125 GeV techni-dilaton at the LHC

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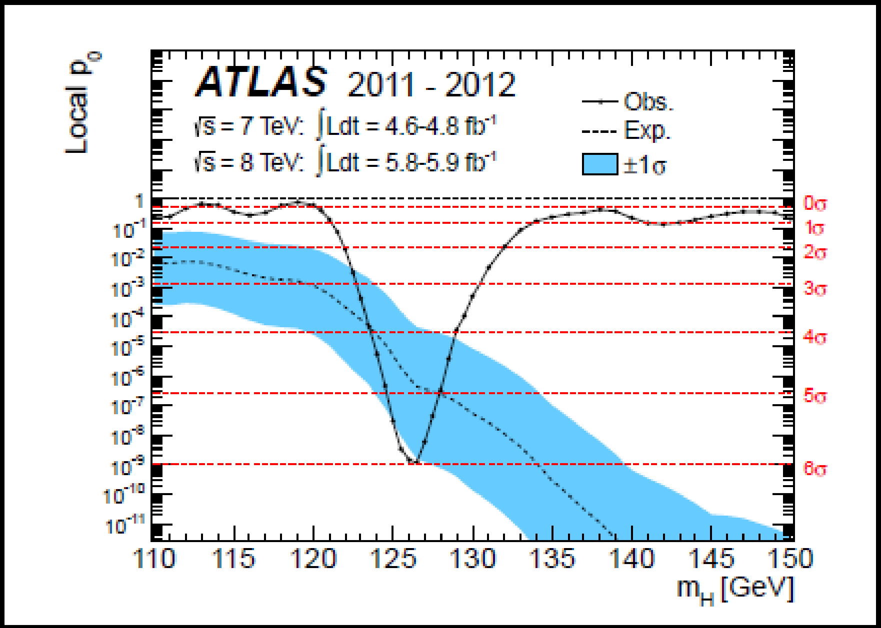
Based on
S.M. and K. Yamawaki (KMI, Nagoya U.),
PRD85 (2012);
PRD86 (2012);
arXiv:1207.5911
arXiv:1209.2017

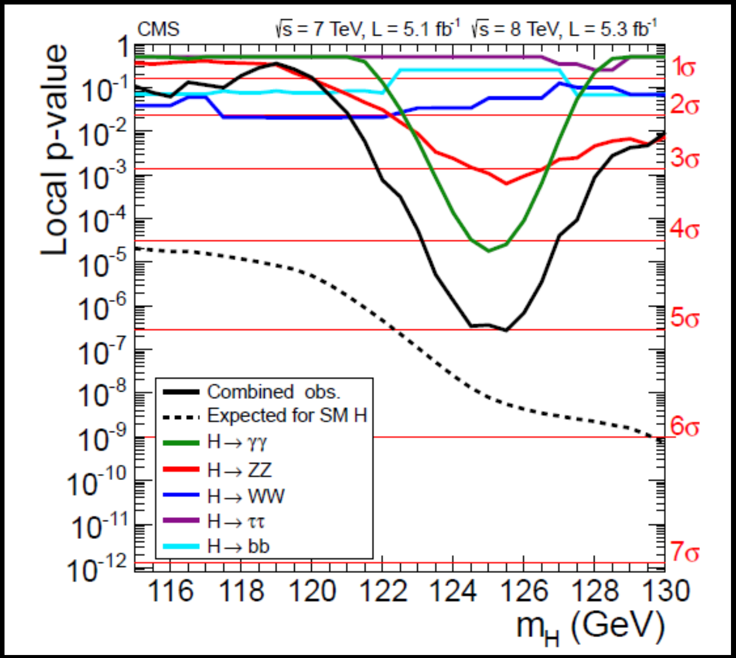
Lattice Meets Experiment 2012:
Beyond the Standard Model
26—27 October 2012, University of Colorado at Boulder

Introduction & brief summary

ATLAS (arXiv: 1207.7214)



CMS (arXiv: 1207.7235)

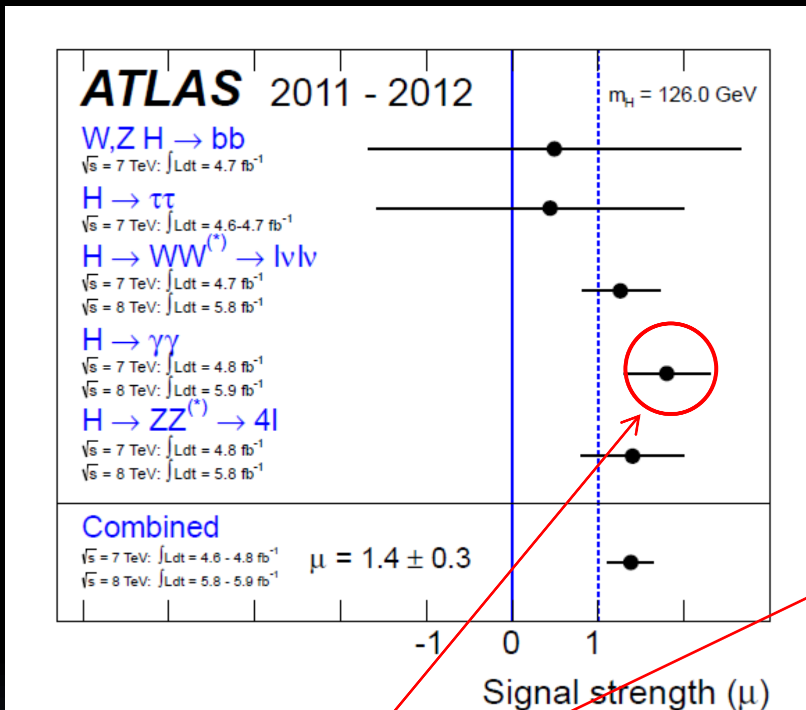


This year is exciting!!

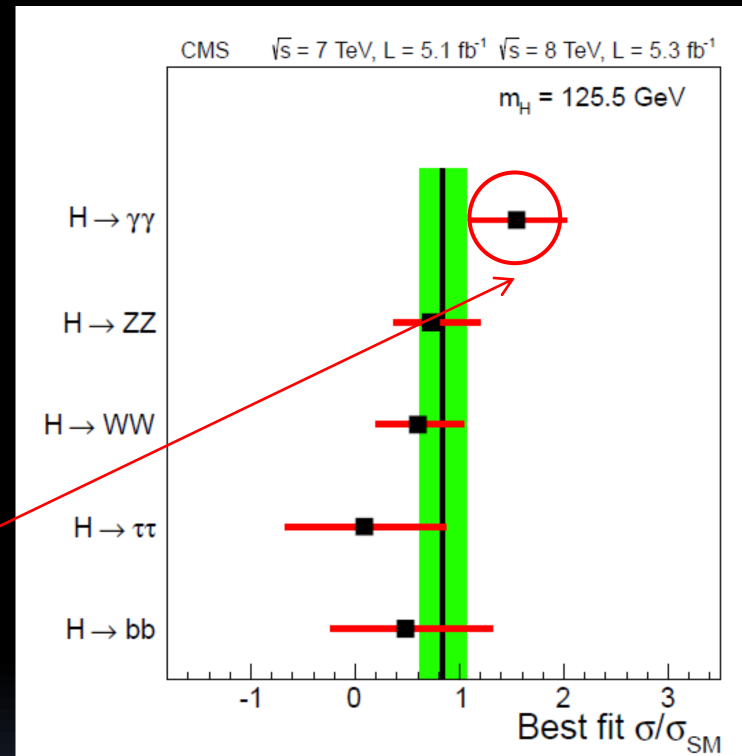
A new boson at around 125 GeV was observed at LHC, through γγ, ZZ*(4l), WW*(2l2nu)

The signal strengths ($\mu = \sigma/\sigma_{SM}$)

ATLAS (arXiv: 1207.7214)



CMS (arXiv: 1207.7235)



Somewhat large diphoton event rate:

μ (diphoton) ∼ 2 implies a "new Higgs boson" (impostor)

beyond the SM !

Is it Techni-dilaton (TD) ?

** TD : composite scalar;*

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

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,

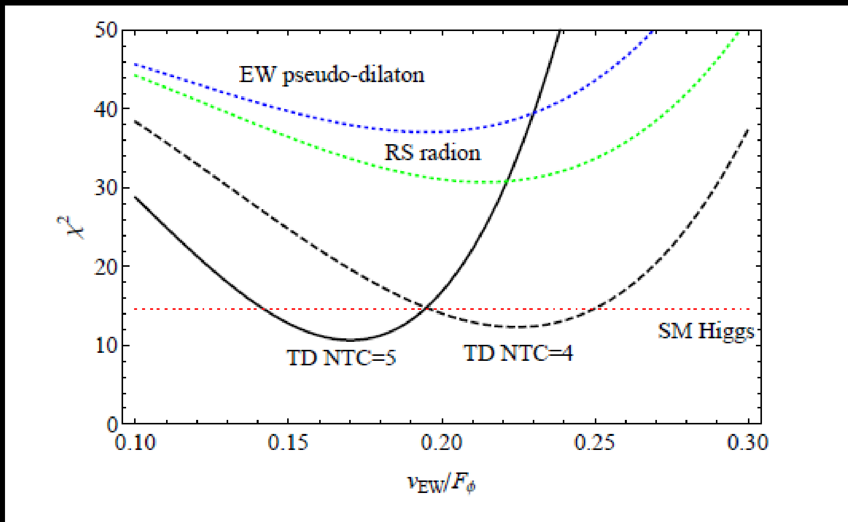
and hence can be, say, ~ 125 GeV.

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

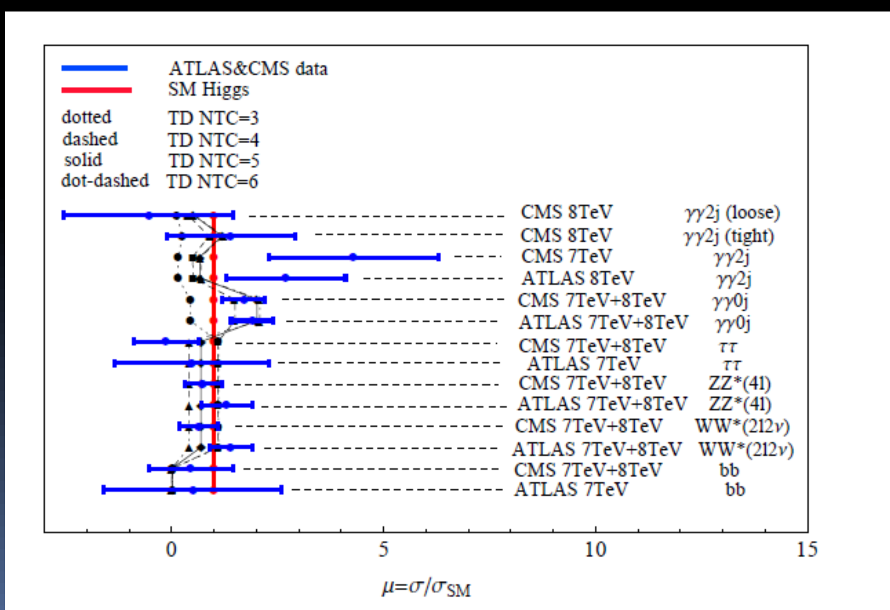
S.M. and K. Yamawaki, PRD85 (2012); PRD86 (2012); arXiv:1207.5911 arXiv:1209.2017

Quick view of main result

S.M. and K. Yamawaki , arXiv:1207.5911



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



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

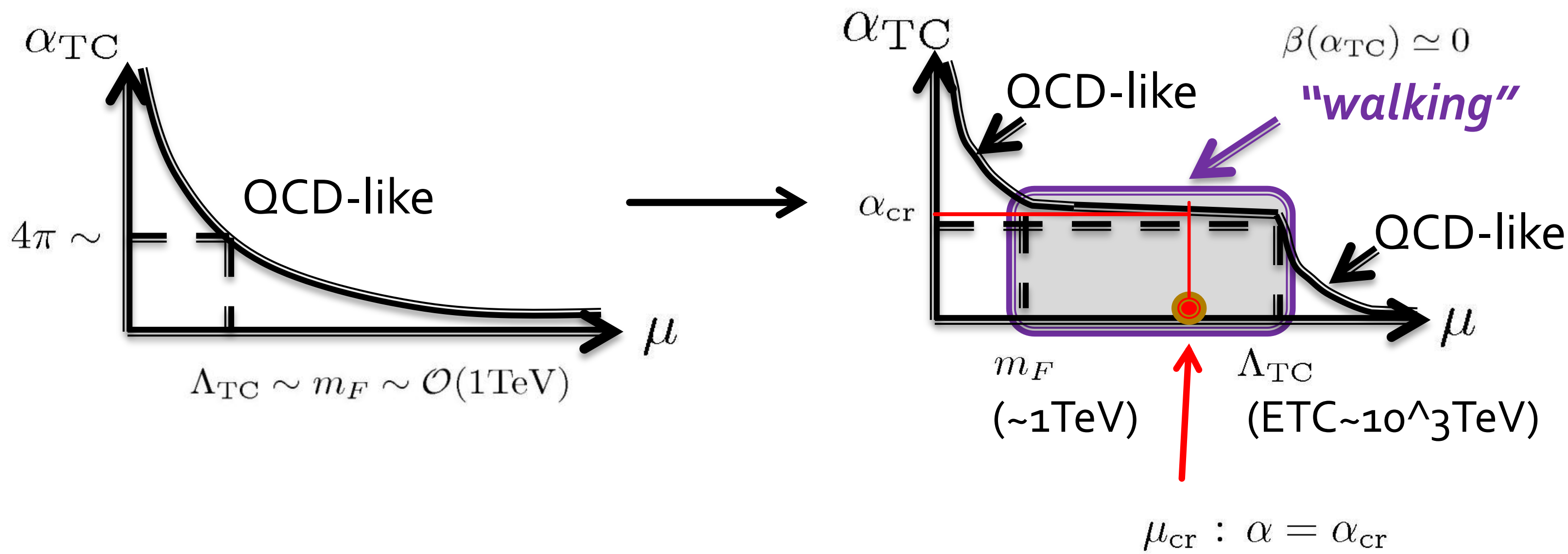
** diphoton rate enhaced by techni-fermions (> W loop contribution)*

** 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



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

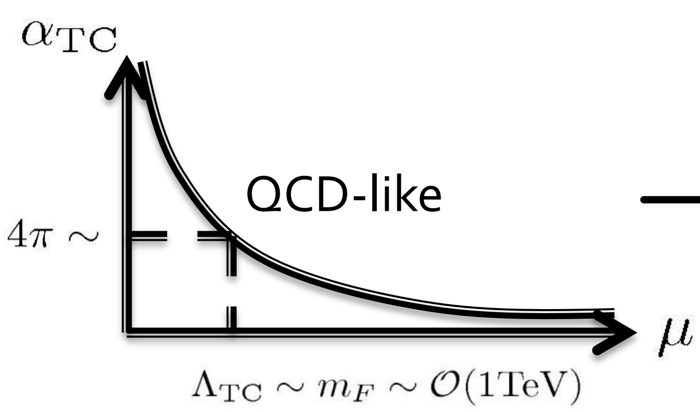
$$m_F \sim \Lambda_{\rm TC} e^{-\frac{\pi}{\sqrt{\alpha/\alpha_{\rm cr}-1}}} \text{ for } \alpha > \alpha_{\rm cr}$$ "Miransky scaling" *Miransky (1985)*

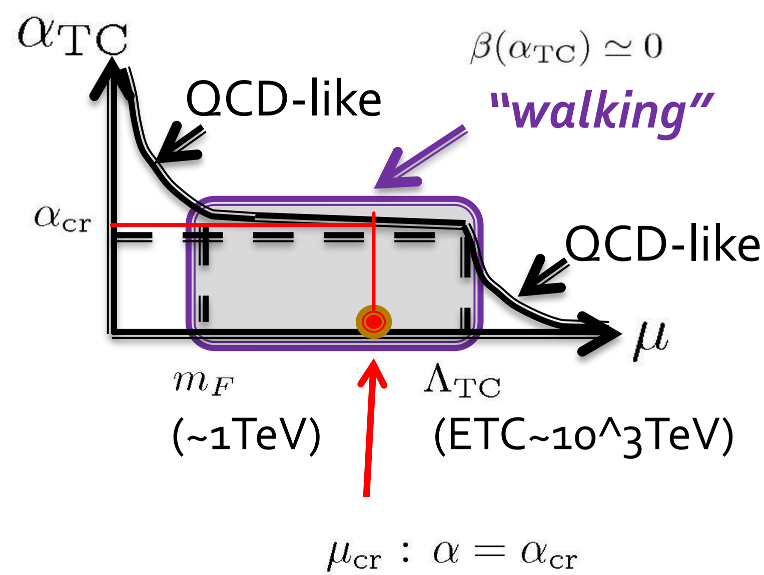
$$\langle \bar{F}F \rangle_{\Lambda_{\rm TC}} \sim \frac{N_{\rm TC}}{4\pi^2} m_F^2 \Lambda_{\rm TC} \longrightarrow \gamma_m \simeq 1$$ (solve FCNC problem)

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

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

Walking TC and techni-dilaton





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

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

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***

$$\partial_\mu D^\mu = \frac{\beta(\alpha)}{4\alpha^2}\langle \alpha G_{\mu\nu}^2\rangle \neq 0 :$$

TD gets massive

★ 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

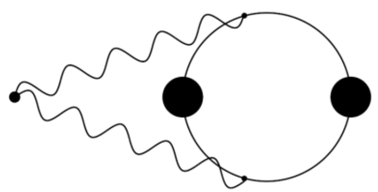
$$M_\phi \sim 4F_\pi$$

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

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

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

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



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

$\rightarrow$ $\boxed{\frac{F_\phi^2}{m_F^2}\cdot\frac{M_\phi^2}{m_F^2} = \text{finite}}$

$M_\phi/m_F \to 0$
only when $F_\phi/m_F \to \infty$, i.e., a decoupled limit.

No exactly massless NGB limit:

★ Holographic estiamte 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**

0 $\longleftarrow$ $z=\epsilon$ $z=z_m$

5d SU(NTF)L x SU(NTF)R

z

$$ds^2 = (L/z)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

UV IR

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

$$+ \mathrm{Tr}\left[D_M \Phi^\dagger D^M \Phi - m_\Phi^2 \Phi^\dagger \Phi\right] + \underline{\frac{1}{2}\partial_M \Phi_X \partial^M \Phi_X \Big)}$$

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

* QCD-fit w/ $\gamma_m = 0$

input

f_π	=	92.4 MeV
M_ρ	=	775 MeV
$\langle \alpha G_{\mu\nu}^2 \rangle / \pi$	=	0.012 GeV^4

fix →

model parameters

ξ	=	3.1
G	=	0.25
zm^-1	=	347 MeV

Model predictions

				measured
M_{a1}	[a1 meson]	:	1.3 GeV	1.2 --- 1.3 GeV
$M_{f_0(1370)}$	[qqbar bound state]	:	1.2 GeV	1.1 --- 1.2 GeV
M_G	[glueball]	:	1.3 GeV	1.4 --- 1.7 GeV (lat.)
$S = -16 \pi L_{10}$	[S parameter]	:	0.31	0.29 --- 0.37
[- <qbar q>]^(1/3)	[chiral condensate]	:	277 MeV	200 --- 250 MeV

Monitoring QCD works well!

*WTC-case with $\gamma_m = 1$

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

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

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

--- TD decay constant (pole residue)

$$\frac{F_\phi}{F_\pi} \simeq \sqrt{2N_{\rm TF}} \cdot \sqrt{J_0^2(x) + J_1^2(x)}\Big|_{x=(M_\phi z_m)\ll 1}$$

$$\simeq \sqrt{2N_{\rm TF}}\,.$$

free from model-parameters !!

→ Exactly-massless NGB limit ("conformal limit") is realized:

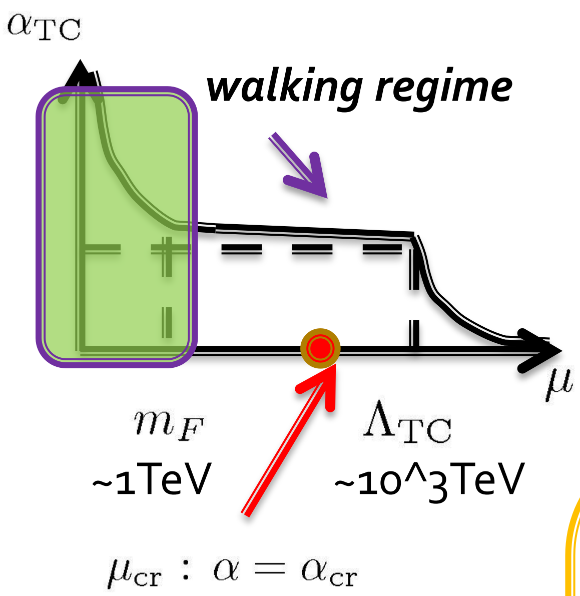
$$\frac{M_\phi}{F_\pi} \to 0 \quad \text{and} \quad \frac{F_\phi}{F_\pi} \to \text{finite}\,, \quad \text{as} \quad G \to \infty\,. \qquad \left[\ \beta(\alpha) \sim \frac{1}{G(1+G)^2} \to 0 \right.$$

in contrast to ladder approximation

Lattice cals will give a conclusive answer

TD Lagrangian below mF

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

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"):

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

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

βF: 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)

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

* 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)

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

* TD couplings to γγ and gg (from L_S)

The same form as SM Higgs couplings except Fϕ and betas

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

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

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 1st and 2nd 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 highly on particle contents of WTC models.*

β_F: TF-loop contribution to beta function

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

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

★ Estimate of $\dfrac{v_{\rm EW}}{F_\phi}$: #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).

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

$$\langle \theta^\mu_\mu \rangle = 4\mathcal{E}_{\rm vac} = \underbrace{-\kappa_V}_{30\%} \left(\frac{N_{\rm TC} N_{\rm TF}}{2\pi^2} \right) m_F^4$$

$$F_\pi^2 = \underbrace{\kappa_F^2}_{30\%} \frac{N_{\rm TC}}{4\pi^2} m_F^2$$

Estimate
w/ uncertainty included

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

★ Estimate of $\frac{v_{\rm EW}}{F_\phi}$:#2 -- Holographic approach

S.M. and K.Yamawaki, 1209.2017

* **TD decay constant for the light TD case w/ G ~ 10:**

$$\frac{F_\phi}{F_\pi} \simeq \sqrt{2N_{\rm TF}} \cdot \sqrt{J_0^2(x) + J_1^2(x)}\Big|_{x=(M_\phi z_m)\ll 1}$$

$$\simeq \underline{\sqrt{2N_{\rm TF}}\,.}$$

free from model-parameters !!

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

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

This is consistent with ladder estimate:

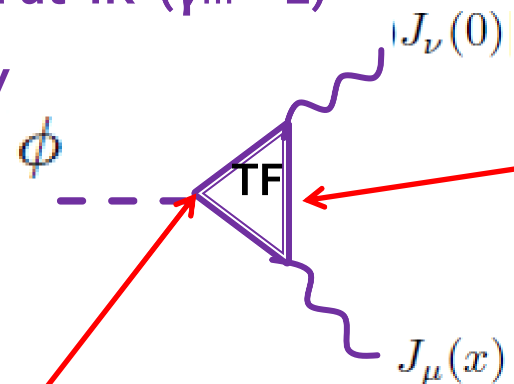
$$\boxed{\frac{v_{\rm EW}}{F_\phi} \simeq \underbrace{(0.1 - 0.3)}_{\text{ladder}} \times \left(\frac{N_D}{4}\right)\left(\frac{M_\phi}{125\,{\rm GeV}}\right)}$$

* 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 ($\gamma_m = 2$)

(well approximated by constant mass)



IR

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

Ladder approx.

IR

Yukawa vertex

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

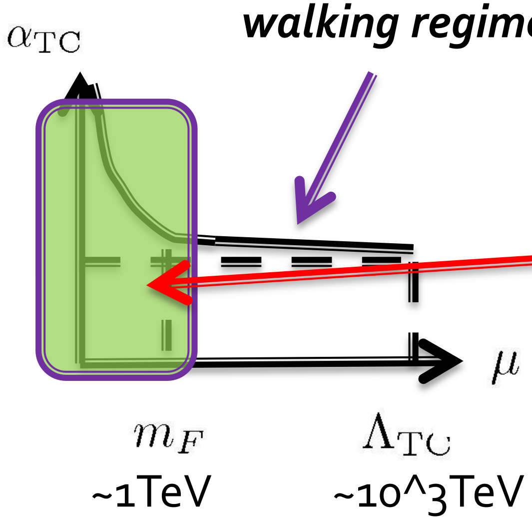
constant

The resultant betas coincide just one-loop perturbative expressions:

$$\boxed{\begin{aligned} \beta_F(g_s) &= \frac{g_s^3}{(4\pi)^2}\frac{4}{3}N_{\rm TC} \\ \beta_F(e) &= \frac{e^3}{(4\pi)^2}\frac{16}{9}N_{\rm TC} \end{aligned}}$$

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

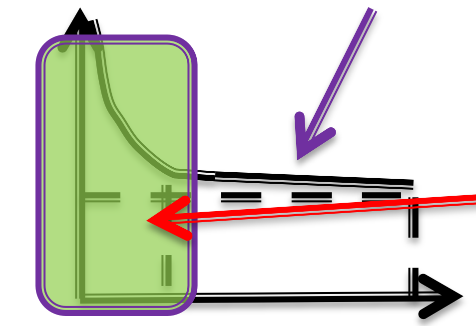
walking regime = scale symm well protected
(natural enough)



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

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

walking regime = scale symm well protected
(natural enough)



Can TD mass be as light as 125GeV below mF?

→ YES!!!

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

Dominant corrections come from top-loop

cutoff by mF ~ 4 π Fπ ~ 1TeV (~ FΦ)

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

naturally light thanks to large FΦ

★ 125 GeV TD signal at the LHC

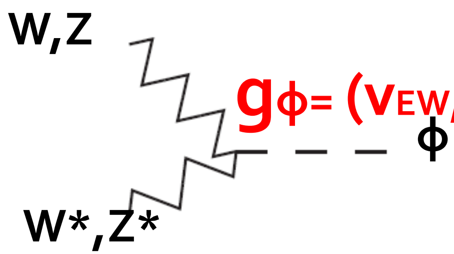
S.M. and K. Yamawaki

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

v.s. SM Higgs

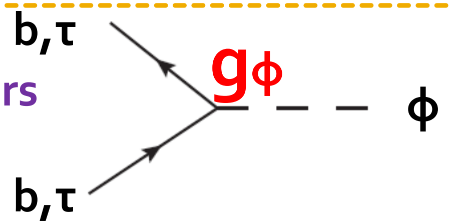
di-weak bosons



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

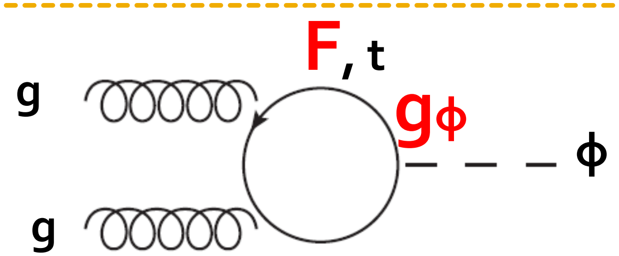
suppressed

quark, lepton pairs



suppressed

digluon

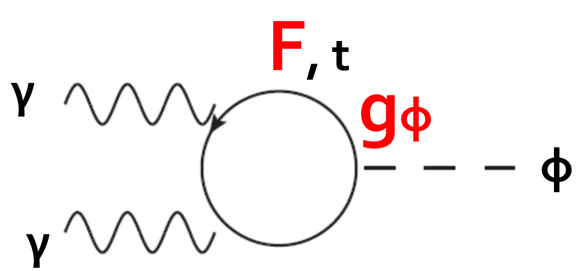


$\beta_F(g_s)$

enhanced

QCD-colored TF contributions

diphoton



$\beta_F(e)$

>> W -loops

enhanced

EM-charged TF contributions

The 125 GeV TD signal strengths

*** decays to bb, tau tau, WW*, ZZ*, diphoton**

bb:

$$\begin{aligned}\mu_{b\bar{b}} &= \frac{\sigma^{\phi}_{\rm VBA}(s)}{\sigma^{h_{\rm SM}}_{\rm VBA}(s)}\frac{BR(\phi\to b\bar{b})}{BR(h_{\rm SM}\to b\bar{b})}\\ &= \frac{\sigma_{W\phi}(s)+\sigma_{Z\phi}(s)}{\sigma_{Wh_{\rm SM}}(s)+\sigma_{Zh_{\rm SM}}(s)}\frac{BR(\phi\to b\bar{b})}{BR(h_{\rm SM}\to b\bar{b})}\end{aligned}$$

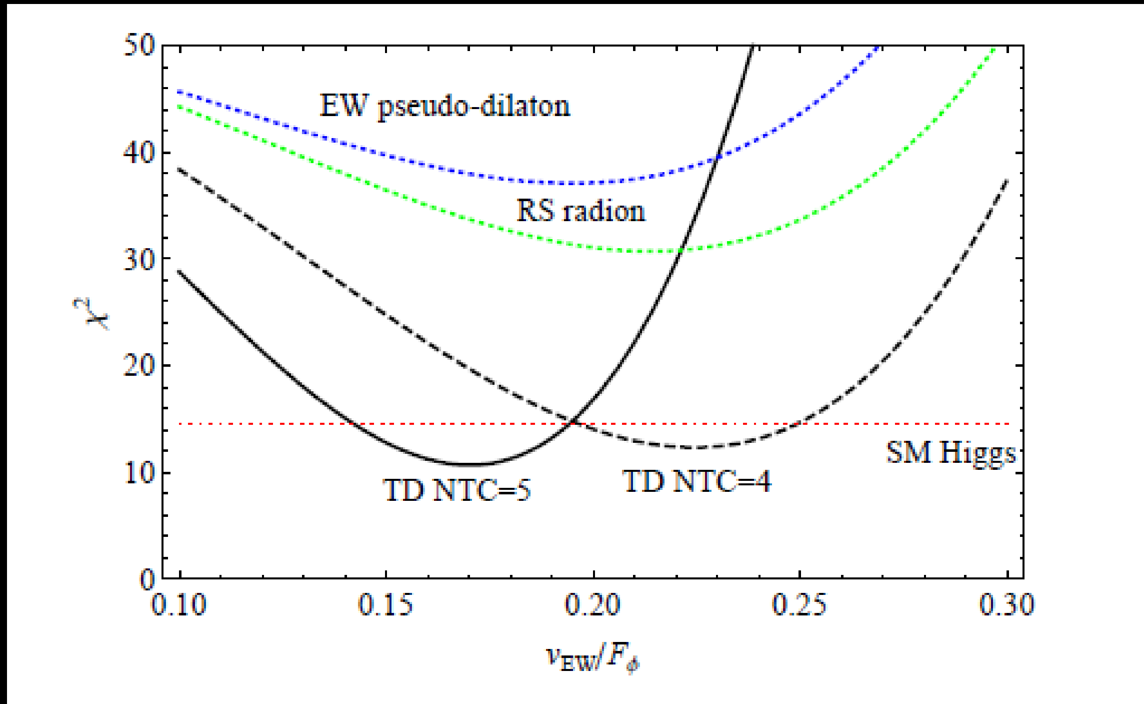
X= tautau, WW*, ZZ*:

$$\mu_X = \frac{\sigma^{\phi}_{\rm GF}(s)+\sigma^{\phi}_{\rm VBF}(s)}{\sigma^{h_{\rm SM}}_{\rm GF}(s)+\sigma^{h_{\rm SM}}_{\rm VBF}(s)}\frac{BR(\phi\to X)}{BR(h_{\rm SM}\to X)}$$

diphoton

$$\begin{aligned}\mu_{\gamma\gamma 0j} &= \frac{\sigma^{\phi}_{\rm GF}(s)}{\sigma^{h_{\rm SM}}_{\rm GF}(s)}\frac{BR(\phi\to X)}{BR(h_{\rm SM}\to X)}\,,\\ \mu_{\gamma\gamma 2j} &= \frac{\xi_{\rm GF}\cdot\sigma^{\phi}_{\rm GF}(s)+\xi_{\rm VBF}\cdot\sigma^{\phi}_{\rm VBF}(s)}{\xi_{\rm GF}\cdot\sigma^{h_{\rm SM}}_{\rm GF}(s)+\xi_{\rm VBF}\cdot\sigma^{h_{\rm SM}}_{\rm VBF}(s)}\\ &\quad\times\frac{BR(\phi\to\gamma\gamma)}{BR(h_{\rm SM}\to\gamma\gamma)}\,,\end{aligned}$$

* chi^2 fit based on the current data on Higgs search categories



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

$N_{\rm TC}$	$(v_{\rm EW}/F_\phi)_{\rm best}$	$\chi^2_{\rm min}/\text{d.o.f}$
4	0.22	$12/13 \simeq 0.9$
5	0.17	$10/13 \simeq 0.7$

* **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)

μ_{Vbb} = 0.006 -- 0.01

μ_{WW*} = 0.9 -- 1.0

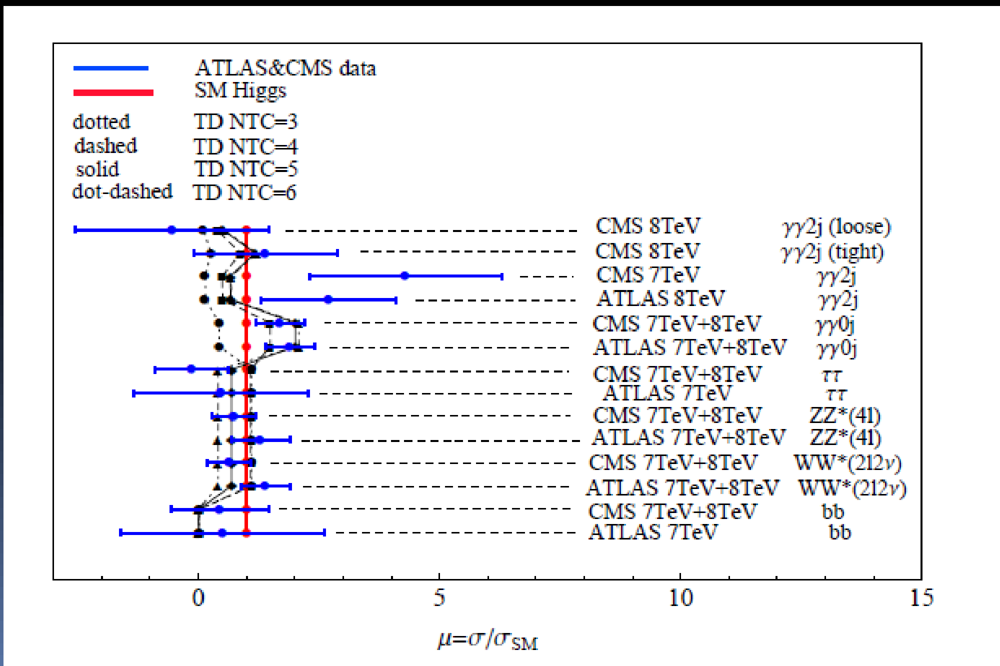
μ_{ZZ*} = 0.7 -- 1.1

$\mu_{\tau\tau}$ = 0.7 -- 1.1

$\mu_{\gamma\gamma 0j}$ = 1.5 -- 2.0

$\mu_{\gamma\gamma 2j}$ = 0.5 -- 0.7

$N_{\rm TC}$	$(v_{\rm EW}/F_\phi)_{\rm best}$	$\chi^2_{\rm min}/{\rm d.o.f}$
4	0.22	$12/13 \simeq 0.9$
5	0.17	$10/13 \simeq 0.7$



Characteristic feature:

Vbb : suppressed

γγoj : 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, $\tau\tau$+jets) will draw a definite conclusion that the TD is favored, or not.

Backup Slides

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

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

AdS/CFT dictionary:

*** UV boundary values = sources**

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

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

*** IR boundary values:**

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

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

* AdS/CFT recipe:

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

classical solutions

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

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

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

dual

ξ : IR value of bulk scalar $\Phi_S \longleftrightarrow \bar{F}F$

G : IR value of bulk scalar $\Phi_G \longleftrightarrow G_{\mu\nu}^2$

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

set explicit breaking sources = 0

matching to current correlators

Π_V
Leading log term

$$\frac{N_{\rm TC}}{12\pi^2}$$

Π_S
Leading log term

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

Π_V
G^2 term

$$c = -\frac{N_{\rm TC}}{192\pi^3}$$

Fix

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)

N_{TC} = 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

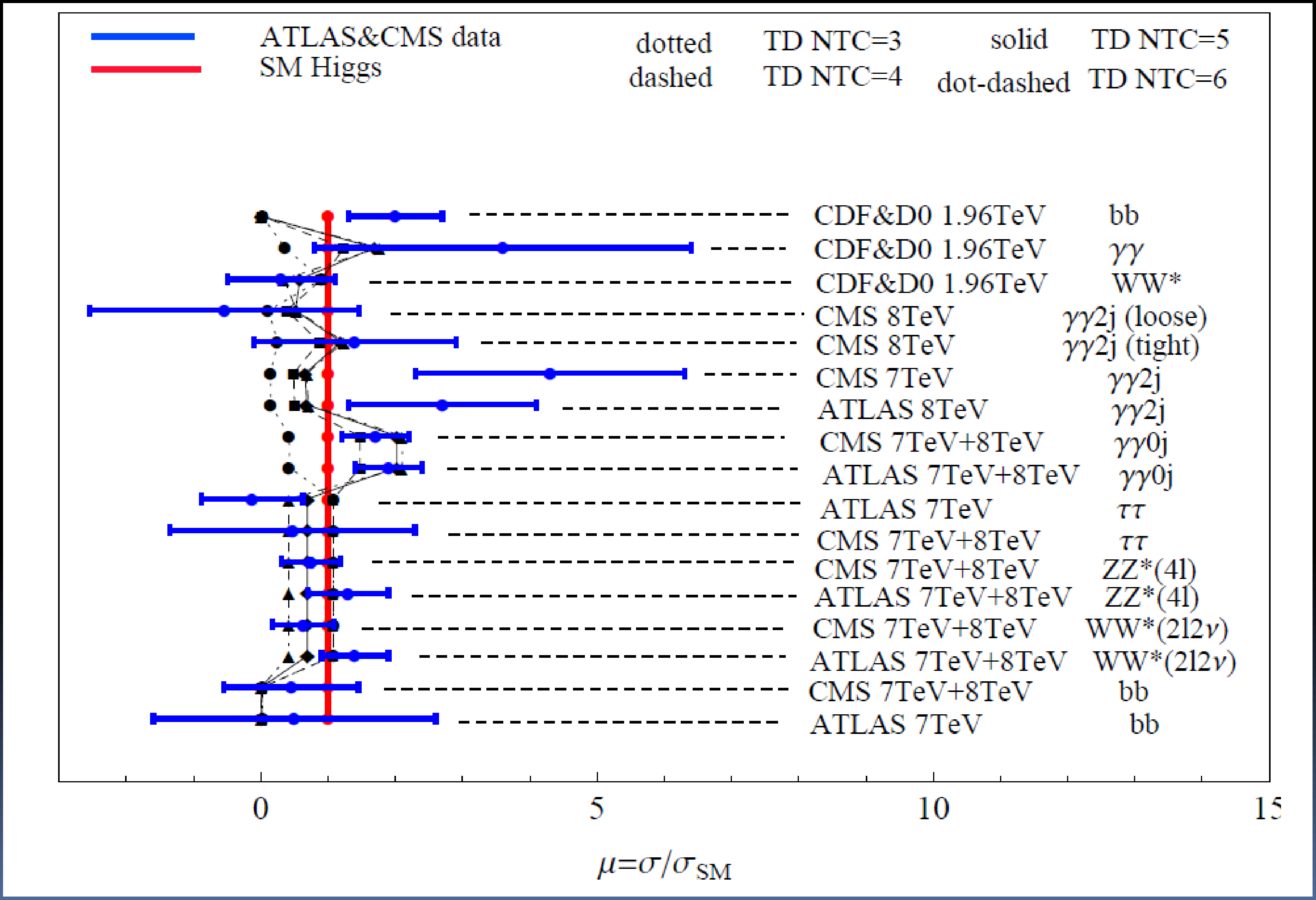
N_{TC} = 4

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

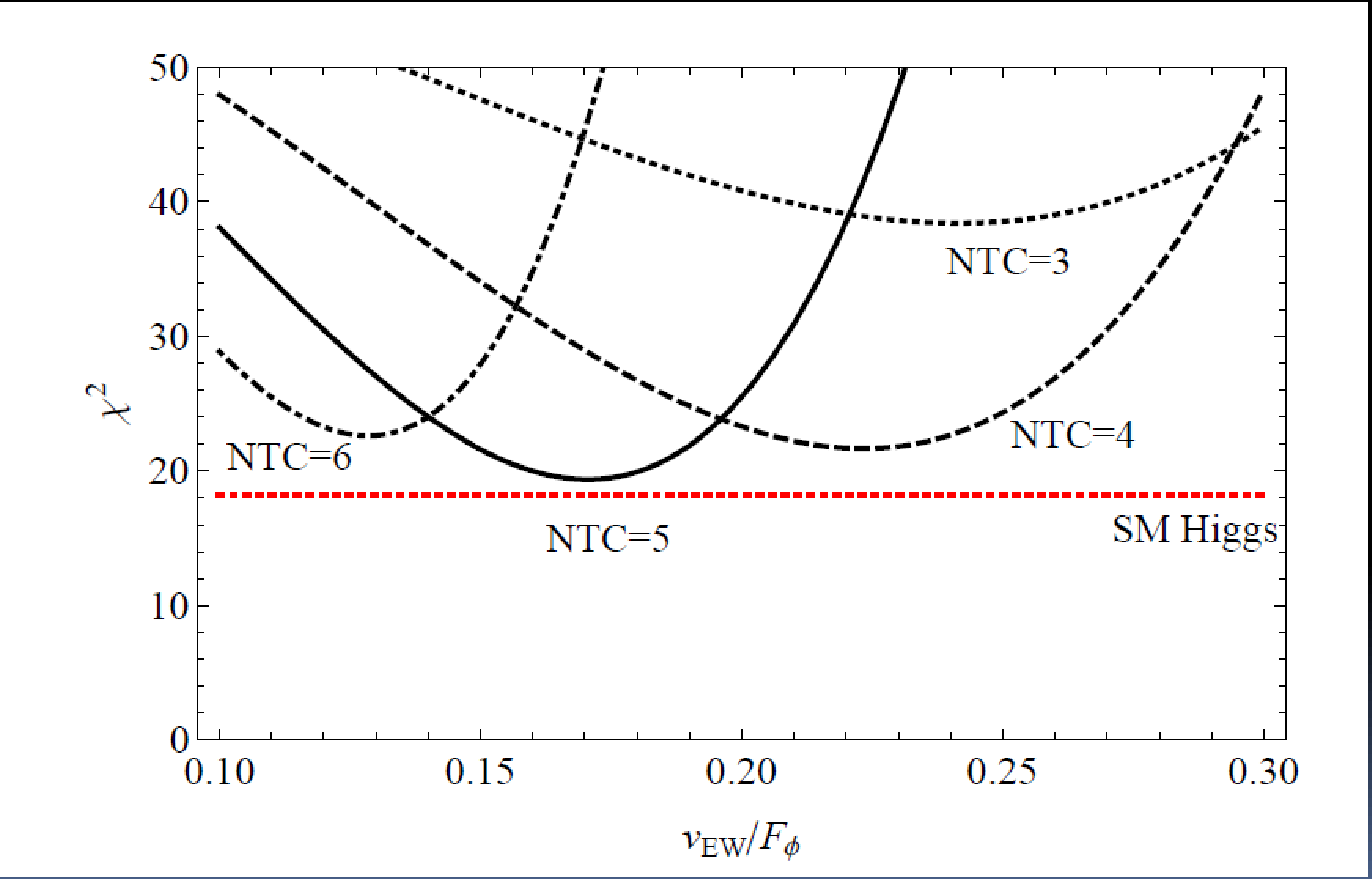
N_{TC} = 5

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

W/ Tevatron data included:



W/ Tevatron data included:



Farhi et al (1981)

One-doublet model (1DM)

$TF_{\rm EW}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix} U \\ D \end{pmatrix}_L$	1	2	0
U_R	1	1	1/2
D_R	1	1	-1/2

Total # of techni-fermions

$$N_{\rm TF} = (N_{\rm TF})_{\rm EW-singlet} + 2N_{\rm D}$$

w/ critical # for mass generation in WTC

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

Appelequist et al (1996)

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

★ *Other pheno. issues in TC scenarios*

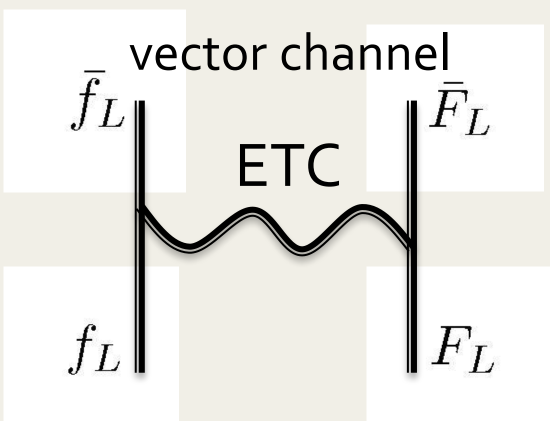
S parameter

$$S \approx N_D \cdot \frac{8\pi F_\pi^2}{M_\rho^2} \simeq \underline{0.3 \cdot N_D} \qquad (\text{for QCD-like})$$

N_D : # EW doublets

too large! Cf: S(exp) < 0.1 around T = 0

One resolution: ***ETC-induced "delocalization" operator*** Chivukula et al (2005)



$$-\frac{1}{\Lambda_{\rm ETC}^2} J^a_{\mu {\rm SM}_L} J^{\mu a}_{{\rm TC}_L}$$

in low-energy

$$J^{\mu a}_{{\rm TC}_L} \to {\rm Tr}[U^\dagger \frac{\sigma^a}{2} i D^\mu U]$$

w/ $U = e^{2i\pi_{\rm eaten}/v_{\rm EW}}$

$$\ni g_W W_\mu - g_Y B_\mu$$

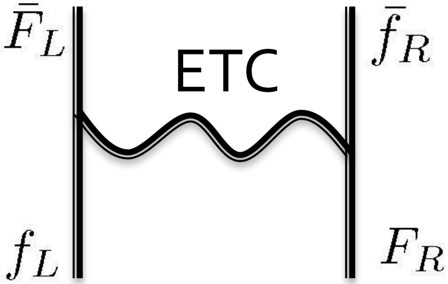
modifies SM f-couplings to W, Z

contributes to S "negatively"

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

$$\boxed{S_{\rm total} \to 0 \ (\text{"ideal delocalization"})}$$

Top quark mass generation



$$m_t \approx \frac{\langle \bar{U} U \rangle_{\rm ETC}}{\Lambda^2_{\rm ETC}} \approx \left(\frac{\Lambda_{\rm TC}}{\Lambda_{\rm ETC}} \right)^2 \Lambda_{\rm TC}$$

ETC scale associated w/ top mass

$$\rightarrow \quad \Lambda^{\rm top}_{\rm ETC} \approx 1{\rm TeV} \left(\frac{\Lambda_{\rm TC}}{1{\rm TeV}} \right)^{3/2} \left(\frac{172{\rm GeV}}{m_t} \right)^{1/2}$$

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)

$$\langle \bar{U} U \rangle_{\rm ETC} \approx \left(\frac{\Lambda_{\rm ETC}}{\Lambda_{\rm TC}} \right)^{\gamma_m} \langle \bar{U} U \rangle_{\rm TC} \qquad 1 < \gamma_m \leq 2$$

boost-up

$$\rightarrow \quad m_t \approx \left(\frac{\Lambda_{\rm TC}}{\Lambda_{\rm ETC}} \right)^{2-\gamma_m} \Lambda_{\rm TC} \leq \Lambda_{\rm TC} \sim 1{\rm TeV}$$

T parameter

(Strong) ETC generates large isospin breaking
→ highly model-dependent issue

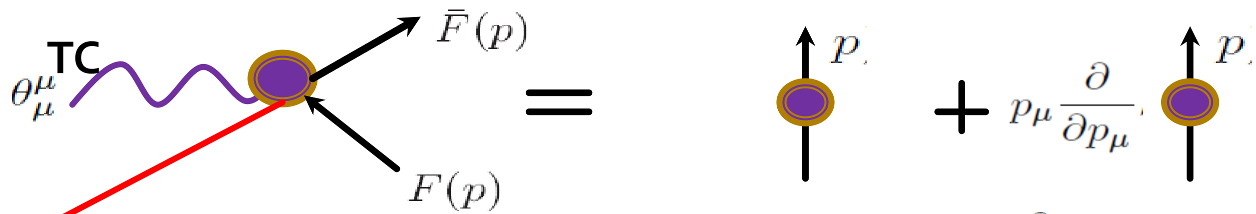
★ *Direct consequences of Ward-Takahashi identities*

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

* Coupling to techni-fermions

$$\lim_{q_\mu \to 0} \int d^4y\, e^{iqy} \langle 0 | T \partial^\mu D_\mu(y) F(x) \bar{F}(0) | 0 \rangle = i\delta_D \langle 0 | T F(x) \bar{F}(0) | 0 \rangle$$

$$= i\,(2d_F + x^\nu \partial_\nu)\, \langle 0 | T F(x) \bar{F}(0) | 0 \rangle$$



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

Dilaton pole dominance

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

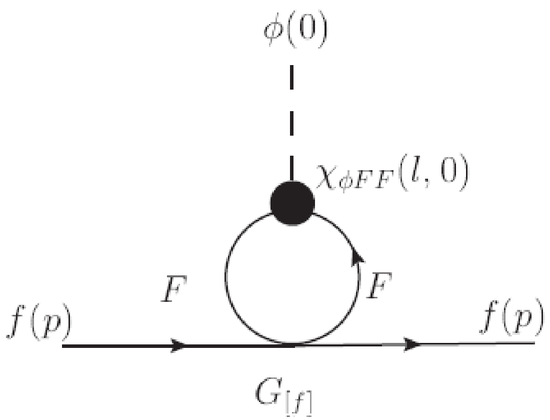
w/ TD decay constant Fphi

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

Yukawa vertex func.

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

* Couplings to SM fermions



ETC induced 4-fermi

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

f-fermion mass:

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

No direct coupling

TC

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

~~transform~~

Techni-fermion loop induces

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

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

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

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

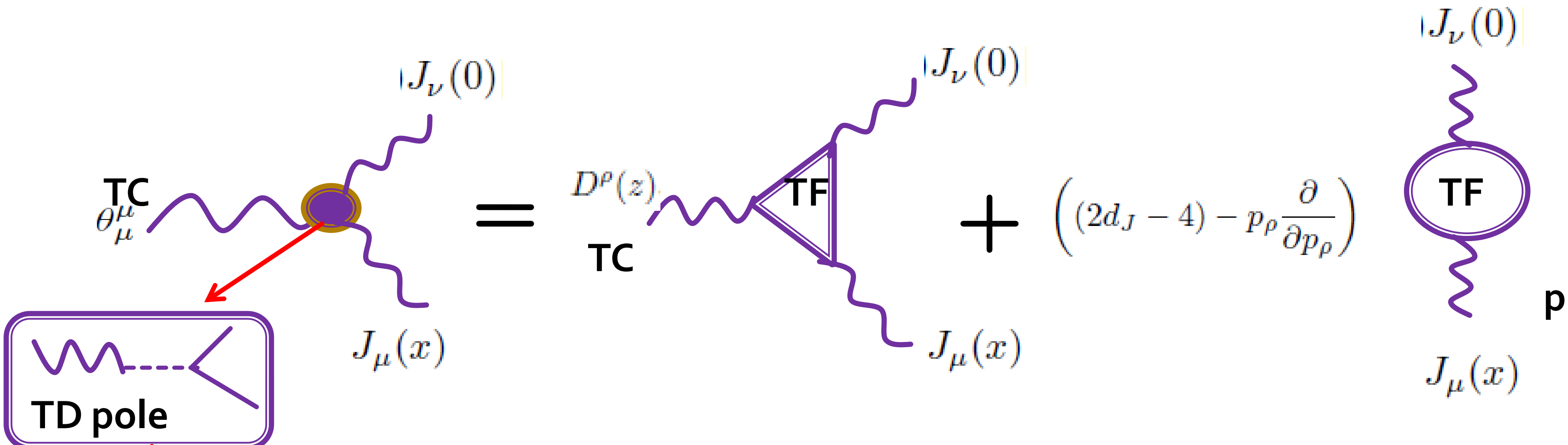
Yukawa coupling to SM-fermion

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

* 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 ($\gamma_m = 2$)

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

β_F: TF-loop contribution to beta function βF: TF-loop contribution to beta function

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

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

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

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

ND = TF -EW-doublets

Coupling to W

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

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

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

Coupling to γγ & gluons

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