Discovering Walking Technicolor at LHC and on the Lattice

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

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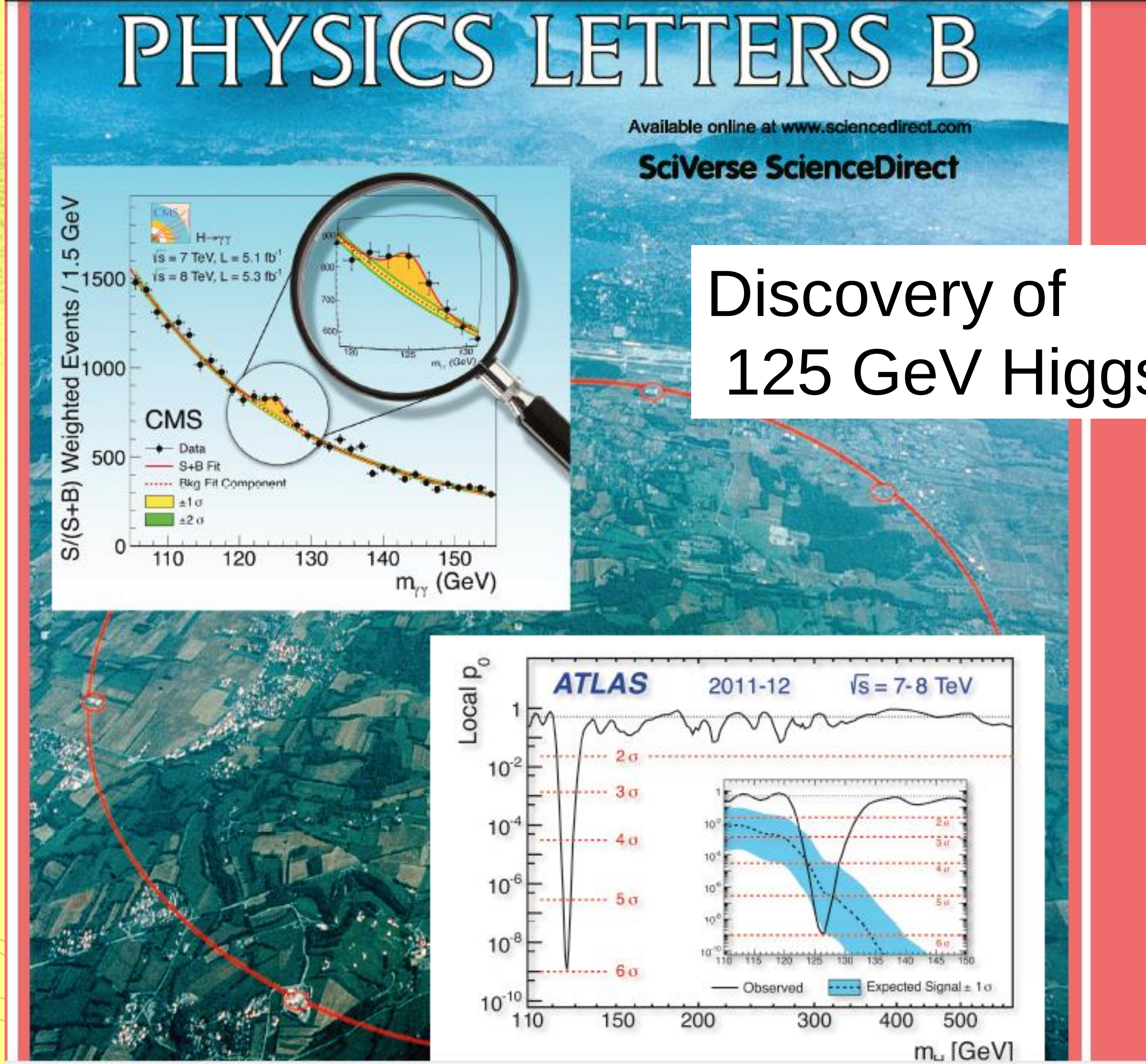
KMI, Nagoya

@Higgs and Beyond

June 7, 2013 Tohoku

Discovery of 125 GeV Higgs



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 :

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

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

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

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

TC was killed 3 times

- FCNC

$$m_{q,l} \ll m_{q,l}^{(\mathrm{exp})}$$

→ Walking TC

$$\gamma_m \simeq 1$$

- S,T,U parameters

$$S/(N_{\mathrm{TC}} N_D) \sim S_{\mathrm{QCD}} \sim 0.3$$

$$S^{(\mathrm{exp})} < 0.1$$

→ (Holographic) Walking TC [or ETC effects]

- 125 GeV Higgs

$$125\ \mathrm{GeV} \ll \Lambda_{\mathrm{TC}} = \mathcal{O}(\mathrm{TeV})$$

→ Walking TC scale inv.

~~Technicolor = Higgsless Model~~

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

~~(No light scalar)~~

Walking Technicolor KY-Bando-Matumoto (1986)

= Composite Higgs Model

Approx. Scale Symmetry

→ **Techni-dilaton**

↔ **125 GeV Composite Higgs**

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.

INSPIRE

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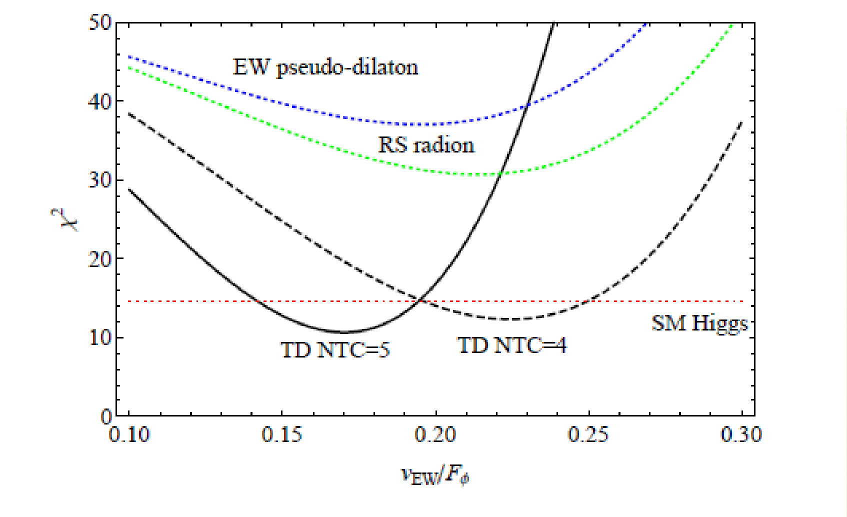
%\cite{Yamawaki:1985zg}
\bibitem{Yamawaki:1985zg}
  K.~Yamawaki, M.~Bando and K.~-i.~Matumoto,
  %``Scale Invariant Technicolor Model and a Technidilaton,''
  Phys.\ Rev.\ Lett.\  {\bf 56}, 1335 (1986).
  %%CITATION = PRLTA,56,1335;%%
```

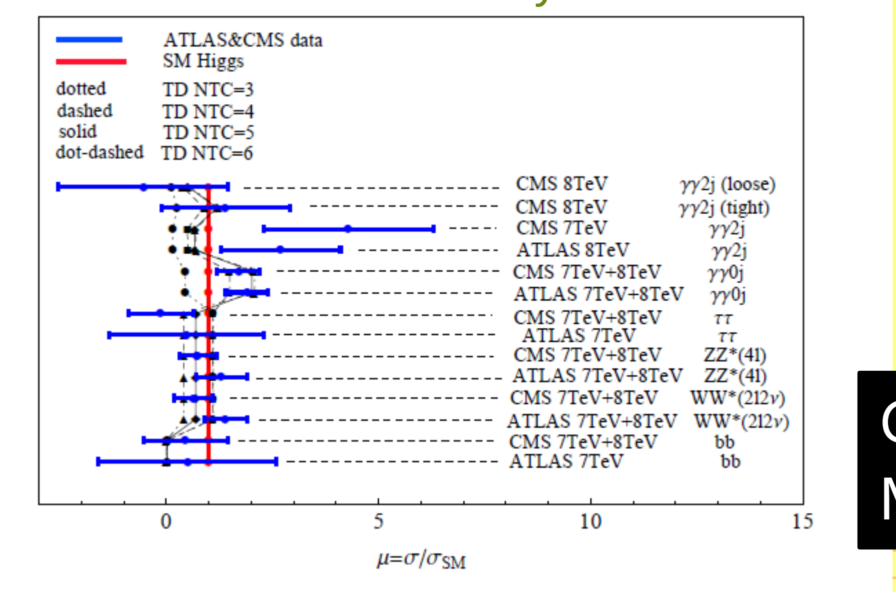
125 GeV Techni-dilaton(TD) at LHC

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***

Consistent with the updated after Moriond/Aspen in March 2013

CONTENTS

- Technicolor: QCD-Scale-up (3 times R.I.P.)
- Walking Technicolor and Techni-dilaton
- Discovering Walking Technicolor at LHC

  Techni-dilaton at 125 GeV
- Discovering Walking Technicolor on the Lattice

  KMI Lattice Project

Technicolor: a Scale-Up of QCD

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

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

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

$$\langle \bar{F}F \rangle \sim (700 \text{ GeV})^3$$

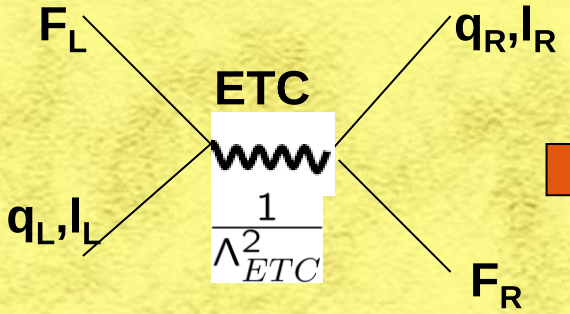
$$\frac{N_{\rm TC}}{N_{\rm C}} \qquad \sqrt{\frac{N_{\rm C}}{N_{\rm TC} N_{\rm D}}}$$

X 2600

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

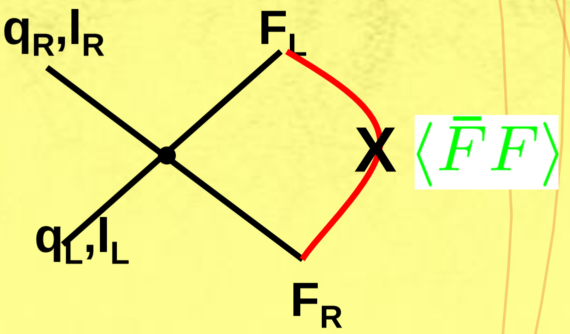
$$\langle \bar{q}q \rangle \sim (250 \text{ MeV})^3$$

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

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

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

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

$$\gamma_m > 1 \quad \Longrightarrow \quad > 10^3$$

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)

Ladder SD

$$m_F \approx 4\Lambda \cdot \exp\left(-\frac{\pi}{\sqrt{\frac{\alpha}{\alpha_{\rm cr}} - 1}}\right)$$

Miransky Scaling

Essential singularity

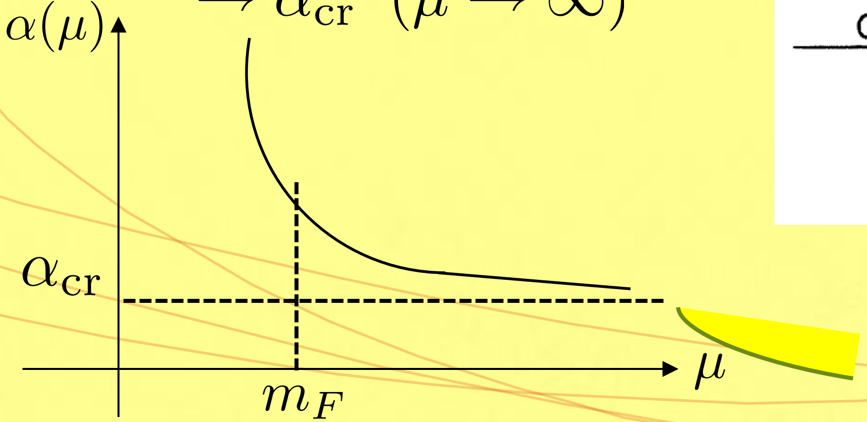
Non-perturbative running ("Walking")

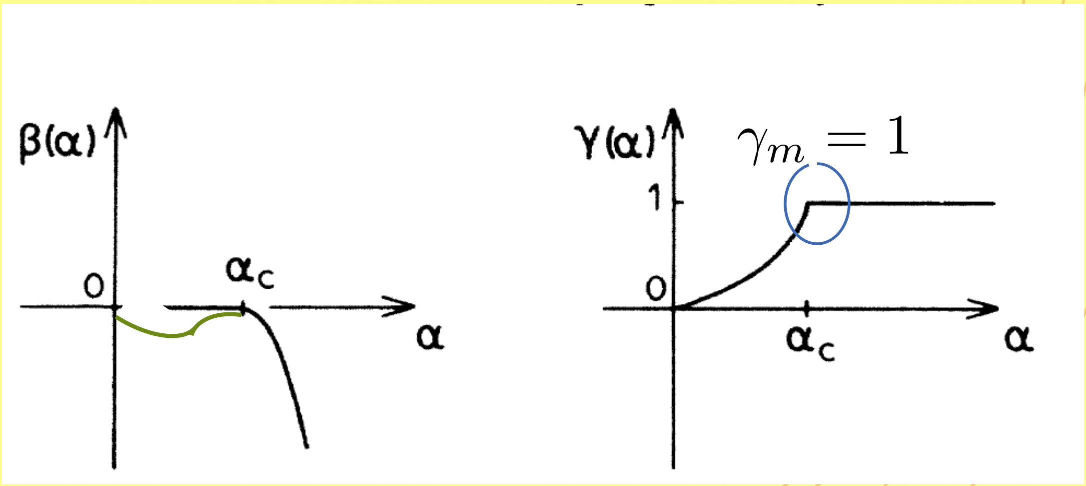
UVFP: not a linear zero
=IRFP

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

$$\alpha(\mu) = \alpha_{\rm cr} + \frac{\pi^2 \alpha_{\rm cr}}{\ln^2\left(\frac{\mu}{\frac{1}{4} m_F}\right)}$$

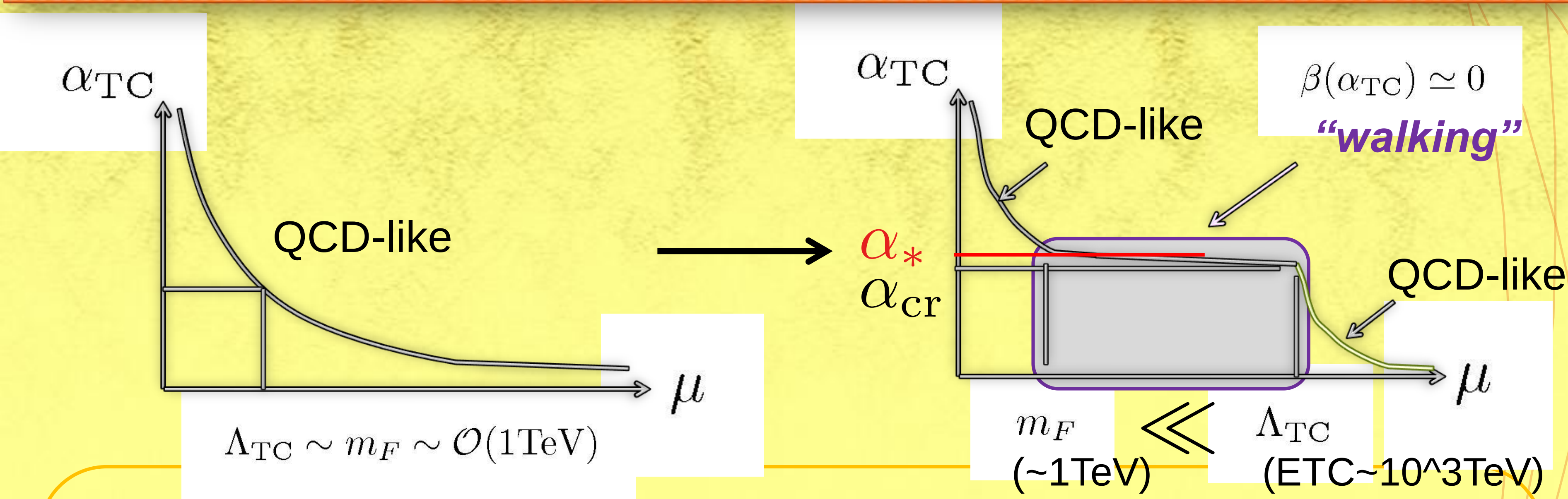
$$\to \alpha_{\rm cr} \quad (\mu \to \infty)$$





KY-Bando-Matumoto (1986)

A schematic view of Walking TC



nonperturbative scale anomaly due to m_F

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

Pseudo NG Boson: Techni-dilaton

Composite Higgs from technifermions having EW charges

Weakly Coupled Light Scalar Composite from Strongly Coupled Dynamics?

Cf: N. Seiberg, Aspen 2013

Naïve Arguments (base on LINEAR sigma model)

$$\mathcal{L}_{\rm SMH} = |\partial_\mu \phi|^2 - \mu^2 |\phi|^2 - \lambda |\phi|^4$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} i\pi_1 + \pi_2 \\ \sigma - i\pi_3 \end{pmatrix}$$

$$\lambda = \frac{1}{2} \frac{m_H^2}{v_{\rm EW}^2} \simeq \frac{1}{2} \left(\frac{125}{250} \right)^2 = \frac{1}{8} \ll 1 \,!!$$

$$\mathcal{L}_{\rm GL} = \frac{1}{2} \left((\partial_\mu \pi_a)^2 + (\partial_\mu \sigma)^2 - \mu^2 (\pi_a^2 + \sigma^2) \right) - \frac{1}{4} \lambda (\pi_a^2 + \sigma^2)^2$$

$$\frac{m_\sigma}{4\pi F_\pi} = \mathcal{O}(1)$$

$$\lambda = \frac{1}{2} \frac{m_\sigma^2}{v_{\rm QCD}^2} = 8\pi^2 \cdot \left(\frac{m_\sigma}{4\pi F_\pi} \right)^2 = \mathcal{O}(8\pi^2) \gg 1$$

GL(linear sigma model) $\neq$ QCD

$$\lambda \to \infty \text{ (Nonlinear } \sigma \text{ model)}$$

$$\mathcal{L}_{\mathrm{NL}\sigma} = \frac{F_\pi^2}{4} \mathrm{Tr}|\partial_\mu U|^2$$

$$U(x) = \exp\left(i \frac{2\pi(x)}{F_\pi} \right) \to g_L\, U(x)\, g_R^\dagger$$

WTC: Scale-Inv.

$$\mathcal{L}_{\mathrm{NL}\sigma} = \frac{F_\pi^2}{4} \cdot \chi^2 \cdot \mathrm{Tr}|\partial_\mu U|^2 + \frac{1}{2}(\partial_\mu \phi)^2$$

ϕ : dilaton

$$\chi(x) = \exp\left(\frac{\phi(x)}{F_\phi} \right) \to e^c \chi((e^{-c} x)$$

$M_\phi \Leftarrow$ Scale anomaly

$$\frac{M_\phi}{4\pi F_\pi} \sim \frac{F_\pi}{F_\phi} \ll 1$$

$$F_\phi^2 M_\phi^2 = -4\langle \theta_\mu^\mu \rangle = \mathcal{O}\left((4\pi F_\pi)^2 F_\pi^2 \right)$$

eff. TD Lagrangian

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

$g_{\phi WW/ZZ}$

i) The scale anomaly-free part:

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

$$\chi^2 = 1 + \frac{2}{F_\phi}\phi + \cdots$$

ii) The expl. br. due to SM (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 SM beta function

iii) The WTC 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 $\Leftarrow \mathcal{L}_S$

* 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 t0 beta function

Weakly Coupled Light Scalar Composite from Strongly Coupled Dynamics?

Cf: N. Seiberg, Aspen 2013

Lightness

$$m_\sigma \ll m_{a_0}, m_\rho, m_{a_1}, \cdots ?$$

Scale inv.

LHC confirmed

Yes !

Weakness

~~$g_{\sigma N \bar{N}}, g_{\sigma\pi\pi}, g_{a_1\rho\pi} \ll 1?$~~

Coupling to SM sector

$$g_{HWW/HZZ} \ll 1, \; g_{Hf\bar{f}} \ll 1?$$

Not a linear sigma model !

SM sector

Weak !

TC sector
(Strongly coupled)

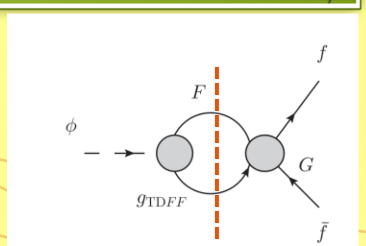
$$g_{MMM},\, g_{MB\bar{B}} \gg \mathcal{O}(1)$$

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

$g_1,\ g_2\ (\ll 1)$

$$g_{\phi FF} = \frac{m_F}{F_\phi} > 1 \left(\gg \frac{F_\pi}{F_\phi} \right)$$

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



$$\frac{m_F}{F_\phi} \cdot \frac{N_{TC}\, m_F^2}{4\pi^2} \cdot \frac{1}{\Lambda_{\rm ETC}^2} \quad (\ll 1)$$

Even needs enhancement !

$$\left(\frac{\Lambda_{\rm ETC}}{m_F}\right)^{\gamma_m}$$

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

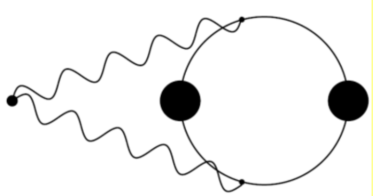
$$M_\phi \sim 4F_\pi \ll M_\rho, M_{a_1}$$

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

*** Using only PCDC still accommodates 125 GeV**

Lightness=Weak Coupling

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



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

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

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

No exactly massless NGB limit:

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

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

Ladder Estimate of $\frac{v_{\rm EW}}{F_\phi}$

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

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

Weaker than SMH

Holographic estimate w/ techni-gluonic effects

$z_m,\ \xi,\ G$

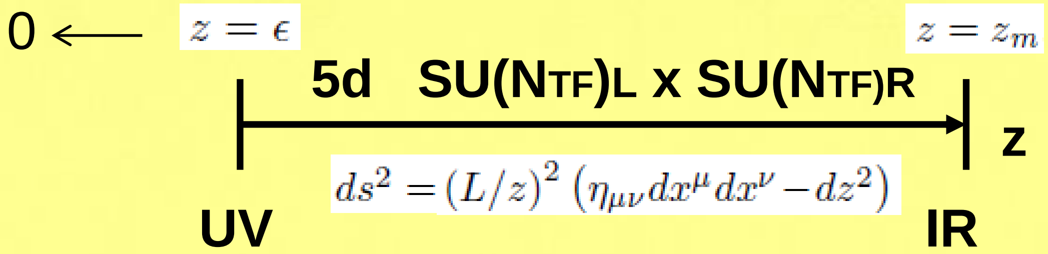
Haba-Matsuzaki-KY, PRD82 (2010) 055007
Matsuzaki- K.Y., PRD86 (2012) 115004 PPLB719 (2013) 115004

* **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



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

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

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
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 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

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

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

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

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

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

holographic-parameter free !!

Indep. of S
(S<0.1 tunable)

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

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

Weaker than SMH

This is consistent with ladder estimate:

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

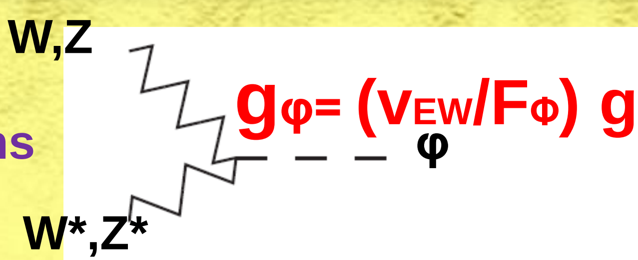
LHC best fit (before Moriond '13)

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

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

v.s. SM Higgs

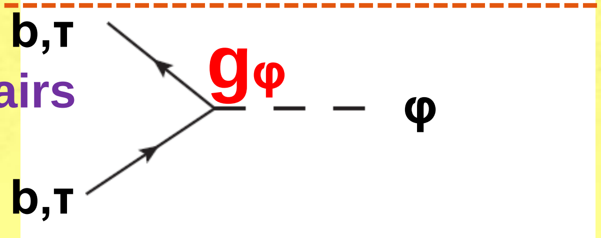
di-weak bosons



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

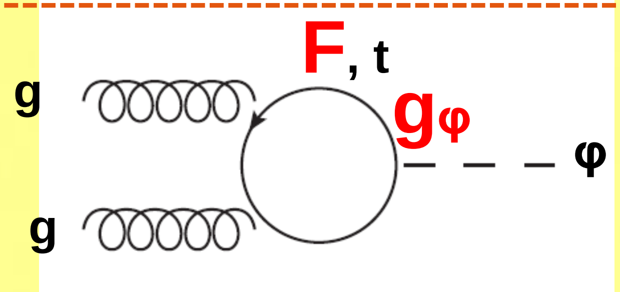
suppressed

quark, lepton pairs



suppressed

digluon

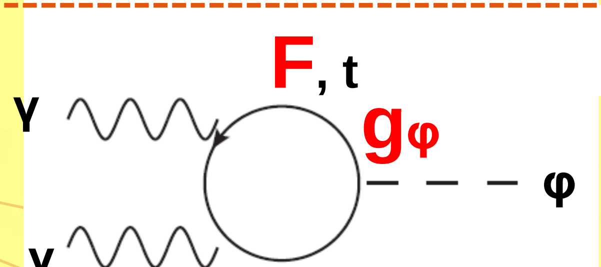


$\beta_F(g_s)$

enhanced

QCD-colored TF contributio

diphoton



$\beta_F(e)$

>> W -loops

enhanced

EM-charged TF contributio

Technifermion loop contributions to $g_{\phi gg}$ $g_{\phi\gamma\gamma}$

$N_{TC}=4$

1/3 10

$$\frac{g_{\phi gg}}{g_{h_{\rm SM}gg}} \simeq \frac{v_{\rm EW}}{F_\phi} \cdot ((3-\gamma_m) + 2N_{\rm TC}) \,,$$ 3

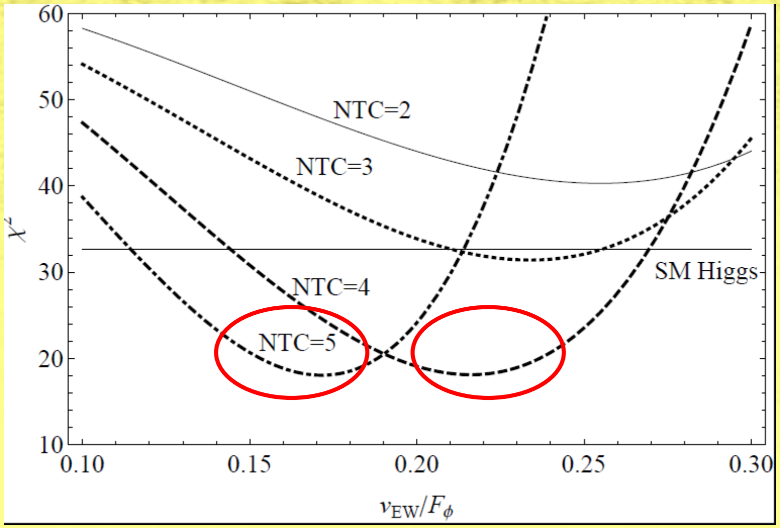
$$\frac{g_{\phi\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq \frac{v_{\rm EW}}{F_\phi} \cdot \left(\frac{63 - 16(3-\gamma_m)}{47} - \frac{32}{47} N_{\rm TC} \right)$$ <1

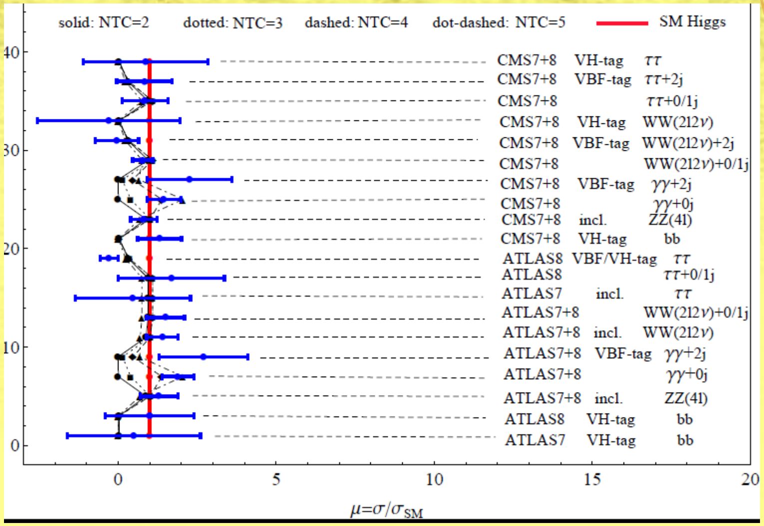
1 $(\gamma_m^t = 2)$

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

***updated after HCP2012**

S. Matsuzaki, 1304.4882





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

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!**

TD signal strengths ($\mu = \sigma \times BR$/SM Higgs) w/ NTC=4, vEW/Fφ = 0.2
vs the data *Moriond EW&QCD (ASPEN) March, 2013*

(i) ggF–tag

TD signal strength	ATLAS (significance)	CMS (significance)
$\mu^{\rm ggF}_{\gamma\gamma} \simeq 1.4$	$\simeq 1.6^{+0.4}_{-0.4}$ $(\sim 6\,\sigma)$	$\simeq 0.5^{+0.5}_{-0.5}$ $(\sim 3\,\sigma)$
$\mu^{\rm ggF}_{WW} \simeq 1.0$	$\simeq 0.8^{+0.4}_{-0.4}$ $(\sim 4\,\sigma)$	$\simeq 0.8^{+0.2}_{-0.2}$ $(\sim 4\,\sigma)$
$\mu^{\rm ggF}_{ZZ} \simeq 1.0$	$\simeq 1.8^{+0.8}_{-0.5}$ $(\sim 6\,\sigma)$	$\simeq 0.9^{+0.5}_{-0.4}$ $(\sim 6\,\sigma)$
$\mu^{\rm ggF}_{\tau\tau} \simeq 1.0$	$\simeq 2.1^{+[illegible]}_{-[illegible]}$ $(< 2\,\sigma)$	$\simeq 0.7^{+[illegible]}_{-0.5}$ $(\sim [illegible]\,\sigma)$

Distinguished from SM Higgs

(ii) VBF –tag

TD signal strength	ATLAS (significance)	CMS (significance)
$\mu^{\rm VBF}_{\gamma\gamma} \simeq 0.4$	$\simeq 1.7^{+0.9}_{-0.9}$ $(< 2\,\sigma)$ w/ VH	$\simeq 1.5^{+1.5}_{-1.1}$ $(< 2\,\sigma)$ w/ VH
$\mu^{\rm VBF}_{WW} \simeq 0.3$	$\simeq 1.7^{+0.8}_{-0.8}$ $(\sim 2\,\sigma)$	$\simeq 0.04^{+0.77}_{-0.57}$ $(< 2\,\sigma)$
$\mu^{\rm VBF}_{ZZ} \simeq 0.3$	$\simeq 1.2^{+3.8}_{-1.4}$ $(< 2\,\sigma)$ w/ VH	$\simeq 1.2^{+5.6}_{-5.6}$ $(< 2\,\sigma)$
$\mu^{\rm VBF}_{\tau\tau} \simeq 0.3$	$\simeq -0.4^{+3.0}_{-2.0}$ $(< 2\,\sigma)$ w/ VH	$\simeq 1.4^{+0.6}_{-0.6}$ $(< 2\,\sigma)$

(iii) VH –tag

TD signal strength	ATLAS (significance)	CMS (significance)
$\mu^{\rm VH}_{\gamma\gamma} \simeq 0.02$	$\simeq 1.8^{+1.5}_{-1.3}$ $(< 2\,\sigma)$ w/ VBF	$\simeq 1.5^{+1.5}_{-1.1}$ $(< 2\,\sigma)$ w/ VBF
$\mu^{\rm VH}_{WW} \simeq 0.01$	N/A	$\simeq -0.3^{+2.3}_{-2.0}$ $(< 2\,\sigma)$
$\mu^{\rm VH}_{ZZ} \simeq 0.01$	$\simeq 1.2^{+3.8}_{-1.4}$ $(< 2\,\sigma)$ w/ VBF	N/A
$\mu^{\rm VH}_{\tau\tau} \simeq 0.01$	$\simeq -0.4^{+3.0}_{-2.0}$ $(< 2\,\sigma)$ w/ VBF	$\simeq 0.8^{+1.5}_{-1.4}$ $(< 2\,\sigma)$
$\mu^{\rm VH}_{bb} \simeq 0.01$	$\simeq -0.4^{+1.0}_{-1.0}$ $(< 2\,\sigma)$	$\simeq 1.3^{+0.7}_{-0.6}$ $(\sim 2\,\sigma)$

Theoretical Issues

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

$$F_\pi,\ F_\phi,\ M_\phi,\ M_\rho, M_{a_1}, M_{\rm baryon},\ etc.$$
$$S, T, U - \text{Parameters}$$

Lattice !

Discovering Walking Technicolor on the Lattice

KMI Lattice Project (LatKMI Collaboration)

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

LatKMI collaboration members

KMI

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








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

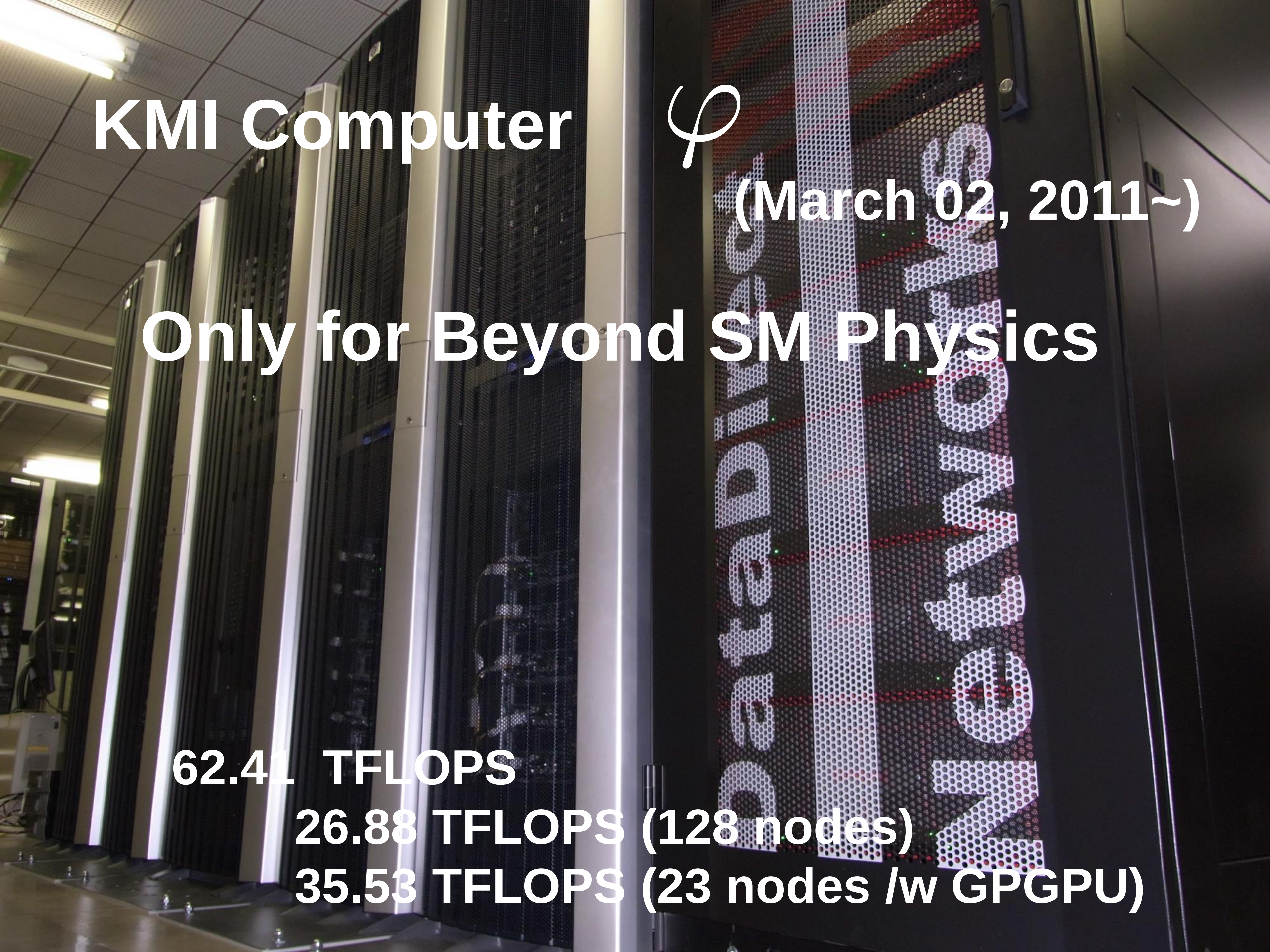
名古屋大学

E. Rinaldi

THE UNIVERSITY OF EDINBURGH

A. Shibata

KEK



KMI Computer φ

(March 02, 2011~)

Only for Beyond SM Physics

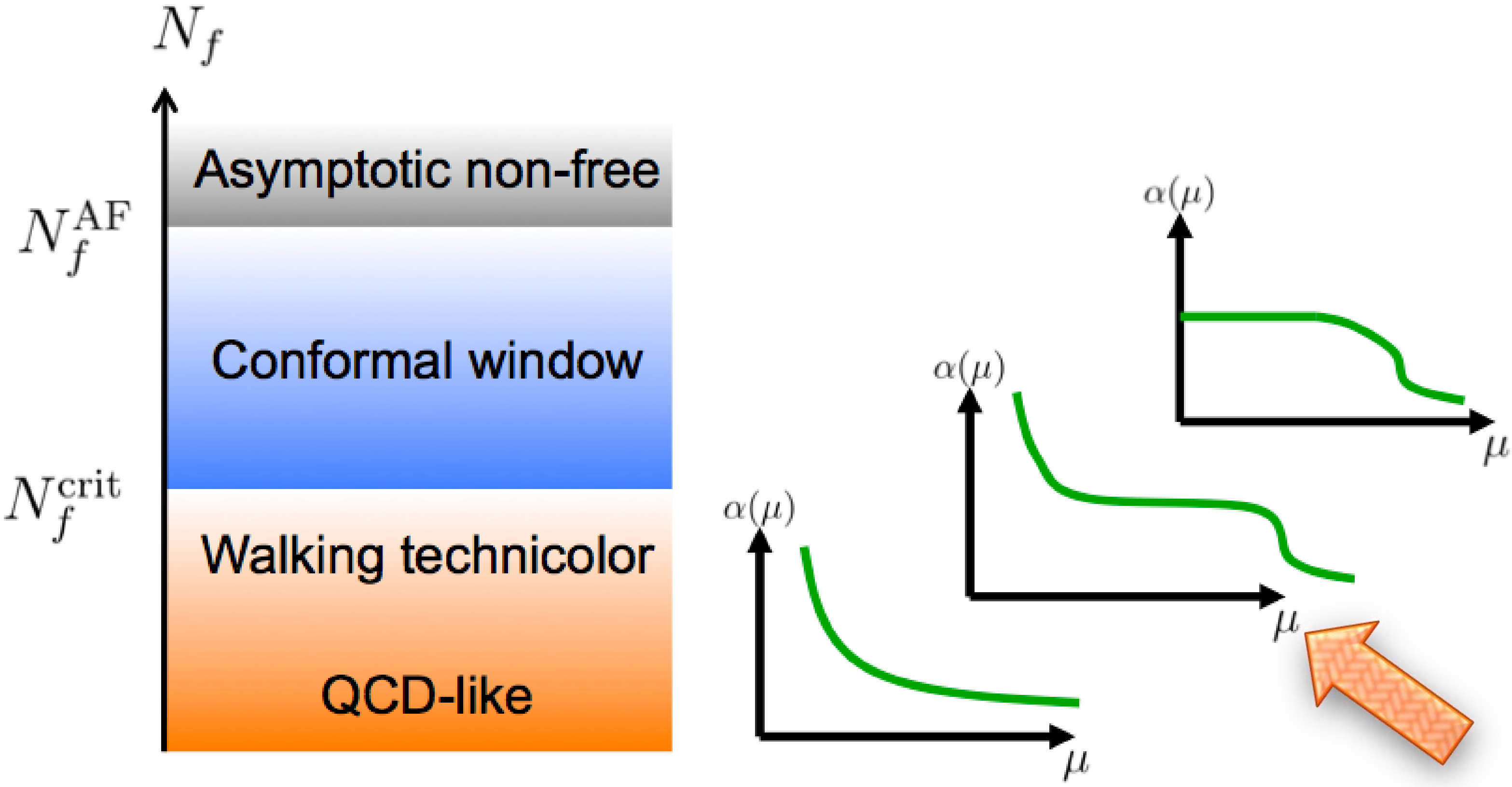
62.41 TFLOPS

26.88 TFLOPS (128 nodes)

35.53 TFLOPS (23 nodes /w GPGPU)

$SU(3);\ N_c = 3$

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



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

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

Recent study of LatKMI Collaboration

LatKMI Collaboration, PRD86, 054506 (2012); D87, 094511 (2013); arXiv:1305.6006

Unique setup for all N_f: Improved staggered action (HISQ/Tree)

Cheapest calculation cost in lattice fermion actions

+ small a systematic error

Simulation parameters

- $\beta \equiv 6/g^2 \rightarrow$ lattice spacing a
- $L, T \sim O(10)$
- $m_f \neq 0 \rightarrow$ IR scales $m_f \gg 1/L$

Large enough L at each m_f: $m_\pi L \gtrsim 6$ ($\gtrsim 4$ in $N_f = 4$)

N_f	β	$L^3 \times T$	m_f
4	3.7	$12^3 \times 18$–$20^3 \times 30$	0.005–0.05
8	3.8	$18^3 \times 24$–$36^3 \times 48$	0.015–0.16
12	3.7	$18^3 \times 24$–$30^3 \times 40$	0.04–0.2
12	4.0	$18^3 \times 24$–$30^3 \times 40$	0.05–0.2

Machines: φ at KMI, CX400 at Kyushu Univ.

Walking candidate & Scalar

- Nf=8 : Walking, $\gamma_m = 0.62 - 0.97$

  LatKMI Collaboration, Phys. Rev. D 87, 094511 (2013).

- Nf=12: Conformal $\gamma_m = 0.4 - 0.5$

  LatKMI Collaboration, Phys. Rev. D86, 054506 (2012)

- Light flavor-singlet scalar (& scalar glueball) in Nf=12

  LatKMI Collaboration, (arXIv: 1302.4577), arXiv:1305.6006

- Light flavor-singlet scalar (& scalar glueball) in Nf=8 (Very Preliminary)

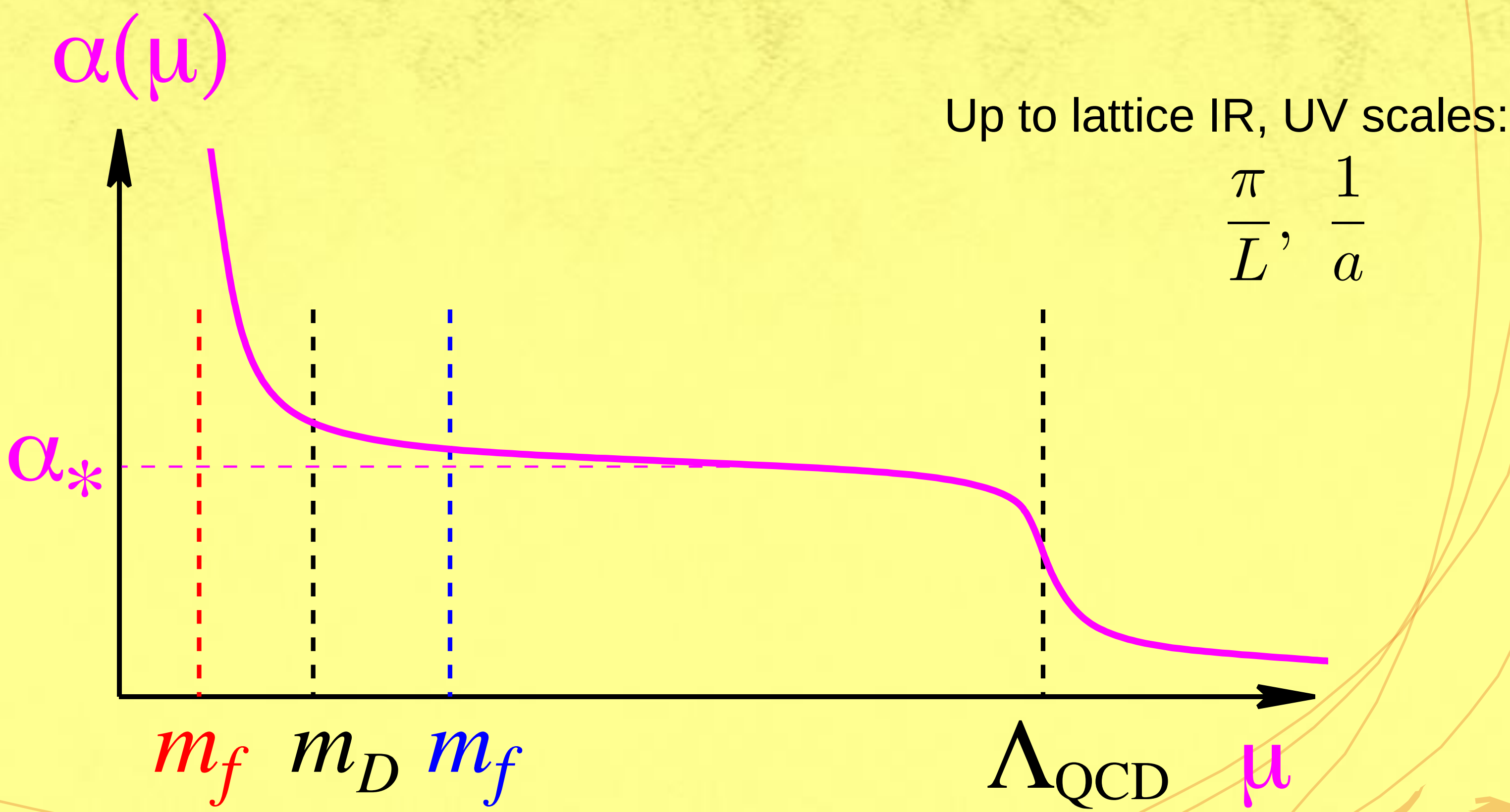
$N_f = 8$

PHYSICAL REVIEW D **87**, 094511 (2013)

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]

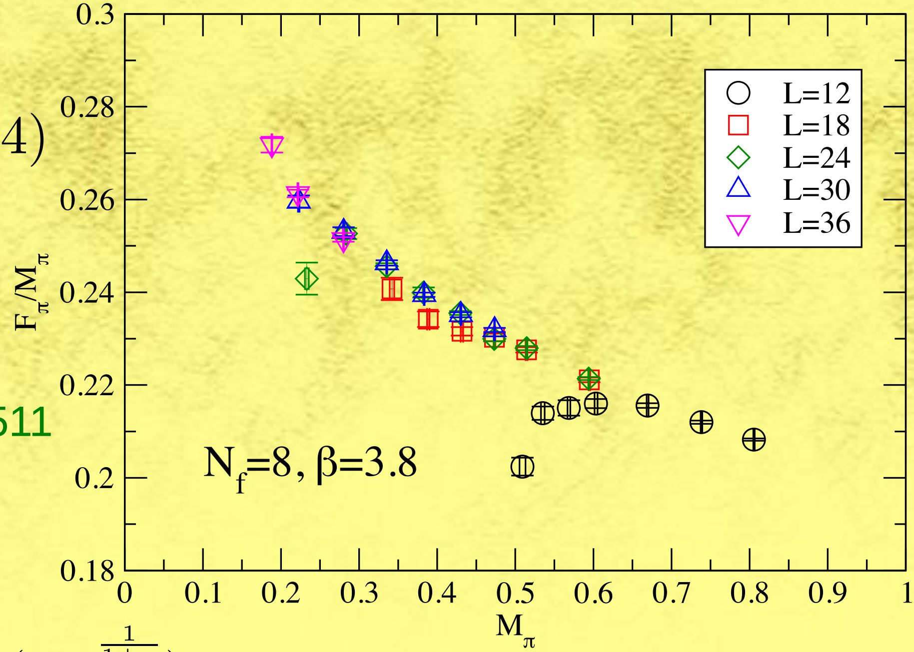
(LatKMI Collaboration)



ChPT $\quad \xi_H \equiv L M_H = f_H(L m_f^{\frac{1}{1+\gamma}})$

ChPT

$(m_f = 0.015 - 0.04)$

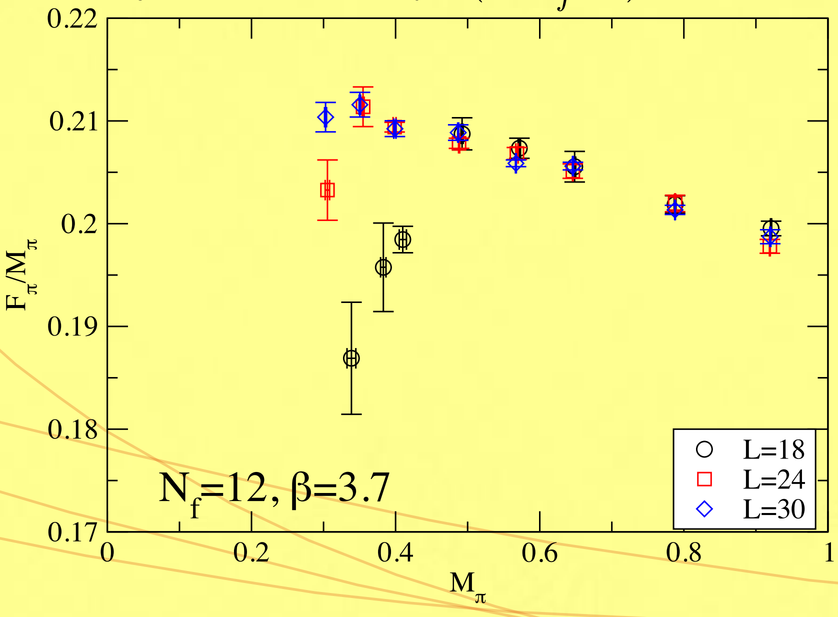


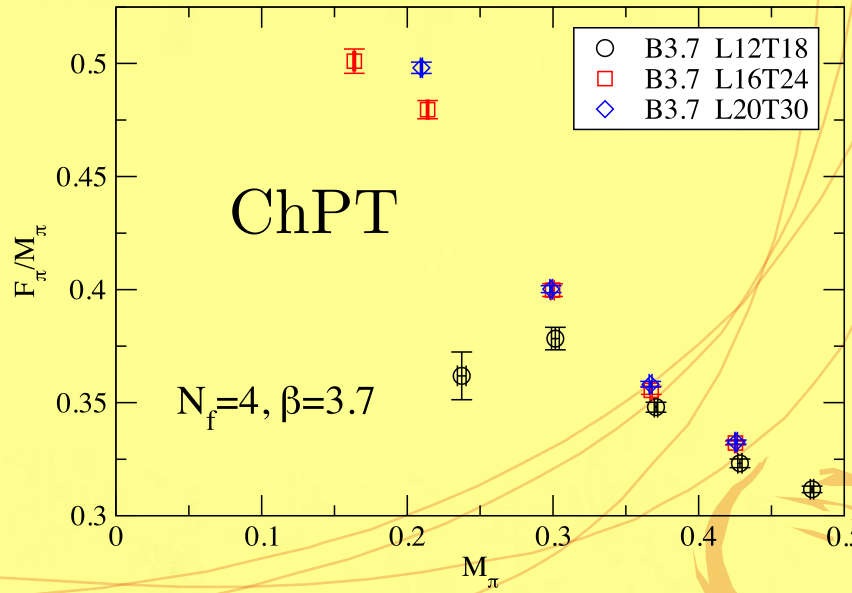
$\xi_H \equiv LM_H = f_H(Lm_f^{\frac{1}{1+\gamma}})$

$(m_f = 0.05 - 0.16)$

LatKMI Coll, PRD 87, 094511 (2013)

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





LatKMI Coll, PRD86 (2012)054506

LatKMI Coll, PRD 87, 094511 (2013)

$N_f = 8$

PHYSICAL REVIEW D **87,** 094511 (2013)

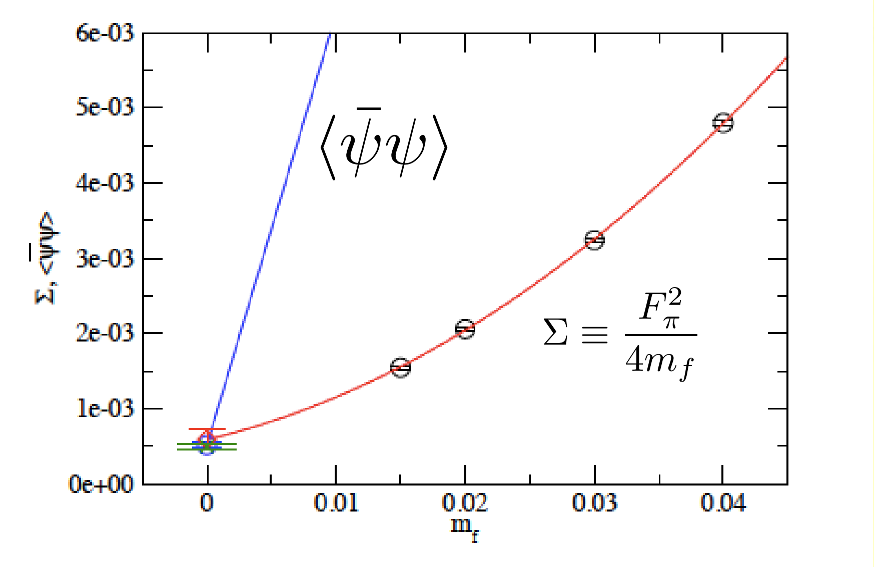
Walking signals in $N_f = 8$ QCD on the lattice

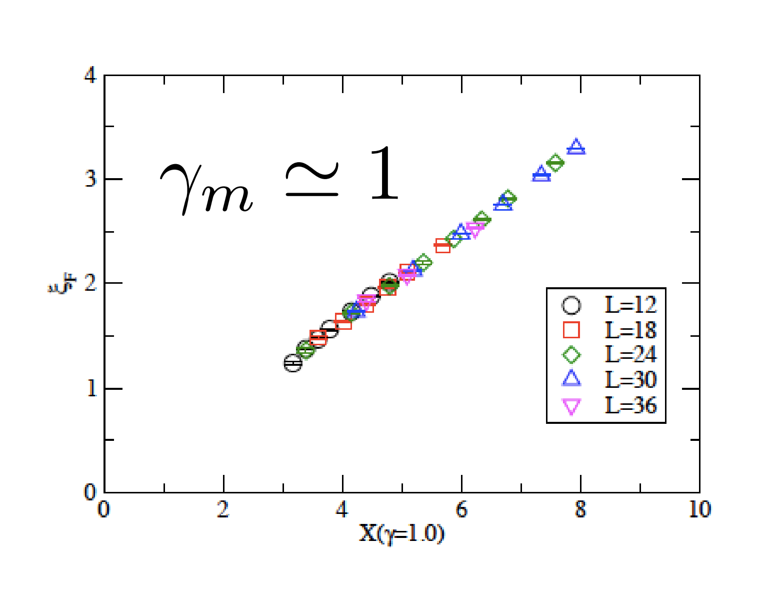
Yasumichi Aoki,[1] Tatsumi Aoyama,[1] Masafumi Kurachi,[1] Toshihide Maskawa,[1] Kei-ichi Nagai,[1] Hiroshi Ohki,[1] Akihiro Shibata,[2] Koichi Yamawaki,[1] and Takeshi Yamazaki[1]

(LatKMI Collaboration)

HISQ $\beta = 3.8$ $L = 12, 18, 24, 30\ (T/L = 4/3)$

SχSB $m_f = 0.015 - 0.04$ ``Conformal'' $m_f = 0.05 - 0.16$

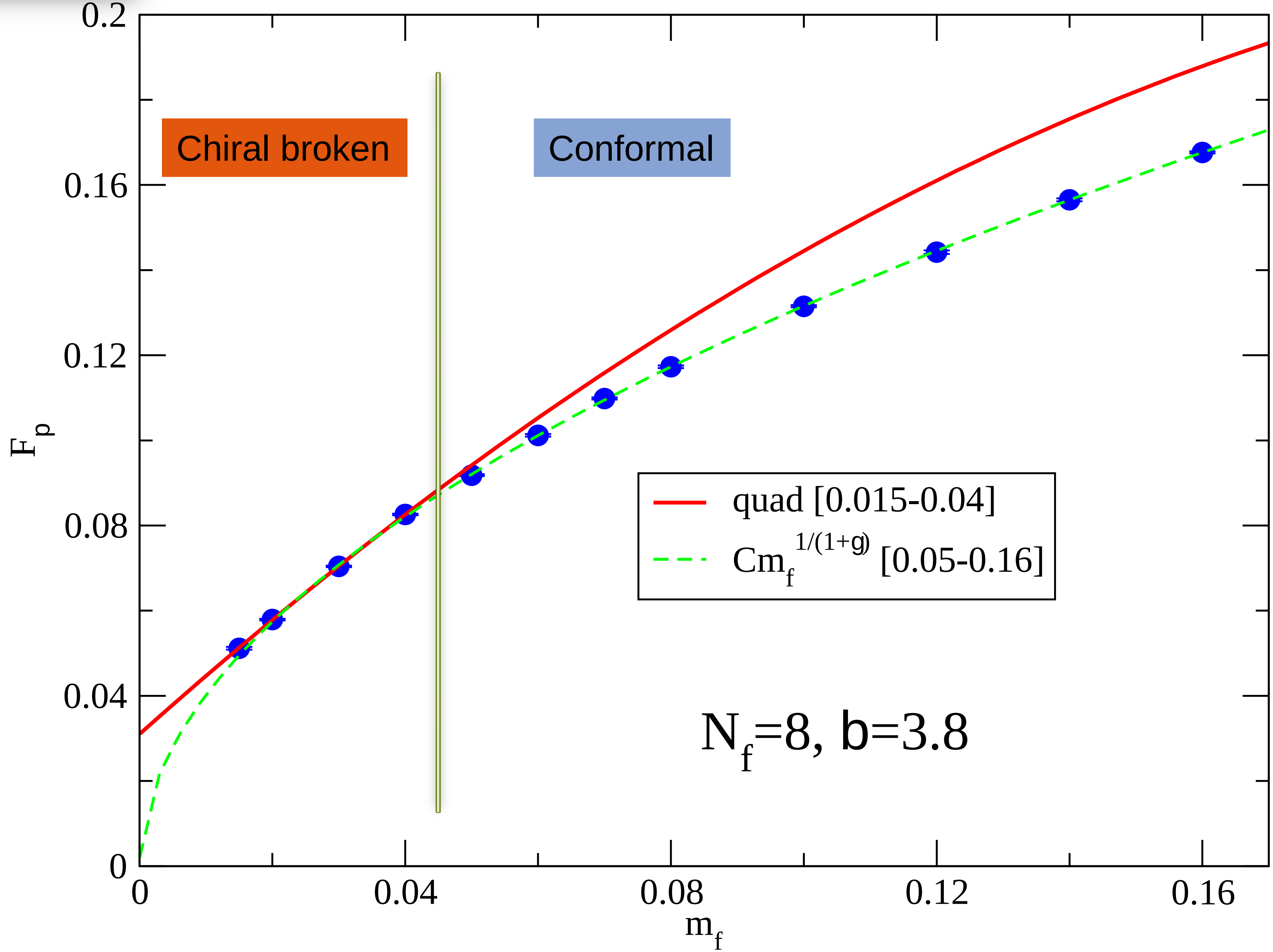




$F_\pi \to\neq 0, M_\pi \to 0, M_\rho \to\neq 0$ at $m_f \to 0$

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

$N_f = 8$



Chiral broken
Conformal
quad [0.015-0.04]
Cm_f^{1/(1+g)} [0.05-0.16]
N_f=8, b=3.8
F_p
m_f
0.2
0.16
0.12
0.08
0.04
0
0
0.04
0.08
0.12
0.16

$N_f = 8$

Nf=8 data

Hyperscaling relation is not for a universal γ_m

$$\gamma(M_\pi) \simeq 0.57, \gamma(F_\pi) \simeq 0.93, \gamma(M_\rho) \simeq 0.80$$

After corrections

$$\gamma \simeq 0.62 - 0.97$$

Universal value (up to correction ansatz)

For large m_f Corrections such as higher power of m_f

Cf: SD equation in the conformal phase $\alpha < \alpha_{\rm cr} \; (N_f > N_f^{\rm cr})$

$$\frac{m_f}{\Lambda} = \xi \left[\frac{\Gamma(1-\gamma_m^*)}{\Gamma(\frac{2-\gamma_*}{2})^2} \left(\frac{m_P}{\Lambda} \right)^{1+\gamma_m^*} + \frac{\Gamma(-1+\gamma_m^*)}{\Gamma(\frac{\gamma_*}{2})^2} \left(\frac{m_P}{\Lambda} \right)^{3-\gamma_m^*} \right].$$

LatKMI Collaboration, Phys. Rev. D85, 074502 (2012)

$N_f = 12$ **Scalar**

Light composite scalar in twelve–flavor QCD on the lattice

Yasumichi Aoki,[1] Tatsumi Aoyama,[1] Masafumi Kurachi,[1] Toshihide Maskawa,[1] Kei-ichi Nagai,[1]
Hiroshi Ohki,[1] Enrico Rinaldi,[1,2] Akihiro Shibata,[3] Koichi Yamawaki,[1] and Takeshi Yamazaki[1]
(LatKMI collaboration)

(arXIv: 1302.4577), arXiv:1305.6006

Nf=12,
β=4.0

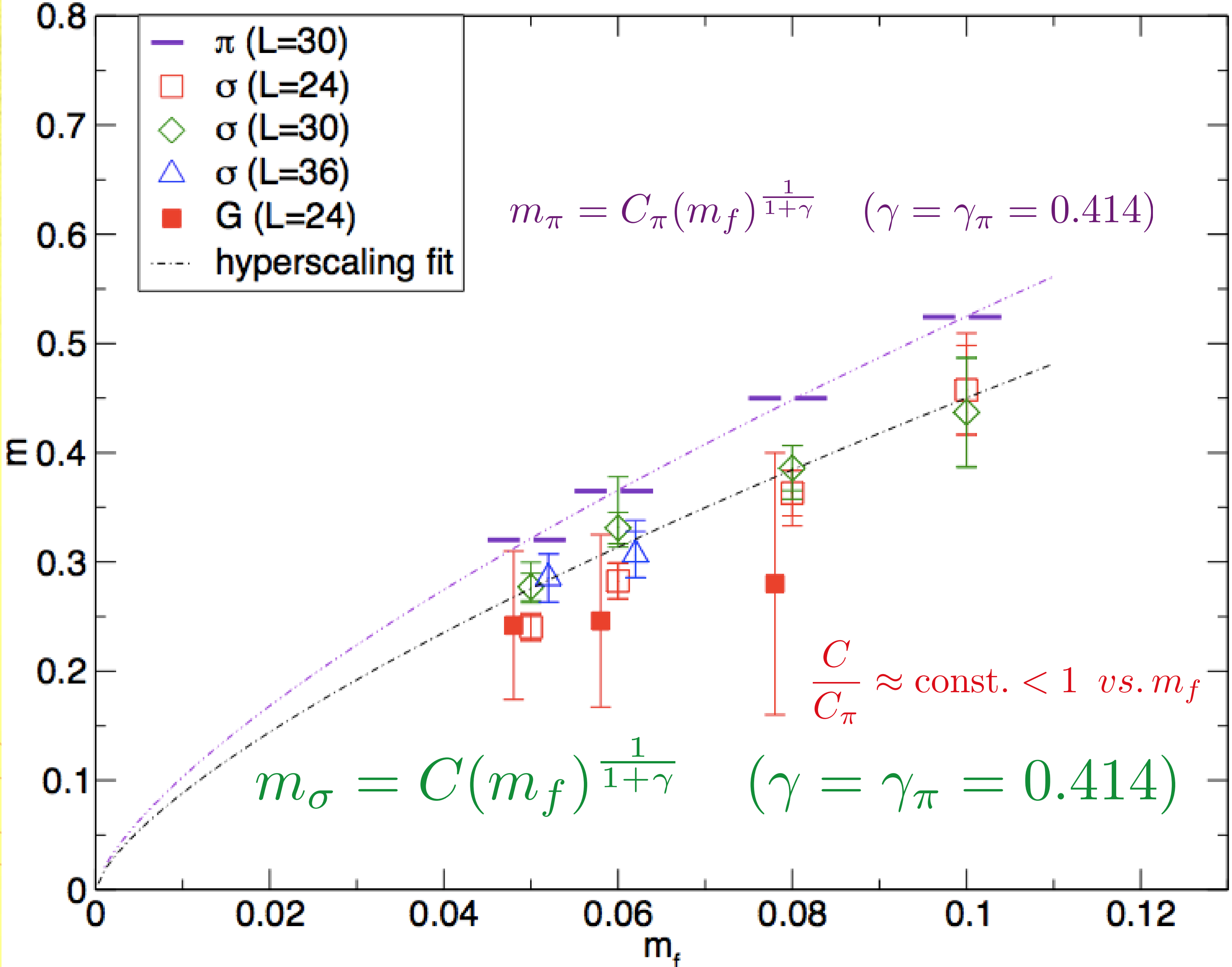
Noise reduction method with Nr=64

$L^3 \times T$	m_f	$N_{\rm cfgs}$	m_σ	m_π	m_σ/m_π
$24^3 \times 32$	0.05	8800	$0.250(15)(^{00}_{01})$	$0.3273(19)^*$	$0.76(5)(^{0}_{0})$
$24^3 \times 32$	0.06	14000	$0.283(16)(^{04}_{01})$	$0.3646(16)^*$	$0.78(4)(^{1}_{0})$
$24^3 \times 32$	0.08	15000	$0.363(21)(^{02}_{22})$	$0.4459(11)$	$0.81(5)(^{0}_{5})$
$24^3 \times 32$	0.10	9000	$0.458(41)(^{32}_{06})$	$0.5210(7)$	$0.88(8)(^{6}_{1})$
$30^3 \times 40$	0.05	8000	$0.284(15)(^{24}_{09})$	$0.3201(16)^*$	$0.89(5)(^{7}_{3})$
$30^3 \times 40$	0.06	14000	$0.337(15)(^{51}_{12})$	$0.3648(9)^*$	$0.92(4)(^{14}_{3})$
$30^3 \times 40$	0.08	15000	$0.386(21)(^{00}_{20})$	$0.4499(8)$	$0.86(5)(^{0}_{4})$
$30^3 \times 40$	0.10	4000	$0.437(50)(^{07}_{09})$	$0.5243(7)$	$0.83(9)(^{1}_{2})$
$36^3 \times 48$	0.05	5000	$0.285(22)(^{00}_{03})$	$0.3204(7)^*$	$0.89(7)(^{0}_{1})$
$36^3 \times 48$	0.06	6000	$0.307(21)(^{23}_{04})$	$0.3636(9)^*$	$0.84(6)(^{6}_{1})$

$N_f = 12$

LatKMI Collaboration, arXiv:1305.6006

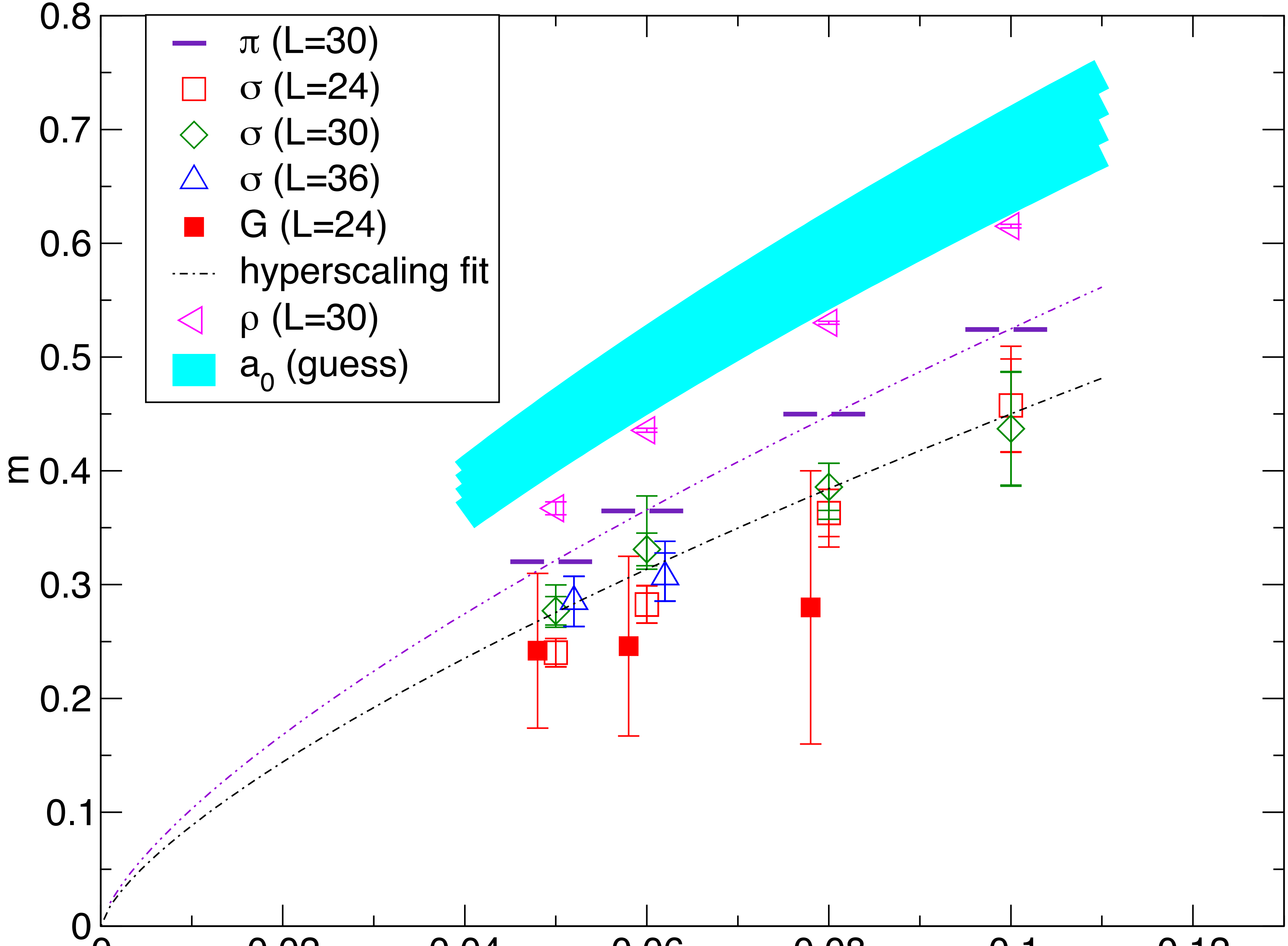
Scalar



$N_f = 12$

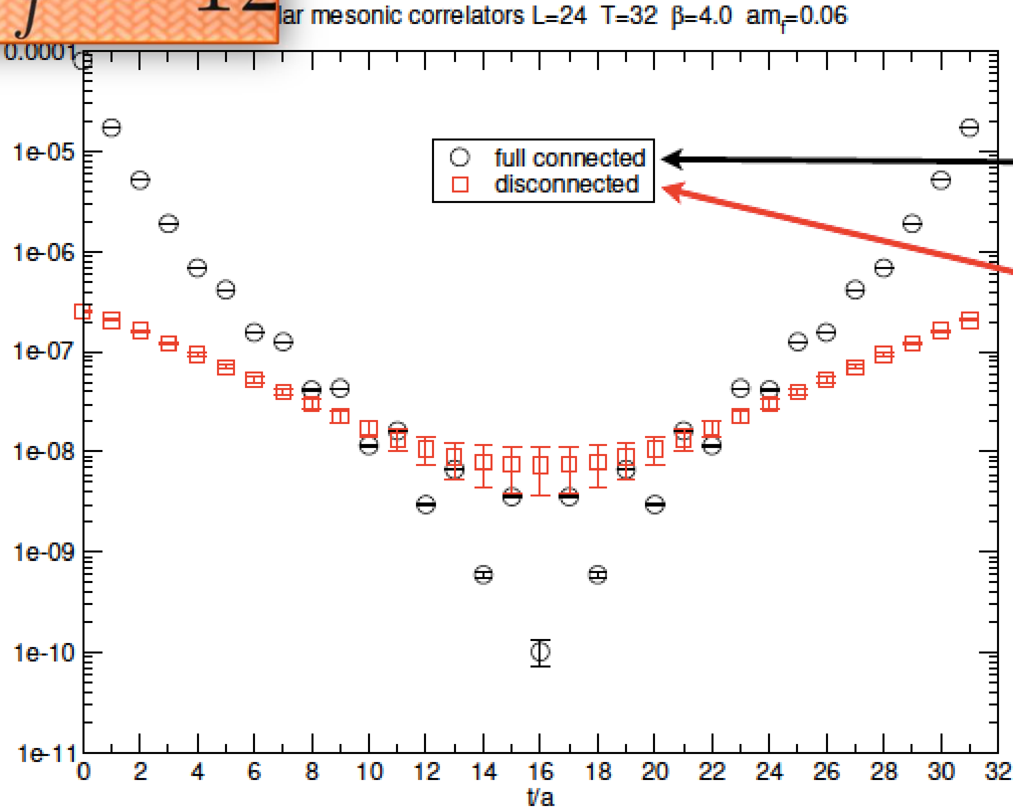
LatKMI Collaboration, arXiv:1305.6006

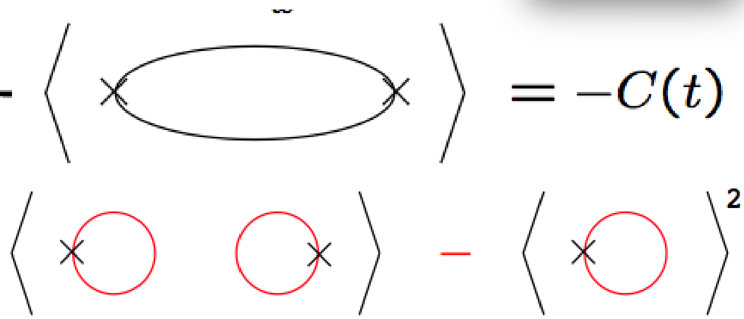
Scalar



$N_f = 12$

Scalar

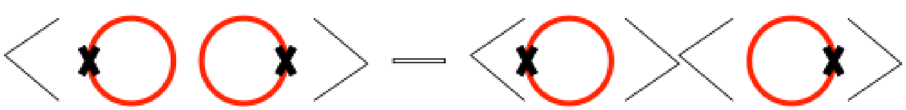




- connected and disconnected correlator measured on 14000 configurations
- 64 stochastic gaussian sources used for the disconnected piece on each configuration
- 2 stochastic gaussian sources used for the connected piece on each configuration

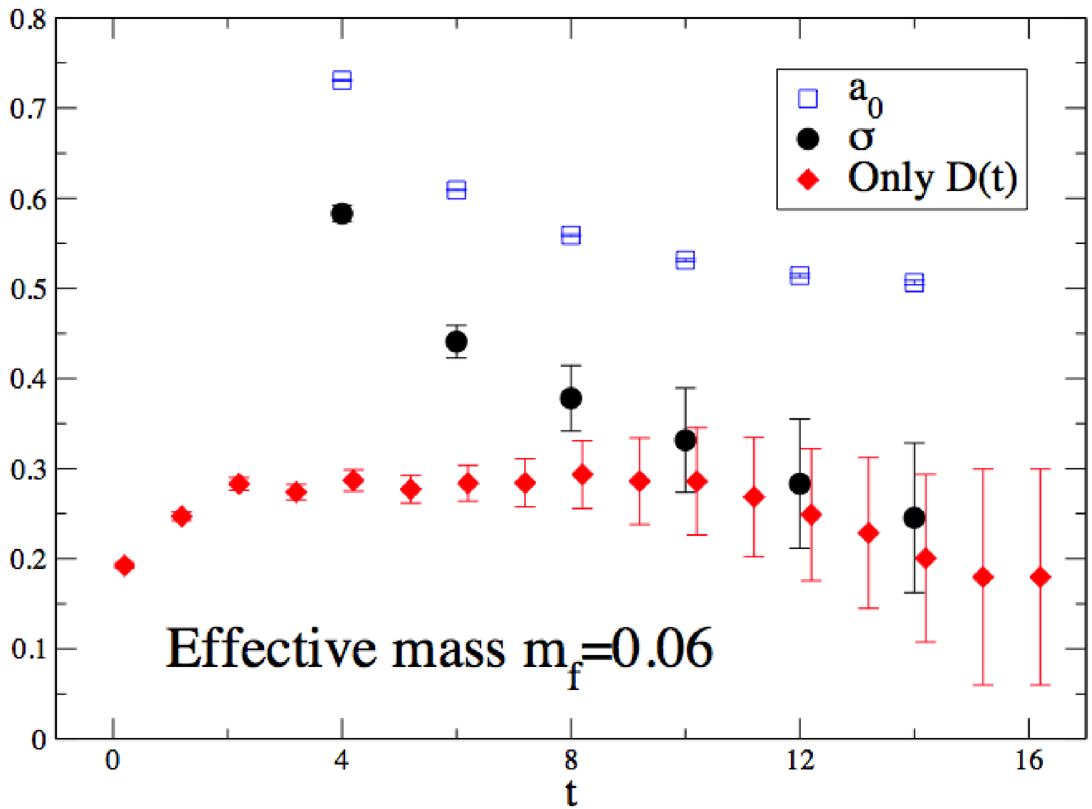
$$C_\sigma(t) = \langle \sum_i^{N_f} \bar{\psi}_i\psi_i(t) \sum_j^{N_f} \bar{\psi}_j\psi_j(0)\rangle = N_f(-C(t) + \underline{N_f} D(t))$$

$$\mathcal{O}_F(t) \equiv \bar{\psi}_i\psi_i(t), \qquad D(t) = \langle \mathcal{O}_F(t)\mathcal{O}_F(0)\rangle - \langle \mathcal{O}_F(t)\rangle\langle \mathcal{O}_F(0)\rangle$$



Effective mass in $N_f = 12$ ($m_f = 0.06, 24^3 \times 32$ with $N_{\text{conf}} = 14000$, Preliminary)

$$m_{\text{eff}}(t) = \log(C_H(t)/C_H(t+1)) \xrightarrow{t \gg 1} m_H$$



Nonsinglet scalar

a_0: $-C_+(2t)$

Singlet scalar

$\sigma : 3D_+(2t) - C_+(2t)$

$m_\sigma < m_{a_0}$

Only $D(t)$

Consistent m_σ

Smaller error

$$X_+(2t) = 2X(2t) + X(2t+1) + X(2t-1)$$

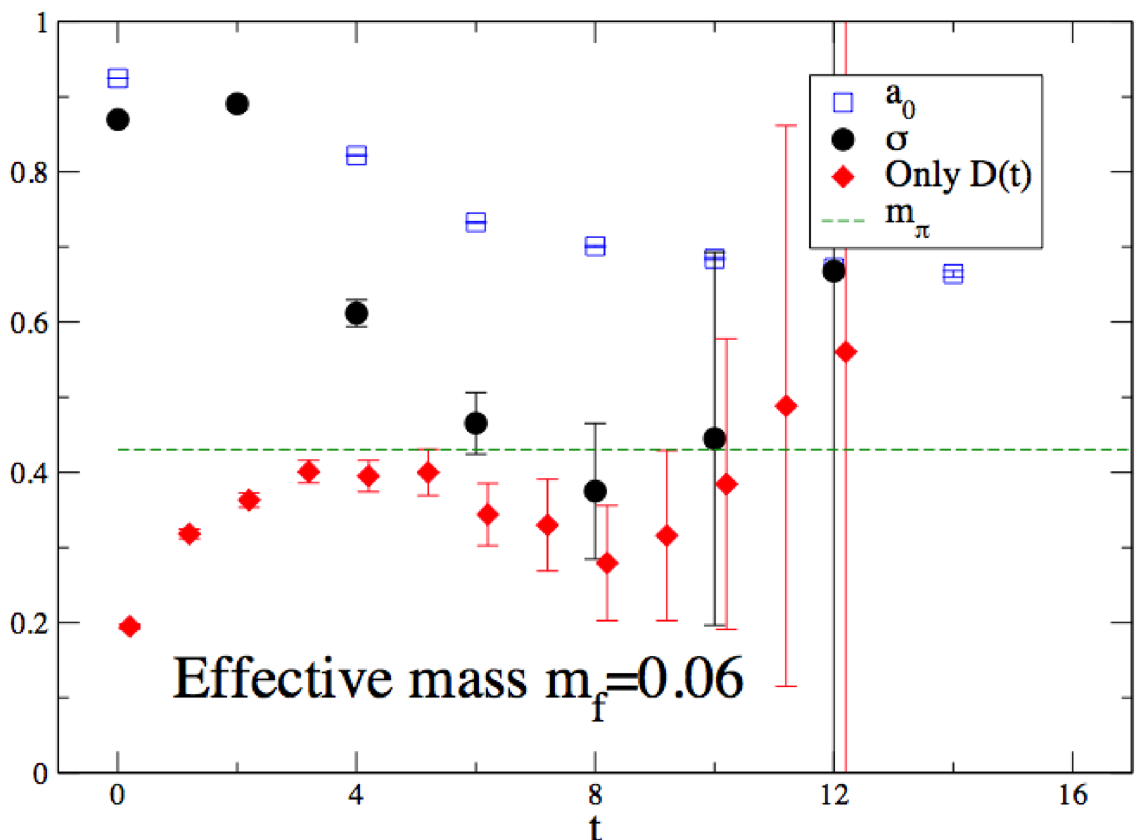
Good signal of m_σ from $D(t)$

$N_f = 8$ Very Preliminary Scalar

Nf=8 β=3. 8

L, T	m_f	confs
24,32	0.06	7600

Noise reduction with Nr=64



Nonsinglet scalar

a_0: $-C_+(2t)$

Singlet scalar

$\sigma : 3D_+(2t) - C_+(2t)$

$m_\sigma \lesssim m_\pi < m_{a_0}$

$F_\pi \sim 0.1$ at $m_f = 0.06$

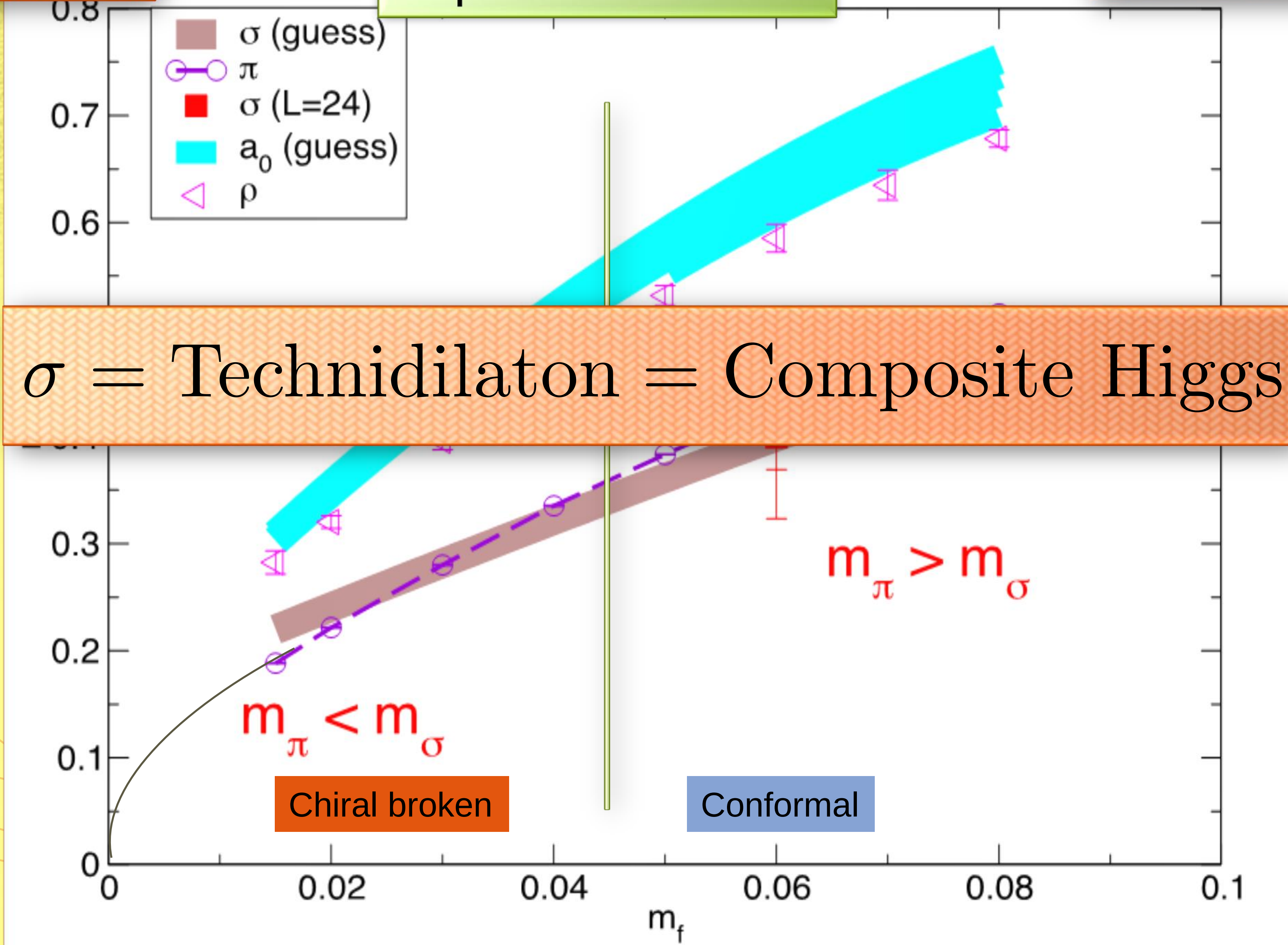
$X_+(2t) = 2X(2t) + X(2t+1) + X(2t-1)$

$m_\sigma \lesssim m_\pi$ at $m_f = 0.06$

$N_f = 8$

Expected Picture

Scalar



σ = Technidilaton = Composite Higgs

Conclusion

- A light composite Higgs can be generated in the Walking Technicolor (Strongly coupled theory) as a Pseudo-NG boson of Scale Symmetry (Techni-dilaton), which is Weakly coupled to the SM particles.
- Techni-dilaton is consistently identified with the 125 GeV Higgs
- Lattice results of LatKMI Collaboration are consistent with

  Nf=12 QCD: conformal behavior

  Nf=8 QCD : walking behavior; chiral broken (mf=0.015-0.04),

  (approx.) conformal (mf =0.05-0.16)
- Lattice results of LatKMI Collaboration observed

  Nf=12: clean signal of a scalar lighter than pion

  Nf=8: indication of a scalar slightly lighter than pion (just for one parameter mf=0.06) (Very preliminary)

  Both reflecting (near) conformality for a wide IR region below the asymptotically free UV region

Hope to give the lattice answer to the theoretical issues before 13/14 TeV LHC

Backup Slides

☆ Other characteristic spectrum in one-family WTC

Chiral symmetry breaking: SU(8)L x SU(8)R → 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)

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

$P^{\pm,3,0}$: 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

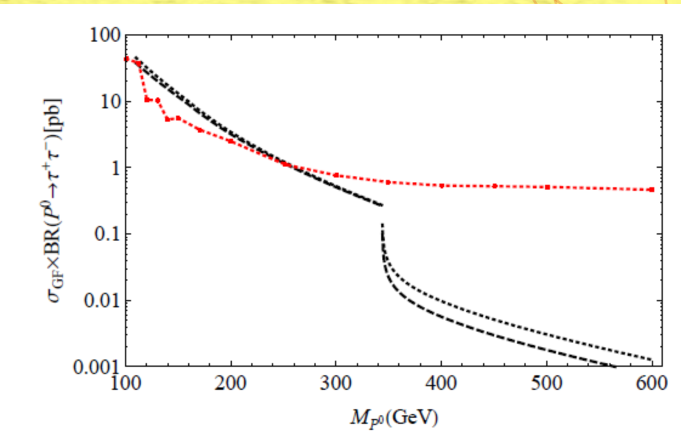
J.Junji, S.Matsuzaki, K.Y.,
PRD87.016006. (2012)

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

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

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

Discovering isospin singlet TPs: P^0 and θ^0_a

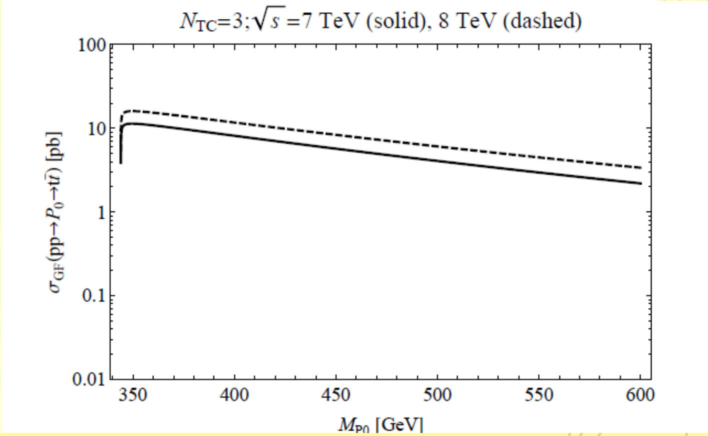


* **produced ONLY from ggF :**
  ~~VBF, VH,~~
* **Predominantly decaying to SM fermions**

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

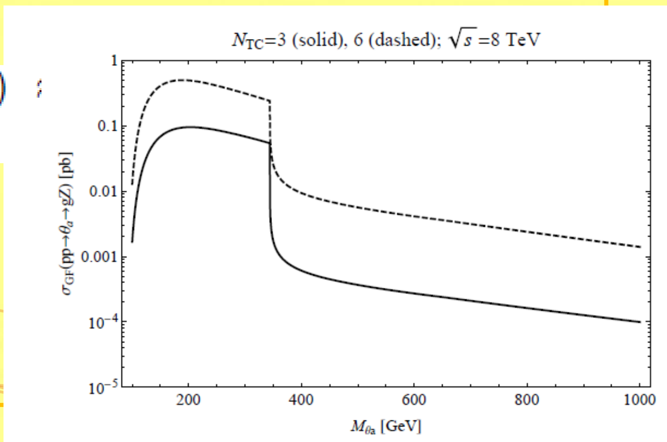


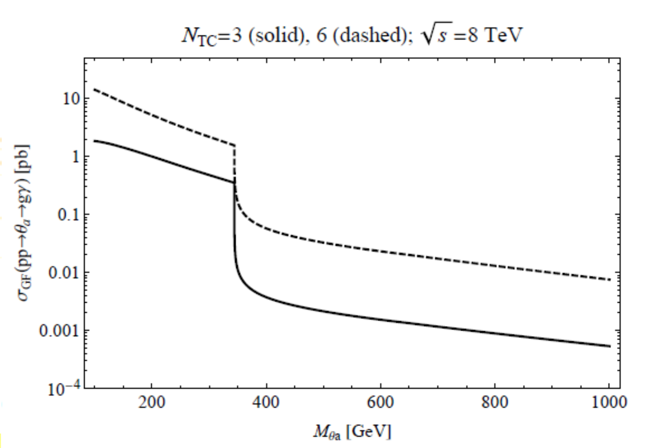
* **decays to glue-gamma/Z**

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

~ 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]

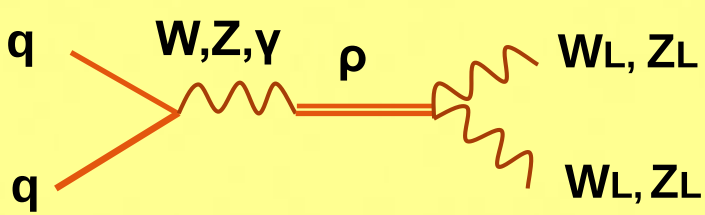
Expected masses :

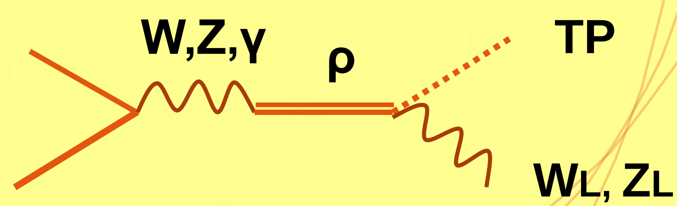
1 ～ 4 TeV

consistent w/
EW precision tests

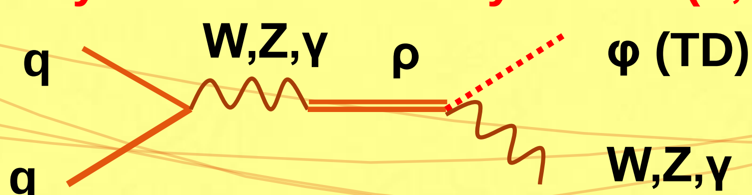
S.Matsuzaki and K.Y., PRD86.115004. (2012)

- **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

* AdS/CFT recipe:

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

classical solutions

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

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

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

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

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

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:**

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

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

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

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

Π_S Leading log term

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

Π_V G^2 term

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

Fix

3 phenomenological input values

F_π = 246 GeV/√N_D = 123 GeV (1FM)

M_Φ = 125 GeV

S = 0.1

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 m_F	: 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 m_F	: 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 m_F	: m_F = 0.85 TeV

Other pheno. issues in TC scenarios

S parameter

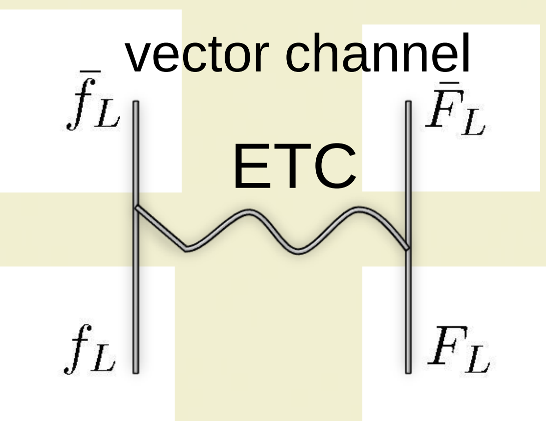
$$S \approx N_D \cdot \frac{8\pi F_\pi^2}{M_\rho^2} \simeq \underline{0.3 \cdot N_D} \qquad \text{(for QCD-like)}$$

N_D : # EW doublets

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

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

vector channel



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

Chivukula-Simmons-He-Kurachi-Tanabashi (2005)

in low-energy

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

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

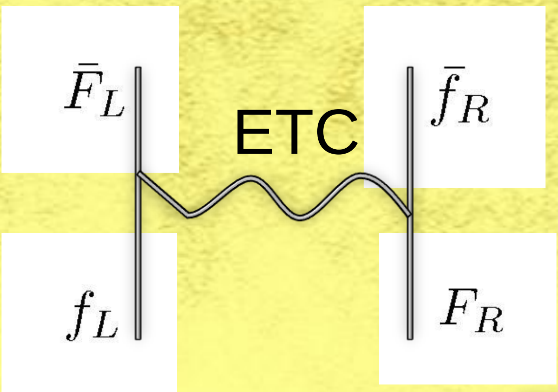
$$\ni g_W W_\mu - g_Y B_\mu$$ modifies SM f-couplings to W, Z

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

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

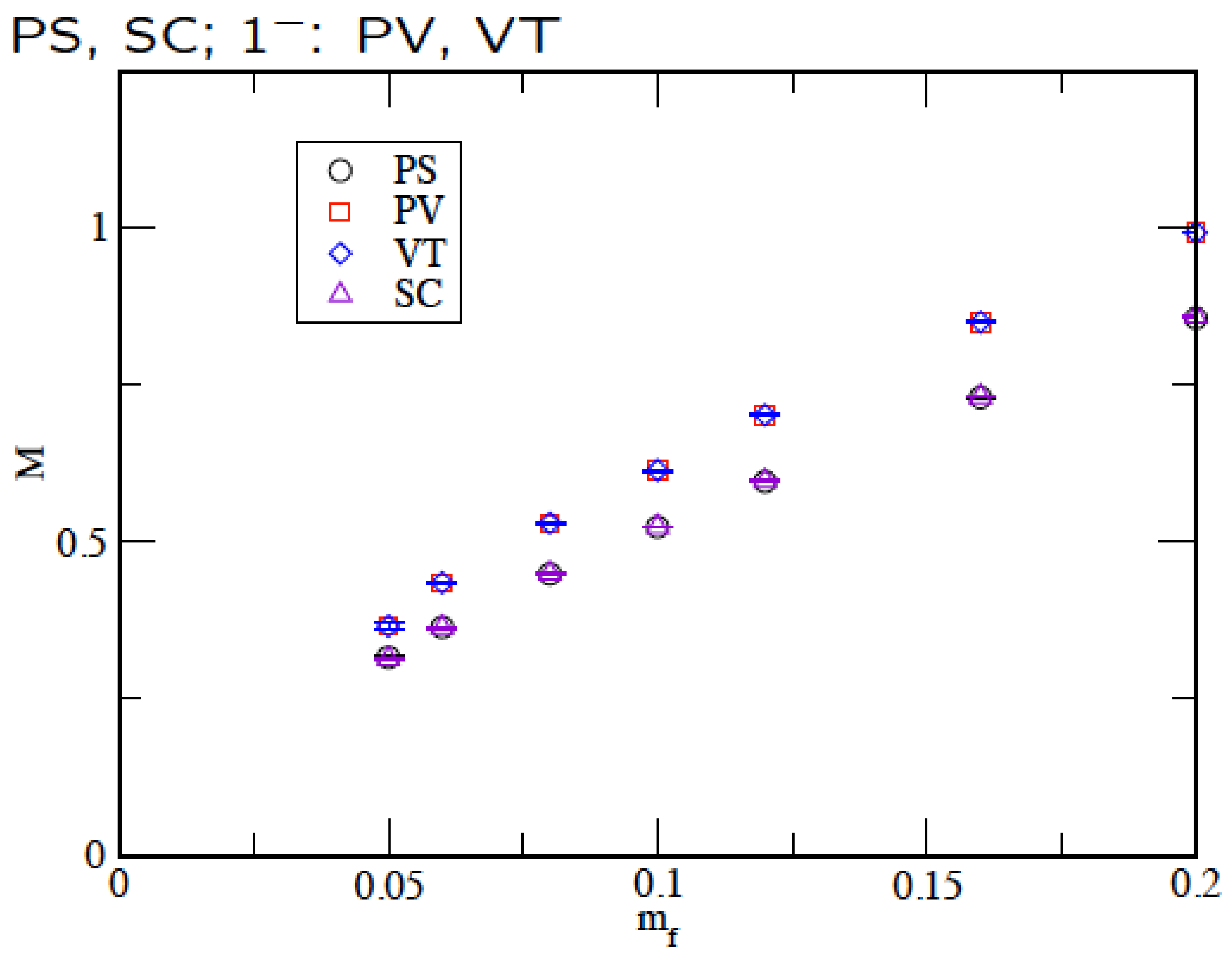
T parameter (Strong) ETC generates large isospin breaking

→ highly model-dependent issue

$N_f = 12$

Nf=12 Taste Symmetry（HISQ）

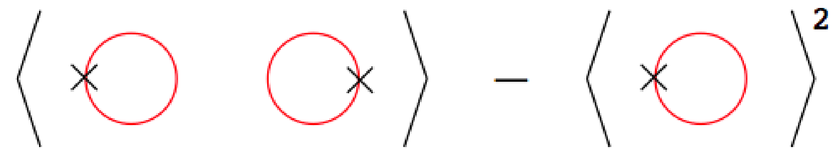
LatKMI Collaboration, PRD86 (2012)054506

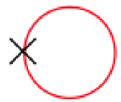


Difficulty

Flavor – singlet scalar

$\langle 0|S(t)S^{\dagger}(0)|0\rangle, \quad S(t) = \sum_{\vec{x}} \overline{\psi}_a(\vec{x},t)\psi_a(\vec{x},t)$

$D(t) =$ 

1.  $= \mathrm{Tr}\left[\psi(x)\overline{\psi}(x)\right] = \mathrm{Tr}\left[D^{-1}[U](x,x)\right]$ at each U

$O(L^3 \times T)$ $D^{-1}[U]$ in naive mehtod

$O(1000)$ $D^{-1}[U]$ in simple mehtod

$\rightarrow O(100)$ $D^{-1}[U]$ in noise reduction method

(Kilcup and Sharpe;NPB283(1987)493, Venkataraman and Kilcup;hep-lat/9711006)

2. $\langle$Large + small$\rangle$ − $\langle$Large$\rangle$ = $\langle$small$\rangle$ + (stat. error)

$\langle$small$\rangle$: $\exp(-m_\sigma t)$; stat. error: independent of t

$\rightarrow O(10000)$ configuration

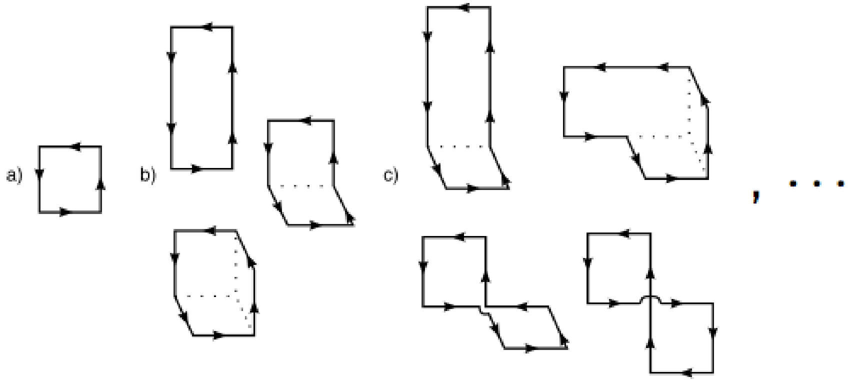
Reduce calculation cost and use huge N_{conf}

Flavor-singlet state from Glueball operator

no EW charge

Flavor-singlet scalar (0^{++}glueball) operator from U

$$O_i = $$



$$\langle 0|O_i(t)O_j^\dagger(0)|0\rangle - \langle 0|O_i|0\rangle\langle 0|O_j^\dagger|0\rangle, \quad i,j = a,b,c$$

Same difficulty as meson operator $\to$ Huge statistical noise

Noise reduction techniques (Lucini, Rago, Rinaldi;JHEP08(2010)119)

- Fatting link
- Large size operator
- Diagonalization of correlation function matrix

Same m_σ is obtained from meson and glueball correlators, in principle.

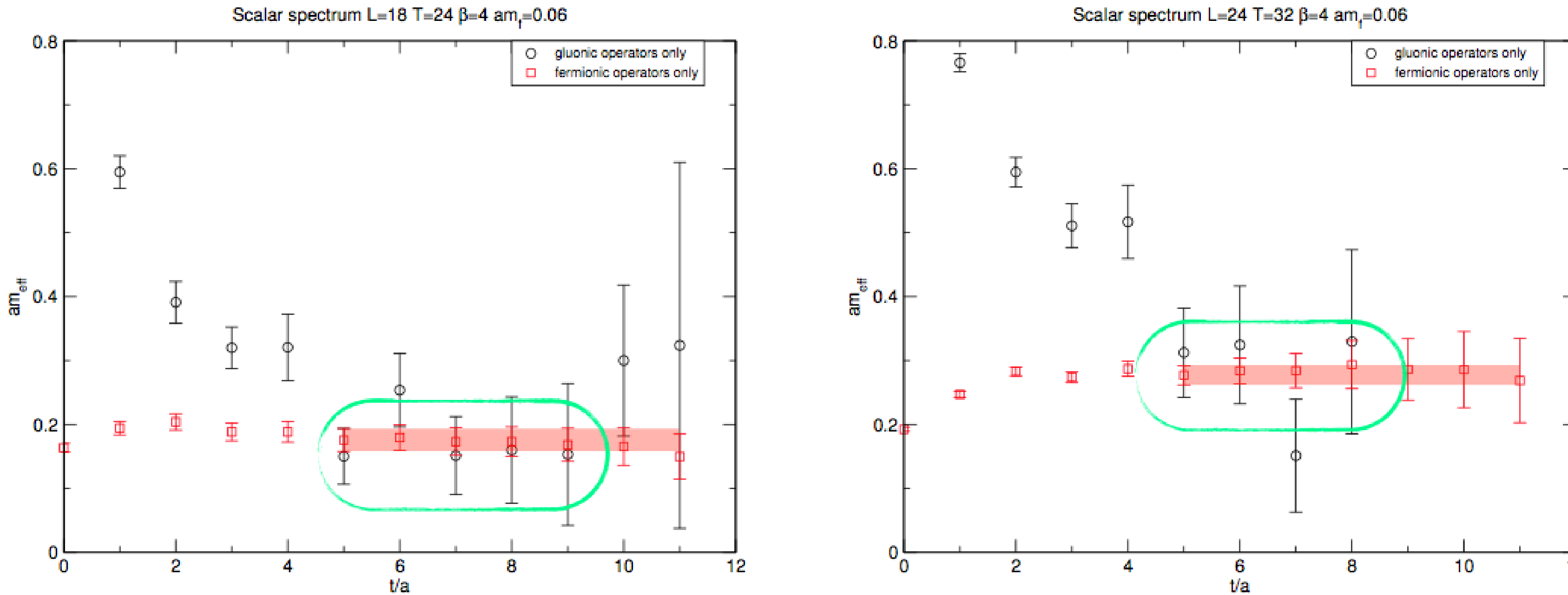
$\to$ Reliability check of result, but never done before

Comparison of effective mass in $N_f = 12$

($m_f = 0.06$, $18^3 \times 24$ with $N_{\rm conf} = 5000$, $24^3 \times 32$ with $N_{\rm conf} = 14000$, Preliminary)

$$m_{\rm eff}(t) = \log(C_H(t)/C_H(t+1)) \xrightarrow{t \gg 1} m_H$$

Glueball correlator and meson $D(t)$

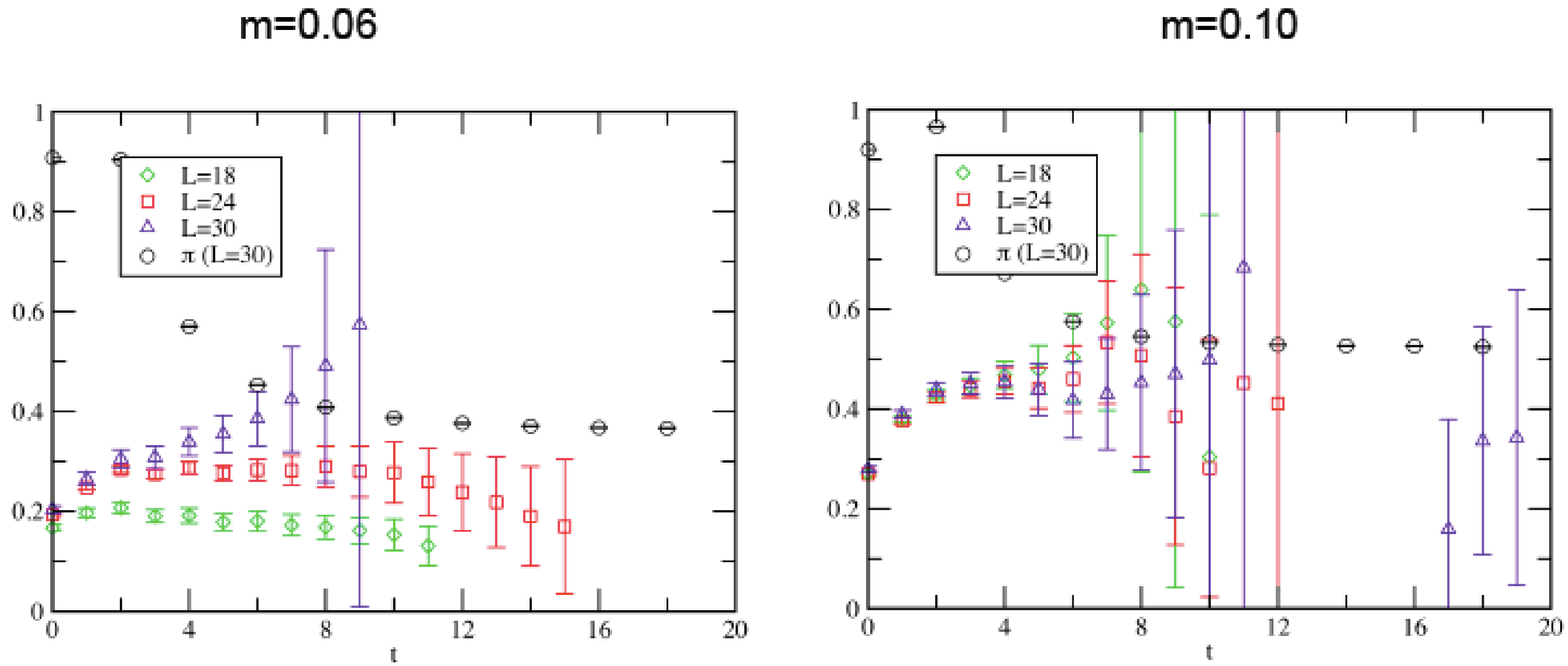


Larger error in glueball correlator

Reasonably consistent in large t

$\rightarrow$ show only meson results

Volume dependence of effective mass from D(t)
L=18, 24, 32 β=4.0 mf=0.06 & 0.10



- At m=0.10, all the results for L=18, 24,30 are consistent.
- At =0.06, mσ(L=18) < mσ(L=24) and large statistical fluctuation in L=30.