125 GeV techni-dilaton at the LHC

Shinya Matsuzaki
Maskawa Institute (Kyoto Sangyo U)

Contents

- Introduction
- Walking technicolor and TD
- 125 GeV TD signal at LHC
- Summary

Based on
S.M. and K. Yamawaki (KMI, Nagoya U.),
PRD85 (2012);
PRD86 (2012);
arXiv:1207.5911
arXiv:1209.2017

Lattice Meets Experiment 2012:
Beyond the Standard Model
26—27 October 2012, University of Colorado at Boulder
A new boson at around 125 GeV was observed at LHC, through $\gamma\gamma$, $ZZ^*$(4l), $WW^*(2l2\nu)$.
The signal strengths ($\mu = \sigma / \sigma_{SM}$)

ATLAS (arXiv: 1207.7214)

CMS (arXiv: 1207.7235)

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!!

arXiv:1209.2017
Quick view of main result


TD (in 1FM) is favored by the current data!!

* diphoton rate enhanced by techni-fermions (> W loop contribution)

* goodness-of-fit performed for each search category

TD can be better than the SM Higgs
Walking technicolor and TD
A schematic view of Walking TC

\[ \alpha_{TC} \sim m_F \sim \mathcal{O}(1 \text{TeV}) \]

*Chiral/EW sym. breaking by dynamical generation of TF mass @\( \mu_{cr} \)

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

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

\[ \gamma_m \sim 1 \] (solve FCNC problem)

wide range walking \( m_F < \mu < \Lambda_{TC} \)

(approx. scale invariance)

(naturalness)
**Walking TC and techni-dilaton**

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

\[ m_F \sim \Lambda_{TC} \left( \frac{\pi}{\sqrt{\alpha / \alpha_{cr}}} \right) \quad \text{for} \quad \alpha > \alpha_{cr} \]

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

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

\[ \partial_\mu D^\mu = \frac{\beta(\alpha)}{4\alpha^2} \left\langle \alpha G_{\mu\nu}^2 \right\rangle \neq 0 \quad \text{TD gets massive} \]

\[ \alpha \text{ starts "running" (walking) up to } m_F \]

\[ \text{Nonpert. scale anomaly induced by } m_F \text{ itself} \]
**Ladder estimate of TD mass**

* LSD + BS in large Nf QCD
  

* LSD via gauged NJL
  

A composite Higgs mass

$$M_\phi \sim 4F_\pi$$

$$\sim 500 \text{ GeV}$$

for one-family model (1FM) still larger than ~ 125 GeV

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

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

where

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

$$M_\phi / m_F \to 0.$$

only when $F_\phi / m_F \to \infty$, i.e., a decoupled limit.

No exactly massless NGB limit:
**Holographic estimation 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

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

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

\[
\begin{align*}
\text{QCD} & : \gamma_m = 0 \\
\text{WTC} & : \gamma_m = 1
\end{align*}
\]
QCD-fit w/ $\gamma_m = 0$

**input**

- $f_\pi = 92.4$ MeV
- $M_\rho = 775$ MeV
- $<\alpha G m^2>/\pi = 0.012$ GeV$^4$

**model parameters**

- $\xi = 3.1$
- $G = 0.25$
- $Z_m^{-1} = 347$ MeV

**Model predictions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{a1}$ [a1 meson]</td>
<td>1.3 GeV</td>
<td>1.2 --- 1.3 GeV</td>
</tr>
<tr>
<td>$M_{f_0}(1370)$ [qqbar bound state]</td>
<td>1.2 GeV</td>
<td>1.1 --- 1.2 GeV</td>
</tr>
<tr>
<td>$M_G$ [glueball]</td>
<td>1.3 GeV</td>
<td>1.4 --- 1.7 GeV (lat.)</td>
</tr>
<tr>
<td>$S = -16\pi L_{10}$ [S parameter]</td>
<td>0.31</td>
<td>0.29 --- 0.37</td>
</tr>
<tr>
<td>$[-&lt;q\bar{q}&gt;]^{(1/3)}$ [chiral condensate]</td>
<td>277 MeV</td>
<td>200 --- 250 MeV</td>
</tr>
</tbody>
</table>

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

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

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

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)

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

Exactly-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

Lattice cals will give a conclusive answer
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 $\pi$

  $$U = e^{2i\pi / F_\pi}, \quad \delta U = x^\nu \partial_\nu U$$

Walking regime

$\alpha_{NC}$

$\sim 1$ TeV

$\Lambda_{TC} \sim 10^3$ TeV

$\mu_{cr} : \alpha = \alpha_{cr}$
Eff. TD Lagrangian \[ \mathcal{L} = \mathcal{L}_{\text{inv}} + \mathcal{L}_S - V_\chi \]

i) The scale anomaly-free part:

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

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

\[ \mathcal{L}_S = -m_f \left( \frac{\chi}{S} \right)^{2-\gamma_m} \cdot \chi \right) \bar{f} f + \log \left( \frac{\chi}{S} \right) \left\{ \frac{\beta_F(g_s)}{2 g_s} G_{\mu\nu}^2 + \frac{\beta_F(e)}{2 e} F_{\mu\nu}^2 \right\} + \cdots \]

reflecting ETC-induced TF 4-fermi w/ (3-\gamma_m)

iii) The scale anomaly part:

\[ V_\chi = \frac{F^2 M^2}{4} \chi^4 \left( \log \chi - \frac{1}{4} \right) \]

\[ \langle \theta^\mu_\mu \rangle = -\delta_D V_\chi \bigg|_{\text{vacuum}} = -\frac{F^2 M^2}{4} \langle \chi^4 \rangle \bigg|_{\text{vacuum}} = -\frac{F^2 M^2}{4} \]

which correctly reproduces the PCDC relation:
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 $\gamma\gamma$ 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
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

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

* \( \gamma_m \simeq 1 \)

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

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


* \( \gamma_m \simeq 2 \),

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

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

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

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

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

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

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

* PCDC (partially conserved dilatation current)

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

* criticality condition

\[ N_{TF} \approx 4 N_{TC} \]

* Pagels-Stokar formula

\[
F_\pi = \frac{v_{EW}}{\sqrt{N_D}}
\]

# of EW doublets

* Recent ladder SD analysis (large Nf QCD)

\[
\frac{v_{EW}}{F_\phi} \approx \frac{1}{8\sqrt{2\pi}} \sqrt{\frac{\kappa_F^4 N_D}{\kappa_V}} \frac{M_\phi}{v_{EW}}
\]

\[
\kappa_V \approx 0.7, \quad \kappa_F \approx 1.4
\]

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);

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

\[
\langle \theta^\mu_\mu \rangle = 4\mathcal{E}_{\text{vac}} = -\kappa_V \left( \frac{N_{TC}N_{TF}}{2\pi^2} \right) m_F^4 \text{ with } 30\% \text{ uncertainty}
\]

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

Estimate w/ uncertainty included

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

\[
\frac{F_\phi}{F_\pi} \approx \sqrt{2N_{TF}} \cdot \sqrt{J_0^2(x) + J_1^2(x)} \bigg|_{x = (M_\phi z_m) \ll 1} \\
\approx \sqrt{2N_{TF}} .
\]

free from model-parameters !!

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

\[
\left. \frac{v_{EW}}{F_\phi} \right|_{holo}^{+1/N_{TC}} \sim 0.2 - 0.4
\]

This is consistent with ladder estimate:

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

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

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 $m_F$?

$\alpha_{TC}$

walking regime = scale symm well protected
(natural enough)

$m_F$
$\sim 1\text{TeV}$

$\Lambda_{TC}$
$\sim 10^3\text{TeV}$

Can TD mass be as light as 125GeV below $m_F$? → YES!!!

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

$\alpha_{TC}$

$\Lambda_{TC} \sim 10^3\text{TeV}$

$\mu$

$m_F \sim 1\text{TeV}$

**Work on the eff. TD Lagrangian:**

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

Dominant corrections come from top-loop cutoff by $m_F \sim 4\pi \, F\pi \sim 1\text{TeV} \sim F\Phi$

**w/** $m_t^2 \approx 2M_\phi^2$

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

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**
  - \(W, Z\)
  - \(W^*, Z^*\)
  - \(b, \tau\)
  - \(g\)

- **quark, lepton pairs**
  - \(b, \tau\)
  - \(g_{\phi} = (v_{EW}/F_{\phi}) g_{H} = (0.1-0.3) g_{H}\)

- **digluon**
  - \(F, t\)
  - \(\beta_F(g_s)\)

- **diphoton**
  - \(\gamma\)
  - \(\beta_F(e)\)

\(\phi \) is suppressed compared to SM Higgs

\(\phi \) in di-weak bosons and quark, lepton pairs is suppressed

\(\phi \) in digluon is enhanced

\(\phi \) in diphoton is enhanced and \(>> W\)-loops
The 125 GeV TD signal strengths

* decays to \( bb, \ tau \ tau, \ WW^*, \ ZZ^*, \ diphoton \)

\( bb: \)

\[
\mu_{bb} = \frac{\sigma_{VBA}^{\phi}(s)}{\sigma_{VBA}^{h_{SM}}(s)} \frac{BR(\phi \to bb)}{BR(h_{SM} \to bb)} = \frac{\sigma_{W\phi}(s) + \sigma_{Z\phi}(s)}{\sigma_{WH_{SM}}(s) + \sigma_{ZH_{SM}}(s)} \frac{BR(\phi \to bb)}{BR(h_{SM} \to bb)}
\]

\( X = \text{tau} \tau, \ WW^*, \ ZZ^*: \)

\[
\mu_X = \frac{\sigma_{GF}^{\phi}(s) + \sigma_{VBF}^{\phi}(s)}{\sigma_{GF}^{h_{SM}}(s) + \sigma_{VBF}^{h_{SM}}(s)} \frac{BR(\phi \to X)}{BR(h_{SM} \to X)}
\]

\( \mu_{\gamma^0j} = \frac{\sigma_{GF}^{\phi}(s)}{\sigma_{GF}^{h_{SM}}(s)} \frac{BR(\phi \to X)}{BR(h_{SM} \to X)}, \)

\( \mu_{\gamma^2j} = \frac{\xi_{GF} \cdot \sigma_{GF}^{\phi}(s) + \xi_{VBF} \cdot \sigma_{VBF}^{\phi}(s)}{\xi_{GF} \cdot \sigma_{GF}^{h_{SM}}(s) + \xi_{VBF} \cdot \sigma_{VBF}^{h_{SM}}(s)} \frac{BR(\phi \to \gamma \gamma)}{BR(h_{SM} \to \gamma \gamma)}, \)

\( \mu_{\gamma^2j} = \frac{\xi_{GF} \cdot \sigma_{GF}^{\phi}(s) + \xi_{VBF} \cdot \sigma_{VBF}^{\phi}(s)}{\xi_{GF} \cdot \sigma_{GF}^{h_{SM}}(s) + \xi_{VBF} \cdot \sigma_{VBF}^{h_{SM}}(s)} \frac{BR(\phi \to \gamma \gamma)}{BR(h_{SM} \to \gamma \gamma)}, \)
* chi\(^2\) fit based on the current data on Higgs search categories

* TD can be better than the SM Higgs (chi\(^2\)/d.o.f= 1.0), due to the enhanced diphoton rate, in contrast to other dilaton/radion scenarios w/o extra BSM contributions like TF
* The best-fit signal strengths (for each category)

<table>
<thead>
<tr>
<th>Signal Strength</th>
<th>Value</th>
<th>-</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{Vbb}$</td>
<td>0.006</td>
<td>--</td>
<td>0.01</td>
</tr>
<tr>
<td>$\mu_{WW^*}$</td>
<td>0.9</td>
<td>--</td>
<td>1.0</td>
</tr>
<tr>
<td>$\mu_{ZZ^*}$</td>
<td>0.7</td>
<td>--</td>
<td>1.1</td>
</tr>
<tr>
<td>$\mu_{\tau\tau}$</td>
<td>0.7</td>
<td>--</td>
<td>1.1</td>
</tr>
<tr>
<td>$\mu_{\gamma\gamma_0j}$</td>
<td>1.5</td>
<td>--</td>
<td>2.0</td>
</tr>
<tr>
<td>$\mu_{\gamma\gamma_2j}$</td>
<td>0.5</td>
<td>--</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Characteristic feature:

- $V_{bb}$: suppressed
- $\gamma\gamma_{0j}$: enhanced
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, ττ+jets) will draw a definite conclusion that the TD is favored, or not.
Backup Slides
\[ S_5 = \int d^4x \int_{\epsilon}^{z_m} d z \sqrt{-g} \frac{1}{g_5^2} e^{cg_5^2 \Phi_X(z)} \left( -\frac{1}{4} \text{Tr} \left[ L_{MN} L^{MN} + R_{MN} R^{MN} \right] 
\right. \\
\left. + \text{Tr} \left[ D_M \Phi^\dagger D^M \Phi - m_\Phi^2 \Phi^\dagger \Phi \right] + \frac{1}{2} \partial_M \Phi_X \partial^M \Phi_X \right) \]

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

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

AdS/CFT dictionary:

* **UV boundary values = sources**

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

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

* **IR boundary values:**

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

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

\[ S_5 \rightarrow S_5[s, g, v, a]_{\text{UV-boundary}} = W_{4D} \]

generating functional sources = UV boundary values for bulk scalar, vector, axial-vector fields

\[ W_{4D} \rightarrow \langle T J(x) J(0) \rangle \quad J = \bar{F} F, G_{\mu \nu}, \bar{F} \gamma_\mu T^\alpha F, \bar{F} \gamma_\mu \gamma_5 T^\alpha F \]

Current collerators \( \Pi_S, \Pi_G, \Pi_V, \Pi_A \)
are calculated as a function of three IR–boundary values and \( \gamma_m \):

\[
\begin{align*}
\xi & : \text{IR value of bulk scalar} \\
G & : \text{IR value of bulk scalar} \\
\zeta_m & : \text{IR-brane position}
\end{align*}
\]

\[
\begin{align*}
\Phi_S & \leftrightarrow \bar{F} F \\
\Phi_G & \leftrightarrow G_{\mu \nu}^2
\end{align*}
\]
The model parameters:

<table>
<thead>
<tr>
<th>( L/g_5^2 )</th>
<th>( M )</th>
<th>( M' )</th>
<th>( \alpha )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Phi_{IR} )</td>
<td>( \Phi_{UV} )</td>
<td>( \Phi_{x\ UV} )</td>
<td>coeff. of ( M )</td>
<td>coeff. of ( \Phi_x )</td>
</tr>
<tr>
<td>( \Phi_{IR\ value} )</td>
<td>( \Phi_{UV\ value} )</td>
<td>( \Phi_{x\ UV\ value} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Phi_{IR\ position} )</td>
<td>5d coupling</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Fix \( F_\pi = 246 \text{ GeV}/\sqrt{N_D} = 123 \text{ GeV} \ (1\text{FM}) \)
- \( M\Phi = 125 \text{ GeV} \)
- \( S = 0.1 \)

3 phenomenological input values

- \( \Pi_V \) Leading log term
- \( \Pi_S \) Leading log term
- \( \Pi_V \) \( G^2 \) term

Matching to current correlators

Set explicit breaking sources = 0

\[
\alpha|_{\gamma_m=1} = \frac{\sqrt{3}}{2} \quad c = -\frac{N_{TC}}{192\pi^3}
\]
### Other holographic predictions (1FM w/ S=0.1)

#### NTC = 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Techni-(\rho), (a_1) masses</td>
<td>(M_{\rho} = M_{a_1} = 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>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Techni-(\rho), (a_1) masses</td>
<td>(M_{\rho} = M_{a_1} = 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>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Techni-(\rho), (a_1) masses</td>
<td>(M_{\rho} = M_{a_1} = 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>
W/ Tevatron data included:

- ATLAS&CMS data
- SM Higgs

Legend:
- dotted
- dashed
- solid
- dot-dashed

Data points:
- CDF&D0 1.96TeV (bb)
- CDF&D0 1.96TeV (γγ)
- CDF&D0 1.96TeV (WW*)
- CMS 8TeV (γγ2j (loose))
- CMS 8TeV (γγ2j (tight))
- CMS 7TeV (γγ2j)
- ATLAS 8TeV (γγ2j)
- CMS 7TeV+8TeV (γγ0j)
- ATLAS 7TeV+8TeV (γγ0j)
- ATLAS 7TeV (ττ)
- CMS 7TeV+8TeV (ττ)
- CMS 7TeV+8TeV (ZZ*(4l))
- ATLAS 7TeV+8TeV (ZZ*(4l))
- CMS 7TeV+8TeV (WW*(2l2ν))
- ATLAS 7TeV+8TeV (WW*(2l2ν))
- CMS 7TeV+8TeV (bb)
- ATLAS 7TeV (bb)
W/ Tevatron data included:
Farhi et al (1981)

One-doublet model (1DM)

<table>
<thead>
<tr>
<th>$TF_{EW}$</th>
<th>$SU(3)_c$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>$D$</td>
<td>1</td>
<td>1</td>
<td>-1/2</td>
</tr>
<tr>
<td>$U_R$</td>
<td>1</td>
<td>1</td>
<td>1/2</td>
</tr>
<tr>
<td>$D_R$</td>
<td>1</td>
<td>1</td>
<td>-1/2</td>
</tr>
</tbody>
</table>

One-family model (1FM)

Total # of techni-fermions

$$N_{TF} = (N_{TF})_{EW-\text{singlet}} + 2N_D$$

w/ critical # for mass generation in WTC

$$N_{TF} \approx 4N_{TC}$$

Appelequist et al (1996)
**Other pheno. issues in TC scenarios**

S parameter

\[ S \approx N_D \cdot \frac{8\pi F_0^2}{M_P^2} \approx 0.3 \cdot N_D \]  
\( N_D : \# \text{ EW doublets} \)  
\( \text{too large!} \quad \text{Cf: } S(\exp) < 0.1 \quad \text{around } T=0 \)

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

\[ J_{\mu}^{\alpha} \rightarrow \text{Tr}[U^\dagger \frac{\sigma^{\alpha}_2}{2} iD^\mu U] \]

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

\[ \Delta S \sim \frac{8\pi}{g_W^2} \left( \frac{v_{EW}}{\Lambda_{ETC}} \right)^2 \]

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

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

ETC scale associated w/ top mass

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

too small!

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

--- makes induced 4-fermi (tt UU) coupling large enough to trigger chiral symm. breaking (almost by NJL dynamics)

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

boost-up

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

\[ T \text{ parameter} \quad \text{(Strong) ETC generates large isospin breaking} \]

\[ \Rightarrow \text{ highly model-dependent issue} \]
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

\[
-L_{\text{ETC}}^{\text{eff}} = G[f] \bar{F}F \bar{f}f
\]

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

$$\lim_{q_\rho \to 0} \int d^4 z \ e^{i q z} \langle 0 | T \partial_\rho D^\rho(z) J_\mu(x) J_\nu(0) | 0 \rangle = \lim_{q_\rho \to 0} \left( -i q_\rho \int d^4 z \ e^{i q z} \langle 0 | T D^\rho(z) J_\mu(x) J_\nu(0) | 0 \rangle \right)$$

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

$$ig_W^2 \text{F.T.} \langle \phi(0) | T J_L^{\mu a}(x) J_L^{\nu b}(0) | 0 \rangle = \frac{2 \beta_F(g)}{F_\phi g^3} (p^2 g_{\mu\nu} - p_\mu p_\nu)$$

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

$\beta_F$: TF-loop contribution to beta function
\[ ig_W^2 \text{F.T.}(\phi(0)|T J_L^{\mu a}(x) J_L^{\nu b}(0)|0) = \frac{2\beta_F(g)}{F_\phi g^3} (p^2 g_{\mu\nu} - p_\mu p_\nu) \]

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

\[ \beta_F: \text{TF-loop contribution to beta function} \]

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

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

**Coupling to W**

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

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

* For unbroken currents coupled to photon, gluon:

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

**Coupling to γγ & gluons**

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