Discovering Walking Technicolor at LHC
-- 125 GeV Techni-dilaton at LHC --

Koichi Yamawaki

(KMI, Nagoya)

March 8, 2013 @Moriond

Kobayashi-Maskawa Institute (KMI)

for the Origin of Particles and the Universe

Nagoya University

Started April 2010

Disciples of Sakata at Nagoya

M. Kobayashi

T. Maskawa

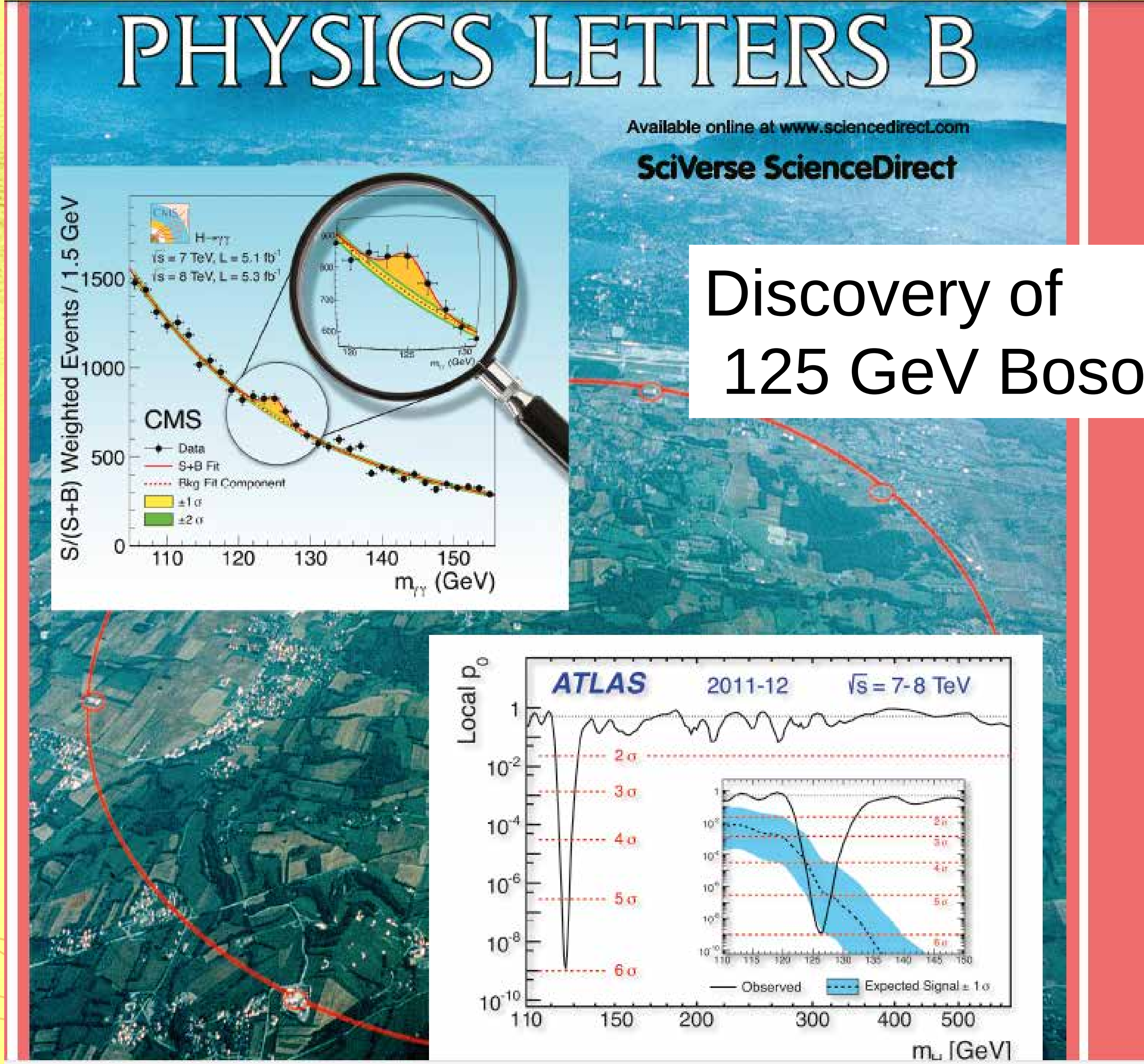
Sakata Model (1965)

Maki-Nakagawa-Sakata (1962)

Shoichi Sakata (1911-1970)
Nagoya Univ. Professor

Composite Model Approach

Discovery of 125 GeV Boson

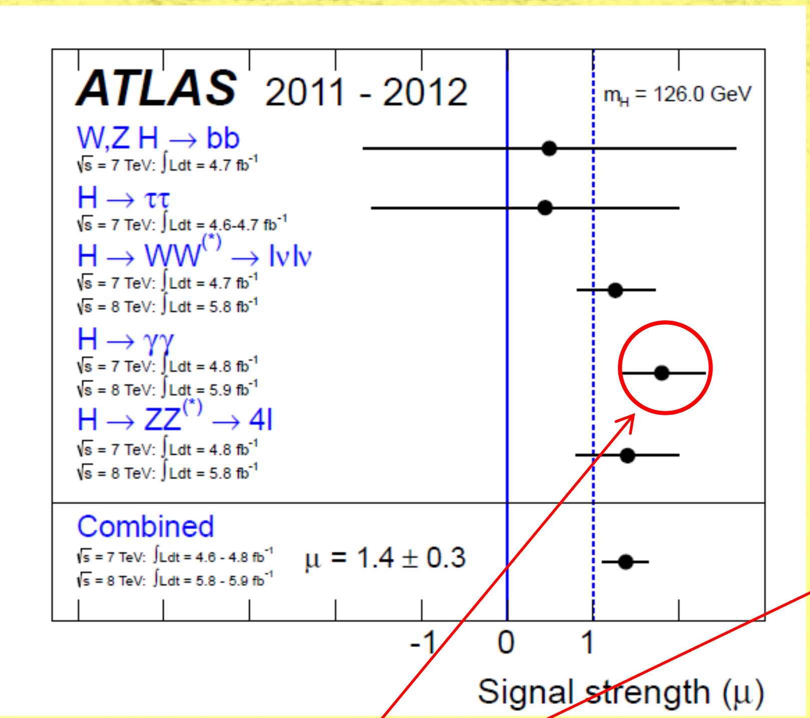


Is this the SM Scalar
or something else?

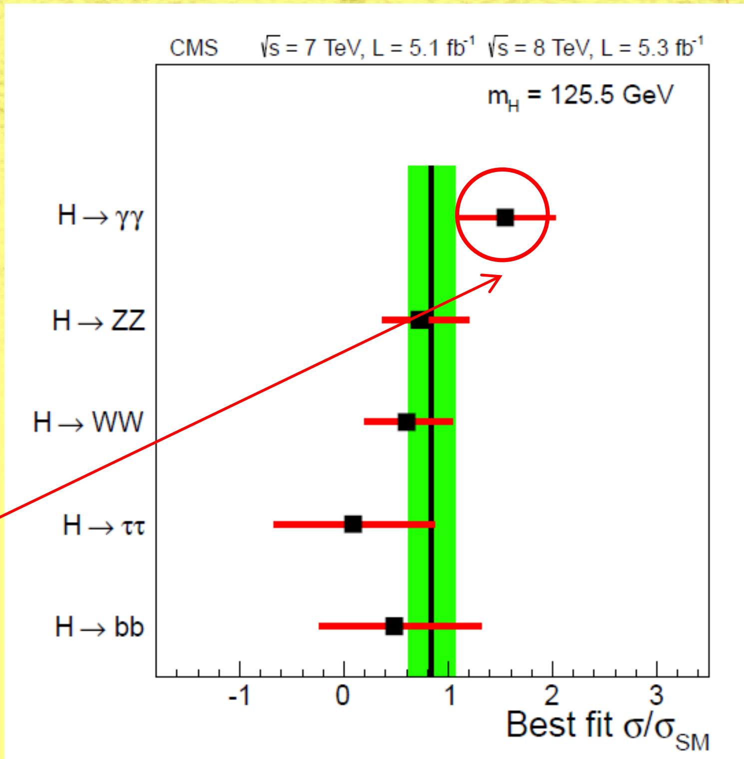
Roughly consistent with the SM Scalar,
but …..

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

ATLAS (PLB 716 (2012) 1)



CMS (PLB 716 (2012) 30)



Somewhat large diphoton event rate:

μ (diphoton) ~ 2 implies a "new scalar boson" (impostor) beyond the SM !

Standard Model is incomplete

- No Dark matter candidates
- Baryogenesis: KM CP violation not enough,
  No 1st order phase transition
- Strong CP Problem: neutron EDM
- …
- Naturalness Problem ⟷ BSM on TeV

  hierarchy & tachyon :

$$|\delta M_H^2| \sim \Lambda^2 \sim (10^{19}\,\mathrm{GeV})^2$$

$$M_H^2 + \delta M_H^2 = -\mathcal{O}((10^2\,\mathrm{GeV})^2)$$

$$\mathrm{Technicolor\ (QCD-like\ Theory)}$$

$$\mathrm{composite}\ \pi \rightarrow m_{W,Z}$$

Folklore:

Technicolor = Higgsless

(No light scalar)

Walking Technicolor KY-Bando-Matumoto (1986)

Approx. Scale Symmetry

⇒ **Techni-dilaton**

⇔ **125 GeV Boson**

Scale-Invariant Hypercolor Model and a Dilaton

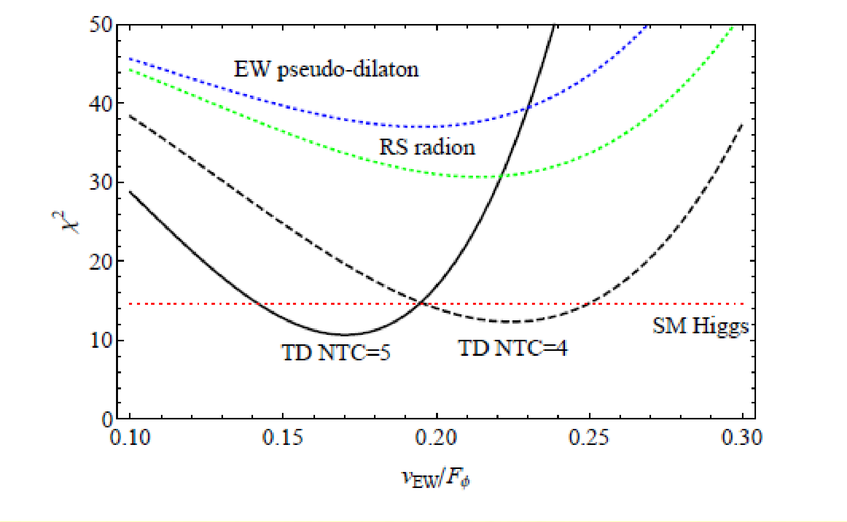
Koichi Yamawaki, Masako Bando,[a] and Ken-iti Matumoto[b]
Department of Physics, Nagoya University, Nagoya 464, Japan
(Received 24 December 1985)

We propose a scale-invariant hypercolor model with a nontrivial ultraviolet fixed point having large anomalous dimension, which resolves the notorious flavor-changing neutral-current problem in hypercolor models, and at the same time predicts a $J^{PC}=0^{++}$ Nambu-Goldstone boson (dilaton) associated with the spontaneous breakdown of the scale invariance.

```
%\cite{Yamawaki:1985zg}
\bibitem{Yamawaki:1985zg}
  K.~Yamawaki, M.~Bando and K.~-i.~Matumoto,
  %``Scale Invariant Technicolor Model and a Technidilaton,''
  Phys.\ Rev.\ Lett.\  {\bf 56}, 1335 (1986).
  %%CITATION = PRLTA,56,1335;%%
  %609 citations counted in INSPIRE as of 07 Mar 2013
```

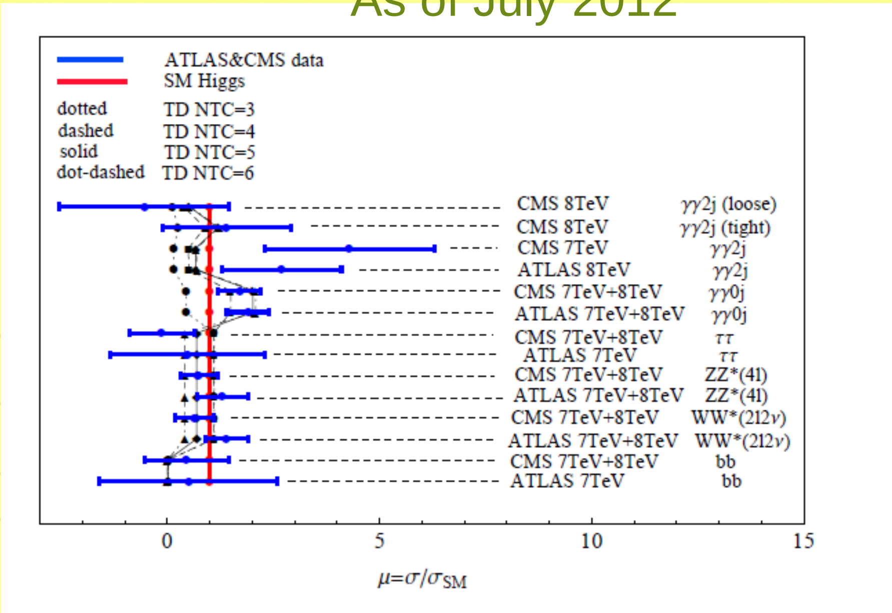
125 GeV Tchni-dilaton(TD) at LHC

S.Matsuzaki and K. Y. ,
PLB719 (2013) 378
PRD86 (2012) 115004



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

As of July 2012



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 Scalar

CONTENTS

- Technicolor: QCD-Scale-up
- Walking Technicolor and Techni-dilaton
- Discovering Walking Technicolor at LHC
  - Techni-dilaton at 125 GeV
- Discovering Walking Technicolor at Lattice
  - KMI Lattice Project

Technicolor: a Scale-Up of QCD

S. Weinberg (1976)
L. Susskind (1979)

$$\text{Composite } \pi \Rightarrow \text{Composite } \pi_{\text{TC}} \rightarrow m_{W,Z}$$

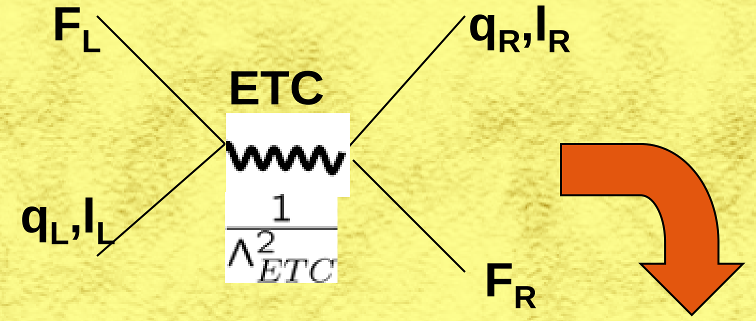
$$H \sim \bar{F}F \qquad F_\pi = 246 \text{ GeV}$$

$$\frac{N_{\text{TC}}}{N_{\text{C}}} \qquad \sqrt{\frac{N_{\text{C}}}{N_{\text{TC}} N_{\text{D}}}}$$

X 2600

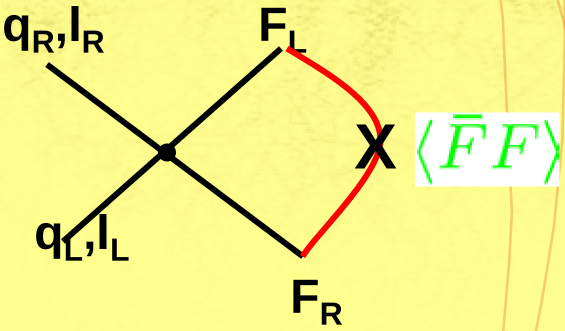
$$\sigma \sim \bar{q}q \qquad f_\pi = 93 \text{ MeV}$$

FCNC Problems:



Mass of Quarks/Leptons

$$m_{q/l} \sim \frac{1}{\Lambda_{ETC}^2} \langle \bar{F} F \rangle$$



FCNC

$$\frac{1}{\Lambda_{ETC}^2} \bar{s} d \bar{s} d < (10^3\,\mathrm{TeV})^{-2}$$

$$m_s < (10^3\,\mathrm{TeV})^{-2} \times (0.7\ \mathrm{TeV})^3 \sim 10^{-1}\,\mathrm{MeV}$$

Needs 10^3 enhancement

By Large Anomalous Dimension γ_m

Holdom (1981)

Pure Assumption of
Existence of Large γ_m
No Concrete Dynamics
No Concrete Value γ_m

$$m_{q/l} = \frac{1}{\Lambda_{\rm ETC}^2} \langle (\bar{T}T)_{\Lambda_{\rm ETC}} \rangle$$

$$\langle \bar{F}F \rangle|_{\Lambda_{ETC}} = Z_m^{-1} \cdot \langle \bar{F}F \rangle|_{\Lambda_{EW}}$$

$$Z_m^{-1} = (\Lambda_{\rm ETC}/\Lambda_{\rm EW})^{\gamma_m} \simeq (10^3)^{\gamma_m}$$

$\gamma_m > 1$ ⟹ $> 10^3$

Walking Technicolor

K.Y., Bando, Matumoto (Dec. 24, 1985)

Ladder Schwinger-Dyson Equation

Scale Invariance $\Leftarrow$ $(\alpha(p) = \text{constant})$

$\gamma_m = 1$ $\Longleftrightarrow$ FCNC Sol.

Techni-dilaton

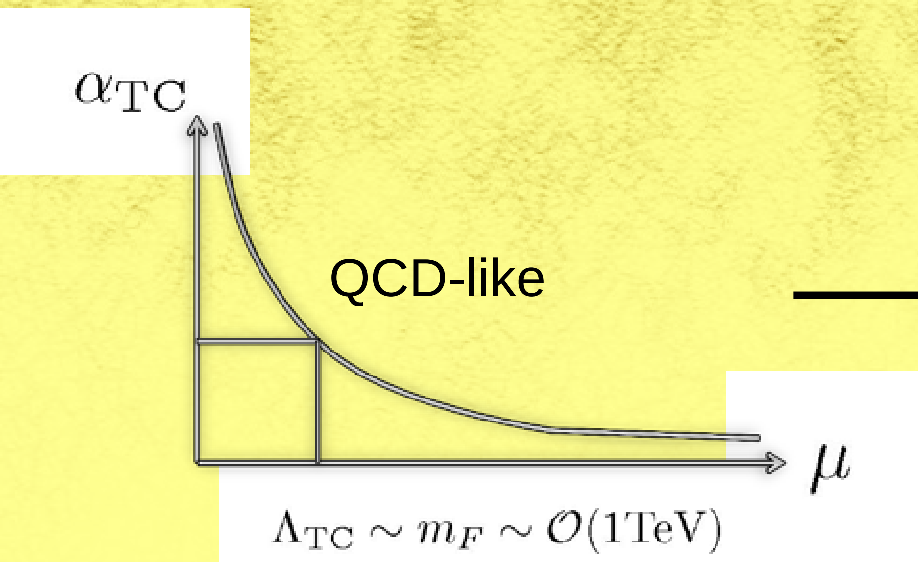
Similar FCNC Sol. without notion of γ_m, Scale Invariance, Techni-dilaton :

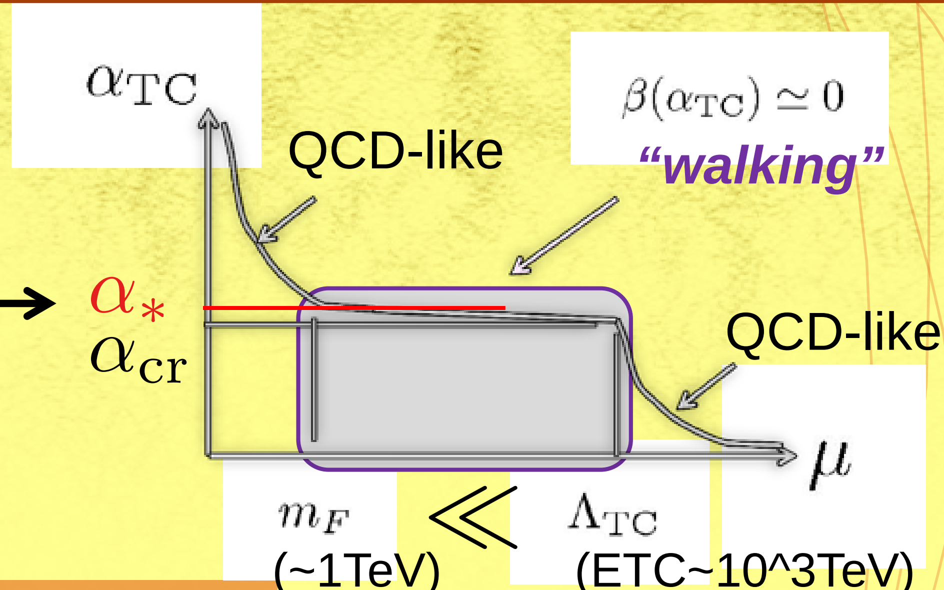
Akiba, Yanagida (Jan. 3, 1986)

Appelquist, Karabali, Wijewardhana (June 2, 1986)

(Holdom (Oct. 12, 1984), pure numerical)

★ A schematic view of Walking TC





***Dynamical TF mass generation by WTC**

$$m_F \simeq \Lambda_{\rm TC} \cdot \exp\left(-\frac{\pi}{\sqrt{\alpha/\alpha_{\rm cr} - 1}}\right) \ll \Lambda_{\rm TC}$$

nonperturbative scale anomaly due to m_F

$$\langle \partial_\mu D^\mu \rangle = \frac{\beta(\alpha)}{4\pi^2} \langle \alpha G_{\mu,\nu}^2 \rangle \ll m_F^4 \; (\ll \Lambda_{\rm TC}^4)$$

Pseudo NG Boson: Techni-dilaton

★ 125 GeV Techni-dilaton at LHC

S. Matsuzaki and K.Y.

PRD85 (2012) 095020 (Ladder)
PRD86 (2012) 035025 (Basic Formulation, Ladder)
PLB719 (2013) 378 (Ladder, Latest fit)
PRD86 (2012) 115004 (Holography, Latest fit)

Model-Independent Result:

Just a simple scaling from the SM Scalar:

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

Model-Dependence:

$\phi\gamma\gamma, \phi gg$ *and* F_ϕ *depending on particle contents of WTC models.*

$$\frac{v_{\rm EW}}{F_\phi} = \mathcal{O}(10^{-1})$$

Suppression ⟷ Enhancement !

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

β_F: TF-loop contribution to beta function

We consider the one-family WTC model

One-doublet model (1DM)

Weinberg(1976), Susskind(1979)

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

Farhi-Susskind (1981)

$TF_{\rm EW}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_L = \begin{pmatrix} U \\ D \end{pmatrix}_L$	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

4 weak-doublets

Holographic estiamte w/ techni-gluonic effects

Haba-Matsuzaki-KY, PRD82 (2010) 055007
Matsuzaki- K.Y., PRD86 (2012) 115004

$$z_m,\ \xi,\ G$$

* **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**

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

$$m_\Phi^2 = -(3-\gamma_m)(1+\gamma_m)/\breve{L}^2$$

QCD $\gamma_m = 0$

WTC $\gamma_m = 1$

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

input

fπ	=	92.4 MeV
Mρ	=	775 MeV
<αGμυ^2>/π	=	0.012 GeV^4

fix →

model parameters

ξ	=	3.1
G	=	0.25
zm^-1	=	347 MeV

Model predictions

			measured
Ma1	[a1 meson] :	1.3 GeV	1.2 --- 1.3 GeV
Mf0(1370)	[qqbar bound state] :	1.2 GeV	1.1 --- 1.2 GeV
MG	[glueball] :	1.3 GeV	1.4 --- 1.7 GeV (lat.)
S = - 16 π L10	[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 $\gamma_m = 1$

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

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

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

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)

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

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

free from holographic-parameters !!

→ **Massless NGB limit ("conformal limit") is realized:**

$$\frac{M_\phi}{F_\pi} \to 0 \quad \text{and} \quad \frac{F_\phi}{F_\pi} \to \text{finite}\,, \quad \text{as} \quad G \to \infty \,. \ (\langle \Phi(z_m) \rangle \sim \xi \to 0)$$

in contrast to ladder approximation

Matsuzak- K.Y., PRD86 (2012) 115004

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

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

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

$$\simeq \sqrt{2N_{\rm TF}} \cdot$$

holographic-parameter free !!

Theoretical Uncertainties: $1/N_{TC}$ corr. (20% ~ 30%)

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

This is consistent with ladder estimate:

LHC best fit (to be shown)

$$\frac{v_{\rm EW}}{F_\phi} \simeq 0.22(N_{\rm TC}=4)$$
$$\simeq 0.17(N_{\rm TC}=5)$$

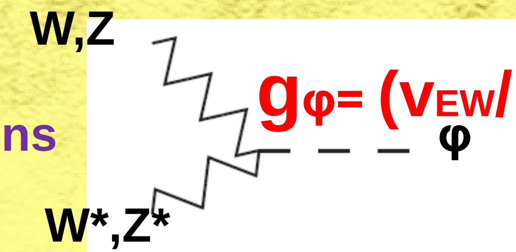
ladder

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

★ *Characteristic features of 125 GeV TD in 1FM (w/ N_{TC}=4,5) at LHC*

v.s. SM Higgs

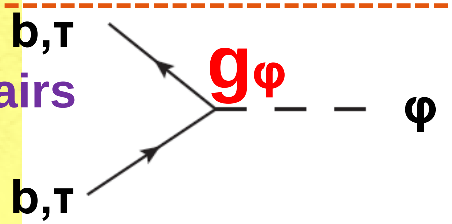
di-weak bosons



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

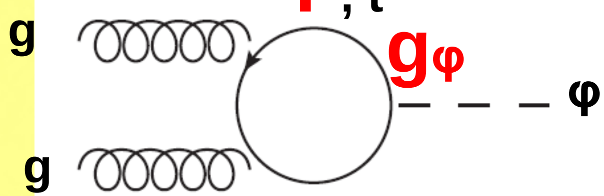
suppressed

quark, lepton pairs



suppressed

digluon

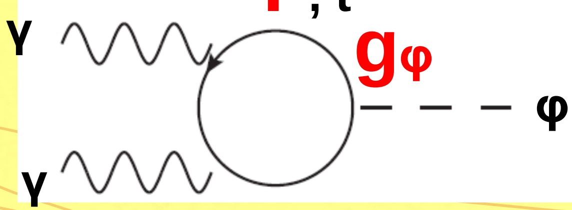


$\beta_F(g_s)$

enhanced

QCD-colored TF contributio

diphoton



$\beta_F(e)$

>> W -loops

enhanced

EM-charged TF contributio

★ The 125 GeV TD signal strengths

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

bb:

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

X= tautau, WW*, ZZ*:

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

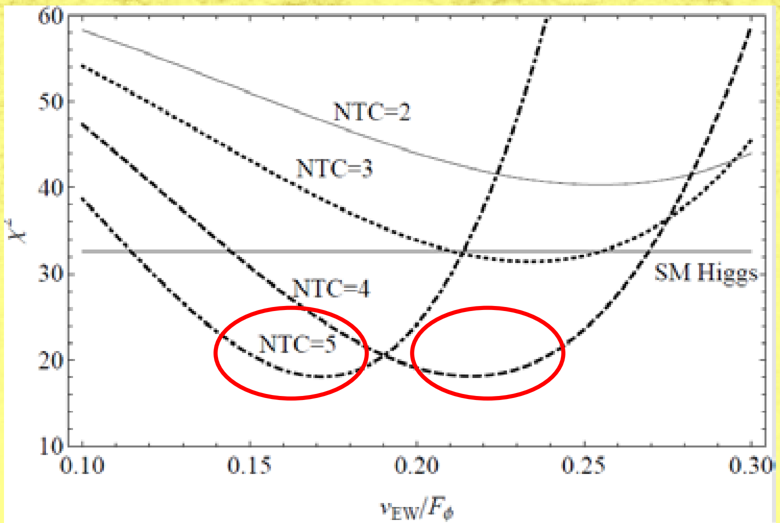
Diphoton:

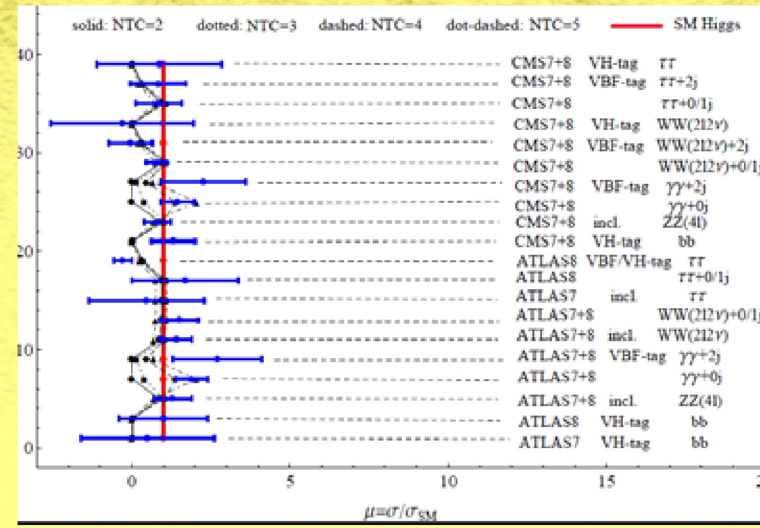
$$\mu_{\gamma\gamma 0j} = \frac{\sigma^{\phi}_{\rm GF}(s)}{\sigma^{h_{\rm SM}}_{\rm GF}(s)} \frac{BR(\phi \to X)}{BR(h_{\rm SM} \to X)},$$

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

The 125 GeV TD signal fitting to the current Higgs search data

*updated after HCP2012





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

N_{TC}	$[v_{EW}/F_\Phi]$best	χ^2 min /d.o.f.
4	0.22	18/19 = 0.95
5	0.17	18/19 = 0.95

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

* The TD charasteristic signal strengths for each category

μ_{ZZ} = 0.7 -- 1.0 (inclusive)

μ_{bb} = 0.006 -- 0.01 (VH-tag)

μ_{WW0j} = 0.8 -- 1.1 (ggF-tag)

μ_{WW2j} = 0.2 -- 0.3 (VBF-tag)

μ_{WW} = 0.006 -- 0.01 (VH-tag)

$\mu_{\tau\tau 0j}$ = 0.8 -- 1.1 (ggF-tag)

$\mu_{\tau\tau 2j}$ = 0.2 -- 0.3 (VBF-tag)

$\mu_{\tau\tau}$ = 0.006 -- 0.01 (VH-tag)

$\mu_{\gamma\gamma 0j}$ = 1.4 -- 2.0 (ggF-tag)

$\mu_{\gamma\gamma 2j}$ = 0.5 -- 0.7 (VBF-tag)

VH & VBF-tags : suppressed

$\gamma\gamma 0j$: enhanced

Discovering the Walking Technicolor at LHC

Road Map

- 125 GeV Techni-dilaton vs SM Scalar:
  $\gamma\gamma$ excess/others suppressed
- Techni-pions around 300-500 GeV
  $$63 - 3 = 60\,\mathrm{pseudo\,NG\,Bosons}$$
  Jia-Matuszaki-K.Y.
  PRD 87 (2012) 016006
- Techni-baryon as a dark matter
- Techni-rho/a_1 on TeV

Theoretical Issues

- Walking Dynamics beyond Ladder/Holography ?
- More Precise Quantitative Predictions?

$$F_\pi,\ F_\phi,\ M_\phi,\ M_\rho, M_{a_1}, M_{\text{baryon}},\ etc.$$

$$S, T, U - \text{Parameters}$$

Lattice !

Discovering the Walking Technicolor on the Lattice

KMI Lattice Project (LatKMI Collaboration)

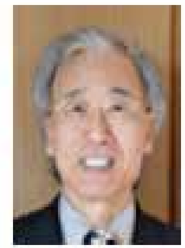
- Finding a candidate of WTC on the Lattice
- Finding a light scalar composite on the Lattice
- Calculating the composite spectra on the Lattice

LatKMI collaboration members

M. Kurachi T. Maskawa K. Nagai K. Yamawaki

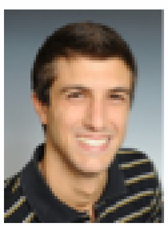




Y. Aoki T. Aoyama T. Yamazaki H. Ohki

名古屋大学



E. Rinaldi

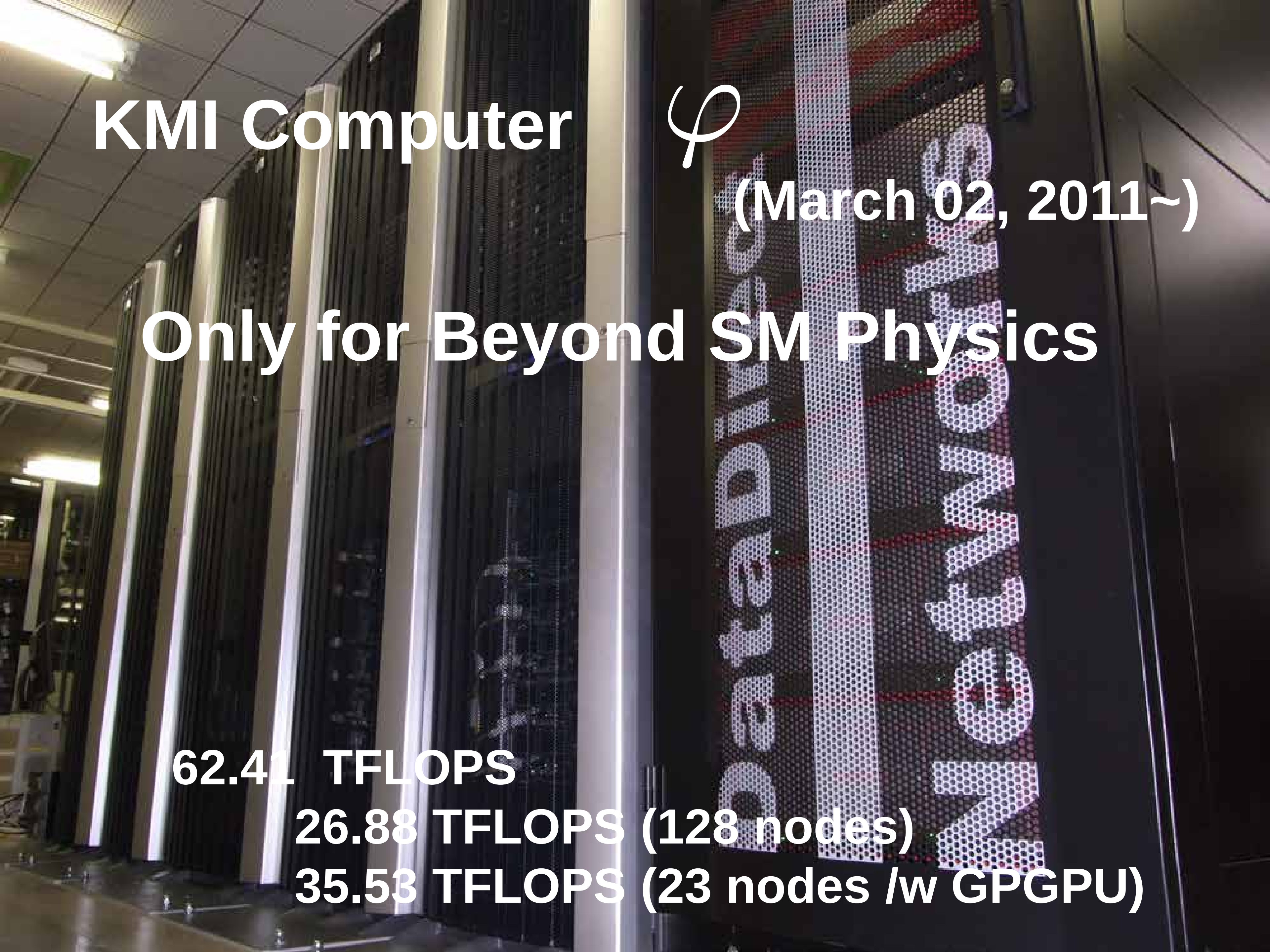
A. Shibata

KEK

KMI Computer φ

(March 02, 2011~)

Only for Beyond SM Physics



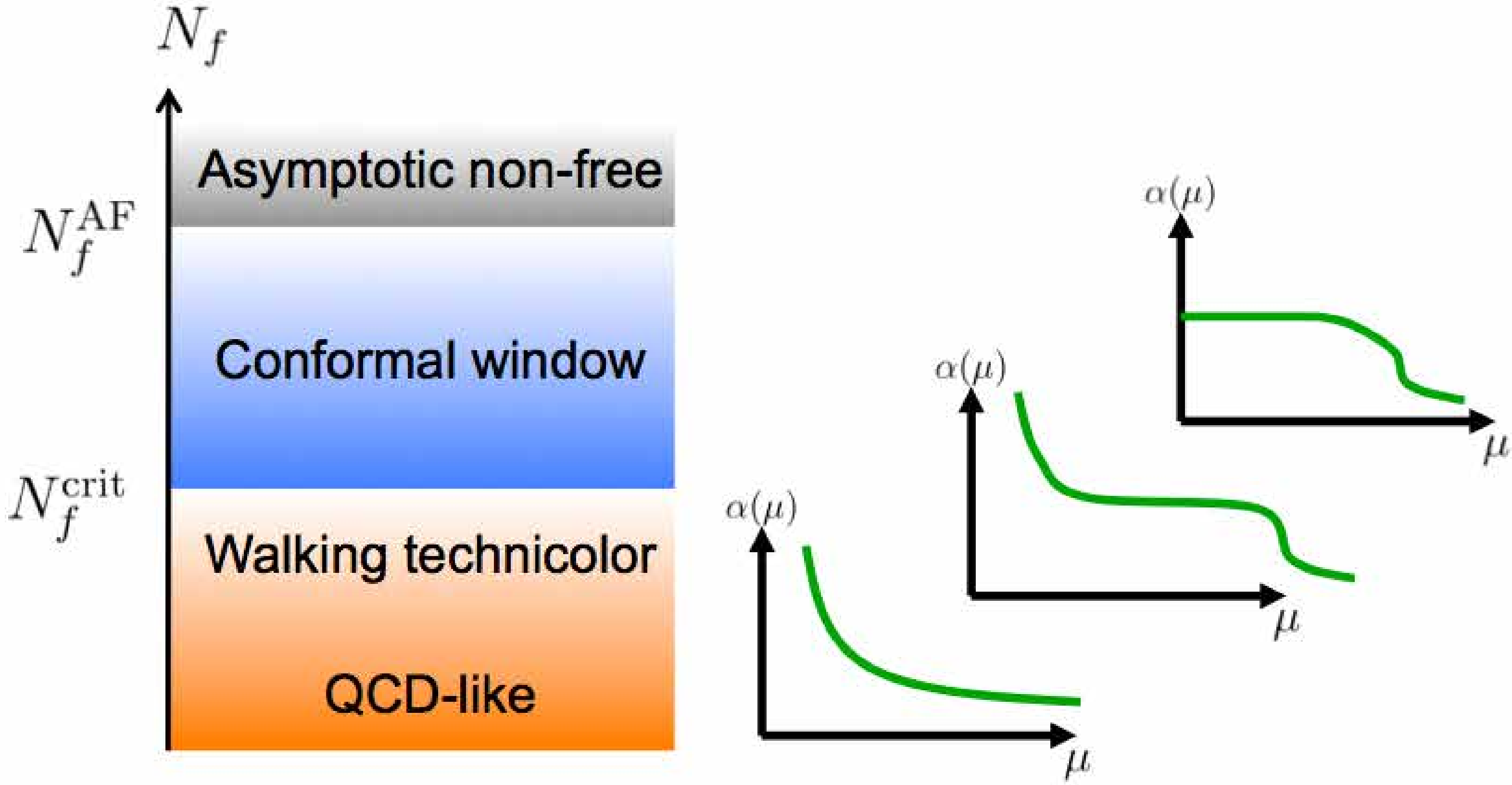
62.41 TFLOPS

26.88 TFLOPS (128 nodes)

35.53 TFLOPS (23 nodes /w GPGPU)

$$SU(3);\ N_c = 3$$

$$N_f = 4, 8, 12, 16 (< N_f^{\mathrm{AF}} = 11N_c/2 = 16.5)$$



$$2-\mathrm{loop}:\ N_f^{\mathrm{crit}} = 8.05$$

$$2-\mathrm{loop} + \text{ ladder SD equation}:\ N_f^{\mathrm{crit}} = 11.9$$

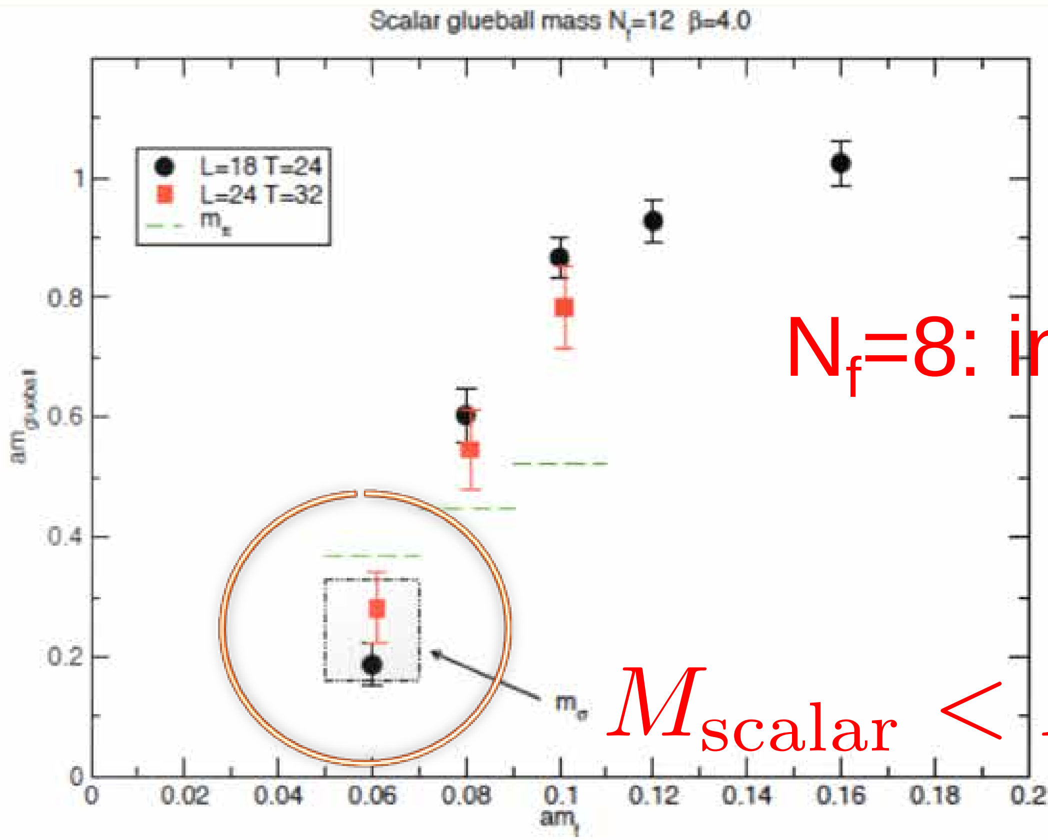
The scalar spectrum of many-flavour QCD*

Yasumichi Aoki[a], Tatsumi Aoyama[a], Masafumi Kurachi[a], Toshihide Maskawa[a], Kei-ichi Nagai[a], Hiroshi Ohki[a], Enrico Rinaldi[a,b]†, Akihiro Shibata[c], Koichi Yamawaki[a], Takeshi Yamazaki[a]

LatKMI collaboration

arXiv: 1302.4577 [hep-lat]

Preliminary



N_f=8: in progress

$M_{\rm scalar} < M_\pi$

Fig. 5. Summary of the fitted scalar glueball masses for $N_f = 12$ QCD at $\beta = 4.0$ and for several bare fermion masses. Some values of the pion mass are shown for comparison. The point on different volumes have been slightly displaced for clarity. The grey box indicates the location

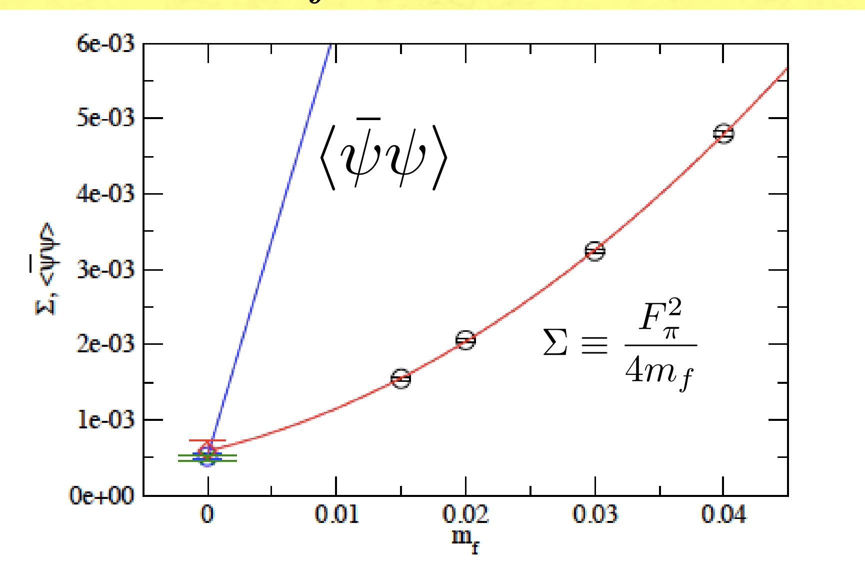
Walking signals in $N_f = 8$ QCD on the lattice

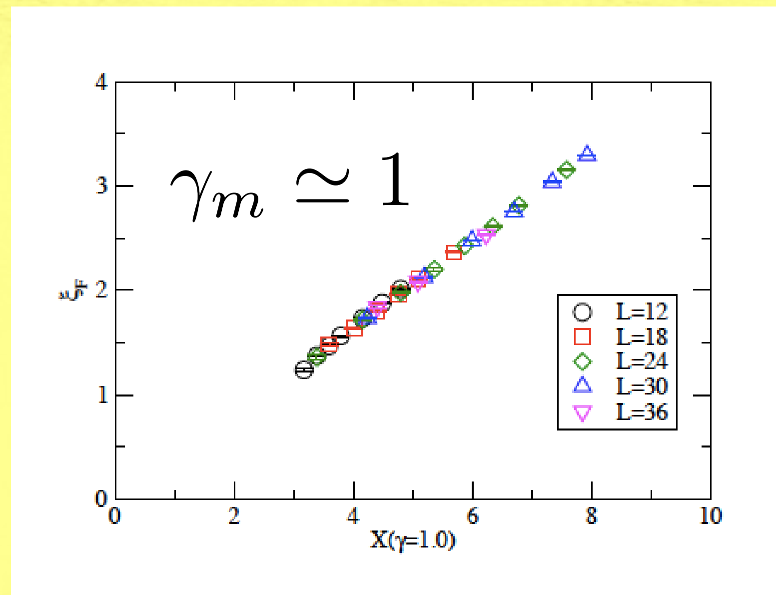
Yasumichi Aoki,[1] Tatsumi Aoyama,[1] Masafumi Kurachi,[1] Toshihide Maskawa,[1]
Kei-ichi Nagai,[1] Hiroshi Ohki,[1] Akihiro Shibata,[2] Koichi Yamawaki,[1] and Takeshi Yamazaki[1]
(LatKMI Collaboration)

arXiv:1302.6859 [hep-lat] |

SχSB $m_f = 0.015 - 0.04$

``Conformal" $m_f = 0.05 - 0.16$





$F_\pi \to \neq 0, M_\pi \to 0, M_\rho \to \neq 0$

at $m_f \to 0$

$$\xi_H \equiv LM_H = f_H(Lm_f^{\frac{1}{1+\gamma}})$$

Thank you

Backup Slides

☆ Other characteristic spectrum in one-family WTC

Chiral symmetry breaking: SU(8)L x SU(8)R à SU(8)V

3 "would-be" NGBs: eaten by W, Z
60 (pseudo) NGB = techni-pions (TPs)

$\theta_a^{\pm,3,0}$: color-octet scalars (# 32)

$\sim \bar{Q}\gamma_5 \lambda_a \tau^{\pm,3,0} Q$

$T_c^{\pm,3,0} (\bar{T}_c^{\pm,3,0})$: color-triplet scalars ("leptoquark") (#24)

$\sim \bar{Q}\gamma_5 \tau^{\pm,3,0} L \text{ (h.c.)}$

$P^{\pm,3,0}$: color-singlet scalars (# 4)

$\sim \bar{Q}\gamma_5 \tau^{\pm,3,0} Q - 3\bar{L}\gamma_5 L$

Expected masses :

300 ～ 500 GeV

J.Junji, S.Matsuzaki, K.Y.,
PRD87.016006. (2012)

Techni-pions: couplings to WW and ZZ highly suppressed (NO NGB-NBG-NGB

à narrow resonances (tot.width ~ 5--10GeV)

J.Junji, S.Matsuzaki, K.Y., PRD87.016006. (2012)

Discovering isospin singlet TPs: P^0 and θ_a^0

- **produced ONLY from ggF :** ~~VBF, VH,~~
- **Predominantly decaying to SM fermions**

$\sigma_{ggF}(pp \to P^0 \to \tau^+\tau^-) \sim 0.1\text{pb}$ **@ ~ 300GeV**

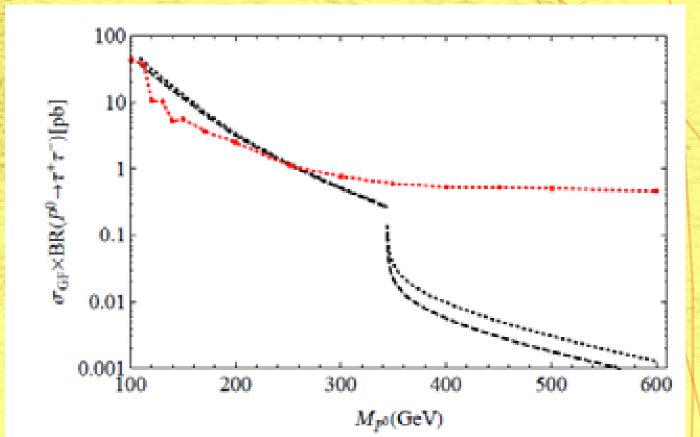
$\sigma_{ggF}(pp \to P^0 \to \bar{t}t) \sim 10\text{pb}$ **@ ~ 400GeV**

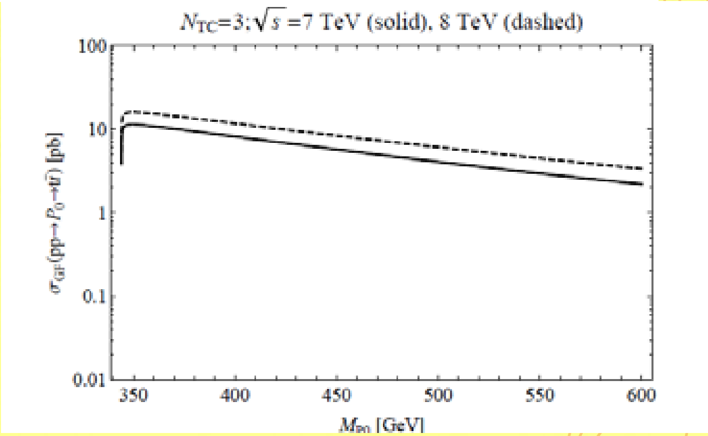
$\sigma_{\rm GF}(pp \to \theta_a) \times {\rm BR}(\theta_a \to t\bar{t}) \simeq 60\,\text{pb}$ **@ ~ 500GeV**

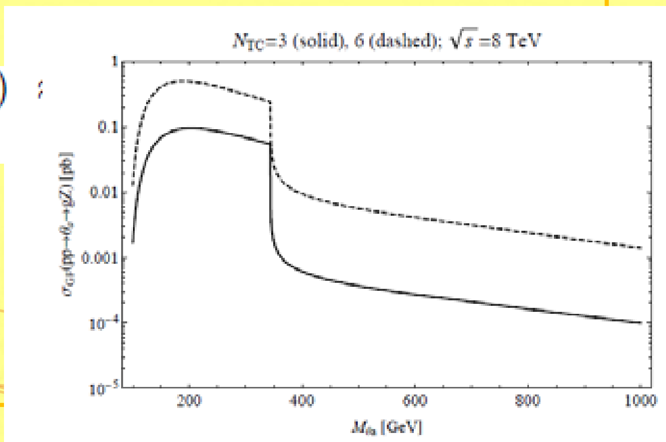
- **decays to glue-gamma/Z**

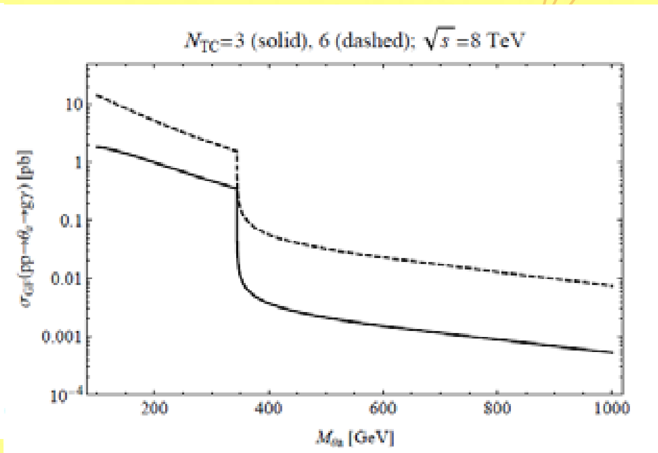
$\sigma_{\rm GF}(pp \to \theta_a \to gZ/\gamma)$ ~ 1 fb

@ ~ 500GeV









* One-family walking techni-rho mesons (#63)

- $\rho_{\theta_a}^{\pm,3,0}$: color-octet vectors (# 32)
- $\rho_{T_c}^{\pm,3,0}$ ($\bar{\rho}_{\bar{T}_c}^{\pm,3,0}$) : color-triplet vectors (# 24)
- $\rho_{P}^{\pm,3,0}$: color-singlet vectors (# 4)
- $\rho_{\pi}^{\pm,3}$: color-singlet vectors (# 3) [corresponding to vector states for eaten NGBs]

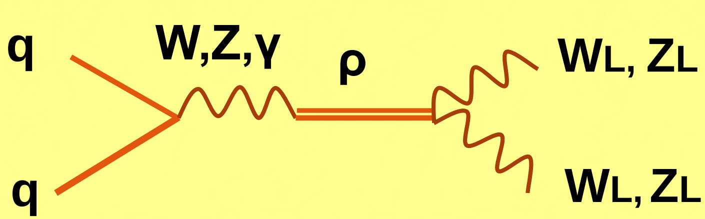
Expected masses :

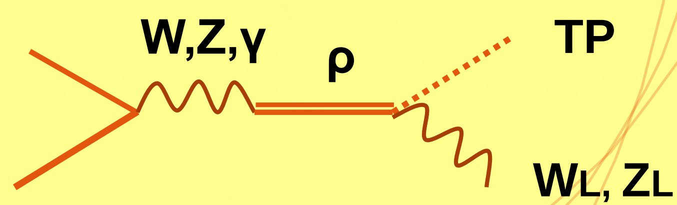
1 ～ 4 TeV

consistent w/
EW precision tests

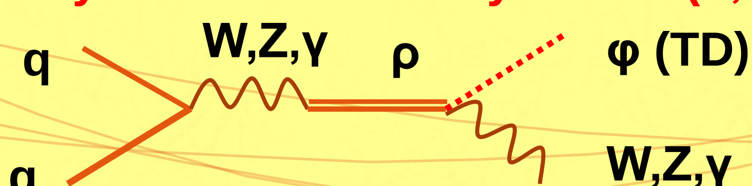
S.Matsuzaki and K.Y., PRD86.115004. (2012)

- **Typical discovery channels: decays to $W_L W_L$ ($Z_L Z_L$)or TP and W_L**





- **Novel discovery channel: decays to W(Z,γ) and TD!**



S.Matsuzaki and K.Y., in progress

★ TD phenomenological Lagrangian

S.M.atsuzaki and K. Y,, PRD86(2012)

* Nonlinear realization of scale symmetry

Nonlinear base χ , TD field Φ

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

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

i) The scale anomly-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"):

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

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:

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

The TD couplings are exactly reproduced by these terms.

★ Ladder estimate of TD mass

$\Lambda_{\rm TC}\,(\sim \Lambda_{\rm ETC})$
$N_f\,(\to N_f^{\rm cr})$

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

Harada-Kurachi-K.Y. (1989)

* **LSD via gauged NJL**

Shuto-Tanabashi-K.Y. (1990); Carena-Wagner (1992) ; Hashimoto (1998)

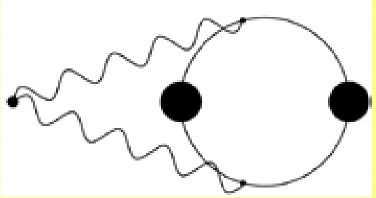
A composite Higgs mass

$$M_\phi \sim 4F_\pi \ll M_\rho, M_{a_1}$$

∼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-Gusynin (1989);
Hashimoto-K.Y. (2011);

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

$$\Rightarrow \quad \frac{F_\phi^2}{m_F^2}\cdot\frac{M_\phi^2}{m_F^2} = \text{finite}$$

No exactly massless NGB limit:

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

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

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

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

$$F_\phi^2 M_\phi^2 = -4\langle\theta_\mu^\mu\rangle$$

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

*** criticality condition**

Appelequist-Terning-Wijewardhana (1996)

$$N_{\rm TF} \simeq 4N_{\rm TC} \quad \leftarrow N_f^{\rm cr} \simeq 4N_c$$

*** 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-K.Y. (2011)

* 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

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

* AdS/CFT recipe:

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

classical solutions

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

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

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

- ξ : IR value of bulk scalar Φ_S $\longleftrightarrow$ (dual) $\bar{F}F$
- G : IR value of bulk scalar Φ_G $\longleftrightarrow$ $G_{\mu\nu}^2$
- z_m : IR-brane position

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

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

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:**

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

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

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

5d coupling → Π_V Leading log term: $\frac{N_{TC}}{12\pi^2}$

coeff. of M → Π_S Leading log term: $\alpha|_{\gamma_m=1} = \frac{\sqrt{3}}{2}$

coeff. of Φ_X → Π_V G^2 term: $c = -\frac{N_{TC}}{192\pi^3}$

matching to current correlators

Fix (Φ IR value, Φ_X IR value, IR brane position) with

3 phenomenological input values

F_π = 246 GeV/$\sqrt{N_D}$ = 123 GeV (1FM)
M_Φ = 125 GeV
S = 0.1

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

NTC = 3

Techni-ρ , a1 masses	:	M_ρ = 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

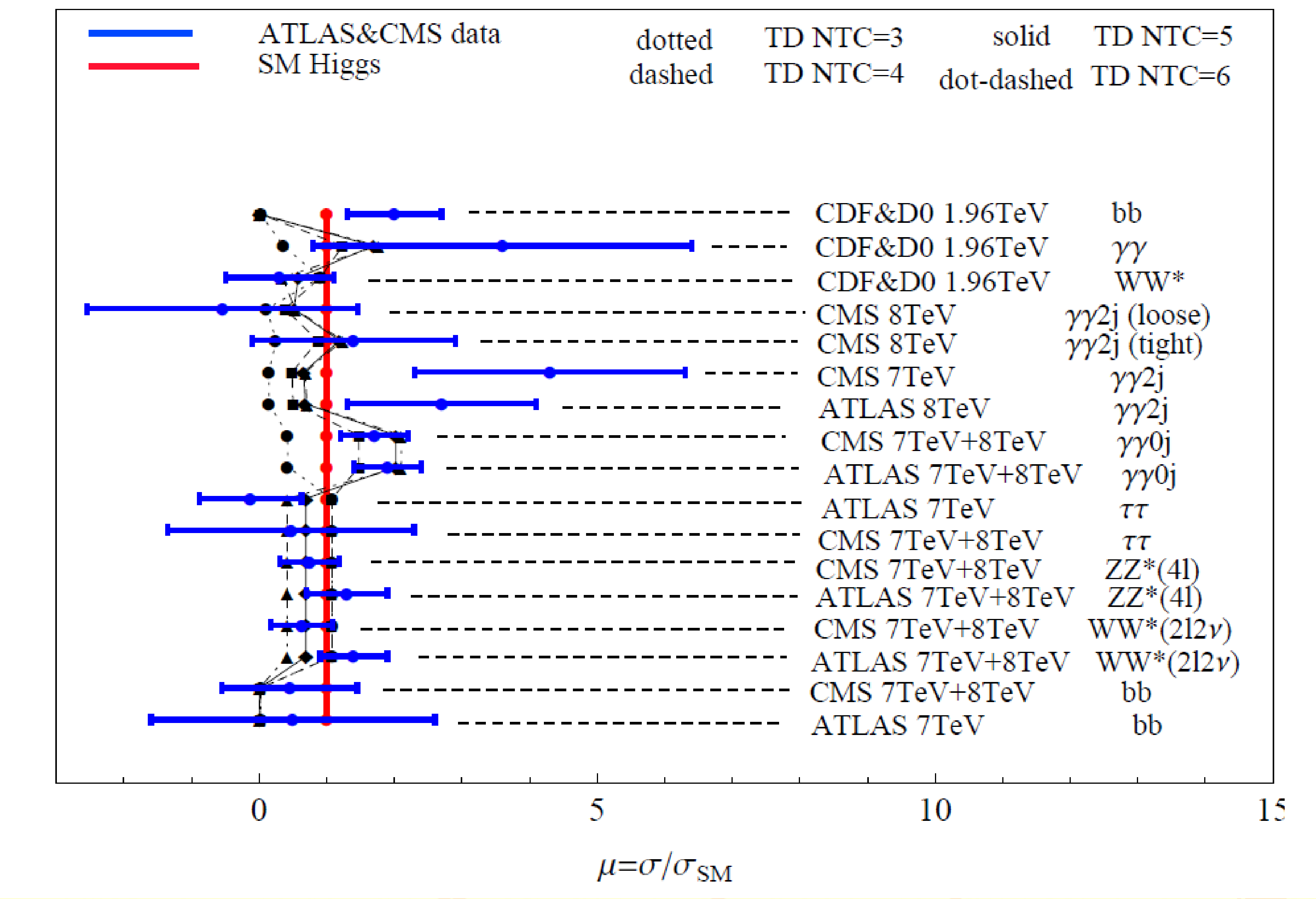
NTC = 4

Techni-ρ , a1 masses	:	M_ρ = 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

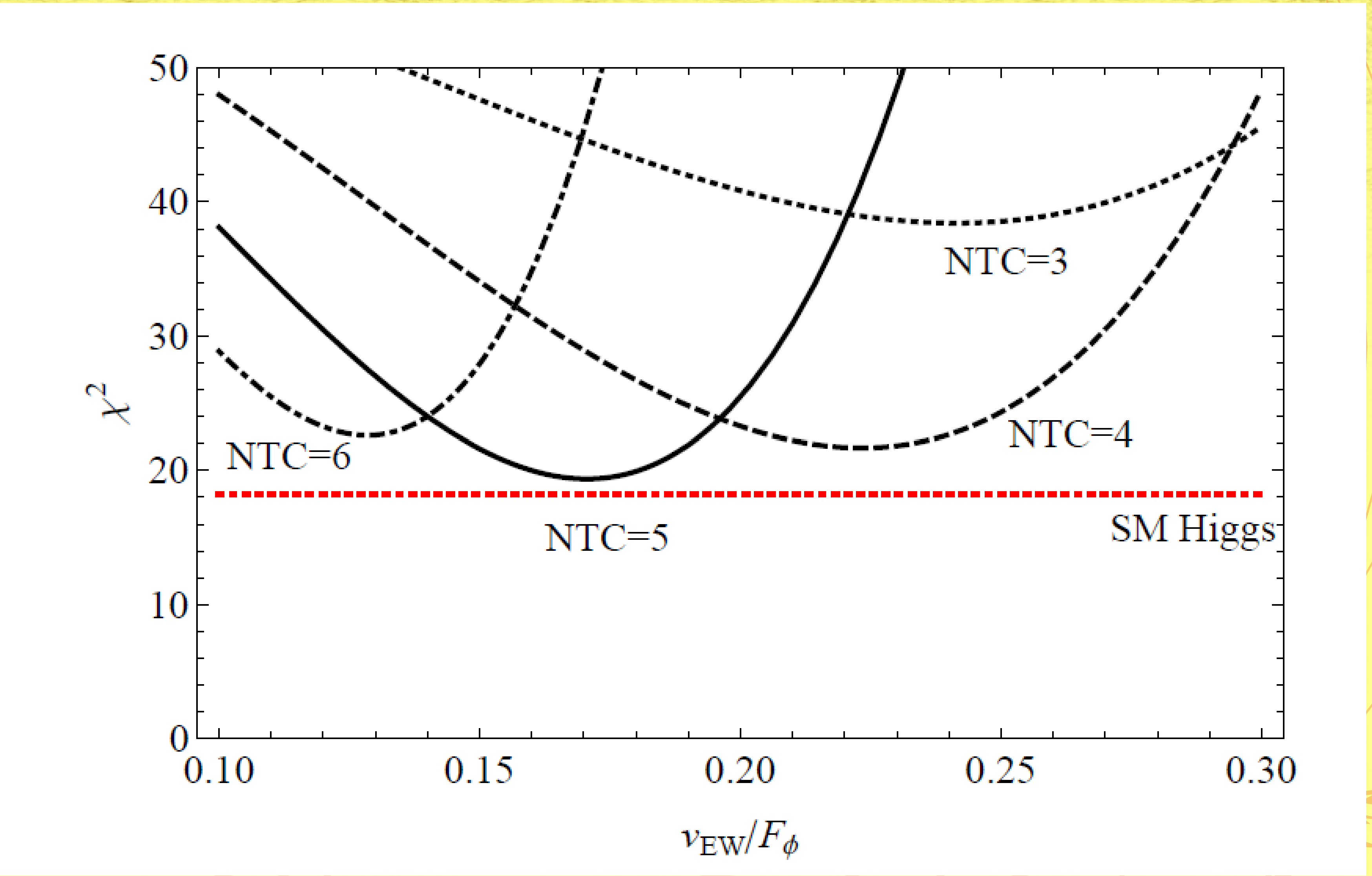
NTC = 5

Techni-ρ , a1 masses	:	M_ρ = 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:



★ Other pheno. issues in TC scenarios

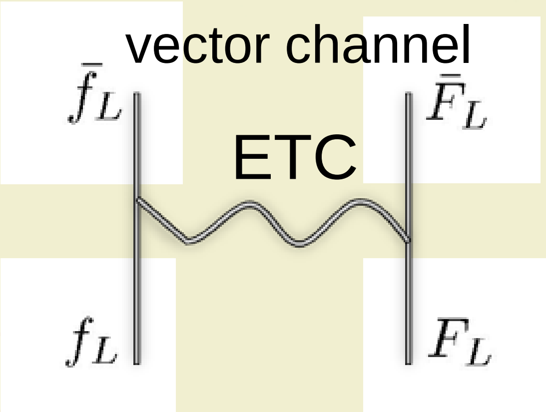
S parameter

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

N_D : # EW doublets

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

One resolution: ***ETC-induced "delocalization" operator***



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

Chivukula-Simmons-He-Kurachi-Tanabashiet al (2005)

in low-energy

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

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

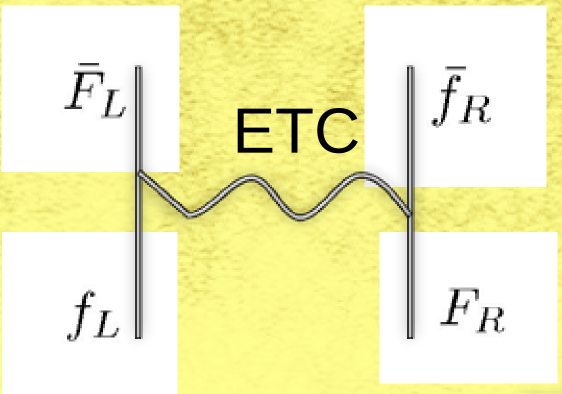
$$\ni g_W W_\mu - g_Y B_\mu$$ modifies SM f-couplings to W, Z

contributes to S "negatively"

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

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

Top quark mass generation



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

ETC scale associated w/ top mass

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

too small!

One resolution: ***Strong ETC*** Miransky-K.Y. (1989), Matumoto(1989), Appelquist-Einhorn-Takeuchi-Wijewardhana (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

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

T parameter (Strong) ETC generates large isospin breaking

à highly model-dependent issue