$\mu_{bb}$</td>
<td>$0.006 , -- , 0.01$ (VH-tag)</td>
</tr>
<tr>
<td>$\mu_{WW0j}$</td>
<td>$0.8 , -- , 1.1$ (ggF-tag)</td>
</tr>
<tr>
<td>$\mu_{WW2j}$</td>
<td>$0.2 , -- , 0.3$ (VBF-tag)</td>
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<td>$\mu_{WW}$</td>
<td>$0.006 , -- , 0.01$ (VH-tag)</td>
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<tr>
<td>$\mu_{\tau\tau0j}$</td>
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<tr>
<td>$\mu_{\tau\tau2j}$</td>
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<tr>
<td>$\mu_{\tau\tau}$</td>
<td>$0.006 , -- , 0.01$ (VH-tag)</td>
</tr>
<tr>
<td>$\mu_{\gamma\gamma0j}$</td>
<td>$1.4 , -- , 2.0$ (ggF-tag)</td>
</tr>
<tr>
<td>$\mu_{\gamma\gamma2j}$</td>
<td>$0.5 , -- , 0.7$ (VBF-tag)</td>
</tr>
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</table>

VH & VBF-tags: suppressed

$\gamma\gamma0j$: enhanced
Summary

* TD is the characteristic light scalar in WTC; the mass can be 125 GeV; protected by approximate scale invariance.

* The couplings to the SM particles take essentially the same forms as those for the SM Higgs, except couplings to diphoton and digluon.

* The 125 GeV TD in 1FM gives the LHC signal favored by current LHC data, notably somewhat large diphoton event rate thanks to extra TF contributions.

* More precise measurements on exclusive categories (e.g., Vbb, $\tau\tau+$dijet) will draw a definite conclusion that the TD is favored, or not.
Backup Slides
More on holographic estimates

S.M. and K.Yamawaki, 1209.2017

* Ladder approximation: gluonic dynamics is neglected

* Deformation of successful AdS/QCD model (Bottom-up approach)
  Da Rold and Pomarol (2005); Erlich, Katz, Son and Stephanov (2005)

  incorporates nonperturbative gluonic effects

\[ S_5 = \int d^4x \int_{\epsilon}^{z_m} dz \sqrt{-g} \frac{1}{g_s^2} e^{g_s^2 \Phi(z)} \left( -\frac{1}{4} \text{Tr} \left[ L_{MN} L^{MN} + R_{MN} R^{MN} \right] + \text{Tr} \left[ D_M \Phi^\dagger D^M \Phi - m_\Phi^2 \Phi^\dagger \Phi \right] + \frac{1}{2} \partial_M \Phi_X \partial^M \Phi_X \right) \]

\[ m_\Phi^2 = -(3 - \gamma_m)(1 + \gamma_m)/L^2 \]

\[ \begin{align*}
  \text{QCD} & : \quad \gamma_m = 0 \\
  \text{WTC} & : \quad \gamma_m = 1
\end{align*} \]
\[ S_5 = \int d^4 x \int_\epsilon^{z_m} d z \sqrt{-g} \frac{1}{g_5^2} e^{c_\Phi g_5^2 \Phi_X(z)} \left( -\frac{1}{4} \text{Tr} \left[ L_{MN} L^{MN} + R_{MN} R^{MN} \right] \right. \\
\left. + \text{Tr} \left[ D_M \Phi^\dagger D^M \Phi - m_\Phi^2 \Phi^\dagger \Phi \right] + \frac{1}{2} \partial_M \Phi_X \partial^M \Phi_X \right) \]

\[ \Phi(x, z) = \frac{1}{\sqrt{2}} \left( v(z) + \sigma(x, z) \right) \exp[i \pi(x, z)/v(z)] \]

\[ \Phi_X(z) = v_X(z), \]

**AdS/CFT dictionary:**

* UV boundary values = sources

\[ \alpha M = \lim_{\epsilon \to 0} Z_m \left( \frac{L}{z} v(z) \right) \bigg|_{z=\epsilon}, \quad Z_m = Z_m (L/z) = \left( \frac{L}{z} \right)^{\gamma_m} \]

\[ M' = \lim_{\epsilon \to 0} Lv_X(z) \bigg|_{z=\epsilon} \]

* IR boundary values:

\[ \xi = Lv(z) \bigg|_{z=z_m} \quad \text{chiral condensate} \quad \langle \bar{T}T \rangle \]

\[ G = Lv_X(z) \bigg|_{z=z_m} \quad \text{gluon condensate} \quad \langle \alpha G^2_{\mu\nu} \rangle \]
* AdS/CFT recipe:

\[ S_5 \quad \longrightarrow \quad S_5[s, g, v, a]|_{\text{UV-boundary}} = W_{4D} \quad \text{generating functional} \]

Classical solutions

Sources = UV boundary values for bulk scalar, vector, axial-vector fields

\[ W_{4D} \quad \longrightarrow \quad \langle T J(x) J(0) \rangle \quad J = \bar{F} F, G^2_{\mu \nu}, \bar{F} \gamma_\mu T^a F, \bar{F} \gamma_\mu \gamma_5 T^a F \]

Current collerators \( \Pi_S, \Pi_G, \Pi_V, \Pi_A \)

are calculated as a function of three IR–boundary values and \( \gamma_m : \)

\[ \begin{align*}
\xi & : \text{IR value of bulk scalar} & \Phi_S & \quad \longleftrightarrow \quad \bar{F} F \\
G & : \text{IR value of bulk scalar} & \Phi_G & \quad \longleftrightarrow \quad G^2_{\mu \nu} \\
\zeta_m & : \text{IR-brane position} & & \quad \text{dual}
\end{align*} \]
The model parameters:

<table>
<thead>
<tr>
<th>ξ</th>
<th>G</th>
<th>z_m</th>
<th>( \frac{L}{g^2_5} )</th>
<th>M</th>
<th>M'</th>
<th>α</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ IR value</td>
<td>Φ_χ IR value</td>
<td>IR brane position</td>
<td>Φ UV value</td>
<td>Φ_χ UV value</td>
<td>coeff. of M</td>
<td>coeff. of Φ_χ</td>
<td></td>
</tr>
</tbody>
</table>

5d coupling

Set explicit breaking sources = 0

Matching to current correlators

\( \Pi_V \) Leading log term

\( \Pi_S \) Leading log term

\( \Pi_V \) \( G^2 \) term

Fix

\( F_\pi = 246 \text{ GeV}/\sqrt{N_D} = 123 \text{ GeV} \) (1FM)

\( M_\Phi = 125 \text{ GeV} \)

\( S = 0.1 \)

3 phenomenological input values

\( \alpha|_{\gamma_m=1} = \frac{\sqrt{3}}{2} \)

\( c = -\frac{N_{TC}}{192\pi^3} \)
### Other holographic predictions \((1FM \ w/ \ S=0.1)\)

#### NTC = 3

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Techni-(\rho), a1 masses</td>
<td>(M_\rho = M_{a1} = 3.5) TeV</td>
</tr>
<tr>
<td>Techni-glueball (TG) mass</td>
<td>(M_G = 19) TeV</td>
</tr>
<tr>
<td>TG decay constant</td>
<td>(F_G = 135) TeV</td>
</tr>
<tr>
<td>Dynamical TF mass (m_F)</td>
<td>(m_F = 1.0) TeV</td>
</tr>
</tbody>
</table>

#### NTC = 4

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Techni-(\rho), a1 masses</td>
<td>(M_\rho = M_{a1} = 3.6) TeV</td>
</tr>
<tr>
<td>Techni-glueball (TG) mass</td>
<td>(M_G = 18) TeV</td>
</tr>
<tr>
<td>TG decay constant</td>
<td>(F_G = 156) TeV</td>
</tr>
<tr>
<td>Dynamical TF mass (m_F)</td>
<td>(m_F = 0.95) TeV</td>
</tr>
</tbody>
</table>

#### NTC = 5

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Techni-(\rho), a1 masses</td>
<td>(M_\rho = M_{a1} = 3.9) TeV</td>
</tr>
<tr>
<td>Techni-glueball (TG) mass</td>
<td>(M_G = 18) TeV</td>
</tr>
<tr>
<td>TG decay constant</td>
<td>(F_G = 174) TeV</td>
</tr>
<tr>
<td>Dynamical TF mass (m_F)</td>
<td>(m_F = 0.85) TeV</td>
</tr>
</tbody>
</table>
After HCP update (1):

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Tagging/Candidate Process</th>
<th>Multi-jet Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS7+8</td>
<td>VH-tag</td>
<td>ττ</td>
</tr>
<tr>
<td>CMS7+8</td>
<td>VBF-tag</td>
<td>ττ+2j</td>
</tr>
<tr>
<td>CMS7+8</td>
<td>VH-tag</td>
<td>ττ+0/1j</td>
</tr>
<tr>
<td>CMS7+8</td>
<td>WW(212ν)</td>
<td>WW(212ν)+2j</td>
</tr>
<tr>
<td>CMS7+8</td>
<td>WW(212ν)+0/1j</td>
<td>WW(212ν)+0/1j</td>
</tr>
<tr>
<td>CMS7+8</td>
<td>VBF-tag</td>
<td>γγ+2j</td>
</tr>
<tr>
<td>CMS7+8</td>
<td>incl. ZZ(4l)</td>
<td></td>
</tr>
<tr>
<td>CMS7+8</td>
<td>VH-tag</td>
<td>bb</td>
</tr>
<tr>
<td>ATLAS8</td>
<td>VBF/VH-tag</td>
<td>ττ</td>
</tr>
<tr>
<td>ATLAS8</td>
<td>incl.</td>
<td>ττ+0/1j</td>
</tr>
<tr>
<td>ATLAS7</td>
<td>incl.</td>
<td>ττ</td>
</tr>
<tr>
<td>ATLAS7+8</td>
<td>WW(212ν)+0/1j</td>
<td>WW(212ν)</td>
</tr>
<tr>
<td>ATLAS7+8</td>
<td>incl. ZZ(4l)</td>
<td>ZZ(4l)</td>
</tr>
<tr>
<td>ATLAS8</td>
<td>VH-tag</td>
<td>bb</td>
</tr>
<tr>
<td>ATLAS7</td>
<td>VH-tag</td>
<td>bb</td>
</tr>
</tbody>
</table>
After HCP update (II):
Other pheno. issues in TC scenarios

S parameter

\[ S \approx N_D \cdot \frac{8\pi F_P^2}{M_P^2} \approx 0.3 \cdot N_D \]  (for QCD-like)

\( N_D \) : # EW doublets

Cf: \( S(\text{exp}) < 0.1 \) around T = 0

too large!

One resolution: **ETC-induced “delocalization” operator**

Chivukula et al (2005)

\[ -\frac{1}{\Lambda_{\text{ETC}}^2} J_{\mu}\text{SM}_L J_{\mu\alpha}^{\text{TC}_L} \]

in low-energy

\[ J_{\mu\alpha}^{\text{TC}_L} \rightarrow \text{Tr}[U^\dagger \frac{g^a}{2} iD^\mu U] \]

\[ \exists g_W W_\mu - g_Y B_\mu \]

modifies SM f-couplings to W, Z

\[ S_{\text{total}} \rightarrow 0 \text{ ("ideal delocalization") } \]
Top quark mass generation

\[ m_t \approx \frac{\langle \bar{U}U \rangle_{ETC}}{\Lambda_{ETC}^2} \approx \left( \frac{\Lambda_{TC}}{\Lambda_{ETC}} \right)^2 \Lambda_{TC} \]

ETC scale associated w/ top mass

\[ \Lambda_{ETC}^{top} \approx 1 \text{TeV} \left( \frac{\Lambda_{TC}}{1 \text{TeV}} \right)^{3/2} \left( \frac{172 \text{GeV}}{m_t} \right)^{1/2} \]

--- too small!

One resolution: **Strong ETC** Miransky et al (1989)

--- makes induced 4-fermi (ttUU) coupling large enough to trigger chiral symm. breaking

\[ \langle \bar{U}U \rangle_{ETC} \approx \left( \frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)^{\gamma_m} \langle \bar{U}U \rangle_{TC} \quad 1 < \gamma_m \leq 2 \]

boost-up

\[ m_t \approx \left( \frac{\Lambda_{TC}}{\Lambda_{ETC}} \right)^{2-\gamma_m} \Lambda_{TC} \leq \Lambda_{TC} \sim 1 \text{TeV} \]

**T parameter** (Strong) ETC generates large isospin breaking

\[ \Rightarrow \text{highly model-dependent issue} \]
Direct consequences of Ward-Takahashi identities


* Coupling to techni-fermions

\[
\lim_{q_\mu \to 0} \int d^4 y e^{i q y} \langle 0 | T \partial^\mu D_\mu(y) F(x) \bar{F}(0) | 0 \rangle = i \delta_D \langle 0 | T F(x) \bar{F}(0) | 0 \rangle \\
= i (2d_F + x^\nu \partial_\nu) \langle 0 | T F(x) \bar{F}(0) | 0 \rangle
\]

Dilaton pole dominance

\[
F_\phi \cdot \langle \phi(q = 0) | T F(x) \bar{F}(0) | 0 \rangle = \delta_D \langle 0 | T F(x) \bar{F}(0) | 0 \rangle.
\]

w/ TD decay constant F\_phi

\[
\langle 0 | D_\mu(x) | \phi(q) \rangle = -i F_\phi q_\mu e^{-i q x}
\]

Yukawa vertex func.

\[
\chi_{\phi FF}(p, q = 0) = \frac{1}{F_\phi} \delta_D S_F^{-1}(p) = \frac{1}{F_\phi} \left(1 - p_\mu \frac{\partial}{\partial p_\mu}\right) S_F^{-1}(p)
\]
**Couplings to SM fermions**

No direct coupling

$$\langle f(p)|\theta^\mu_\mu(0)|f(p)\rangle = 0.$$  

Techni-fermion loop induces

$$\mathcal{L}_{ETC}^{\text{eff}} = G_{[f]} \bar{F} F \bar{f} f$$

ETC induced 4-fermi

f-fermion mass:

$$m_f = -G_{[f]} \langle \bar{F} F \rangle$$

Yukawa coupling to SM-fermion

$$g_{\phi ff} = \frac{(3 - \gamma_m) m_f}{F_\phi}$$
**Couplings to SM gauge bosons**

WT identity $\Rightarrow$ scale anomaly term $+$ anomaly-free term

\[
\lim_{q_\rho \to 0} \int d^4 z \ e^{iqz} \langle 0 | T \partial_\rho D^\rho(z) J_\mu(x) J_\nu(0) | 0 \rangle = \lim_{q_\rho \to 0} \left( -iq_\rho \int d^4 z \ e^{iqz} \langle 0 | T D^\rho(z) J_\mu(x) J_\nu(0) | 0 \rangle \right) + i \delta_D \langle 0 | T J_\mu(x) J_\nu(0) | 0 \rangle,
\]

The loop integrals are actually saturated by IR contributions ($\gamma_m = 2$)

\[
ig_W^2 \ \text{F.T.} \langle \phi(0) | T J^\mu_L(x) J^\nu_L(0) | 0 \rangle = \frac{2\beta_F(g)}{F_\phi g^3} (p^2 g_{\mu\nu} - p_\mu p_\nu)
\]

$\beta_F$: TF-loop contribution to beta function

\[
+ \frac{2i}{F_\phi} \left( g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) [\Pi_{LL}(0) + O(p^4 \Pi''(0))]
\]
\[ i g_W^2 \text{F.T.} \langle \phi(0) | T J_L^{\mu a}(x) J_L^{\nu b}(0) | 0 \rangle = \frac{2 \beta_F(g)}{F_\phi g^3} \left( p^2 g_{\mu \nu} - p_\mu p_\nu \right) \]

\[ + \frac{2i}{F_\phi} \left( g_{\mu \nu} - \frac{p_\mu p_\nu}{p^2} \right) \left[ \Pi_{LL}(0) + \mathcal{O}(p^4 \Pi''(0)) \right] \]

* For SU(2)W gauge bosons: W – “broken” currents

\[ \Pi_{LL}(0) = N_D \frac{F_\pi^2}{4} = \frac{v_{EW}^2}{4} \]

\[ N_D = \text{TF - EW-doublets} \]

* For unbroken currents coupled to photon, gluon:

\[ \Pi(0) = 0. \]

**Coupling to W**

\[ \mathcal{L}_{\phi WW} = \frac{2m_W^2}{F_\phi} \phi W_\mu^a W^{\mu a} \]

**Coupling to \( \gamma \gamma \) & gluons**

\[ \mathcal{L}_{\phi \gamma \gamma, gg} = \frac{\phi}{F_\phi} \left[ \frac{\beta_F(e)}{2e^3} F_{\mu \nu}^2 + \frac{\beta_F(g_s)}{2g_s^3} G_{\mu \nu}^2 \right] \]

\( \beta_F: \) TF-loop contribution to beta function