# Discovering Walking Technicolor at LHC and on the Lattice

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April 24, 2013@Higgs Centre, Edinburgh

# Kobayashi-Maskawa Institute
## for the Origin of Particles and the Universe
## Nagoya University
## Since April 2010

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# Disciples of Sakata at Nagoya

M. Kobayashi

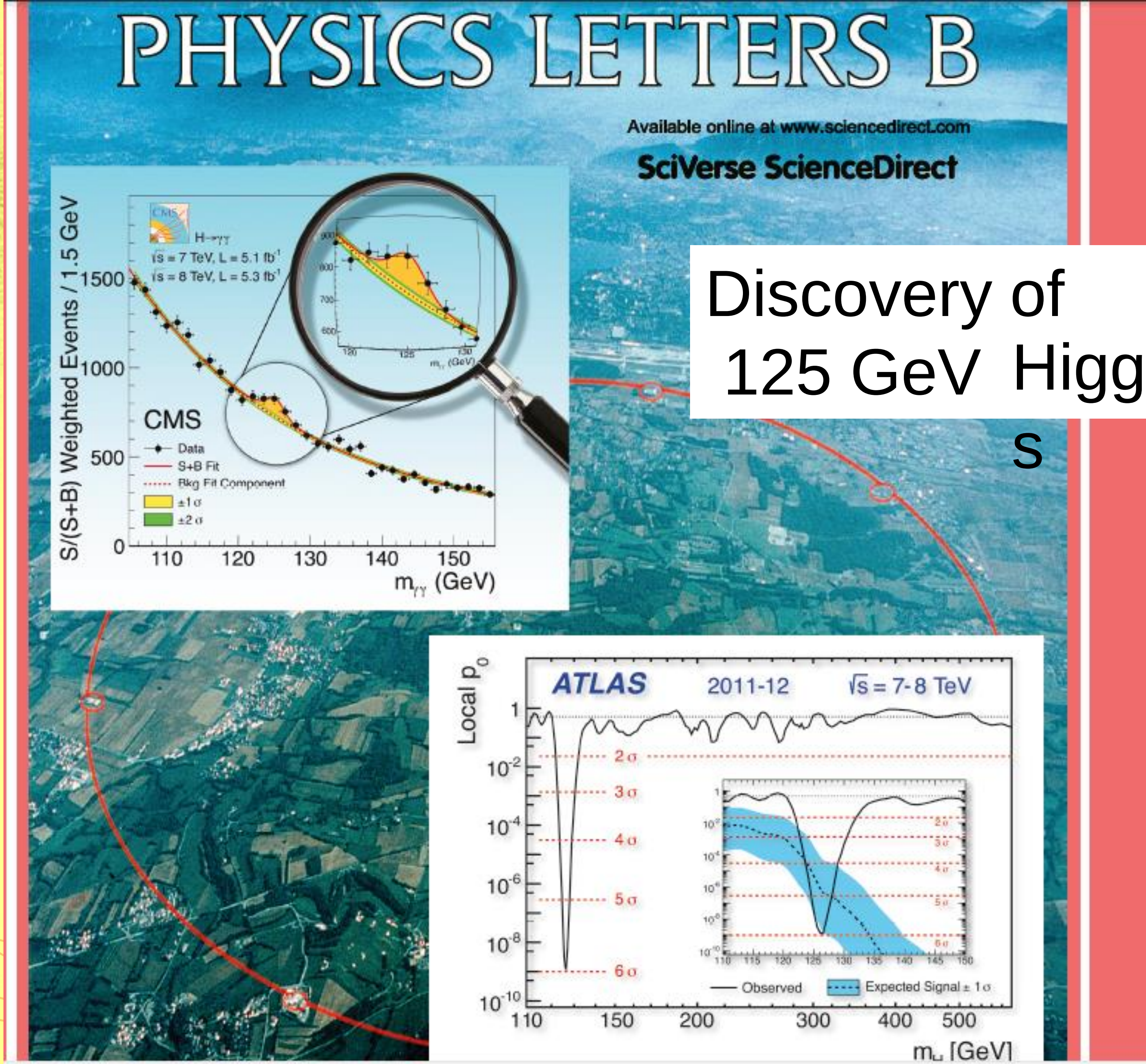
Shoichi Sakata (1911-1970)
Nagoya Univ. Professor

T. Maskawa

Sakata Model (1965)

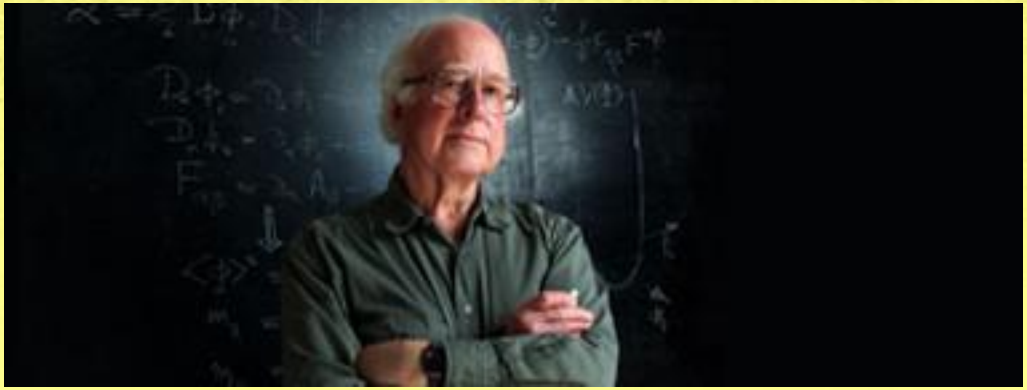
Maki-Nakagawa-Sakata (1962)

Composite Model Approach




Discovery of
125 GeV Higgs

# What is Higgs ?



Roughly consistent with the SM Higgs,
but …..

# 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 = Composite Higgs Model

KY-Bando-Matumoto (1986)

Approx. Scale Symmetry

⇒ **Techni-dilaton**

⇔ **125 GeV Composite Higgs**

NUMBER 13 PHYSICAL REVIEW LETTERS 31 MARCH 1986

# 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)

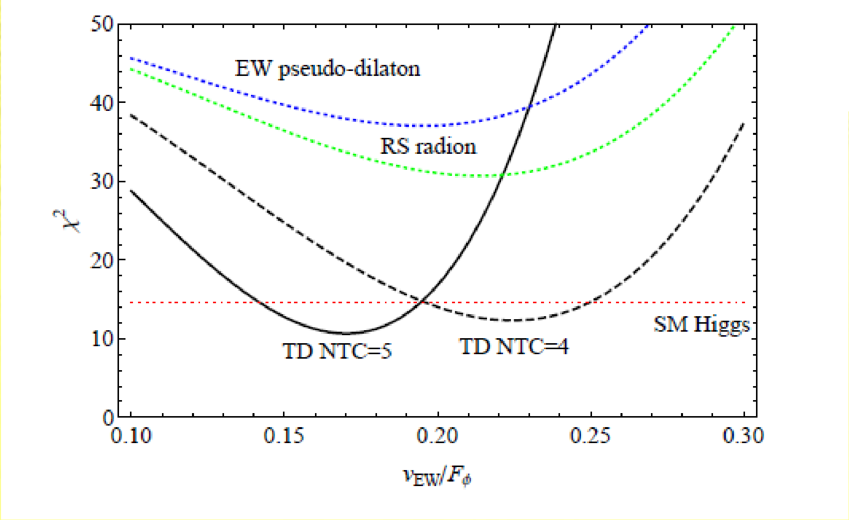
We propose a scale-invariant hypercolor model with a nontrivial ultraviolet fixed point having large anomalous dimension, which resolves the notorious flavor-changing neutral-current problem in hypercolor models, and at the same time predicts a $J^{PC}=0^{++}$ Nambu-Goldstone boson (dilaton) associated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

INSPIRE

%\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;%%
%615 citations counted in INSPIRE as of 19 Apr 2013%

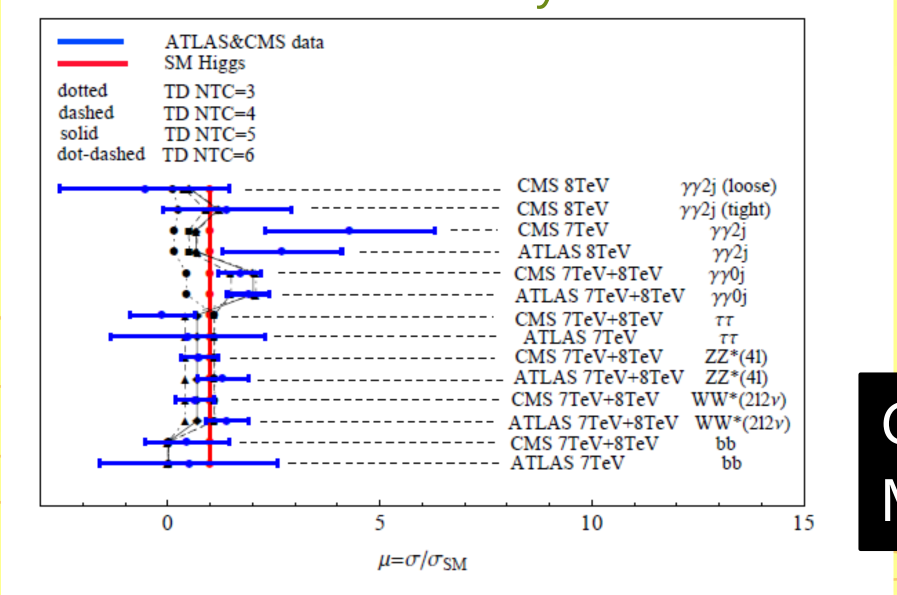
# 125 GeV Techni-dilaton(TD) at LHC

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**

# Weakly Coupled Light Scalar Composite from Strongly Coupled Dynamics?

Cf: N. Seiberg, Aspen 2013

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

$$\left.\frac{M_\phi}{4\pi F_\pi}\right|_{\gamma_m=1, G\gg 1} \sim \frac{1}{G} \ll 1$$ (Scale Invariance)

Yes !

$$\frac{g_{\phi f \bar{f}}}{g_{H f \bar{f}}} = \frac{g_{\phi WW/ZZ}}{g_{HWW/ZZ}} = (3-\gamma_m)\frac{v_{\rm EW}}{F_\phi} < 1$$

SM sector

TC sector
(Strongly coupled)

Weak !

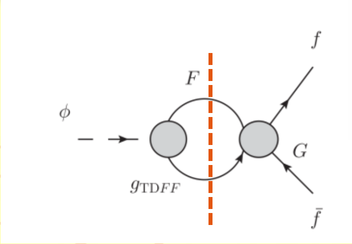
$$g_{MMM}, g_{MB\bar{B}} \gg \mathcal{O}(1)$$

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

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

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

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




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

Even needs enhancement !

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

# 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)

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

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

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

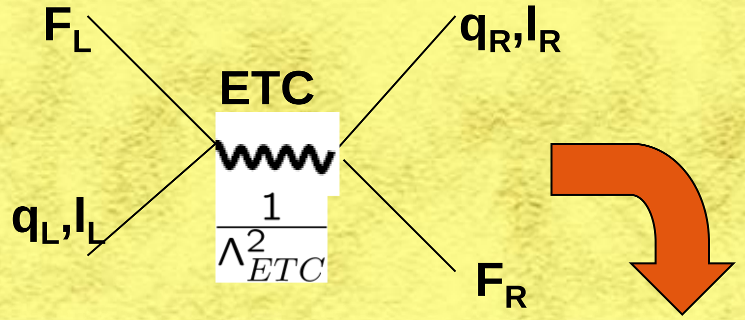
$$\frac{N_{\rm TC}}{N_{\rm C}} \qquad \sqrt{\frac{N_{\rm C}}{N_{\rm TC} N_{\rm D}}}$$

X 2600

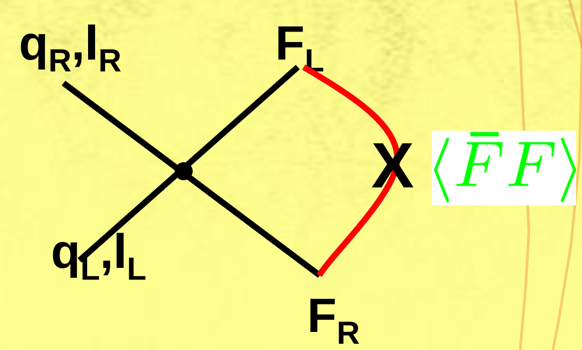
$$\sigma \sim \bar{q}q \qquad f_\pi = 93 \text{ MeV}$$

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

# FCNC Problems:




## Mass of Quarks/Leptons




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

**FCNC**

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

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

**Needs $10^3$ enhancement**

# By Large Anomalous Dimension $\gamma_m$

**Holdom (1981)**

Pure Assumption of
Existence of Large $\gamma_m$
No Concrete Dynamics
No Concrete Value $\gamma_m$

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

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

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

$\gamma_m > 1$ ⟹ $> 10^3$

# Walking Technicolor

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

## Ladder Schwinger-Dyson Equation

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

$\gamma_m = 1$ ⟺ FCNC Sol.

Techni-dilaton

Similar FCNC Sol. without notion of $\gamma_m$, Scale Invariance, Techni-dilaton :

**Akiba, Yanagida (Jan. 3, 1986)**

**Appelquist, Karabali, Wijewardhana (June 2, 1986)**

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

# Ladder SD

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

**Miransky Scaling**

**Essential singularity**

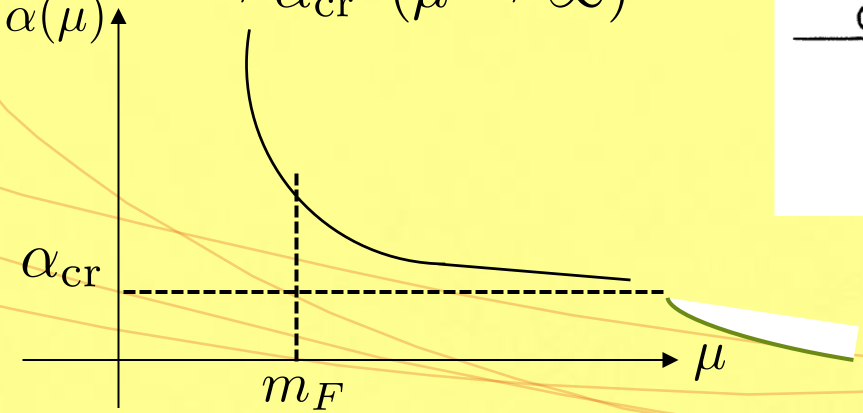
Non-perturbative running ("Walking")

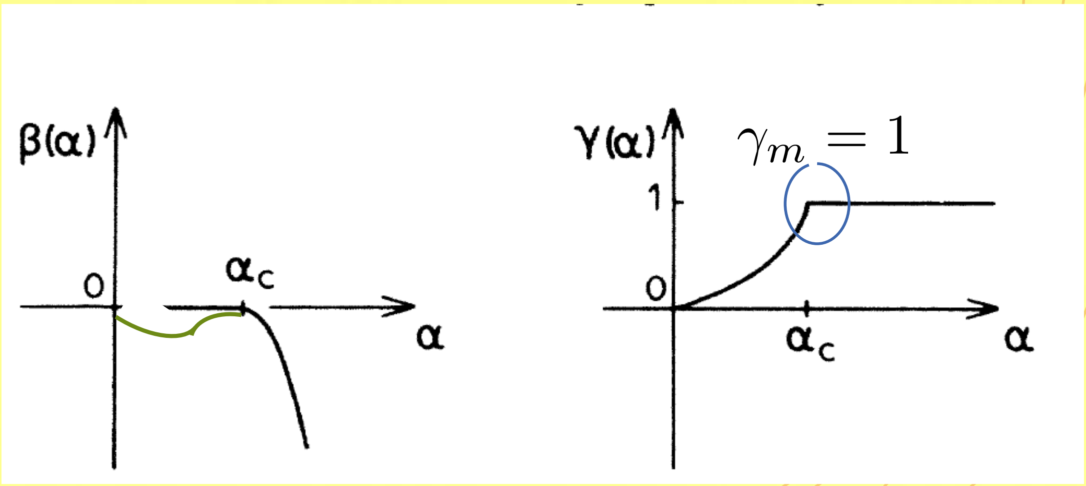
UVFP: not a linear zero
=IRFP

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

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

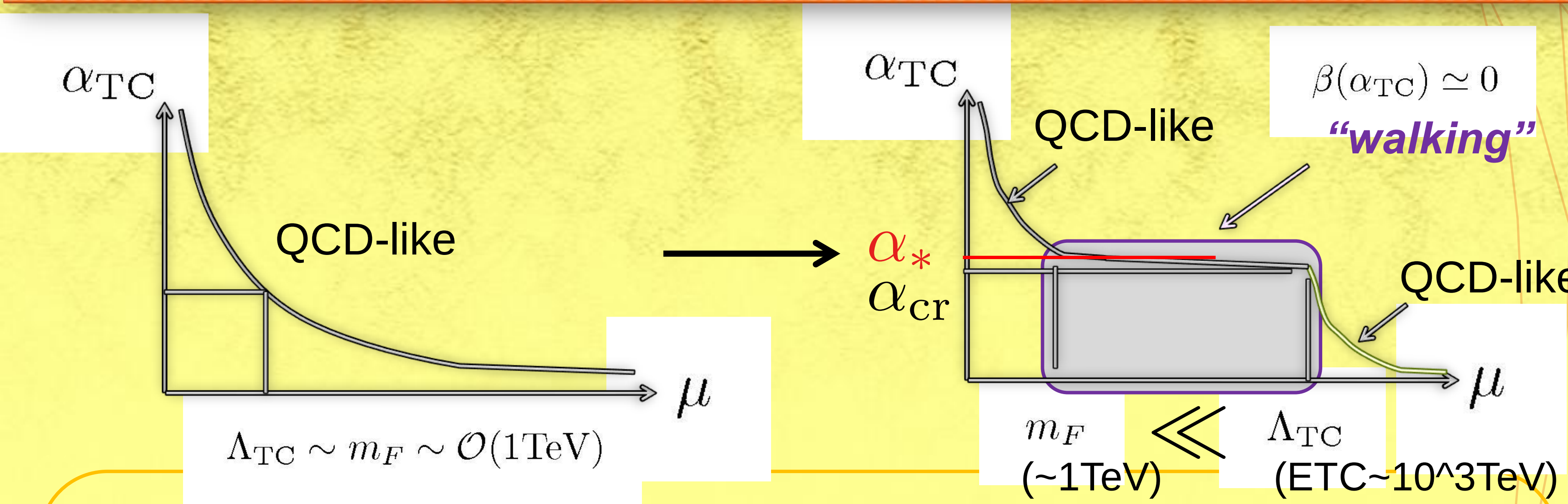
$$\to \alpha_{cr} \quad (\mu \to \infty)$$




**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

# 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**

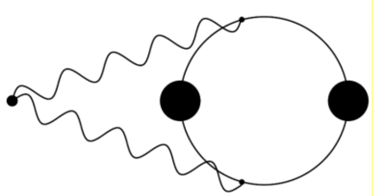
$$M_\phi \sim 4F_\pi \ll M_\rho, M_{a_1}$$

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

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

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

**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**

0 ⟵ $z = \epsilon$ $z = z_m$

**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**

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

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

**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 |
| 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)

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

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 holographic-parameters !!

⟹ Massless NGB limit ("conformal limit") is realized:

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

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:**

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

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

Indep. of S
(S<0.1 tunable)

**holographic-parameter free !!**

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

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

**Weaker than SMH**

**This is consistent with ladder estimate:**

LHC best fit (before Moriond '13)

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

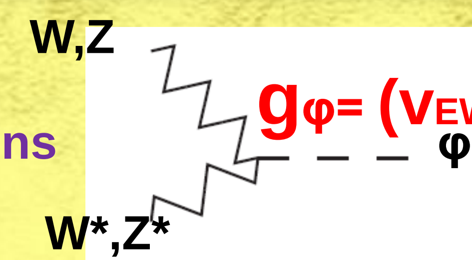
ladder

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

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

**v.s. SM Higgs**

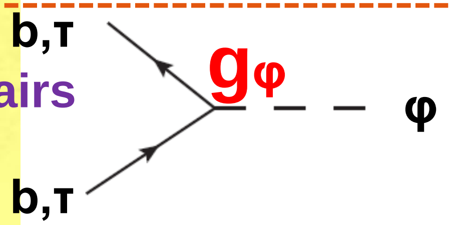
**di-weak bosons**




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

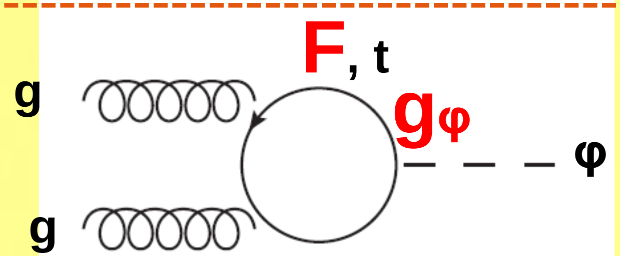
**suppressed**

**quark, lepton pairs**




**suppressed**

**digluon**

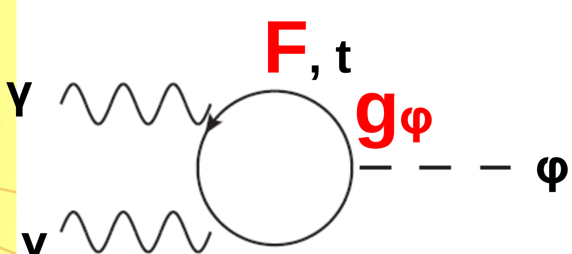



$\beta_F(g_s)$

**enhanced**

**QCD-colored TF contributio**

**diphoton**




$\beta_F(e)$

**>> W -loops** **enhanced**

**EM-charged TF contributio**

# 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

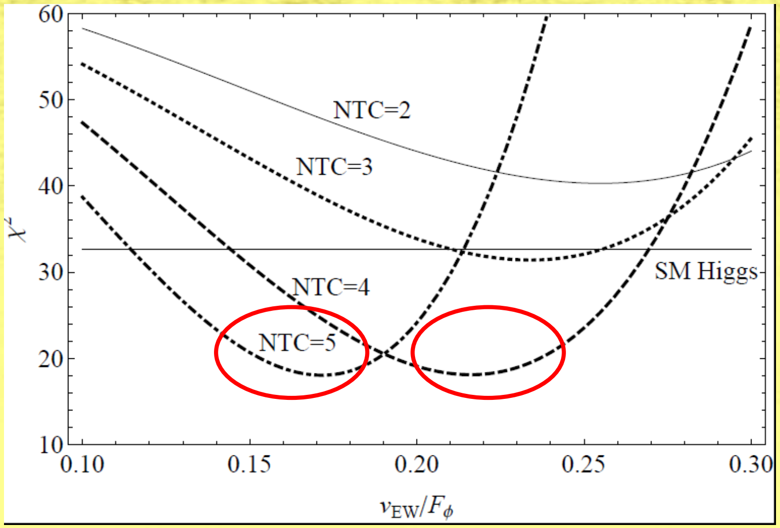
$$\frac{g_{\phi\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq \frac{v_{\rm EW}}{F_\phi} \cdot \left( \frac{63 - 16(3-\gamma_m)}{47} - \frac{32}{47} N_{\rm TC} \right)$$ <1

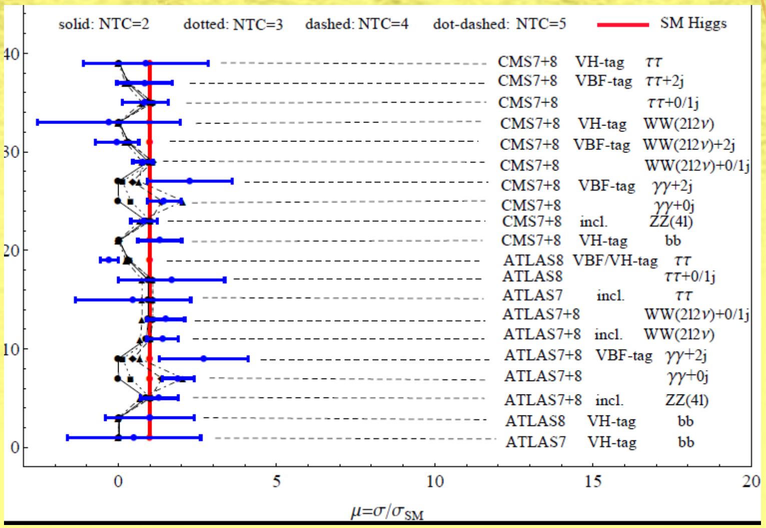
1 $(\gamma_m^t = 2)$

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

***updated after HCP2012**

S. Matsuzaki, 1304.4882




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

| $N_{TC}$ | $[v_{EW}/F_\Phi]$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 ($\mu = \sigma$ x BR/SM Higgs) vs the data*

w/ NTC=4, vEW/Fφ = 0.2

*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] | $(< 2\,\sigma)$ | $\simeq 0.7$ [illegible] | [illegible] |

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?

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

**Lattice !**

# 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

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








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

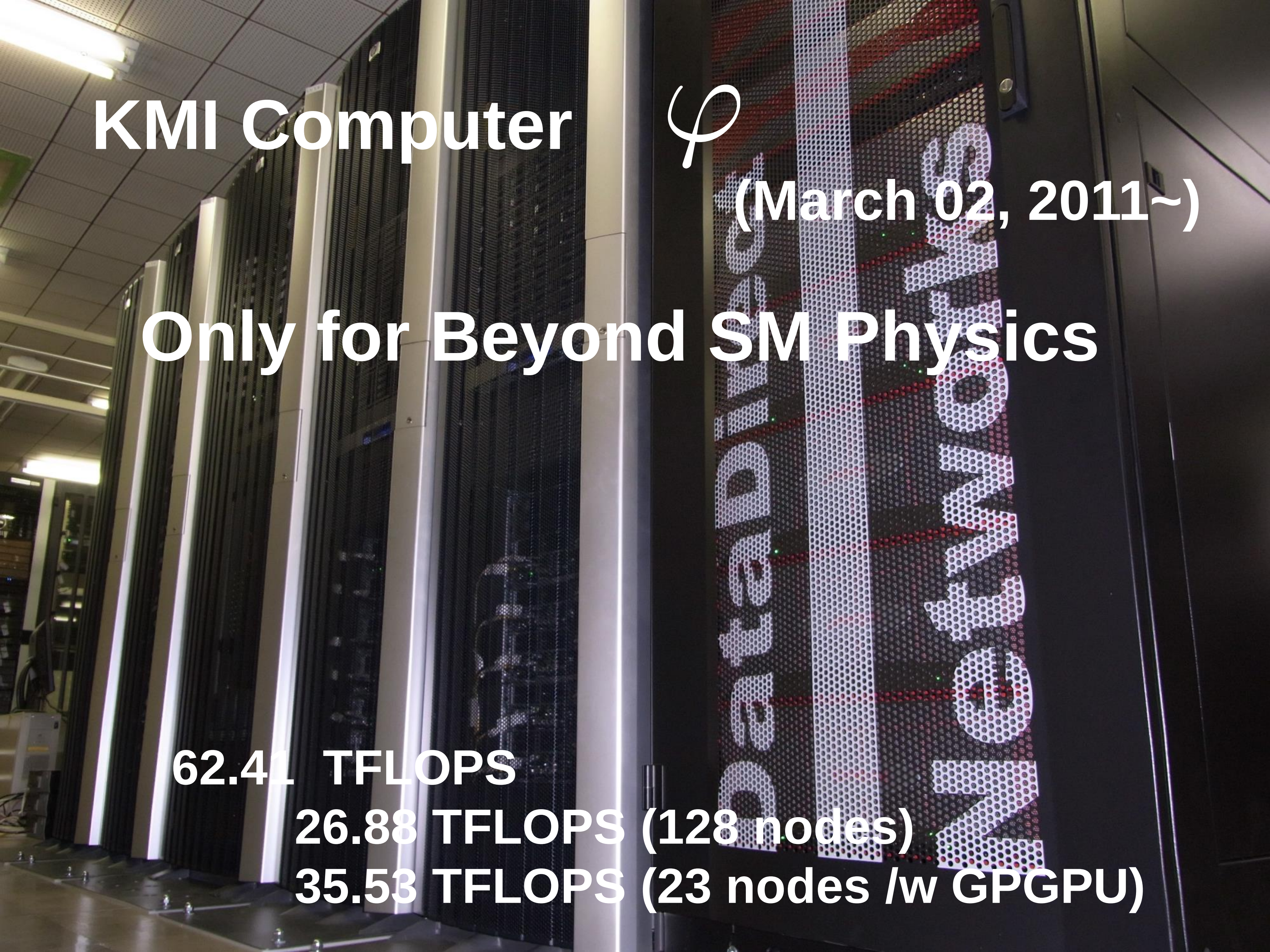
名古屋大学

E. Rinaldi

THE UNIVERSITY OF EDINBURGH

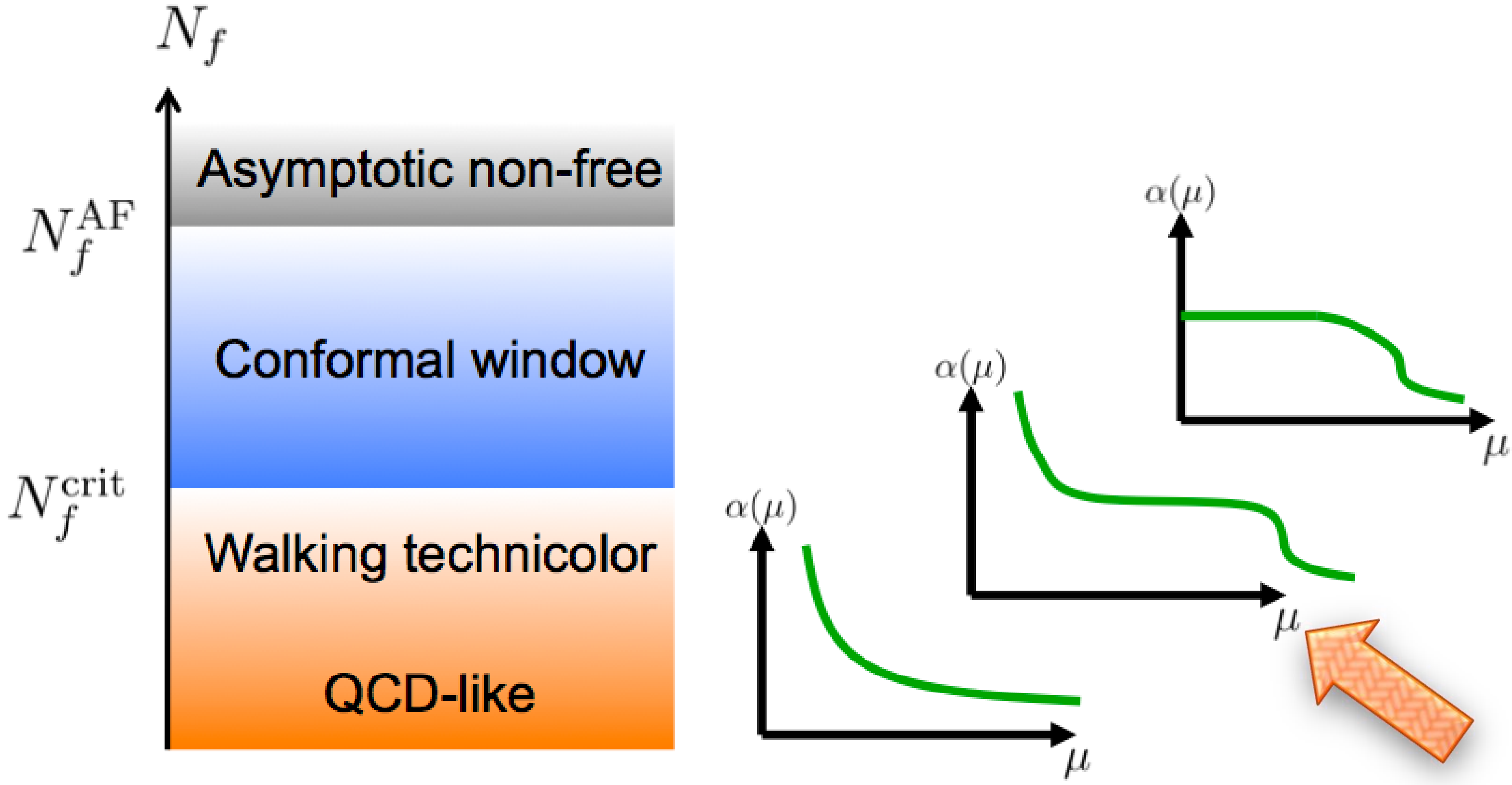
A. Shibata

KEK


KMI Computer $\varphi$
(March 02, 2011~)
Only for Beyond SM Physics
62.41 TFLOPS
26.88 TFLOPS (128 nodes)
35.53 TFLOPS (23 nodes /w GPGPU)
DataDirect
NETWORKS

$SU(3);\ N_c = 3$

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




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

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

# Recent study of LatKMI Collaboration

PRD86(2012)054506; arXiv:1302.6859

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 $N_f = 4$)

| | $N_f$ | $\beta$ | $L^3 \times T$ | $m_f$ |
|---|---|---|---|---|
| Deep $\chi$SB | 4 | 3.7 | $12^3 \times 18$–$20^3 \times 30$ | 0.005–0.05 |
| Walking | 8 | 3.8 | $18^3 \times 24$–$36^3 \times 48$ | 0.015–0.16 |
| Conformal | 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: $\varphi$ at KMI, CX400 at Kyushu Univ.

# Walking candidate & Scalar

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

LatKMI Collaboration, arXIv: 1302.6859

- Light flavor-singlet scalar (& scalar glueball)

LatKMI Collaboration, arXIv: 1302.4577

+ new data (Preliminary)

in Nf=12 (Conformal , $\gamma_m = 0.4 - 0.5$ )

LatKMI Collaboration, PRD86 (2012)054506

- Light flavor-singlet scalar (& scalar glueball)

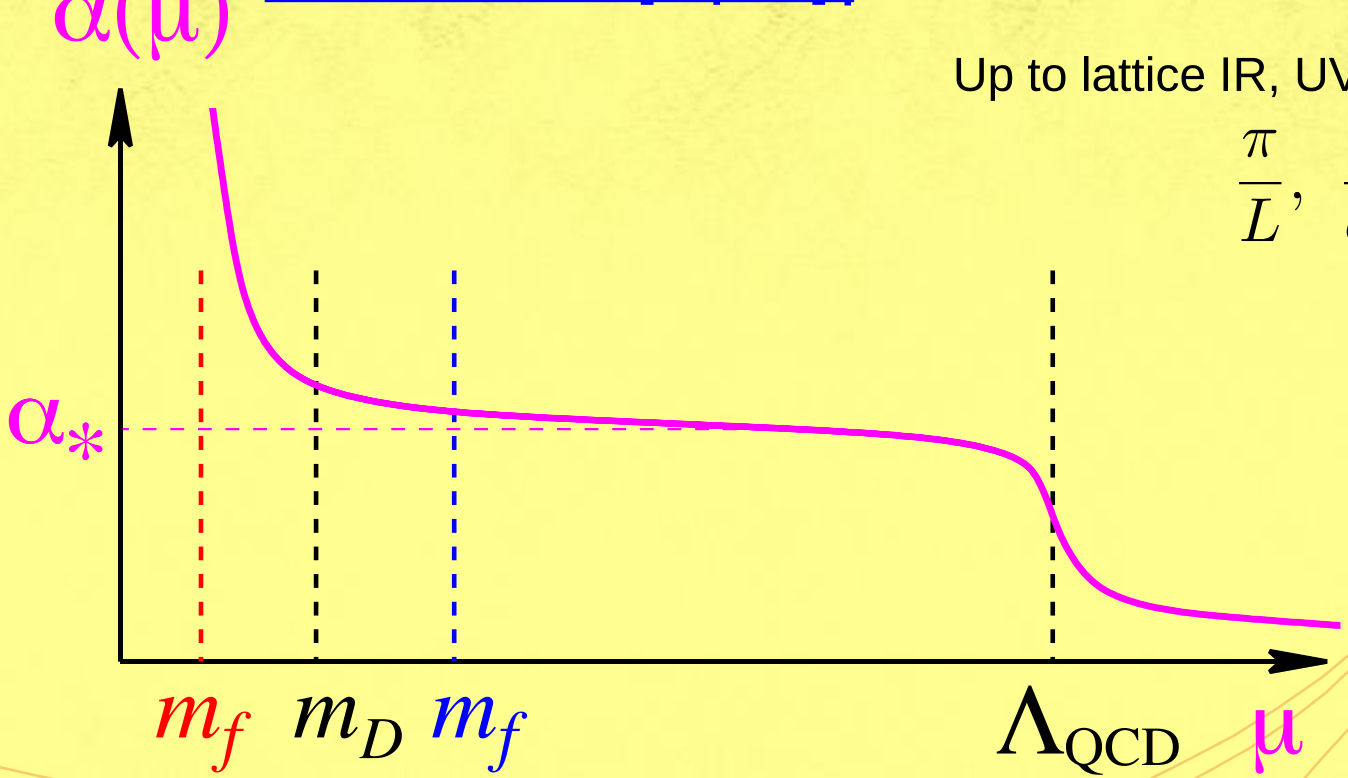
in Nf=8 (Very Preliminary)

$N_f = 8$

# 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] |



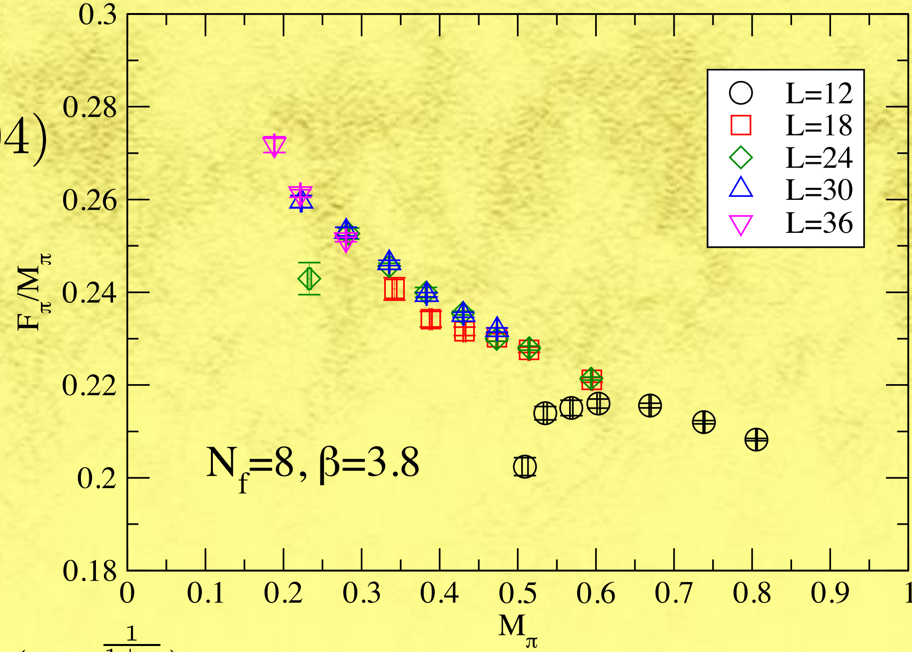

Up to lattice IR, UV scales:

$$\frac{\pi}{L}, \ \frac{1}{a}$$

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

ChPT

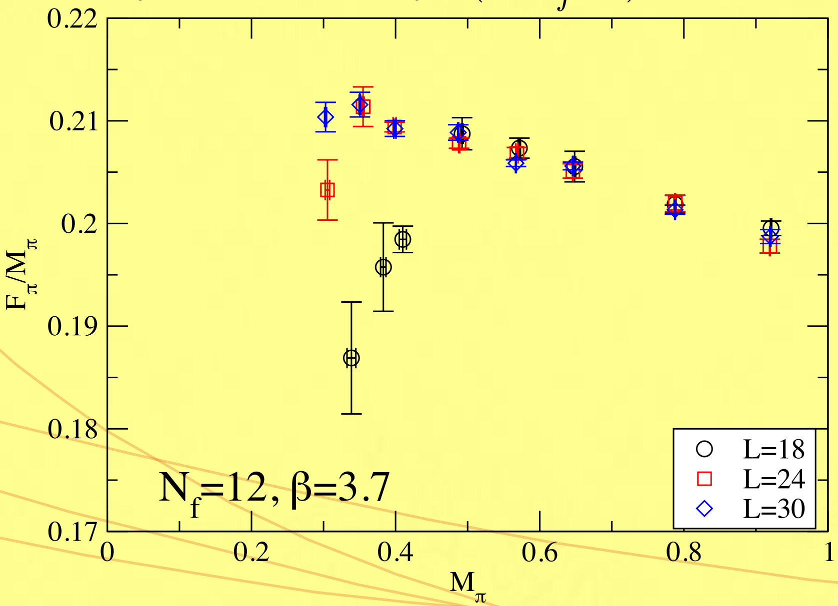
$(m_f = 0.015 - 0.04)$

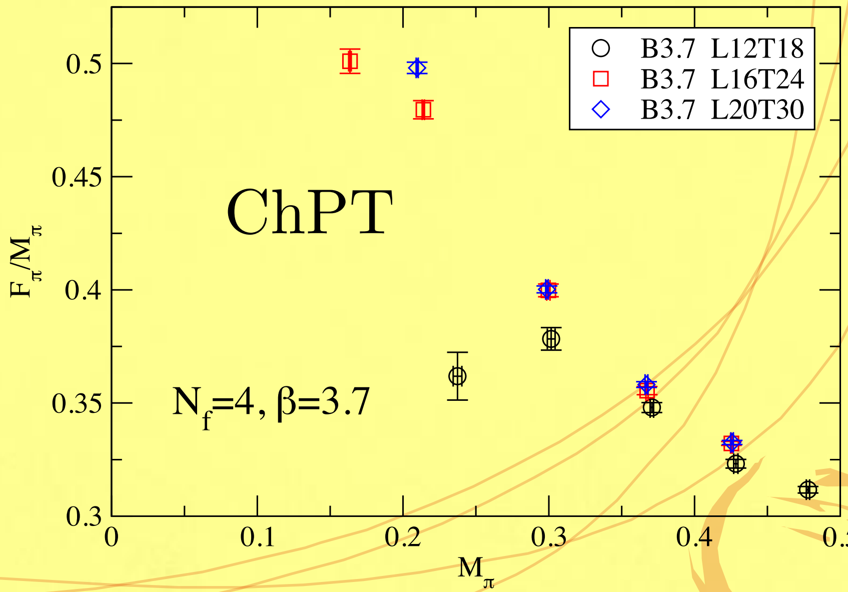



$\xi_H \equiv LM_H = f_H(Lm_f^{\frac{1}{1+\gamma}})$

$(m_f = 0.05 - 0.16)$

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




LatKMI Collaboration, PRD86 (2012)054506

$N_f = 8$

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

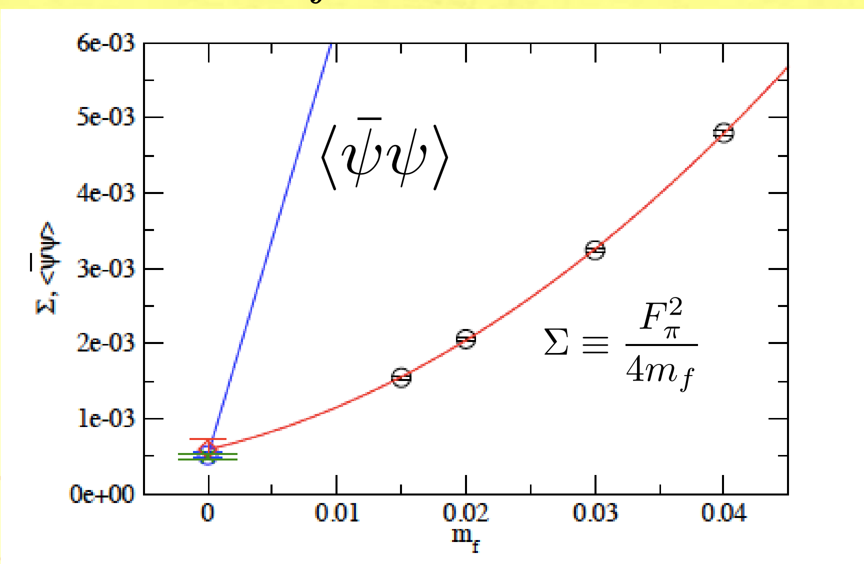
Yasumichi Aoki,[1] Tatsumi Aoyama,[1] Masafumi Kurachi,[1] Toshihide Maskawa,[1]
Kei-ichi Nagai,[1] Hiroshi Ohki,[1] Akihiro Shibata,[2] Koichi Yamawaki,[1] and Takeshi Yamazaki[1]
(LatKMI Collaboration)

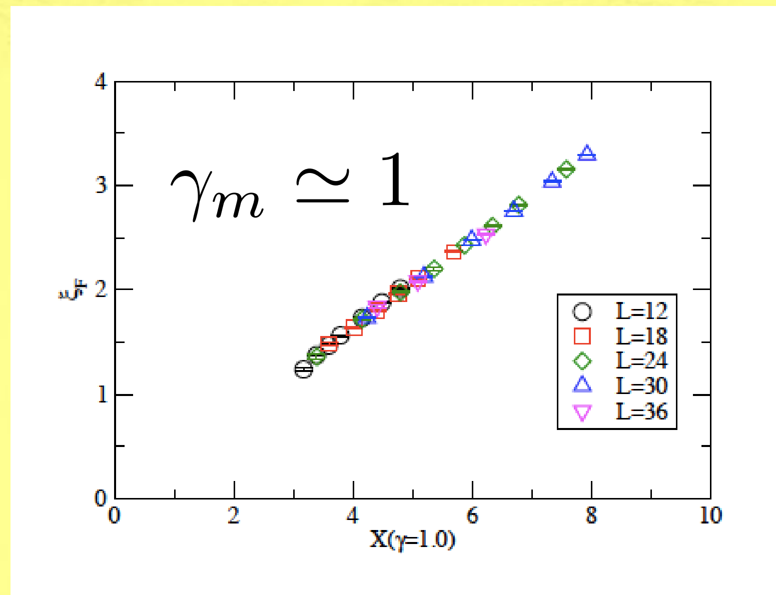
HISQ $\beta = 3.8$ $L = 12, 18, 24, 30$ $(T/L = 4/3$

arXiv:1302.6859 [hep-lat] |

SχSB $m_f = 0.015 - 0.04$

``Conformal'' $m_f = 0.05 - 0.16$



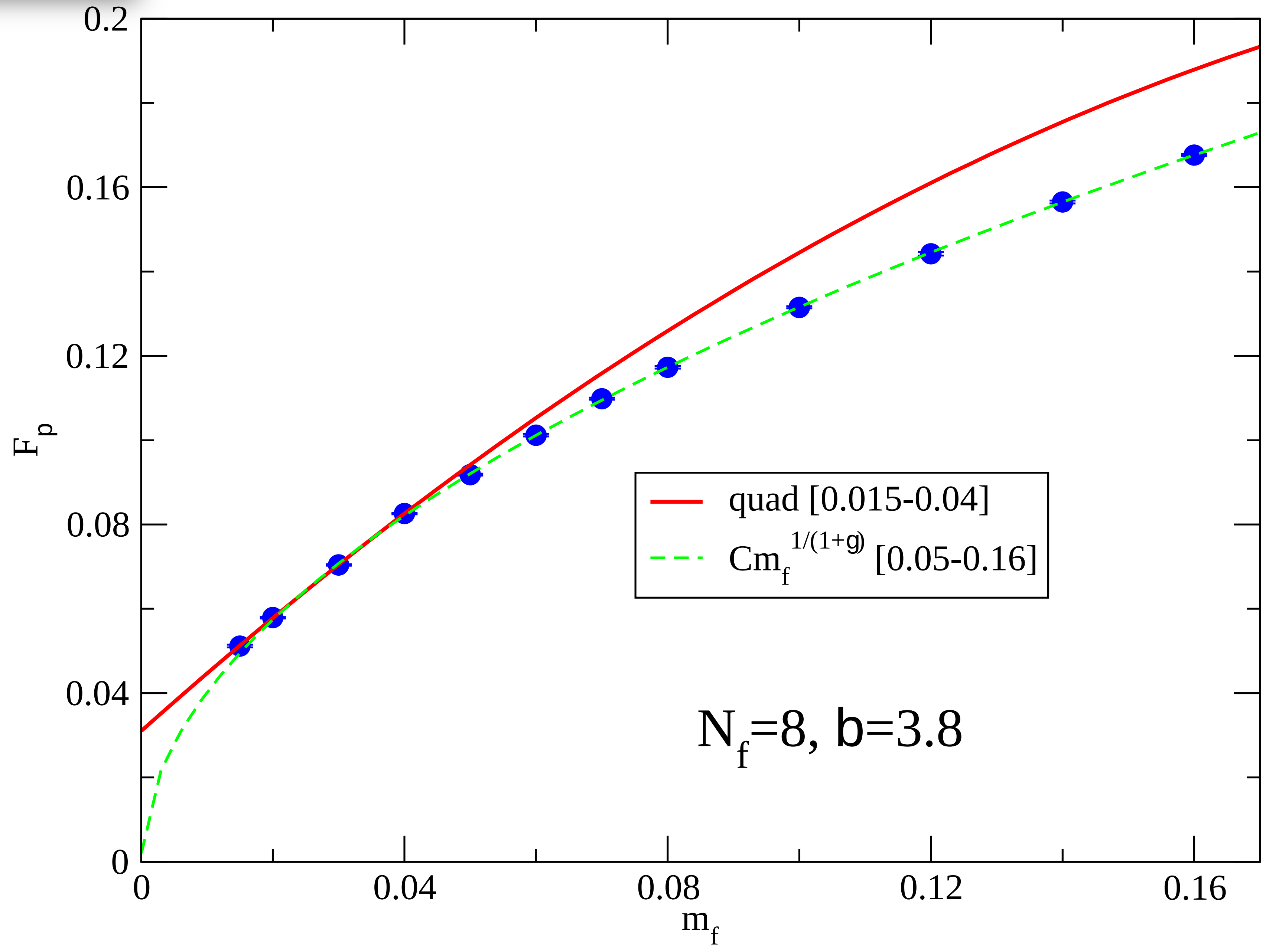




$F_\pi \to\neq 0, M_\pi \to 0, M_\rho \to\neq 0$

at $m_f \to 0$

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

# $N_f = 8$



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

# $N_f = 8$

## Nf=8 data

Hyperscaling relation is not for a universal $\gamma_m$

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

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 $\alpha < \alpha_{\rm cr} \; (N_f > N_f^{\rm cr})$

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

$N_f = 12$

Scalar

# 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]

and new results

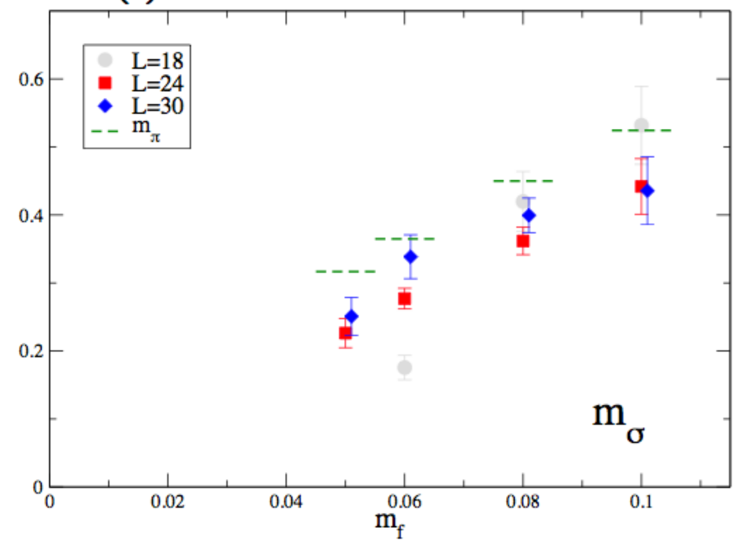
Noise reduction method with Nr=64

| $L, T$ | $m_f$ | confs |
|---|---|---|
| 18,24 | 0.06 | 5000 |
| | 0.08 | 5000 |
| | 0.10 | 5000 |
| 24,32 | 0.05 | 3600 |
| | 0.06 | 14000 |
| | 0.08 | 15000 |
| | 0.10 | 9000 |
| 30,40 | 0.05 | 1500 |
| | 0.06 | 3800 |
| | 0.08 | 10000 |
| | 0.10 | 4000 |

## $m_f$ dependence in $N_f = 12$ (Preliminary)

$m_\sigma$ from effective mass of $D(t)$ at $t = 5$

Nf=12, β=4.0

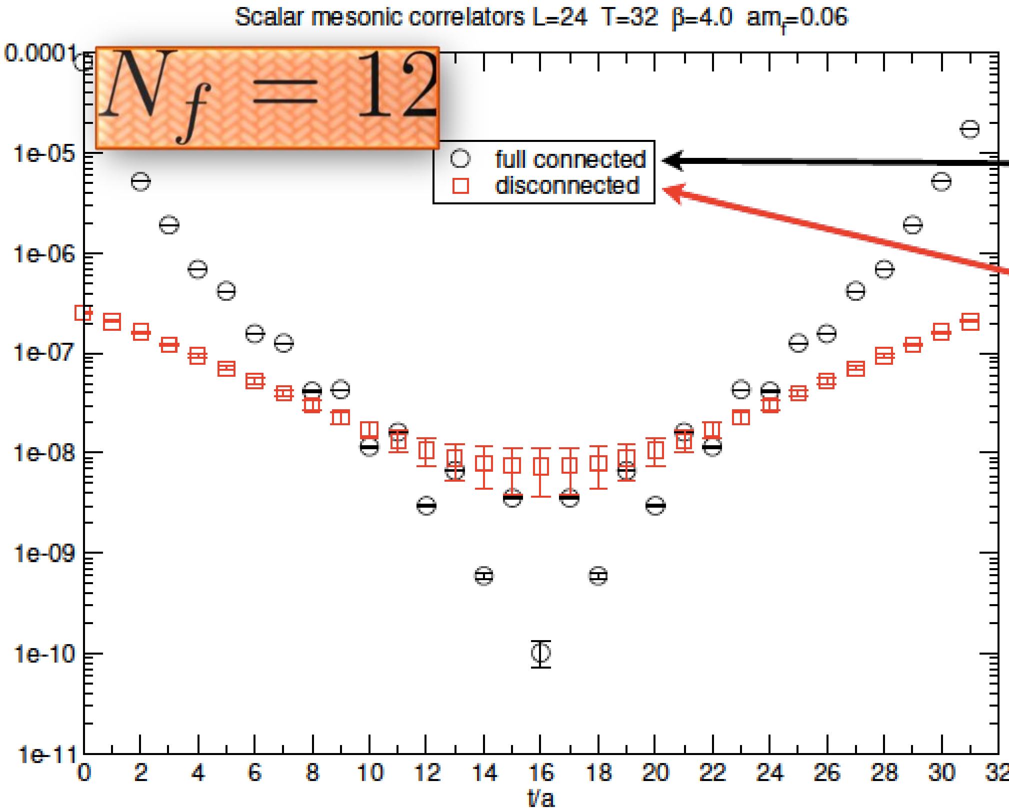



Flavor-singlet scalar is relatively light?

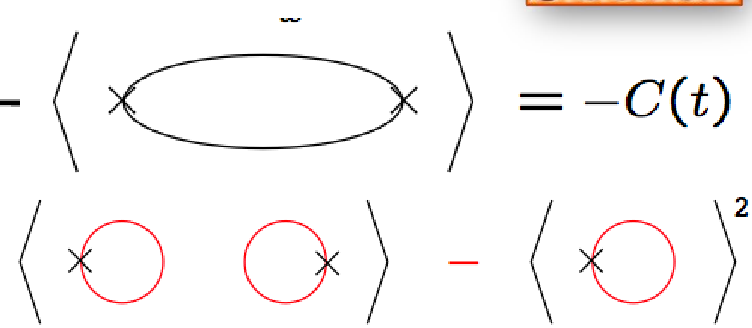
Lighter than $\pi$

Hyperscaling is seen as in $m_\pi$?

$N_f = 12$



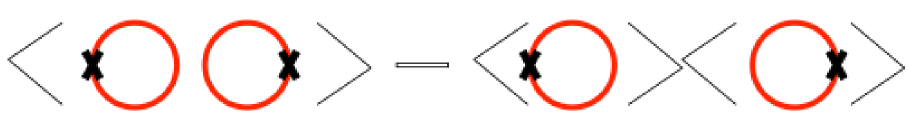

**Scalar**




- 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

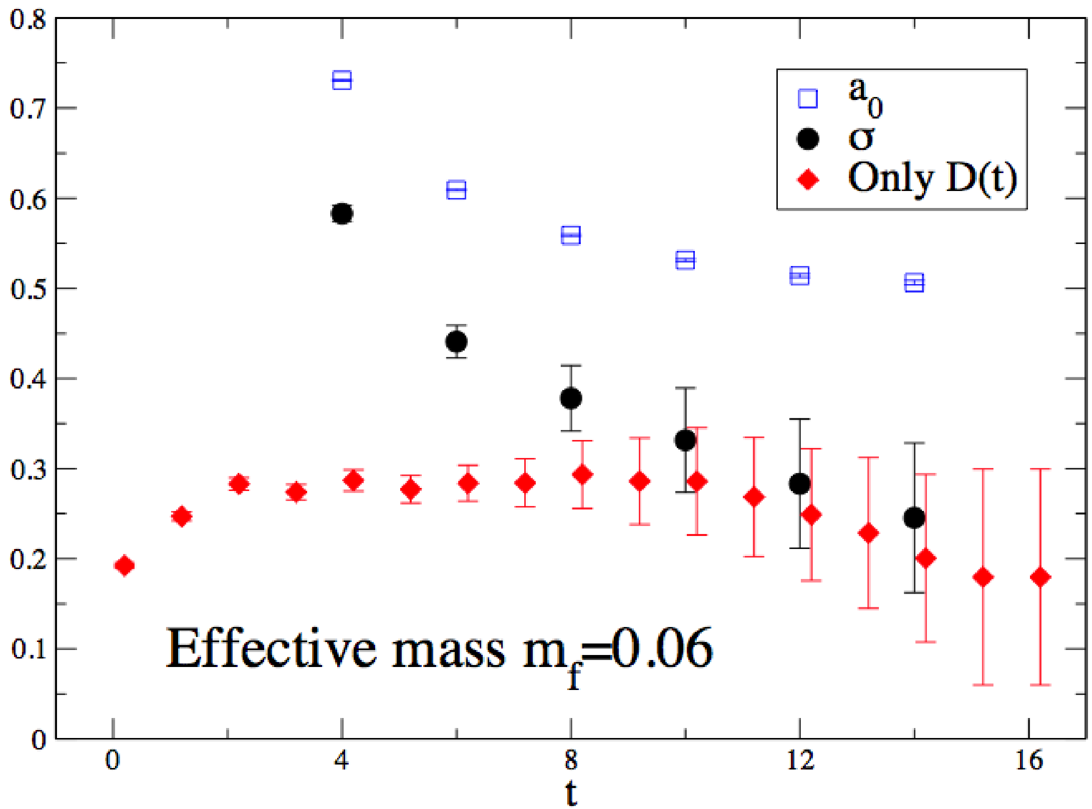
$$C_\sigma(t) = \langle \sum_i^{N_f} \bar{\psi}_i\psi_i(t) \sum_j^{N_f} \bar{\psi}_j\psi_j(0)\rangle = N_f(-C(t) + \underline{N_f} D(t))$$

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



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

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




Nonsinglet scalar

$a_0$: $-C_+(2t)$

Singlet scalar

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

$m_\sigma < m_{a_0}$

Only $D(t)$

Consistent $m_\sigma$

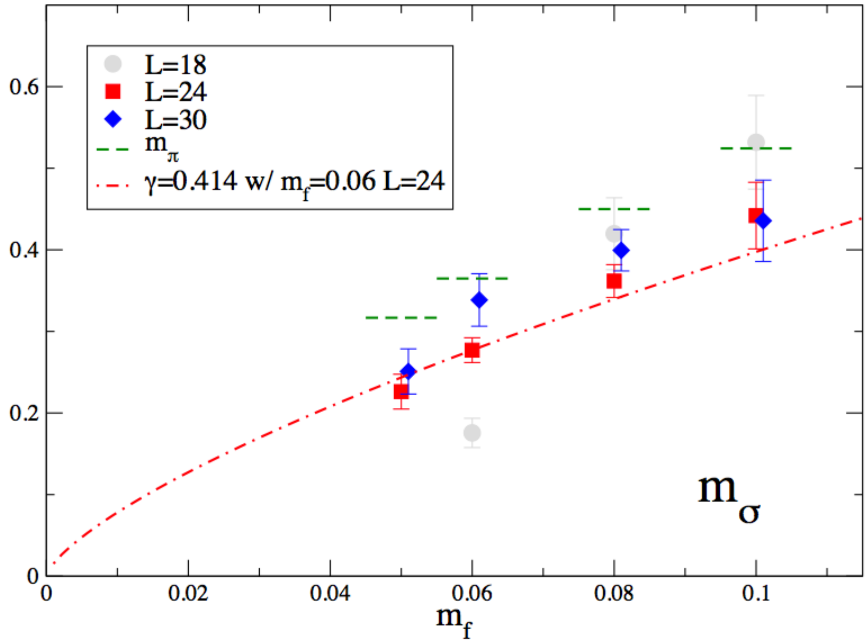
Smaller error

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

Good signal of $m_\sigma$ from $D(t)$

# $m_f$ dependence in $N_f = 12$ (Preliminary)

$m_\sigma$ from effective mass of $D(t)$ at $t = 5$




Flavor-singlet scalar is relatively light?

Lighter than $\pi$

Hyperscaling is seen as in $m_\pi$?

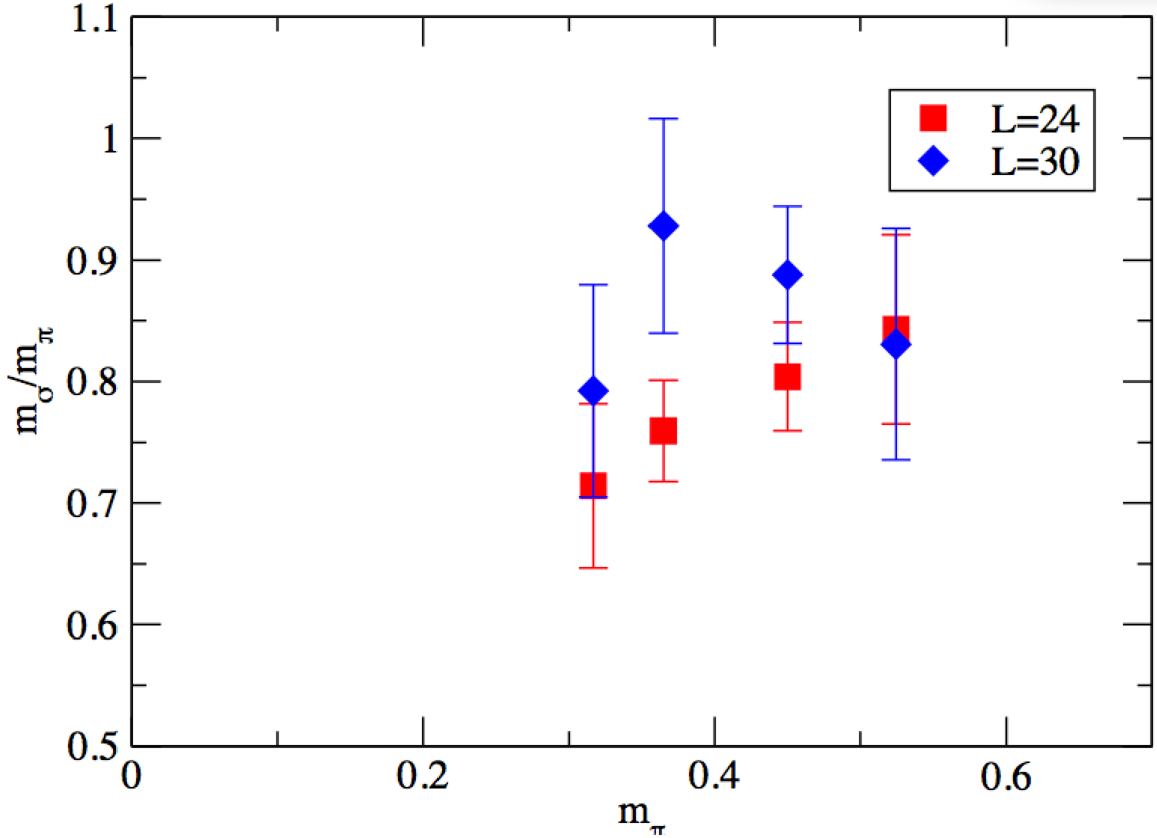
$m_\sigma = C m_f^{1/(1+\gamma)}$ with $\gamma = 0.414$ from hyperscaling of $m_\pi$

LatKMI Collaboration, PRD86 (2012)054506

$m_\sigma$ from effective mass of $D(t)$ at $t = 5$

Scalar

$N_f = 12$




Hyperscaling is seen as in $m_\pi$?

$$\frac{m_\sigma}{m_\pi} \xrightarrow{m_f \to 0} \text{constant}$$

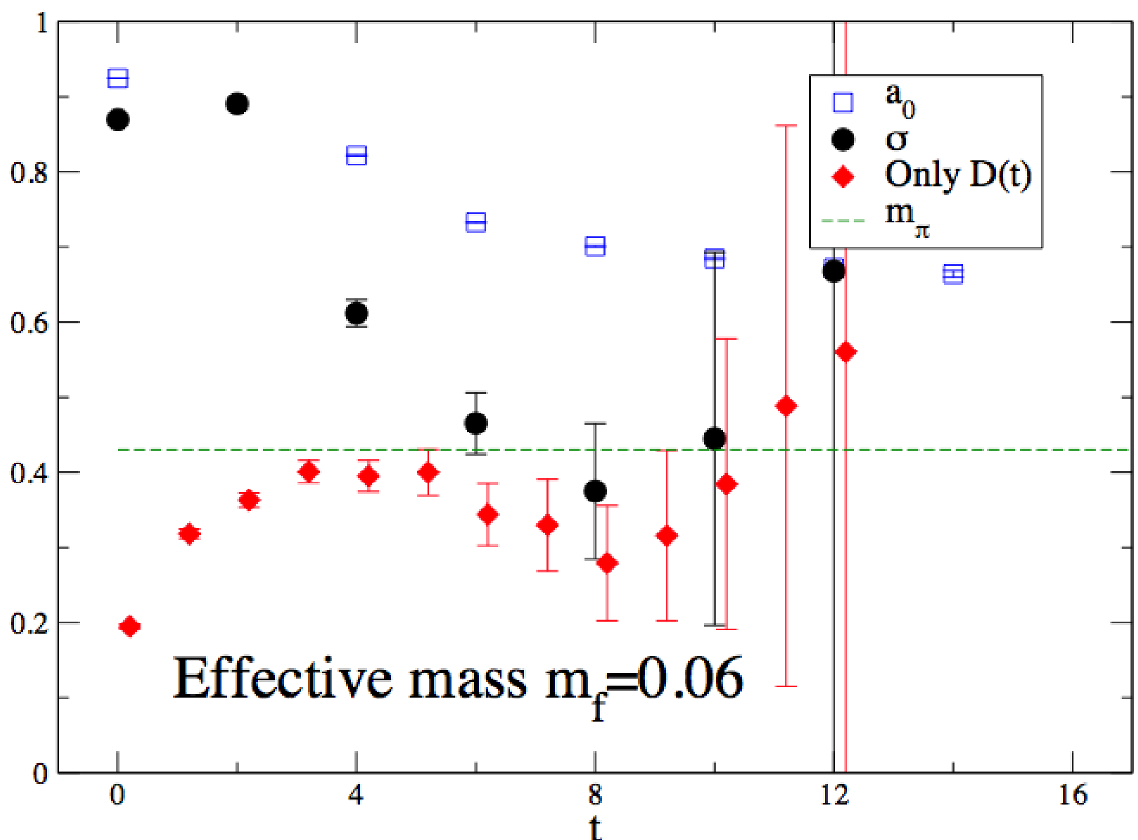
Not inconsistent with hyperscaling

$N_f = 8$ 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 $m_f = 0.06$

# 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 (Preliminary)

  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

* 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

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

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

$\xi$ : IR value of bulk scalar $\Phi_S \longleftrightarrow \bar{F}F$ (dual)

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

$z_m$ : IR-brane position

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

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

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

**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:**

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

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

**The model parameters:**

| $\xi$ | $\mathcal{G}$ | $z_m.$ | $\frac{L}{g_5^2}$ | $M$ | $M'$ | $\alpha$ | $c$ |
|---|---|---|---|---|---|---|---|
| Φ IR value | $\Phi_X$ IR value | IR brane position | 5d coupling | Φ UV value | $\Phi_X$ UV value | coeff. of M | coeff. of $\Phi_X$ |

set explicit breaking sources = 0

matching to current correlators

$\Pi_V$ Leading log term

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

$\Pi_S$ Leading log term

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

$\Pi_V$ G^2 term

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

**Fix**

**3 phenomenological input values**

**$F_\pi$ = 246 GeV/√$N_D$ = 123 GeV (1FM)**

**$M_\Phi$ = 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*

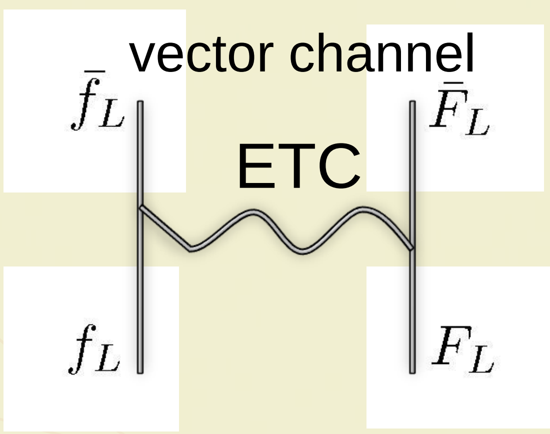
## S parameter

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

$N_D$ : # EW doublets

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

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




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

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

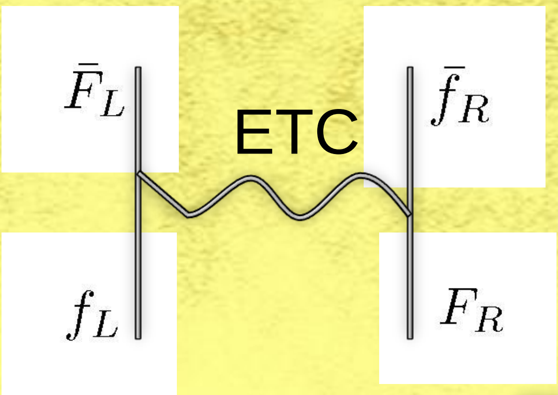
$\ni g_W W_\mu - g_Y B_\mu$ modifies SM f-couplings to W, Z

contributes to S "negatively"

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

$S_{\rm total} \to 0$ ("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

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

**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**

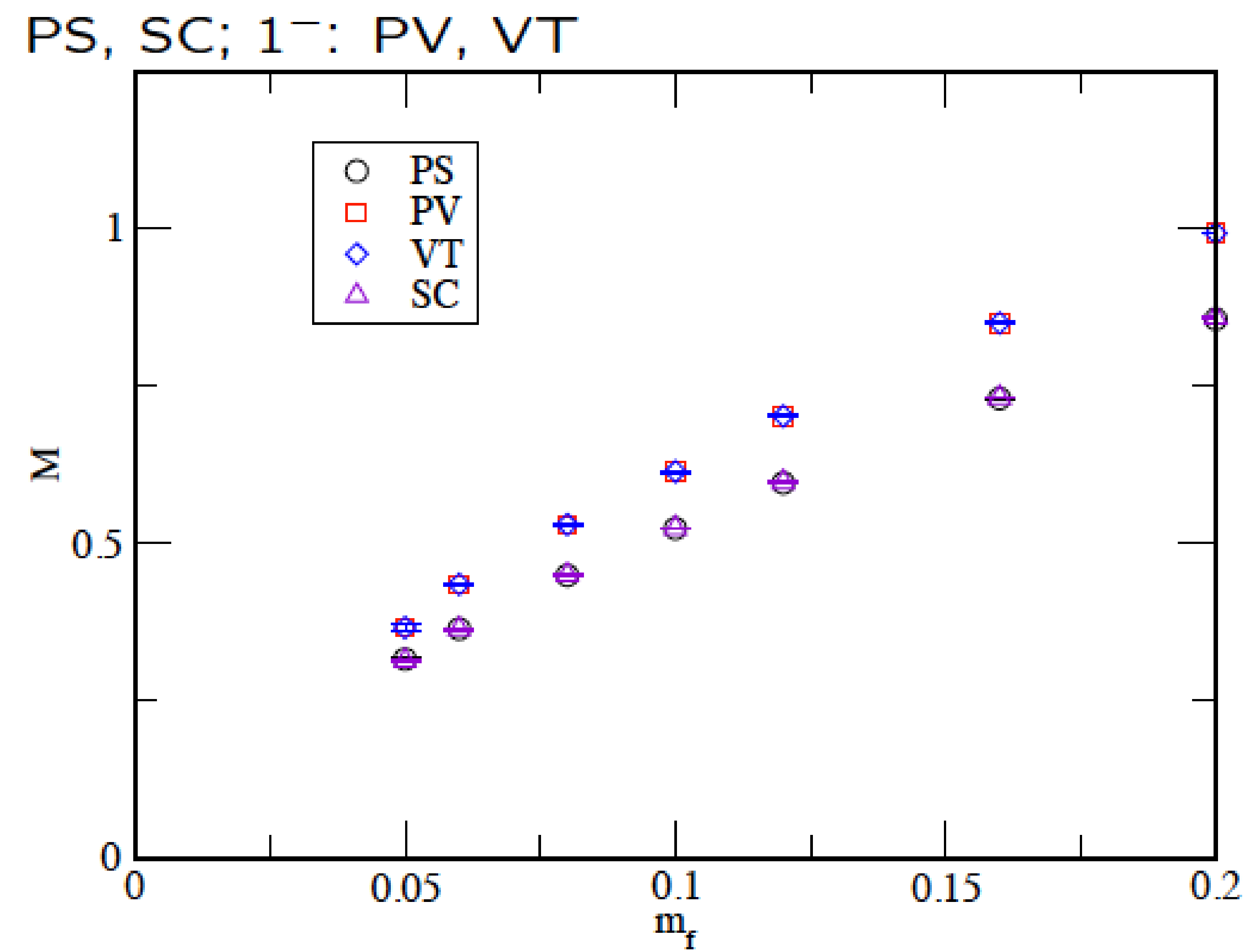
$$\longrightarrow \quad m_t \approx \left( \frac{\Lambda_{\rm TC}}{\Lambda_{\rm ETC}} \right)^{2-\gamma_m} \Lambda_{\rm TC} \leq \Lambda_{\rm TC} \sim 1{\rm TeV}$$

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

$N_f = 12$

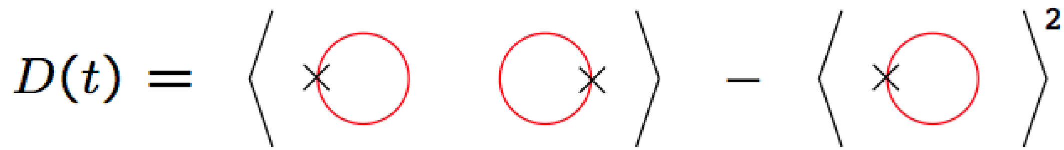
# Nf=12 Taste Symmetry（HISQ）

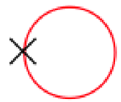
LatKMI Collaboration, PRD86 (2012)054506



## Difficulty    Flavor – singlet scalar

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



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 $t$

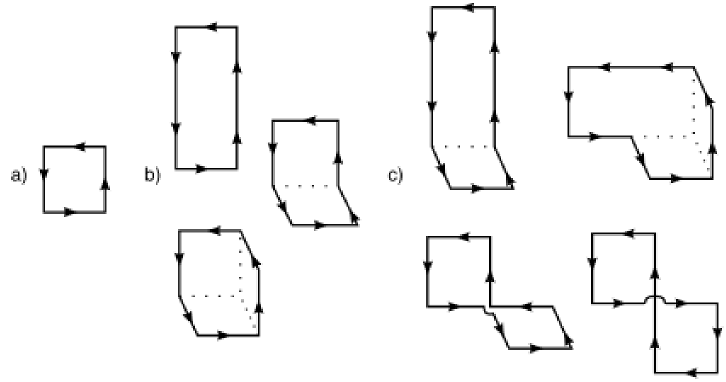
$\rightarrow O(10000)$ configuration

Reduce calculation cost and use huge $N_{\mathrm{conf}}$

# Flavor-singlet state from Glueball operator

no EW charge

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

$O_i =$  $, \cdots$



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

Same difficulty as meson operator → Huge statistical noise

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

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

Same $m_\sigma$ is obtained from meson and glueball correlators, in principle.

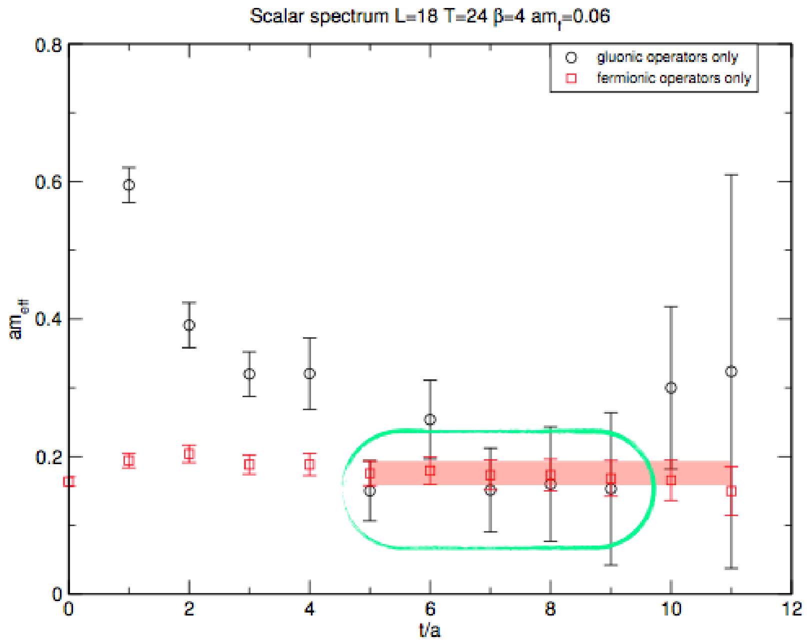
→ Reliability check of result, but never done before

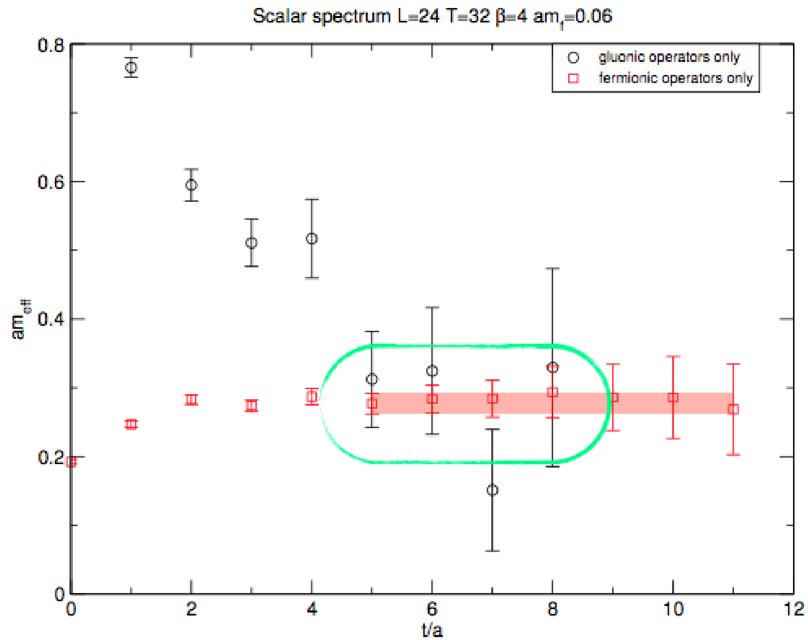
# Comparison of effective mass in $N_f = 12$

($m_f = 0.06$, $18^3 \times 24$ 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 $D(t)$



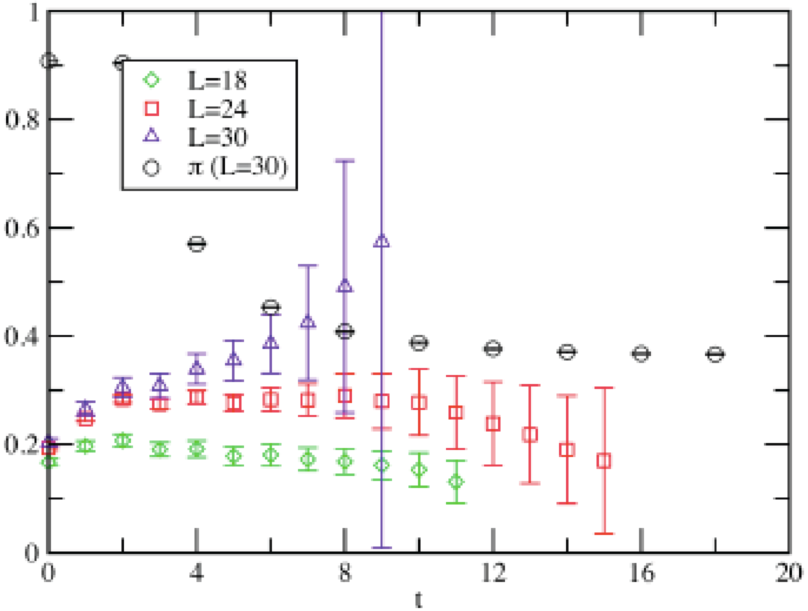

Larger error in glueball correlator

Reasonably consistent in large $t$

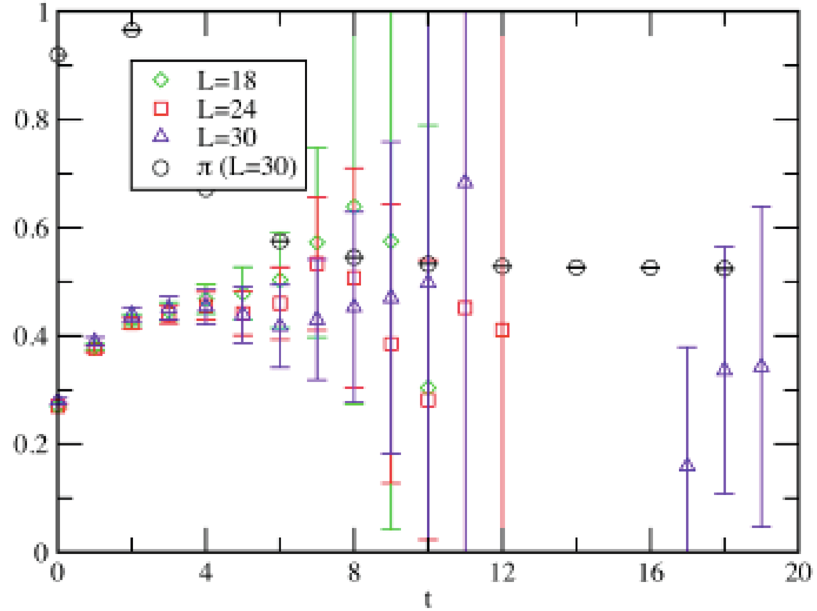
$\rightarrow$ show only meson results

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

m=0.06




m=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.