Walking Technihadrons at the LHC

Shinya Matsuzaki
Institute for Advanced Research & Department of Physics, Nagoya U.

Collaborators:
M.Kurachi, K.Yamawaki (KMI, Nagoya U)
K.Terashi (Tokyo U)  (involving works in progress)

References:
S.M. and K. Yamawaki, PRD85, 86, 86 ('12),
PRD87, PLB719, 1304.4882 ('13), 1403.0467, 1404.3048
and works in progress

@ PPP, YITP  07/31/2014
Contents

1. Introduction
   --- walking technicolor (WTC)
   and technidilaton (TD)

2. TD as the LHC Higgs boson
   --- coupling properties,
   consistency with current status

3. Walking technipions and technirho mesons
   --- current LHC limits and discovery channels

4. Summary
1. Introduction

Current status on 125 GeV Higgs discovered at LHC

* measured coupling properties consistent w/ the SM Higgs so far
* BUT, is it really the SM Higgs?
  --- origin of mass put in by hand?
  --- unnatural elementary Higgs?
It could be a composite scalar, “Technidilaton (TD)”

* TD = a composite scalar:

-- predicted in walking technicolor (WTC)
  giving dynamical origin of mass by technifermion condensate

-- arises as a pNGB for SSB of (approximate) scale symmetry
technifermion condensate

-- lightness protected by the scale symmetry
  and hence can be, say, \( \sim 125 \text{ GeV} \).

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

S.M. and K. Yamawaki, PRD85,86 (’12), PLB719 (’13);
S.M. 1304.4882; S.M. talk at SCGT14mini (’14)

LatKMI Collaboration, PRD89 (’14)
S.M. and K. Yamawaki, PRD86 (’12)
* Walking TC can be viable, solve problems by which QCD-like TC was killed:

- **FCNC**
  \[ m_{q,l} \ll m_{q,l}^{(\text{exp})} \]

- **S, T, U parameters**
  \[ \frac{S}{(N_{\text{TC}} N_D)} \sim S_{\text{QCD}} \sim 0.3 \]
  \[ S^{(\text{exp})} < 0.1 \]

- **125 GeV Higgs**
  \[ 125 \text{ GeV} \ll \Lambda_{\text{TC}} = \mathcal{O}(\text{TeV}) \]

(Holographic) Walking TC
[or ETC effects]

Walking TC scale inv.

Yamawaki, Bando, Matumoto (‘86)

Haba, Matsuzaki, Yamawaki (‘08,’10,)

Matsuzaki, Yamawaki (‘12,’13)
TD phenomenological Lagrangian


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

* 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:

\[ \mathcal{L}_{\text{inv}} = \frac{F_{\pi}^{2}}{4} \chi^{2} \text{Tr} \left[ D_{\mu} U^{\dagger} D^{\mu} U \right] + \frac{F_{\phi}^{2}}{2} \partial_{\mu} \chi \partial^{\mu} \chi \]

ii) The anomalous part (made invariant by including spurion field "S"):

\[ \mathcal{L}_{S} = -m_{f} \left( \left( \frac{\chi}{S} \right)^{2 - \gamma_{m}} \cdot \chi \right) \bar{f} f \]

\[ + \log \left( \frac{\chi}{S} \right) \left\{ \frac{\beta_{F}(g_{s})}{2g_{s}} G_{\mu\nu}^{2} + \frac{\beta_{F}(e)}{2e} F_{\mu\nu}^{2} \right\} + \ldots \]

reflecting ETC-induced TF 4-fermi w/ (3-\(\gamma_{m}\))

iii) The scale anomaly part:

\[ V_{\chi} = \frac{F_{\phi}^{2} M_{\phi}^{2}}{4} \chi^{4} \left( \log \chi - \frac{1}{4} \right) \]

\[ \langle \theta_{\mu}^{\mu} \rangle = -\delta_{D} V_{\chi} \bigg|_{\text{vacuum}} = -\frac{F_{\phi}^{2} M_{\phi}^{2}}{4} \langle \chi^{4} \rangle \bigg|_{\text{vacuum}} = -\frac{F_{\phi}^{2} M_{\phi}^{2}}{4} \]

which correctly reproduces the scale anomaly in the underlying WTC
TD couplings to the SM particles

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

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

* TD couplings to γγ and gg (from L_S)

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

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

β_F: TF-loop contribution to beta function

The same form as SM Higgs couplings except FΦ and betas
* TD couplings to SM fermions

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

* $\gamma_m \sim 1$

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

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


* $\gamma_m \sim 2$

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

\[
\frac{g_{\phi f f}}{g_{h_{SM} f f}} = \frac{1}{2} v_{EW} \frac{1}{F_\phi}
\]
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:

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

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

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

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

\[
\mathcal{L}_{\phi\gamma\gamma,gg} = \frac{\phi}{F_\phi} \left[ \frac{\beta_F(e)}{e^3} F_{\mu\nu}^2 + \frac{\beta_F(g_s)}{2g_s^3} G_{\mu\nu}^2 \right]
\]
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, $\phi$-γγ depending on particle contents of WTC models.

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

$\beta_F$: TF-loop contribution to beta function
* relevant production processes at LHC

similar to SM Higgs:

- $ggF$, VBF, VH, ttH

* relevant decay channels
(for $N_{TC}=4$)

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi \rightarrow gg$</td>
<td>$\sim 75%$</td>
</tr>
<tr>
<td>$\Phi \rightarrow bb$</td>
<td>$\sim 19%$</td>
</tr>
<tr>
<td>$\Phi \rightarrow WW$</td>
<td>$\sim 3.5%$</td>
</tr>
<tr>
<td>$\Phi \rightarrow \tau\tau$</td>
<td>$\sim 1.1%$</td>
</tr>
<tr>
<td>$\Phi \rightarrow ZZ$</td>
<td>$\sim 0.4%$</td>
</tr>
<tr>
<td>$\Phi \rightarrow \gamma\gamma$</td>
<td>$\sim 0.1%$</td>
</tr>
</tbody>
</table>

enhanced by extra colored techni-quark contribution

S.M. and K. Yamawaki, PLB719 ('13); S.M. 1304.4882;
The signal strength fit to the LHC-Run I full data

One-parameter fit \((F\phi)\)

<table>
<thead>
<tr>
<th>(N_{TC})</th>
<th>([v_{EW}/F\phi])_{best}</th>
<th>(\chi^2) min /d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.28</td>
<td>37/17 = 2.2</td>
</tr>
<tr>
<td>4</td>
<td>0.24</td>
<td>19/17 = 1.1</td>
</tr>
<tr>
<td>5</td>
<td>0.17</td>
<td>33/17 = 1.9</td>
</tr>
</tbody>
</table>

Compared w/ SM Higgs
\(\chi^2/d.o.f = 17/18 = 1.0\)

Current LHC has favored TD at almost the same level as SM Higgs!
Characteristic coupling property of $125 \text{ GeV TD in 1FM (w/ } N_{TC}=4) \text{ at the LHC}$

\[ g_{\Phi} = \left( \frac{v_{EW}}{F} \right) g_{H} = 0.24 g_{H} \]

- di-weak bosons
  - $w, z$
  - $w^*, z^*$

- quark, lepton pairs
  - $b, \tau$

- digluon

- diphoton

- v.s. SM Higgs
  - suppressed

- QCD-colored TF contributions

- EM-charged TF contributions

- moderately enhanced
  - $\beta_{F}(g_s)$

- moderately suppressed
  - $\beta_{F}(e)$
The TD signal strengths ($\mu = \sigma \times \text{BR}/\text{SM Higgs}$) vs. the current data (i)

(i) ggF+ttH category

* Data as of ICHEP2014

<table>
<thead>
<tr>
<th>TD signal strength</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\gamma\gamma}^{ggF+ttH}$ $\simeq$ 1.6</td>
<td>1.6 $\pm$ 0.25</td>
<td>1.13 $\pm$ 0.35</td>
</tr>
<tr>
<td>$\mu_{ZZ}^{ggF+ttH}$ $\simeq$ 1.1</td>
<td>1.8 $\pm$ 0.35</td>
<td>0.83 $\pm$ 0.28</td>
</tr>
<tr>
<td>$\mu_{WW}^{ggF+ttH}$ $\simeq$ 1.1</td>
<td>0.82 $\pm$ 0.36</td>
<td>0.72 $\pm$ 0.37</td>
</tr>
<tr>
<td>$\mu_{TT}^{ggF+ttH}$ $\simeq$ 1.1</td>
<td>1.1 $\pm$ 1.2</td>
<td>1.1 $\pm$ 0.46</td>
</tr>
</tbody>
</table>

* one-family model w/ NTC=4, $v_{EW}/F_{\phi} = 0.24$
The TD signal strengths ($\mu = \sigma \times \text{BR}/\text{SM Higgs}$) vs the current data (ii)

(ii) VBF + VH category

<table>
<thead>
<tr>
<th>TD signal strength</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\gamma\gamma}^{\text{VBF+VH}} \approx 0.9$</td>
<td>$1.7 \pm 0.63$</td>
<td>$1.16 \pm 0.59$</td>
</tr>
<tr>
<td>$\mu_{ZZ}^{\text{VBF+VH}} \approx 0.7$</td>
<td>$1.2 \pm 1.3$</td>
<td>$1.45 \pm 0.76$</td>
</tr>
<tr>
<td>$\mu_{WW}^{\text{VBF+VH}} \approx 0.7$</td>
<td>$1.7 \pm 0.79$</td>
<td>$0.62 \pm 0.53$</td>
</tr>
<tr>
<td>$\mu_{\tau\tau}^{\text{VBF+VH}} \approx 0.7$</td>
<td>$1.6 \pm 0.75$</td>
<td>$0.94 \pm 0.41$</td>
</tr>
<tr>
<td>$\mu_{bb}^{\text{VBF+VH}} \approx 0.03$</td>
<td>$0.20 \pm 0.64$</td>
<td>$1.0 \pm 0.50$</td>
</tr>
</tbody>
</table>

* Consistent within about 1 sigma error
* VBF: ~30% contamination from ggF, compensating direct VBF coupling suppression: $gg \rightarrow \Phi + gg$ highly enhanced compared to SM Higgs case!
* Smaller VBF+VH signal (particularly, bb-channel), compared to the SM Higgs
SM Higgs, or TD?
-- Conclusive answer needs high statistic LHC-Run II !

What do we expect next to discovery of the "Higgs"?

New particles signaling the WTC as BSM

= > Walking techni-pions & techni-vector mesons (technirrho mesons) !

= smoking-gun of WTC
3. Walking technipions and technirho mesons

* One-family (Farhi-Susskind) model w/ $SU(8)_L \times SU(8)_R \rightarrow SU(8)_V$

<table>
<thead>
<tr>
<th>$T_{F_{EW}}$</th>
<th>$SU(3)_c$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_L = \begin{pmatrix} U \ D \end{pmatrix}_L$</td>
<td>3</td>
<td>2</td>
<td>1/6</td>
</tr>
<tr>
<td>$L_L = \begin{pmatrix} N \ E \end{pmatrix}_L$</td>
<td>1</td>
<td>2</td>
<td>-1/2</td>
</tr>
<tr>
<td>$U_R$</td>
<td>3</td>
<td>1</td>
<td>2/3</td>
</tr>
<tr>
<td>$D_R$</td>
<td>3</td>
<td>1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$N_R$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$E_R$</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
</tbody>
</table>

Can be “walking” : suggested by LatKMI collaboration , [PRD87 (’13), 1309.0711] and can have a light TD [1403.500]

* By TF condensation, 63 NGBs emerge: 3 = eaten by W,Z

Coupling properties fixed by $SU(8)_L \times SU(8)_R / SU(8)_V$, scale-inv. chiral Lagrangian

60 = *pseudos, Technipions*

Get masses due to EW and ETC gauges

pNGB masses are of $O$(TeV), due to the walking feature

J. Jia, S.M. and K. Yamawaki, PRD86 (’12)
M. Kurachi, S.M. and K. Yamawaki, 1403.0467
* Current LHC limits on 60 technipions

M. Kurachi, S. M. and K. Yamawaki, 1403.0467

<table>
<thead>
<tr>
<th>techni-pion</th>
<th>color</th>
<th>isospin</th>
<th>current</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta^i_a$</td>
<td>octet</td>
<td>triplet</td>
<td>$\frac{1}{\sqrt{2}} \bar{Q}<em>a \gamma</em>\mu \gamma_5 \lambda_a \tau^i Q$</td>
</tr>
<tr>
<td>$\theta_a$</td>
<td>octet</td>
<td>singlet</td>
<td>$\frac{1}{2\sqrt{2}} \bar{Q}<em>a \gamma</em>\mu \gamma_5 \lambda_a Q$</td>
</tr>
<tr>
<td>$T^i_c$ (\bar{T}^i_c)</td>
<td>triplet</td>
<td>triplet</td>
<td>$\frac{1}{\sqrt{2}} \bar{Q}<em>c \gamma</em>\mu \gamma_5 \tau^i L$ (h.c.)</td>
</tr>
<tr>
<td>$T_c$ (\bar{T}_c)</td>
<td>triplet</td>
<td>singlet</td>
<td>$\frac{1}{2\sqrt{2}} \bar{Q}<em>c \gamma</em>\mu \gamma_5 L$ (h.c.)</td>
</tr>
<tr>
<td>$P^i$</td>
<td>singlet</td>
<td>triplet</td>
<td>$\frac{1}{2\sqrt{3}} (\bar{Q}<em>\gamma</em>\mu \gamma_5 \tau^i Q - 3\bar{L}<em>\gamma</em>\mu \gamma_5 \tau^i L)$</td>
</tr>
<tr>
<td>$P^0$</td>
<td>singlet</td>
<td>singlet</td>
<td>$\frac{1}{4\sqrt{3}} (\bar{Q}<em>\gamma</em>\mu \gamma_5 Q - 3\bar{L}<em>\gamma</em>\mu \gamma_5 L)$</td>
</tr>
</tbody>
</table>

Most stringent constraints from

$pp \rightarrow ggF \rightarrow$ isosinglet technipions $\rightarrow$ tt

and scalar leptoquark search for color-triplet $T_c$

exclude TP w/ masses

\[
\begin{align*}
\text{color-octet (}$\theta_\ast$\text{)} & < 1.5—1.6 \text{ TeV} \\
\text{color-triplet (}$T_c$\text{)} & < 1.0—1.1 \text{ TeV} \\
\text{color-singlet (}$P$\text{)} & < 800 \text{ GeV}
\end{align*}
\]

depending on # of Ntc and size of $S^{(TC)}$ (for details, see 1403.0467)
Search for walking techni-rho mesons @ LHC
M.Kurachi, S.M. and K. Yamawaki, 1404.3048
M.Kurachi, S.M., K.Terashi and K.Yamawaki, work in progress

63 vector mesons in a way similar to TPs

<table>
<thead>
<tr>
<th>Techni-rho meson</th>
<th>color</th>
<th>isopin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^0_{\Theta \bar{q}}$</td>
<td>octet</td>
<td>triplet</td>
</tr>
<tr>
<td>$\rho^0_{{\bar{\Omega}} \bar{q}}$</td>
<td>octet</td>
<td>singlet</td>
</tr>
<tr>
<td>$\rho^0_{Tc} (\bar{\rho}^0_{Tc})$</td>
<td>triplet</td>
<td>triplet</td>
</tr>
<tr>
<td>$\rho^0_{Tc} (\bar{\rho}^0_{Tc})$</td>
<td>triplet</td>
<td>triplet</td>
</tr>
<tr>
<td>$\rho^i_P$</td>
<td>singlet</td>
<td>triplet</td>
</tr>
<tr>
<td>$\rho^0_P$</td>
<td>singlet</td>
<td>singlet</td>
</tr>
<tr>
<td>$\rho^i_{\Pi}$</td>
<td>singlet</td>
<td>triplet</td>
</tr>
</tbody>
</table>

Coupling properties fixed by

\[
[SU(8)_L \times SU(8)_R \times [SU(8)_V]_{HLS}]/SU(8)_V
\]

scale-inv. Hidden Local Symmetry (HLS) Lagrangian

Refs. for HLS
Bando, et al. PRL 54 (‘85); Bando, et al, NPB 259 (‘85);
Bando, et al, PTP 79 (‘88); Bando, et al, PR 164 (‘88)
* Relevant couplings: $\rho \rightarrow f-f$, $\rho \rightarrow \pi - W/Z$, $\rho \rightarrow W - W/Z$ and interesting interactions involving TD (Higgs):

* Dominant production process @ LHC = > Drell-Yan

model parameters fixed:

VMD, $F_\pi = v_{EW}/2$, $F_\Phi \sim 1.1\text{TeV}$ (best-fit); varying $M_\rho$
$\rho_P^0$ Color-singlet Iso-singlet

**Branching ratio**

Higgs-gamma channel is dominant below Techni-Pion threshold

Color-triplet Techni-Pions ($M_T = 2$ TeV)
$\rho^0_{\theta \alpha}$

**Color-octet Iso-singlet**

**Branching ratio**

- $\phi g$
- $\bar{b}b$
- $\bar{t}t$
- $jj$

**Higgs-gluon channel is dominant below Techni-Pion threshold**

**Color-triplet Techni-Pions**

$(M_T = 2$ TeV)
$\rho_P^0$ Color-singlet Iso-singlet

$\sigma(pp \rightarrow \rho_P^0 \rightarrow \phi \gamma) \times \text{BR}(\phi \rightarrow gg) \approx 75\%$

Maybe it's challenging...

excluded by di-lepton search
\[ \rho_{\theta_a}^0 \] Color-octet Iso-singlet

\[ \sigma(pp \rightarrow \rho_{\theta_a}^0 \rightarrow \phi g) \times \text{BR} (\phi \rightarrow gg) \approx 75\% \]

It's promising!!

excluded by di-jet search

14 TeV LHC
8 TeV LHC
**Color-Octet $\rho_8 \rightarrow g + \Phi$**

**Color-octet technirhosp: $\rho_8 \rightarrow g + \Phi (\Phi \rightarrow gg)$**

$m_{\rho_8} \leq 1.6$ TeV excluded by 8 TeV dijet resonance search

$\Rightarrow m_{\rho_8} = 1.7, 2.0$ and $2.3$ TeV chosen as benchmark points

**Event Selection:**
- $\geq 2$ jets $p_T > 500,400$ GeV
- Either one of them $= 115 < m_{\text{jet}} < 145$ GeV, other jet $= m_{\text{jet}} < 115$ GeV

**Considered Backgrounds:** multi-jets (PYTHIA)

Cut and count in a sliding $M$ window

<table>
<thead>
<tr>
<th>$\sqrt{s}$ = 8 TeV</th>
<th>$m_{\rho_8}$ [TeV]</th>
<th>$\sigma \cdot \text{BR}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.7</td>
<td>$\sim 300$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$\sim 70$</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>$\sim 20$</td>
</tr>
</tbody>
</table>

**Preliminary**

**8 TeV, 20 fb$^{-1}$**

$\rho_8^{TC} \rightarrow g\Phi^{TC} (\rightarrow gg)$

$\rho_8^{int,2} > 500,400$ GeV

$115 < M_{jj(\ell\ell)} < 145$ GeV

$M_{\rho(\ell\ell)} < 115$ GeV

**Table:**

<table>
<thead>
<tr>
<th>$m_{\rho_8}$ [TeV]</th>
<th>$M_{jj}$ [TeV]</th>
<th>$S$</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.7-2.0</td>
<td>45</td>
<td>5.3</td>
</tr>
<tr>
<td>2.3</td>
<td>2.1-2.3</td>
<td>8 (46)</td>
<td>1.5 (4.3)</td>
</tr>
</tbody>
</table>

$(\sqrt{s} = 14$ TeV, 10 fb$^{-1})$

**Promising channel to probe the model**
3. Summary

- Walking TC is viable for LHC-run II, in searching for BSM

- 125 GeV Higgs = could be the Technidilaton (→ LHC Run II)

- Probing the WTC is argent task, promising via smoking-gun: technipion & techni-vectors, masses of order of just reach for upcoming Run II in particular, processes involving TD intrinsic to WTC!

Stay tune with WTC!!

Thank you very much!