Technidilaton in light of LHC-Run II

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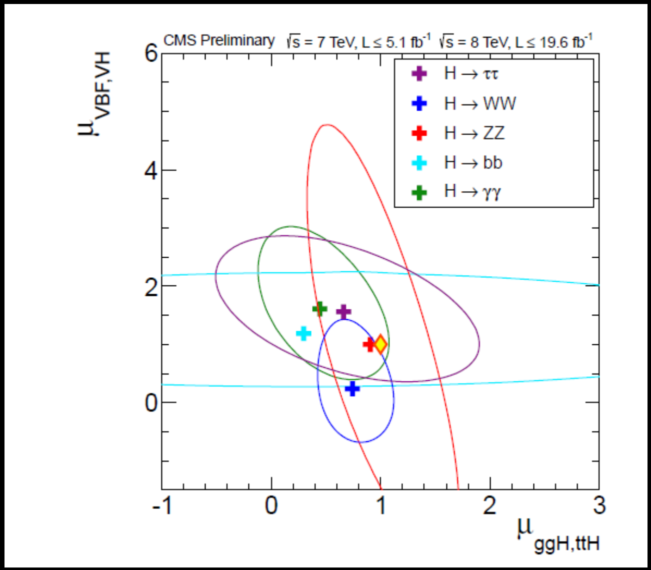
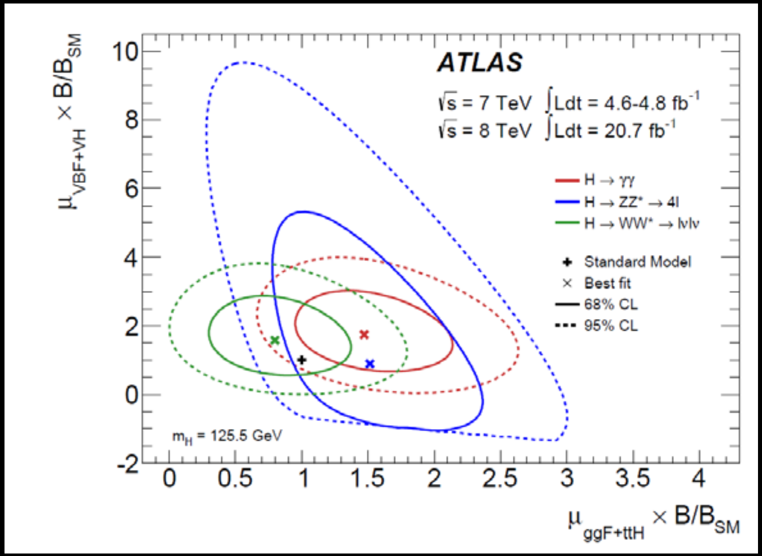
Current status on 125 GeV Higgs discovered at LHC

CMS-PAS-HIG-13-005



ATLAS: PLB726 (2013)



* 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, Techni-dilaton (TD)

* TD : composite scalar:

Yamawaki et al (1986); Bando et al (1986)

-- predicted in walking technicolor
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
(naturalness), and hence can be, say, ~ 125 GeV.

S.M. and K. Yamawaki (2012)

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

Today: comparison is updated

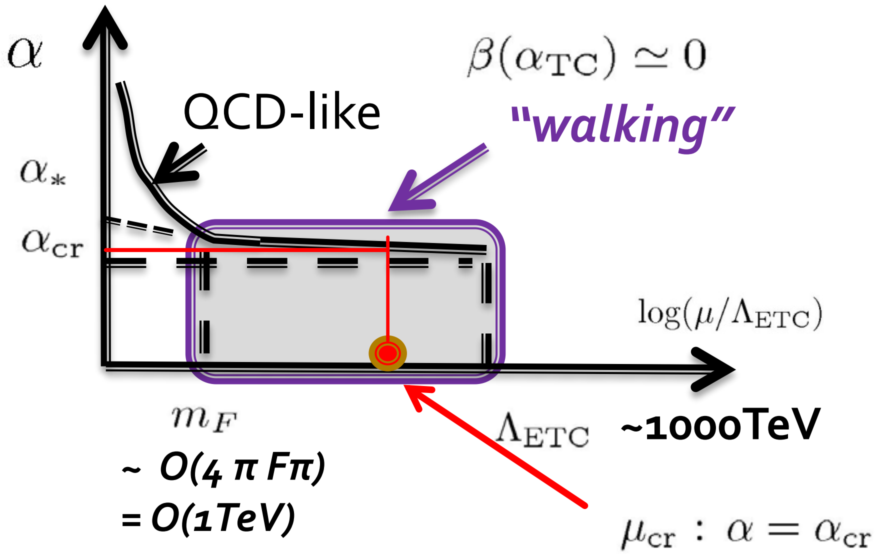
Contents of this talk:

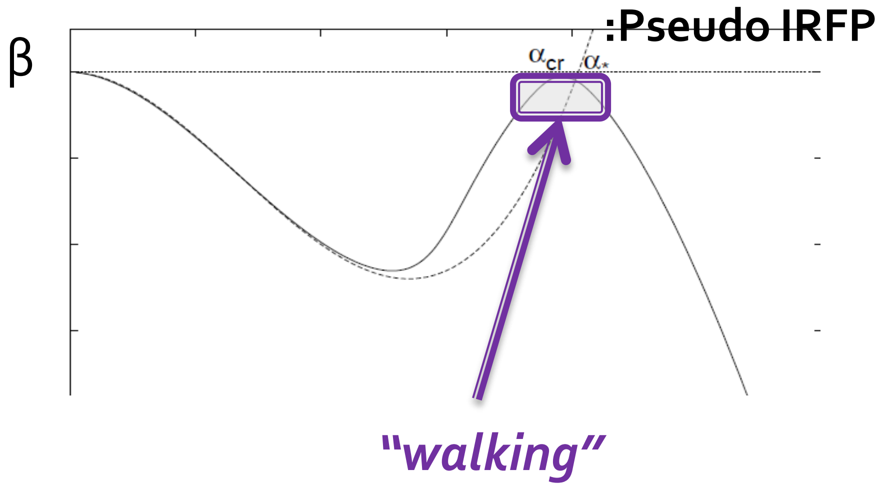
1. Introduction
2. Walking TC and Technidilaton
3. 125 GeV TD signal vs. current LHC data
4. Toward LHC-Run II
5. Summary

2. Walking technicolor and TD

Yamawaki et al (1986); Bando et al (1986)

★ *Walking TC and techni-dilaton*





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

$$m_F \sim \Lambda_{\rm TC} e^{-\frac{\pi}{\sqrt{\alpha/\alpha_{\rm cr}-1}}} \ \text{for}\ \alpha > \alpha_{\rm cr}$$ SSB of (approximate) scale sym.

→ *α starts "running" (walking) up to mF*

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

→ *Nonpert. scale anomaly induced by mF itself*

$$\partial_\mu D^\mu = \frac{\beta_{\rm NP}(\alpha)}{4\alpha^2}(\alpha G_{\mu\nu}^2) \neq 0 :$$ **TD gets massive**

★ Light techni-dilaton

S.M and K.Yamawaki , PRD86 (2012)

* One suggestion from holographic formula for TD mass

$$G \sim \frac{\langle \alpha G_{\mu\nu}^2 \rangle}{F_\pi^4}$$

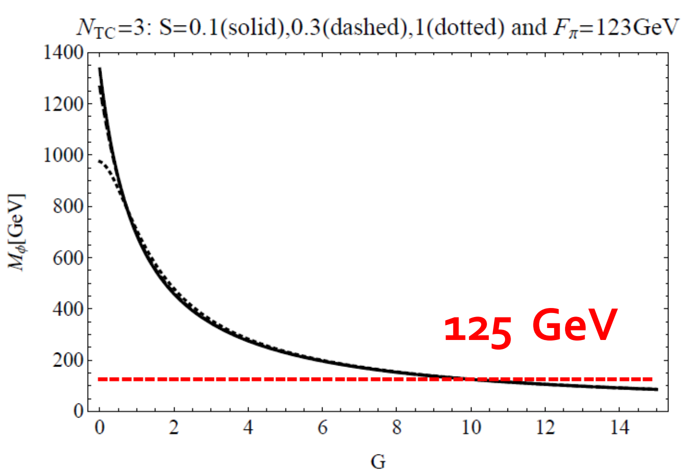
--- TD mass (lowest pole of dilatation current correlator)

"conformal limit"

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

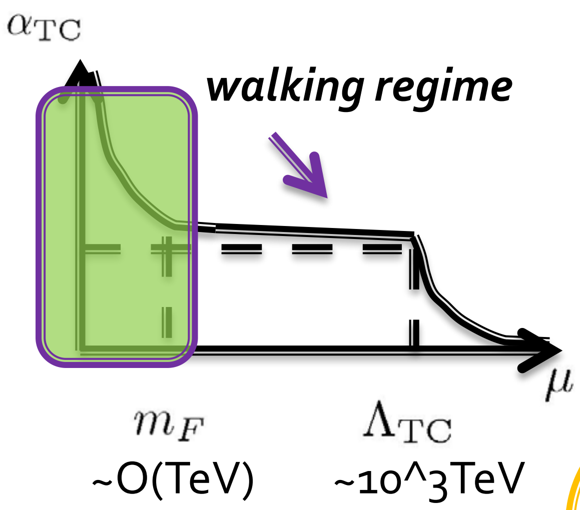
$$\left[\beta(\alpha) \sim \frac{1}{G(1+G)^2} \to 0 \right.$$

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



TD Lagrangian below m_F

S.M. and K. Yamawaki, PRD86 (2012)



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

governed by TD and other light TC hadrons

* Nonlinear realization of scale and chiral symmetries

Nonlinear base χ for scale sym. w/ TD field Φ

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

TD decay constant FΦ $\quad \delta\phi = F_\phi + x^\nu \partial_\nu \phi$

Nonlinear base U for chiral sym. w/ TC pion field π

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

eff. TD Lagrangian $\mathcal{L} = \mathcal{L}_{\rm inv} + \mathcal{L}_S - V_\chi$

i) The scale anomaly-free part:

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

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

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

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

β_F: TF-loop contribution to beta function

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:

$$\langle\theta_\mu^\mu\rangle = -\delta_D V_\chi\Big|_{\rm vacuum} = -\frac{F_\phi^2 M_\phi^2}{4}\langle\chi^4\rangle\Big|_{\rm vacuum} = -\frac{F_\phi^2 M_\phi^2}{4}$$

TD couplings to the SM particles

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

$$g_{\phi WW/ZZ} = \frac{2m_{W/Z}^2}{F_\phi}$$

* 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

TD couplings to the SM particles

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

$$g_{\phi WW/ZZ} = \frac{2m_{W/Z}^2}{F_\phi}$$

The same form as SM Higgs couplings except Fϕ and betas

* 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

* 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 realitic masses w/o FCNC concerning 1^{st} and 2^{nd} generations

$$\frac{g_{\phi ff}}{g_{h_{\rm SM}ff}} = 2\frac{v_{\rm EW}}{F_\phi}$$

Miransky et al (1989); Matsumoto (1989); Appelquist et al (1989)

* $\gamma_m \simeq 2,$

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

$$\frac{g_{\phi ff}}{g_{h_{\rm SM}ff}} = 1\frac{v_{\rm EW}}{F_\phi}$$

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:

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

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

But, note ϕ-gg, ϕ-γγ *depending on particle contents of WTC models.*

β_F: TF-loop contribution to beta function

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

To be concerete, we consider ***one-family model (1FM)***

$TF_{\rm EW}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_L = \begin{pmatrix} U \\ D \end{pmatrix}_L$	3	2	1/6
$L_L = \begin{pmatrix} N \\ E \end{pmatrix}_L$	1	2	-1/2
U_R	3	1	2/3
D_R	3	1	-1/3
N_R	1	1	0
E_R	1	1	-1

evaluate betas at one-loop level:

$$\beta_F(g_s) = \frac{g_s^3}{(4\pi)^2}\frac{4}{3}N_{\rm TC},$$

$$\beta_F(e) = \frac{e^3}{(4\pi)^2}\frac{16}{9}N_{\rm TC}.$$

3. 125 GeV TD Signal vs. LHC-Run I Data

** relevant production processes at LHC*

similar to SM Higgs:

ggF, VBF, VH, ttH

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

		BR
$\Phi \to gg$	:	~ 75%
$\Phi \to bb$	:	~ 19 %
$\Phi \to WW$	:	~ 3.5%
$\Phi \to \tau\tau$	:	~ 1.1 %
$\Phi \to ZZ$	:	~ 0.4%
$\Phi \to \gamma\gamma$	:	~ 0.1%

enhanced by extra colored techni-quark contribution

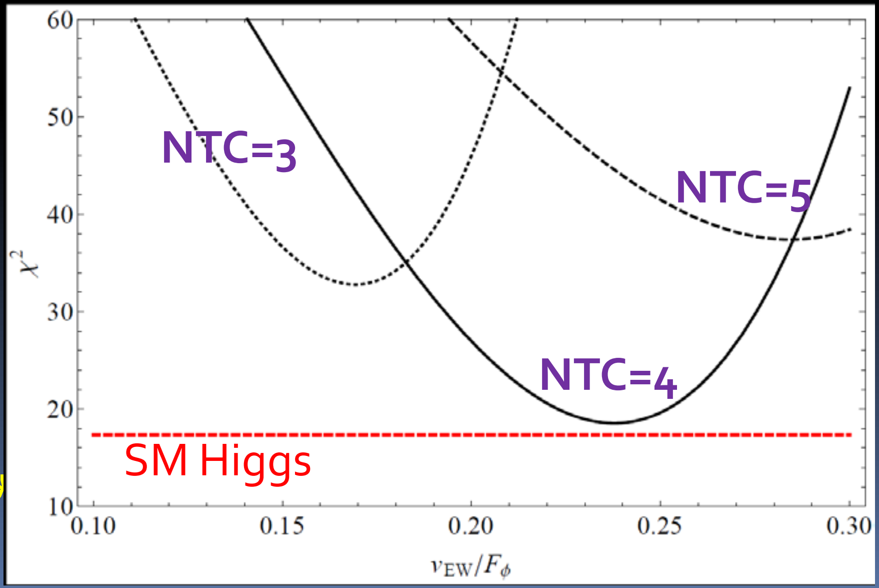
★ *The signal strength fit to the LHC-Run I full data*

Updated from S.M. and Yamawaki PLB719(2013)

One-parameter fit (F_ϕ)

$$\chi^2 = \sum_{i \in \text{events}} \left(\frac{\mu_i - \mu_i^{\exp}}{\sigma_i} \right)^2$$

N_{TC}	$[v_{EW}/F_\Phi]_{best}$	χ^2 min /d.o.f.
3	0.28	37/17 = 2.2
4	0.24	19/17 = 1.1
5	0.17	33/17 = 1.9



Compared w/ SM Higgs χ^2/d.o.f = 17/18 = 1.0

Current LHC has favored TD at almost the same level as SM Higgs!

The TD signal strengths ($\mu = \sigma \times BR/SM$ Higgs) vs. the current data (i)

(i) ggF+ttH category

TD signal strength	ATLAS	CMS
$\mu_{\gamma\gamma}^{\rm ggF+ttH} \simeq 1.6$	1.6 ± 0.25	0.52 ± 0.60
$\mu_{ZZ}^{\rm ggF+ttH} \simeq 1.1$	1.8 ± 0.35	0.90 ± 0.45
$\mu_{WW}^{\rm ggF+ttH} \simeq 1.1$	0.82 ± 0.36	0.72 ± 0.37
$\mu_{\tau\tau}^{\rm ggF+ttH} \simeq 1.1$	1.1 ± 1.2	1.1 ± 0.46

* one-family model w/ NTC=4, $v_{EW}/F_\phi = 0.24$

* Consistent at 1 sigma level (except CMS-diphoton)

The TD signal strengths (μ = σ x BR/SM Higgs) vs the current data (ii)

(ii) VBF +VH category

TD signal strength	ATLAS	CMS
$\mu_{\gamma\gamma}^{\mathrm{VBF+VH}} \simeq 0.9$	1.7 ± 0.63	1.5 ± 1.3
$\mu_{ZZ}^{\mathrm{VBF+VH}} \simeq 0.7$	1.2 ± 1.3	1.0 ± 2.4
$\mu_{WW}^{\mathrm{VBF+VH}} \simeq 0.7$	1.7 ± 0.79	0.62 ± 0.53
$\mu_{\tau\tau}^{\mathrm{VBF+VH}} \simeq 0.7$	1.6 ± 0.75	0.94 ± 0.41
$\mu_{bb}^{\mathrm{VBF+VH}} \simeq 0.03$	0.20 ± 0.64	1.0 ± 0.50

* Consistent within 2 sigma error
* VBF: contamination from ggF by about 30% taken into account, except bb channel (b-tag)
* Smaller VBF+VH signal (particularly, bb-channel), compared to the SM Higgs

→ Conclusive answer needs high statistic LHC-Run II !

4. Toward LHC Run-II

Determining TD decay constant FΦ

Precise estimate is needed for LHC-Run II

* **Theoretical predictions so far**

S.M. and Yamawaki (2012)

ladder approximation:

$$\frac{v_{\rm EW}}{F_\pi} \simeq (0.1 - 0.3)$$

holographic estimate:

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

More rigorous estimate should be made directly by lattice simulations!

--- needs a way of measuring FΦ on lattice

It is actually provided by scale-invariant ChPT!

Scale-invariant ChPT (sChPT) -- Determining TD decay constant F_ϕ and mass M_ϕ on lattice

S.M. and K. Yamawaki, 1311.3784 (2013)

*** sChPT is formulated so as to reproduce chiral/scale WT identity:**

$$\theta^\mu_\mu = \partial_\mu D^\mu = \frac{\beta_{\rm NP}(\alpha)}{4\alpha} G^2_{\mu\nu} + (1+\gamma_m) N_f \bar\psi m_f \psi$$

$$\partial_\mu J_5^{a\mu} = \bar\psi \{T^a, m_f\} i\gamma_5 \psi \,,$$

hard-breaking term　　*soft- breaking term*

and PCDC (and PCAC) at the leading O(p^2):

$$\langle \phi | \theta^\mu_\mu | 0 \rangle = F_\phi M_\phi^2$$

$$\theta^\mu_\mu = (\theta^\mu_\mu)^{\rm hard}_{m_f=0} + (\theta^\mu_\mu)^{\rm soft}_{m_f \neq 0}$$

$$\langle \phi | (\theta^\mu_\mu)^{\rm hard}_{m_f=0} | 0 \rangle = F_\phi m_\phi^2$$

$$\langle \phi | (\theta^\mu_\mu)^{\rm soft}_{m_f\neq 0} | 0 \rangle = F_\phi \tilde m_\phi^2$$

$$(\theta^\mu_\mu)^{\rm hard}_{m_f=0} = \frac{\beta(\alpha)}{4\alpha} G^2_{\mu\nu}$$

$$(\theta^\mu_\mu)^{\rm soft}_{m_f\neq 0} = (1+\gamma_m) N_f m_f \bar\psi \psi$$

Soft-breaking mass

Note the dilaton mass formula

as direct consequence of WT (and PCDC):

$$M_\phi^2 = m_\phi^2 + \tilde{m}_\phi^2$$

hard-breaking mass (chiral-limit mass)

$$m_\phi^2$$

Soft-breaking mass proportional to mf:

$$\tilde{m}_\phi^2 = (3-\gamma_m)(1+\gamma_m) N_f m_f \frac{\langle\bar{\psi}\psi\rangle}{F_\phi^2} = (3-\gamma_m)(1+\gamma_m) N_f \frac{F_\pi^2}{2F_\phi^2} m_\pi^2$$

* Building-blocks and order-counting rule

$$U\,, \qquad \chi\,, \qquad \mathcal{M}\,, \qquad S$$

i) nonlinear bases

for chiral symmetry: $U = e^{2i\pi/F_\pi}$

for scale symmetry: $\chi = e^{\phi/F_\phi}$

ii) spurion fields $\mathcal{M}$ and S (explicit breaking)

$$\langle \mathcal{M} \rangle = \bar{m}_\pi^2 \times \mathbf{1}_{N_f \times N_f} \text{ and } \langle S \rangle = \bar{1}$$

iii) chiral & scale transformation properties

$$U \to g_L \cdot U \cdot g_R^\dagger \qquad \delta U(x) = x_\nu \partial^\nu U(x)$$

$$\mathcal{M} \to g_L \cdot \mathcal{M} \cdot g_R^\dagger \qquad \delta \mathcal{M}(x) = x_\nu \partial^\nu \mathcal{M}(x)$$

$$\chi \to \chi \qquad \delta\chi(x) = (1 + x_\nu \partial^\nu)\chi(x)$$

$$S \to S \qquad \delta S = (1 + x_\nu \partial^\nu) S(x)$$

iii) order counting rule

$$U \sim \chi \sim S \sim \mathcal{O}(p^0)\,,$$

$$\mathcal{M} \sim m_f \sim \mathcal{O}(p^2)\,,$$

$$\partial_\mu \sim m_\pi \sim M_\phi \sim \mathcal{O}(p)$$

*The leading-order O(p^2) chiral and scale-invariant Lagrangian

$$\mathcal{L}_{(2)} = \mathcal{L}^{\rm inv}_{(2)} + \mathcal{L}^{S}_{(2)\rm hard} + \mathcal{L}^{S}_{(2)\rm soft}$$

$$\mathcal{L}^{\rm inv}_{(2)} = \frac{F_\phi^2}{2}(\partial_\mu \chi)^2 + \frac{F_\pi^2}{4}\chi^2 {\rm tr}[\partial_\mu U^\dagger \partial^\mu U]$$

(Matsuzaki, Yamawaki, 2012)

$$\mathcal{L}^{S}_{(2)\rm hard} = -\frac{F_\phi^2}{4} m_\phi^2 \chi^4 \left(\log\frac{\chi}{S} - \frac{1}{4}\right)$$

(Matsuzaki, Yamawaki, 2012)

$$\mathcal{L}^{S}_{(2)\rm soft} = \frac{F_\pi^2}{4}\left(\frac{\chi}{S}\right)^{3-\gamma_m} \cdot S^4 {\rm tr}[\mathcal{M}^\dagger U + U^\dagger \mathcal{M}] - \frac{(3-\gamma_m)F_\pi^2}{8}\chi^4 \cdot \left(N_f {\rm tr}[\mathcal{M}^\dagger \mathcal{M}]\right)^{1/2}$$

(Leung, Love, Bardeen, 1989)

PCDC (partially conserved dilatation current)

$$\langle \theta^\mu_\mu \rangle|_{m_f=0} = -\frac{F_\phi^2 m_\phi^2}{4} \quad \textbf{(chiral limit)}$$

Modified PCDC

$$\langle \theta^\mu_\mu \rangle|_{m_f\neq 0} = -\frac{F_\phi^2 m_\phi^2}{4} - (1+\gamma_m) N_f \frac{m_\pi^2 F_\pi^2}{2}$$

reproduces the anomalous WT identity:

$$\langle \theta^\mu_\mu \rangle|^{\rm NP}_{m_f\neq 0} = \frac{\beta_{\rm NP}(\alpha)\langle G_{\mu\nu}^2\rangle}{4\alpha} + (1+\gamma_m) N_f m_f \langle \bar\psi\psi\rangle$$

Note: soft-breaking term is uniquely fixed by stabilization of dilaton potential in the presence of current mass mf

* Dilaton mass formula at O(p^2) is reproduced:

Dilaton mass formula: (chiral-limit mass) + slope × (soft-breaking mass)

$$M_\phi^2 = m_\phi^2 + s\, m_\pi^2,$$
$$s \equiv \frac{(3-\gamma_m)(1+\gamma_m)}{4} \cdot \frac{2N_f F_\pi^2}{F_\phi^2} \simeq \frac{2N_f F_\pi^2}{F_\phi^2} \equiv r$$

$\gamma_m \simeq 1$

*** Given Nf , Fπ,**
-- slope (s) → Fϕ
-- intercept → mϕ
simultaneously measured via plot

M_ϕ^2 vs m_π^2

*** Slope "s" : used for self-consistency check of lattice simulations**

* *Prefactor* $\frac{(3-\gamma_m)(1+\gamma_m)}{4} \simeq 1 + \mathcal{O}(\delta^2)$ *fairly insensitive to exact value of* γ_m *in walking theory*

$\delta = 1 - \gamma_m \ll 1$ for $\gamma_m \simeq 1$

* $\frac{2N_f F_\pi^2}{F_\phi^2} \equiv r$ *is Independent of Nf*

M_ϕ^2 vs m_π^2 plot of mock-up data

$$M_\phi^2 = m_\phi^2 + s \cdot m_\pi^2,$$
$$s \equiv \frac{(3-\gamma_m)(1+\gamma_m)}{4} \cdot \frac{2N_f F_\pi^2}{F_\phi^2} \simeq \frac{2N_f F_\pi^2}{F_\phi^2}$$

sample: one-family model of walking technicolor

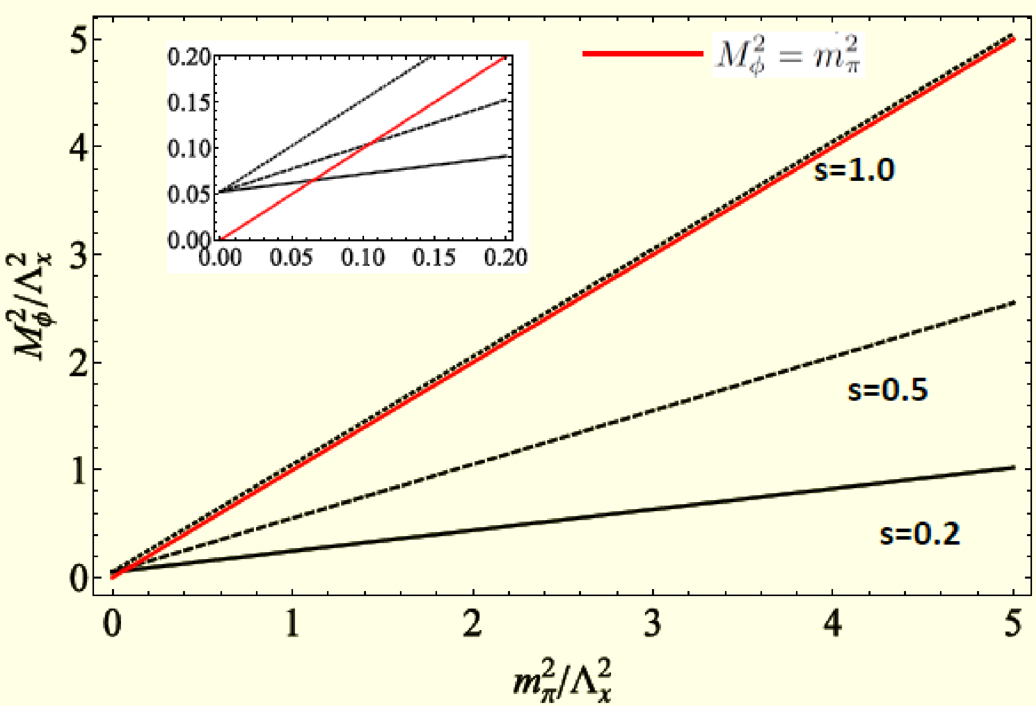
i) $N_f = 8$ (4 weak-doublets) $F_\pi = v_{\rm EW}/\sqrt{4} \simeq 123$ GeV

ii) dilaton = technidilaton ≡ the LHC Higgs

set chiral-limit mass (intercept) $m_\phi = 125$ GeV

iii) take slope parameter "s" = (0.2, 0.5, 1.0) → $F_\phi \simeq (1100, 700, 500)$ GeV

$\Lambda_\chi = 4\pi F_\pi/\sqrt{N_f}$



Holography (large Ntc limit)
(S.M. and K.Yamawaki, 2012)

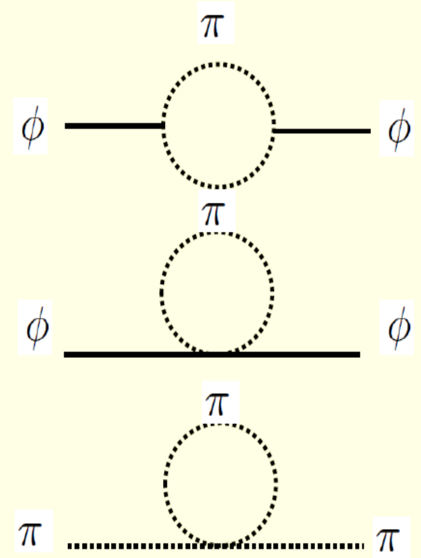
Just a sample value in between

Fitting to LHC phenomenology
(S.M. and K.Yamawaki, 2012 and this talk)

* Chiral log (pion mass) corrections to dilaton mass at O(p^4)

$$
\begin{aligned}
M_\phi^2 &= m_\phi^2 \left[1 + r \cdot \frac{N_f^2 - 1}{2N_f^2} \mathcal{X} \log \frac{m_\pi^2}{\mu^2} \right] \\
&\quad + r \cdot m_\pi^2 \left[\frac{2(N_f^2 - 1)}{N_f^2} \mathcal{X} \log \frac{m_\pi^2}{\mu^2} \right] \\
&\quad + s \cdot m_\pi^2 \left[1 + \frac{N_f^2 - 4}{4N_f^2} \mathcal{X} \log \frac{m_\pi^2}{\mu^2} \right] \\
&\quad + (\text{counter terms renormalized at } \mu)
\end{aligned}
$$

$$\mathcal{X} \equiv m_\pi^2 / \Lambda_\chi^2$$

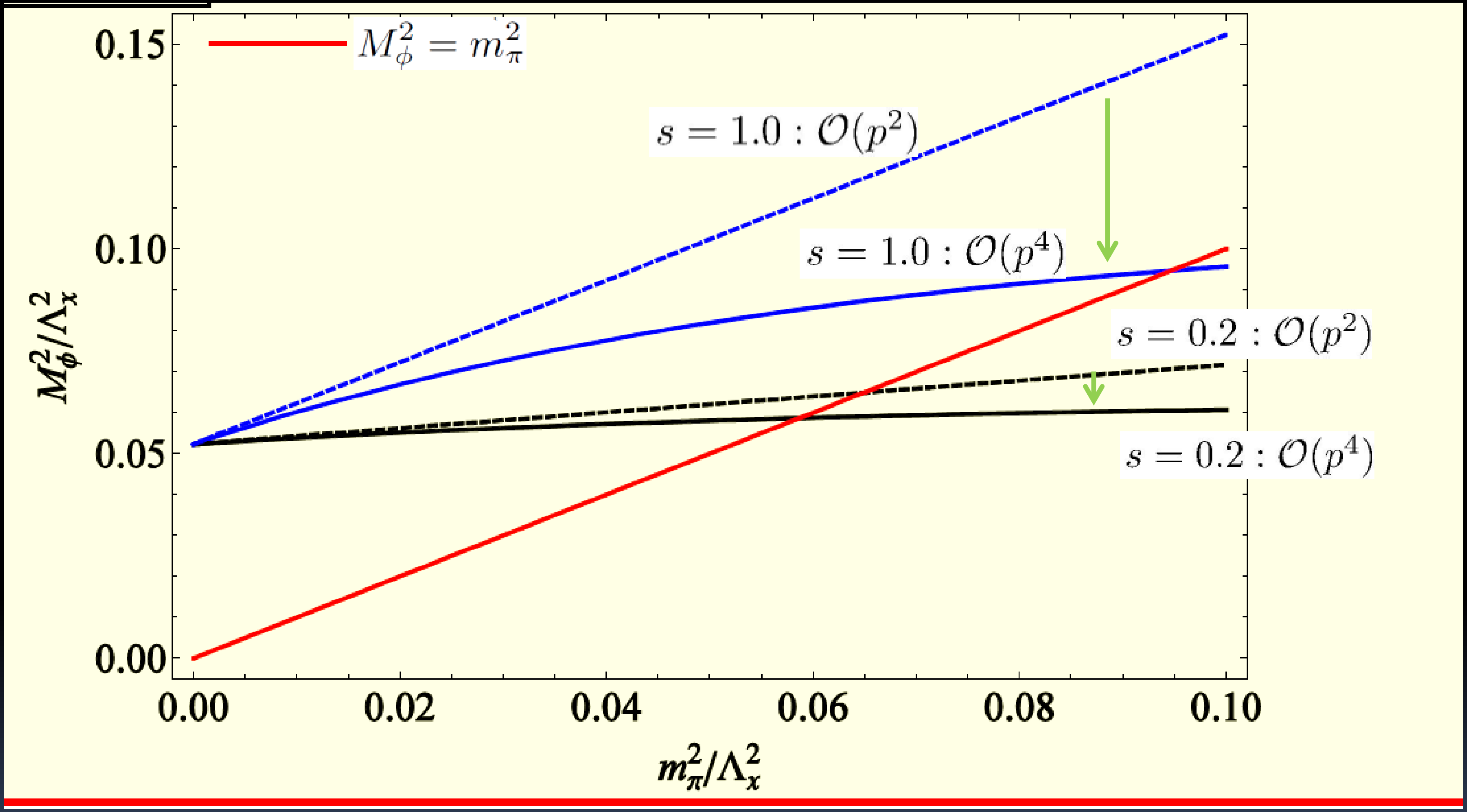


Counterterms:

$$
\begin{aligned}
\mathcal{L}_{(4)}^{\text{counterterm}} &= L_4 \,\mathrm{tr}[\partial_\mu U^\dagger \partial^\mu U] \mathrm{tr}[\mathcal{M}^\dagger U + U^\dagger \mathcal{M}] \cdot S^2 \\
&+ L_5 \,\mathrm{tr}[\partial_\mu U \partial^\mu U^\dagger (\mathcal{M}^\dagger U + U^\dagger \mathcal{M})] \cdot S^2 \\
&+ L_6 \,(\mathrm{tr}[\mathcal{M}^\dagger U + U^\dagger \mathcal{M}])^2 \cdot S^4 \\
&+ L_8 \,\mathrm{tr}[\mathcal{M}^\dagger U \mathcal{M}^\dagger U + \mathcal{M} U^\dagger \mathcal{M} U^\dagger] \cdot S^4 \\
&+ H_2 \,\mathrm{tr}[\mathcal{M}^\dagger \mathcal{M}] \cdot S^4 + L_4^\chi \,\partial_\mu \chi \partial^\mu \chi \mathrm{tr}[\mathcal{M}^\dagger U + U^\dagger \mathcal{M}] \\
&+ L_6^\chi \,(\mathrm{tr}[\mathcal{M}^\dagger U + U^\dagger \mathcal{M}])^2 \cdot \left[\left(\frac{\chi}{S} \right)^4 - 1 \right] \cdot S^4 \\
&+ L_8^\chi \,\mathrm{tr}[\mathcal{M}^\dagger U \mathcal{M}^\dagger U + \mathcal{M} U^\dagger \mathcal{M} U^\dagger] \cdot \left[\left(\frac{\chi}{S} \right)^4 - 1 \right] \cdot S^4 \\
&+ H_2^\chi \,\mathrm{tr}[\mathcal{M}^\dagger \mathcal{M}] \cdot \left[\left(\frac{\chi}{S} \right)^4 - 1 \right] \cdot S^4 \,, \qquad (11)
\end{aligned}
$$

* Plot of M_ϕ vs. M_π at $O(p^4)$

w/ assuming counterterms =0 @ $\mu=\Lambda_\chi$



Chiral log corrections get significant as $m_\pi \to 0$
--- crucial for chiral-limit TD mass and decay constant!

5. Summary

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

* The 125 GeV TD in 1FM gives the LHC signal consistent w/ current LHC data.

* More precise measurements in VBF+VH categories will tell us whether TD is the LHC Higgs, or not.

* Toward LHC-Run II:

  --- needs rigorous estimate of TD decay constant

  --- it is doable on lattices via dilaton mass formula.

* Smoking gun of WTC:

  discovering walking TPs & Techni-rhos

  (Terashi & Kurachi's talks)

Backup Slides

★ More on holographic estiamtes

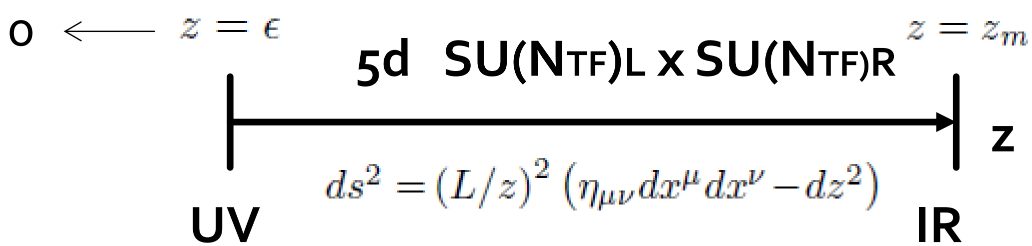
S.M. and K.Yamawaki, 1209.2017

* **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**



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

$$m_\Phi^2 = -(3 - \gamma_m)(1 + \gamma_m)/\breve{L}^2 \quad \begin{cases} \text{QCD} & \gamma_m = 0 \\ \text{WTC} & \gamma_m = 1 \end{cases}$$

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

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

AdS/CFT dictionary:

$$\Phi_X(z) = v_X(z)\,,$$

*** UV boundary values = sources**

$$\alpha M = \lim_{\epsilon \to 0} Z_m \left(\frac{L}{z} v(z) \right) \Big|_{z=\epsilon}, \qquad Z_m = Z_m(L/z) = \left(\frac{L}{z} \right)^{\gamma_m}$$

$$M' = \lim_{\epsilon \to 0} L v_X(z) \Big|_{z=\epsilon}$$

*** IR boundary values:**

$\xi = L v(z) \Big|_{z=z_m}$ ⟷ **chiral condensate** $\langle \bar{T} T \rangle$

$\mathcal{G} = L v_X(z) \Big|_{z=z_m}$ ⟷ **gluon condensate** $\langle \alpha G_{\mu\nu}^2 \rangle$

* **AdS/CFT recipe:**

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

classical solutions (→ S_5)

sources = UV boundary values for bulk scalar, vector, axial-vector fields (→ s, g, v, a)

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

Current collerators $\Pi_S, \Pi_G, \Pi_V, \Pi_A$
are calculated as a function of three IR –boundary values and γ_m **:**

- ξ **: IR value of bulk scalar** $\Phi_S \longleftrightarrow \bar{F}F$ (dual)
- G **: IR value of bulk scalar** $\Phi_G \longleftrightarrow G^2_{\mu\nu}$
- z_m **: IR-brane position**

The model parameters:

ξ	$\mathcal{G}$	z_m.	$\frac{L}{g_5^2}$	M	M'	α	c
Φ IR value	Φ_X IR value	IR brane position	5d coupling	Φ UV value	Φ_X UV value	coeff. of M	coeff. of Φ_X

M, M': set explicit breaking sources = 0

matching to current correlators

$\frac{L}{g_5^2}$ → Π_V Leading log term → $\frac{N_{TC}}{12\pi^2}$

α → Π_S Leading log term → $\alpha|_{\gamma_m=1} = \frac{\sqrt{3}}{2}$

c → Π_V G^2 term → $c = -\frac{N_{TC}}{192\pi^3}$

Fix (ξ, $\mathcal{G}$, z_m) ← **3 phenomenological input values**

F_π = 246 GeV/√N_D = 123 GeV (1FM)

M_Φ = 125 GeV

S = 0.1

S.M. and K.Yamawaki, 1209.2017

Other holographic predictions (1FM w/ S=0.1)

NTC = 3

Techni-ρ, a1 masses	:	$M_\rho = M_{a1} = 3.5$ TeV
Techni-glueball (TG) mass	:	$M_G = 19$ TeV
TG decay constant	:	$F_G = 135$ TeV
dynamical TF mass mF	:	$m_F = 1.0$ TeV

NTC = 4

Techni-ρ, a1 masses	:	$M_\rho = M_{a1} = 3.6$ TeV
Techni-glueball (TG) mass	:	$M_G = 18$ TeV
TG decay constant	:	$F_G = 156$ TeV
dynamical TF mass mF	:	$m_F = 0.95$ TeV

NTC = 5

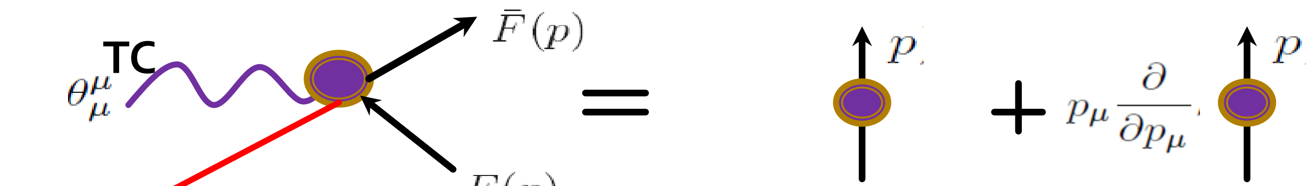
Techni-ρ, a1 masses	:	$M_\rho = M_{a1} = 3.9$ TeV
Techni-glueball (TG) mass	:	$M_G = 18$ TeV
TG decay constant	:	$F_G = 174$ TeV
dynamical TF mass mF	:	$m_F = 0.85$ TeV

★ *Direct consequences of Ward-Takahashi identities*

S.M. and K. Yamawaki, PRD86 (2012)

* Coupling to techni-fermions

$$\lim_{q_\mu \to 0} \int d^4y\, e^{iqy} \langle 0|T\partial^\mu D_\mu(y) F(x)\bar{F}(0)|0\rangle = i\delta_D \langle 0|TF(x)\bar{F}(0)|0\rangle$$
$$= i\left(2d_F + x^\nu \partial_\nu\right) \langle 0|TF(x)\bar{F}(0)|0\rangle$$



$$-S_F^{-1}(p) - ip_\mu \frac{\partial}{\partial p_\mu} S_F^{-1}(p)$$

Dilaton pole dominance

$$F_\phi \cdot \langle \phi(q=0)|TF(x)\bar{F}(0)|0\rangle = \delta_D \langle 0|TF(x)\bar{F}(0)|0\rangle$$

w/ TD decay constant Fphi

$$\langle 0|D_\mu(x)|\phi(q)\rangle = -iF_\phi q_\mu e^{-iqx}$$

Yukawa vertex func.

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

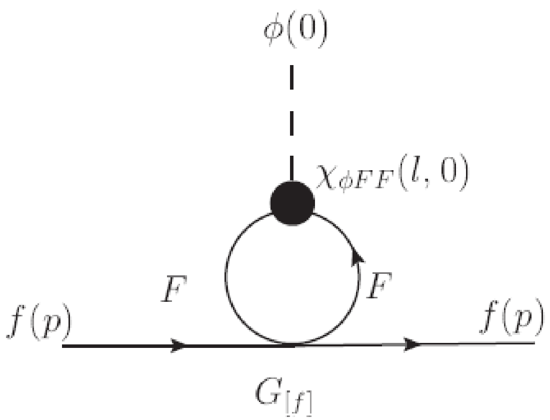
* Couplings to SM fermions

No direct coupling

TC

$$\langle f(p)|\theta^{\mu}_{\mu}(0)|f(p)\rangle = 0\,.$$

~~transform~~



ETC induced 4-fermi

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

Techni-fermion loop induces

$$-\frac{iG_{[f]}}{F_\phi}\int\frac{d^4l}{(2\pi)^4}{\rm Tr}[S_F(l)\cdot\delta_D S_F^{-1}(l)\cdot S_F(l)]$$

$$= \frac{iG_{[f]}}{F_\phi}\cdot\delta_D\int\frac{d^4l}{(2\pi)^4}{\rm Tr}[S_F(l)]$$

$$= -i\frac{G_{[f]}}{F_\phi}\delta_D\langle\bar{F}F\rangle$$

$$\delta_D\langle\bar{F}F\rangle = (3-\gamma_m)\langle\bar{F}F\rangle$$

f-fermion mass:

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

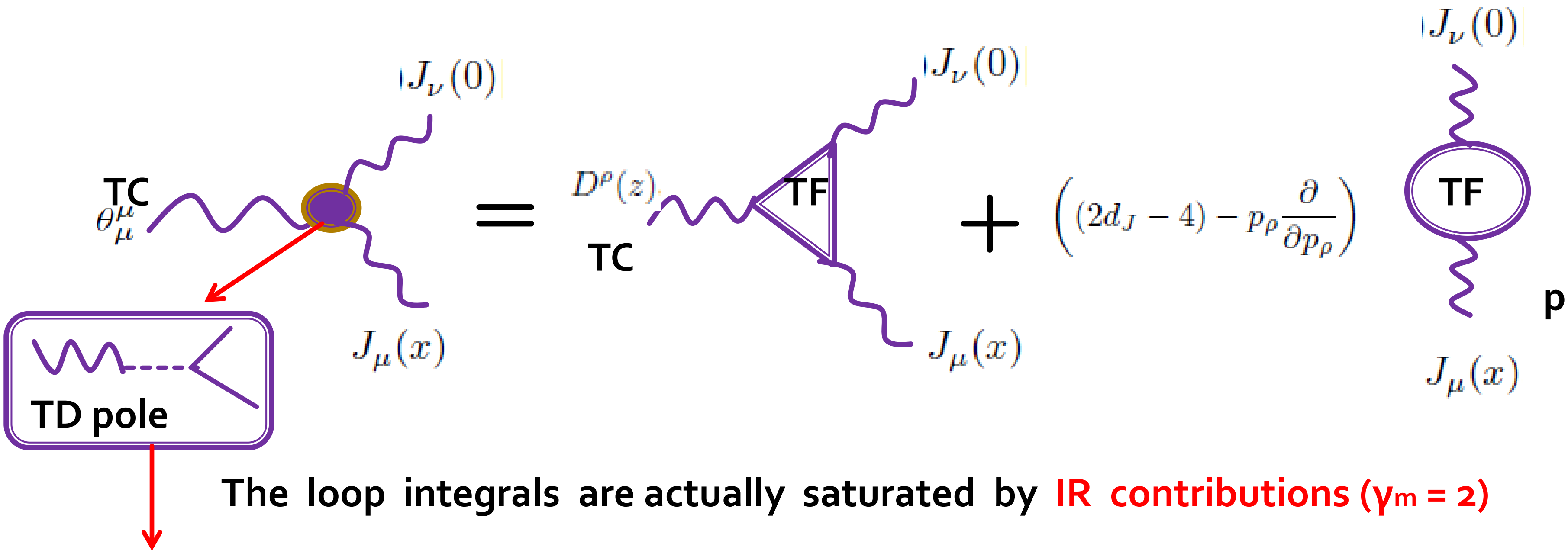
Yukawa coupling to SM-fermion

$$g_{\phi ff} = \frac{(3-\gamma_m)m_f}{F_\phi}$$

* Couplings to SM gauge bosons

WT identity → scale anomaly term + anomaly-free term

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



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

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

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

β_F: TF-loop contribution to beta function

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

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

β_F: TF-loop contribution to beta function

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

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

N_D = TF -EW-doublets

Coupling to W

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

*** For unbroken currents coupled to photon, gluon:**

$$\Pi(0) = 0.$$

Coupling to γγ & gluons

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

★ Ladder estimate of TD mass

* **LSD + BS in large Nf QCD**

Harada et al (1989); Kurachi et al (2006)

* **LSD via gauged NJL**

Shuto et al (1990); Bardeen et al (1992); Carena et al (1992) ; Hashimoto (1998)

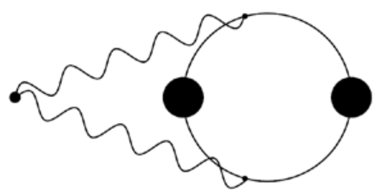
A composite Higgs mass

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

∼500 GeV for one-family model (1FM) still larger than ~ 125 GeV

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

$$F_\phi^2 M_\phi^2 = -4\langle \theta_\mu^\mu \rangle = \frac{\beta(\alpha)}{\alpha}\langle G_{\mu\nu}^2 \rangle \simeq 3\eta m_F^4$$



Miransky et al (1989): Hashimoto et al (2011):

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

→ $\frac{F_\phi^2}{m_F^2} \cdot \frac{M_\phi^2}{m_F^2} =$ **finite**

$M_\phi/m_F \to 0$

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

No massless NGB limit:

★ Estimate of $\frac{v_{\rm EW}}{F_\phi}$: #1 – Ladder approximation

*** PCDC (partially conserved dilatation current)**

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

*** criticality condition** Appelequist et al (1996)

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

*** Pagels-Stokar formula**

$$F_\pi = v_{\rm EW}/\sqrt{N_D}$$

# of EW doublets

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

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

*** Recent ladder SD analysis (large Nf QCD)**

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

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);
Hadron spectrum : K. -I. Aoki et al (1991); M. Harada et al (2004).

$$\frac{N_{\rm TF}}{4N_{\rm TC}} \simeq 1 \pm 0.3$$

$$\langle \theta^\mu_\mu \rangle = 4\mathcal{E}_{\rm vac} = -\kappa_V \left(\frac{N_{\rm TC}N_{\rm TF}}{2\pi^2}\right) m_F^4$$

30%

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

30%

Estimate w/ uncertainty included

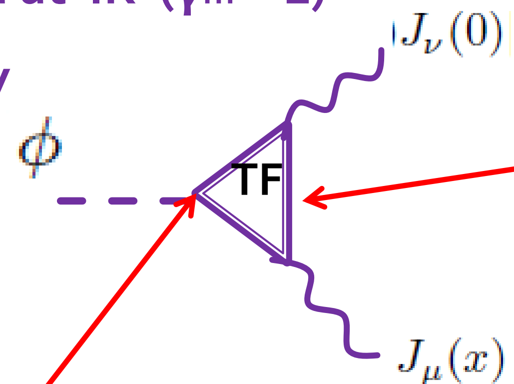
$$\frac{v_{\rm EW}}{F_\phi} \simeq (0.1 - 0.3) \times \left(\frac{N_D}{4}\right)\left(\frac{M_\phi}{125\,{\rm GeV}}\right)$$

* 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 (γ_m = 2)

(well approximated by constant mass)



IR

$$S_F(p) = \frac{1}{p - \Sigma(p)} \;\Rightarrow\; \boxed{\frac{1}{p - m_F}}$$

Ladder approx.

Yukawa vertex

IR

$$\chi_{\phi FF}(p, q=0) = \frac{1}{F_\phi}\delta_D S_F^{-1}(p) = \frac{1}{F_\phi}\left(1 - p_\mu \frac{\partial}{\partial p_\mu}\right) S_F^{-1}(p) \;\Rightarrow\; \frac{(3-\gamma_m)\Sigma(p^2)}{F_\phi} \;\Rightarrow\; \boxed{\frac{m_F}{F_\phi}}$$

constant

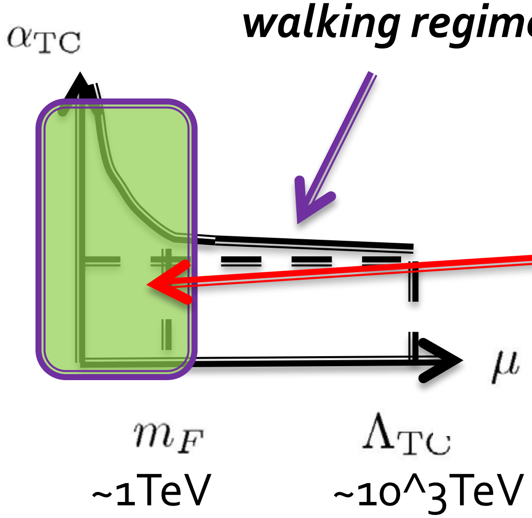
The resultant betas coincide just one-loop perturbative expressions:

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

$$\beta_F(e) = \frac{e^3}{(4\pi)^2}\frac{16}{9}N_{\rm TC}$$

TD mass stability below m_F S.M. and K. Yamawaki, PRD86 (2012)

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

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

cutoff by m_F ~ $4\pi F_\pi$ ~ 1TeV (~ F_ϕ) : $\delta M_\phi^2 \approx -\frac{3}{4\pi^2}\frac{m_t^2}{F_\phi^2}\cdot m_F^2$

w/ $m_t^2 \simeq 2M_\phi^2$

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

naturally light thanks to large F_ϕ (i.e. weak coupling)