Light composite flavor-singlet scalar in large N_f QCD

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(LatKMI Collaboration)

Refs. PRD86(2012)054506, PRD87(2013)094511, PRL111(2013)162001, PoS(LATTICE 2013)070;arXiv:1309.0711, and updates

Sakata Memorial KMI Mini-Workshop on
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  - Recent studies in our project
- Results of flavor-singlet scalar
  - Difficulty of calculation
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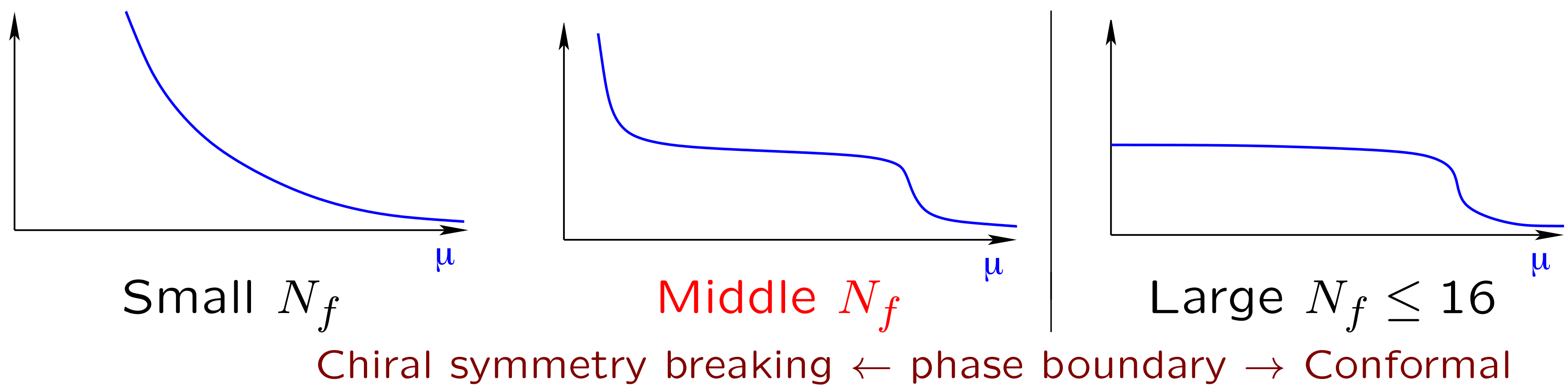
Walking technicolor

N_f massless fermions + SU(N_{TC}) gauge at $O(1)$ TeV

Model requirement:

- Spontaneous chiral symmetry breaking
- Slow running (walking) coupling in wide scale range

SU(3) gauge theory



- Large anomalous mass dimension $\gamma^* \sim 1$ in walking region

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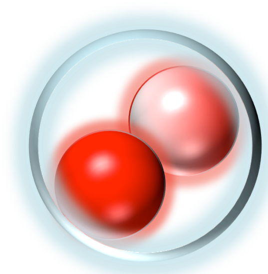
- Higgs $\approx$ Light composite scalar
  pNGB (technidilaton)
  of scale symmetry breaking



$$m_{\mathrm{Higgs}}/v_{\mathrm{EW}} \sim 0.5 = m_\sigma/(\sqrt{N_d}F)$$

F : decay constant, N_d : number of weak doublets

usual QCD $m_\sigma/F \sim$ 4–5

Conditions of walking technicolor

- Spontaneous chiral symmetry breaking
- Slow running (walking) coupling in wide scale range
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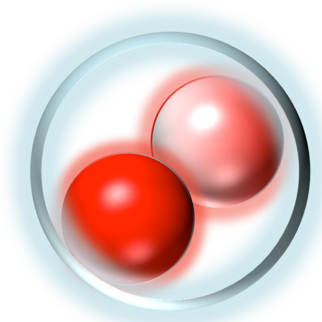
- Light composite scalar

Question: Such a theory really exists?

Nonperturbative calculation is important.

$\rightarrow$ numerical calculation with lattice gauge theory



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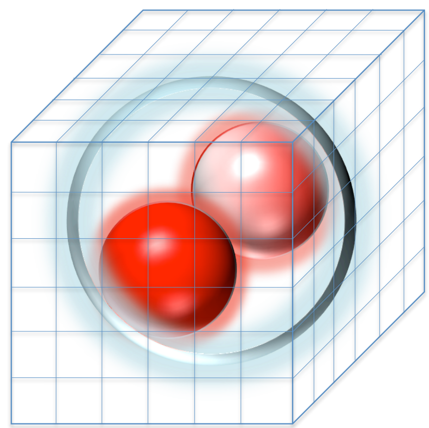


Recent studies in our project

Purpose in our project

Search for candidate of walking technicolor

Systematic investigation of N_f dependence

SU(3) gauge theory with $N_f = 0, 4, 8, 12, 16$ fermions

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

Cheaper calculation cost + small lattice systematic error

HISQ: '07 HPQCD and UKQCD; HISQ/Tree: '12 Bazakov *et al.*

Basic physical quantities: m_π, F_π, m_ρ, $\langle\overline{\psi}\psi\rangle$

$N_f = 4$: PRD86(2012)054506:PRD87(2013)094511 [Poster: Kurachi]

$N_f = 8$: PRD87(2013)094511 [Talk: Nagai (Thu.)]

$N_f = 12$: PRD86(2012)054506 [Talk: Ohki (Thu.)]

$N_f = 8$ may be candidate of walking theory

some results updated from papers

[Poster]

$N_f = 12$ glueball: [Rinaldi], $N_f = 16$: [Yamazaki]

Recent study of LatKMI Collaboration

Search for candidate of walking technicolor

$N_f = 12$: PRD86(2012)054506; $N_f = 8$: PRD87(2013)094511

chiral broken $\to$ walking $\to$ conformal increasing N_f

Signal of phase

- Chiral broken phase

  Simulations at $m_f \neq 0$

$$m_f \to 0:\ m_\pi \to 0 \text{ and } F_\pi \neq 0 \Rightarrow \frac{F_\pi}{m_\pi} \xrightarrow{m_\pi \to 0} \infty$$

- Conformal phase

Simulations at $m_f \neq 0$: scale invariance breaking

$\to$ bound states (mesons)

Hyperscaling with anomalous dimension γ^* at small m_f

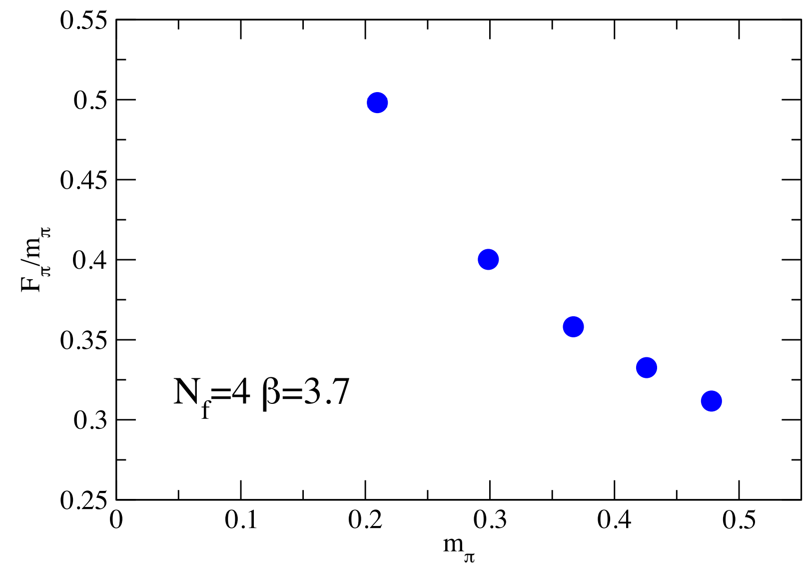
$$\begin{aligned} m_H &= C_H\ m_f^{1/(1+\gamma^*)} \\ F_\pi &= C_F\ m_f^{1/(1+\gamma^*)} \end{aligned} \Rightarrow \frac{F_\pi}{m_\pi} \xrightarrow{m_\pi \to 0} \text{constant}$$

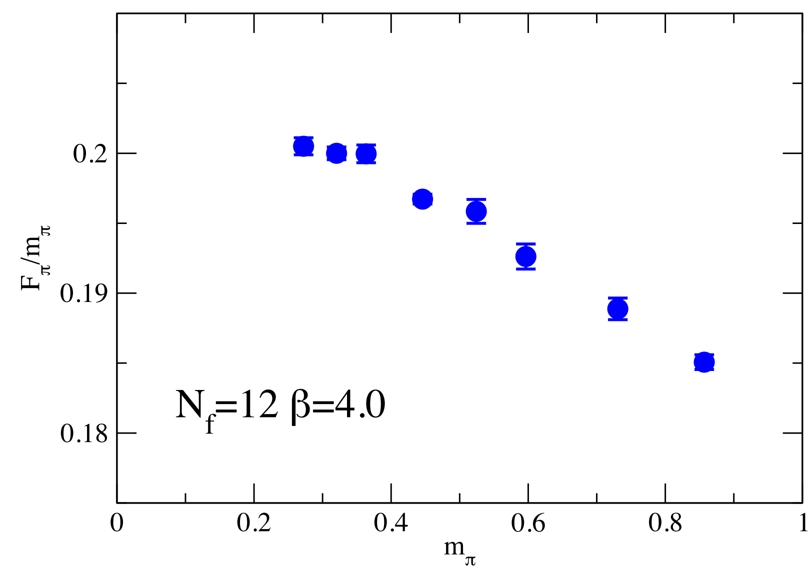
Different $m_f(m_\pi)$ dependence in two phases

Recent study of LatKMI Collaboration

$N_f = 12$: PRD86(2012)054506; $N_f = 8$: PRD87(2013)094511 + updates

$F_\pi / m_\pi \to \infty$ $\qquad$ $F_\pi / m_\pi \to$ constant





Recent study of LatKMI Collaboration

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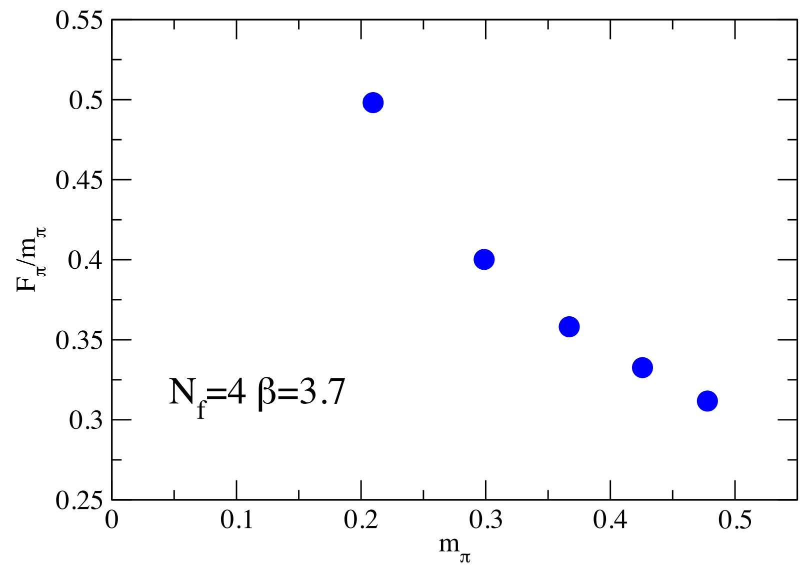
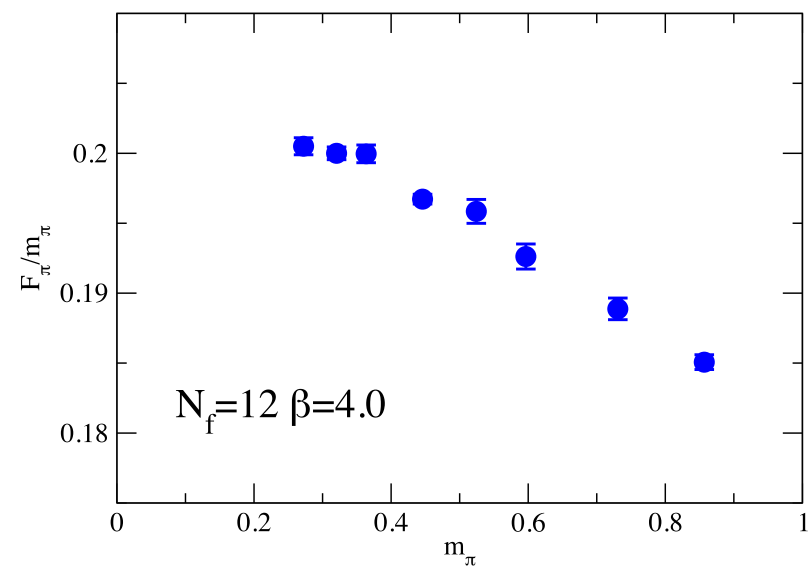
Chiral broken



Conformal



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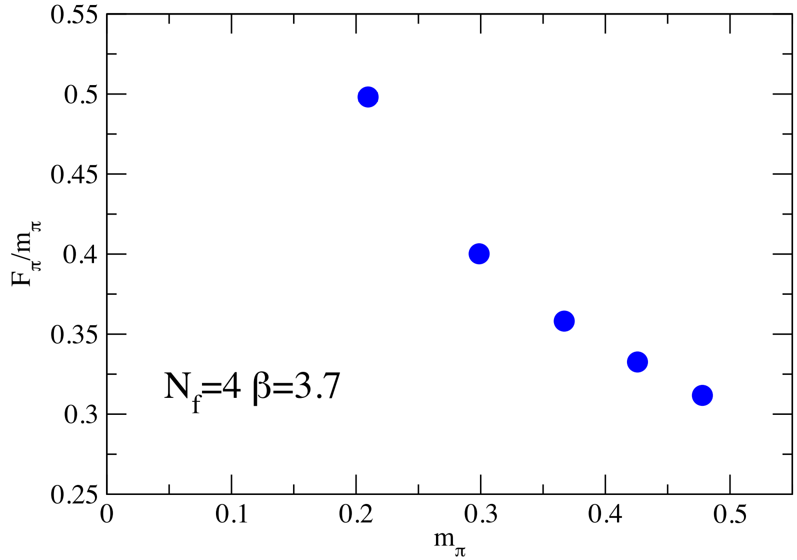

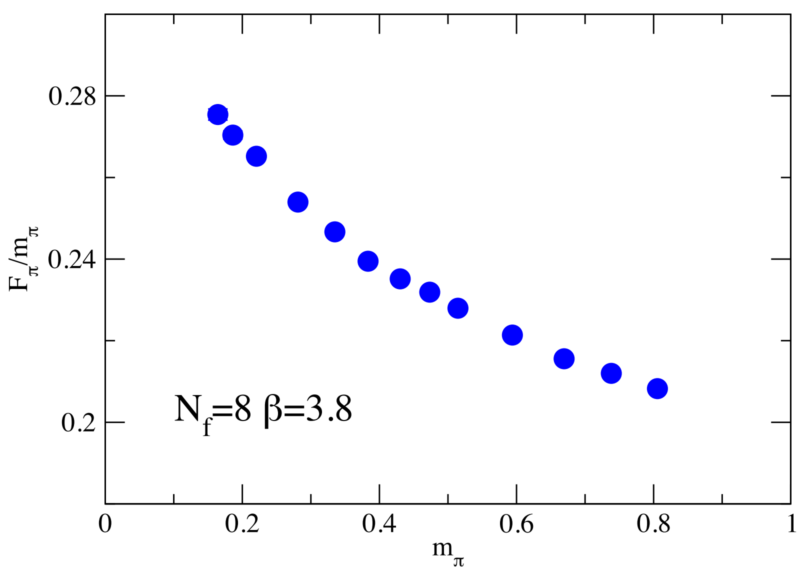

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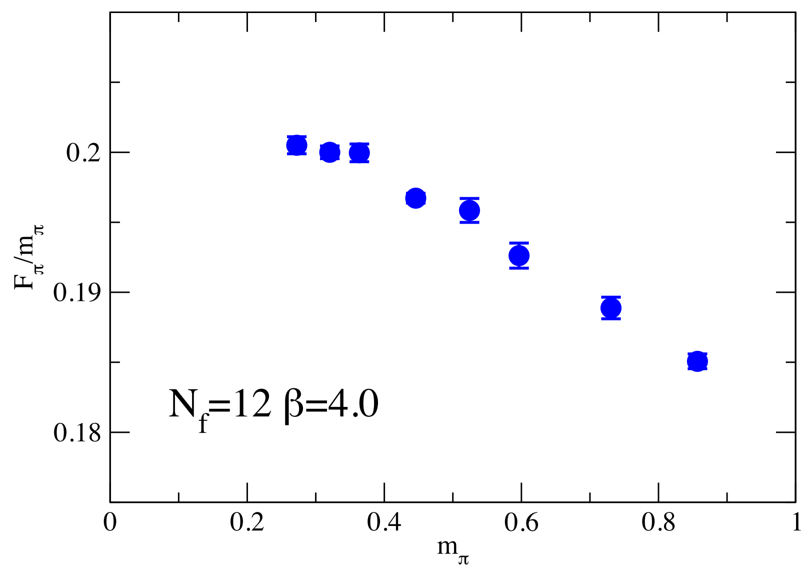
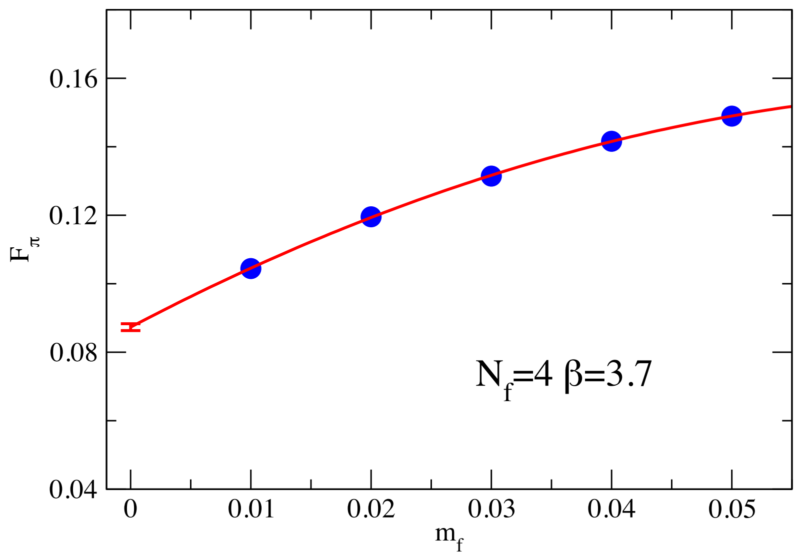


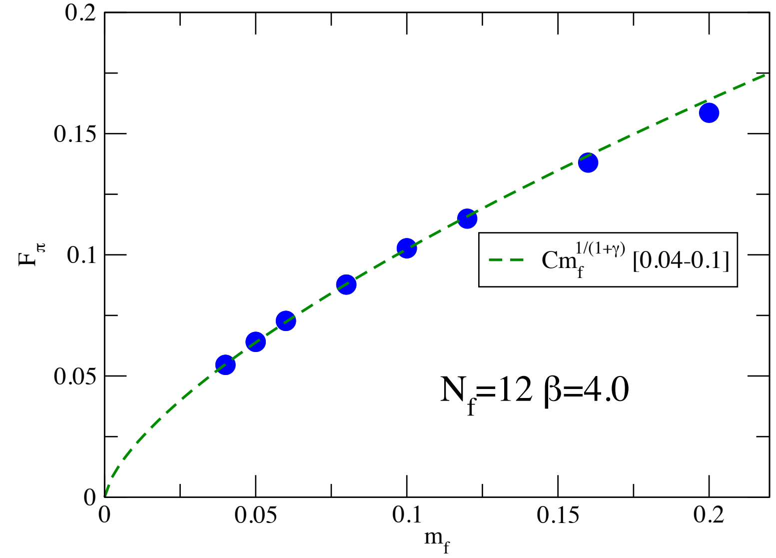
Recent study of LatKMI Collaboration

$N_f = 12$: PRD86(2012)054506; $N_f = 8$: PRD87(2013)094511 + updates

Chiral broken $F_\pi \to F \neq 0$



Conformal $F_\pi \to C m_f^{1/(1+\gamma)}$



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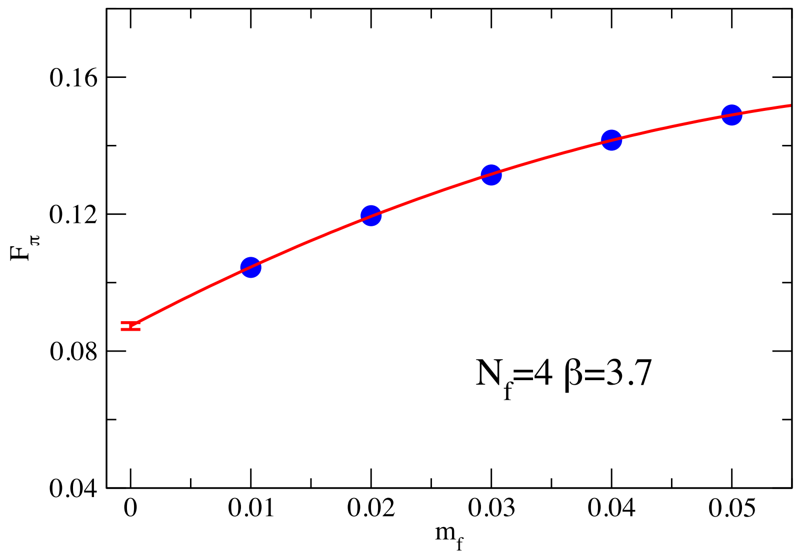

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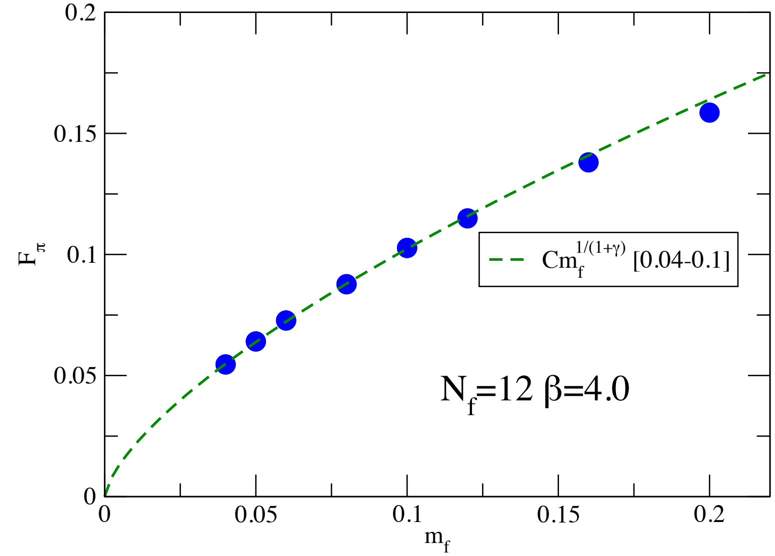
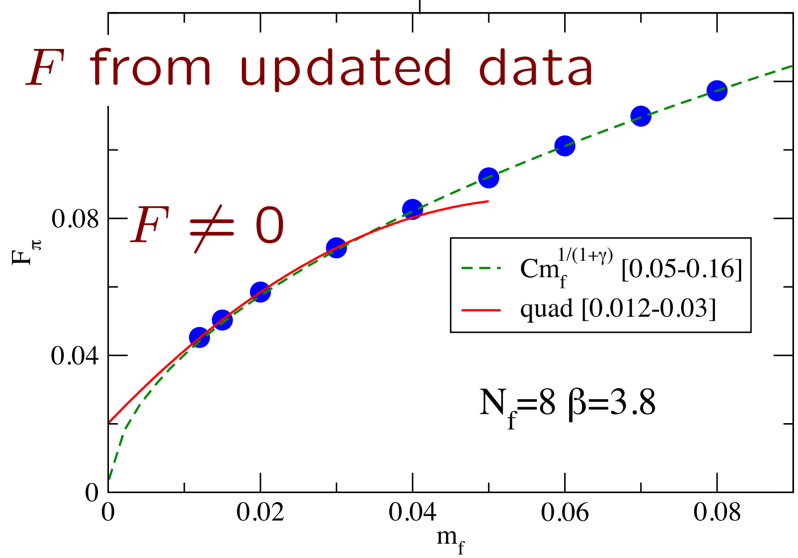


F from updated data



Recent study of LatKMI Collaboration

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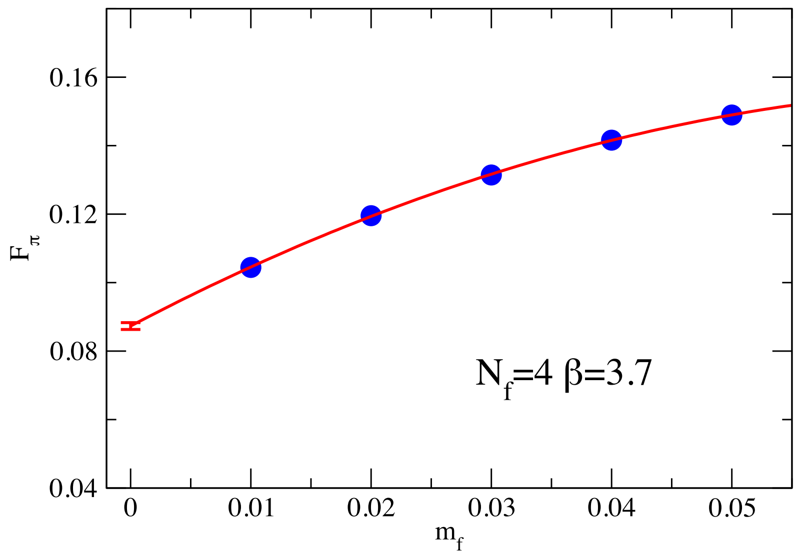

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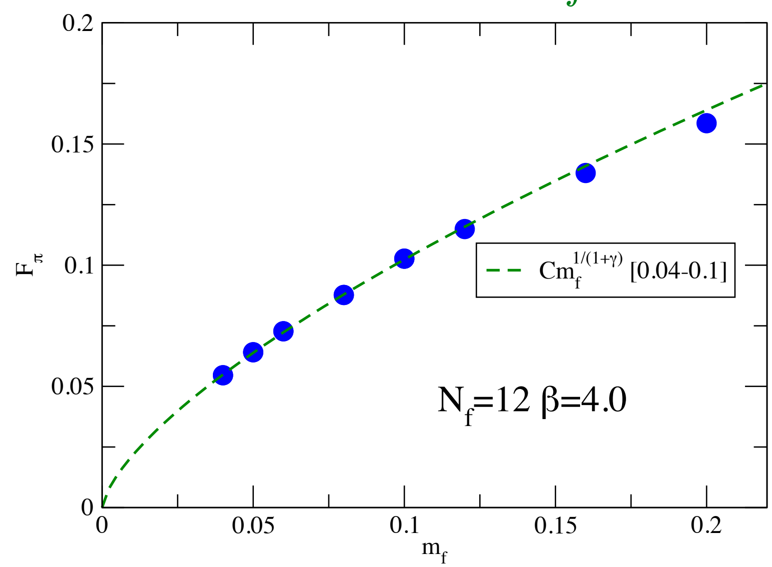

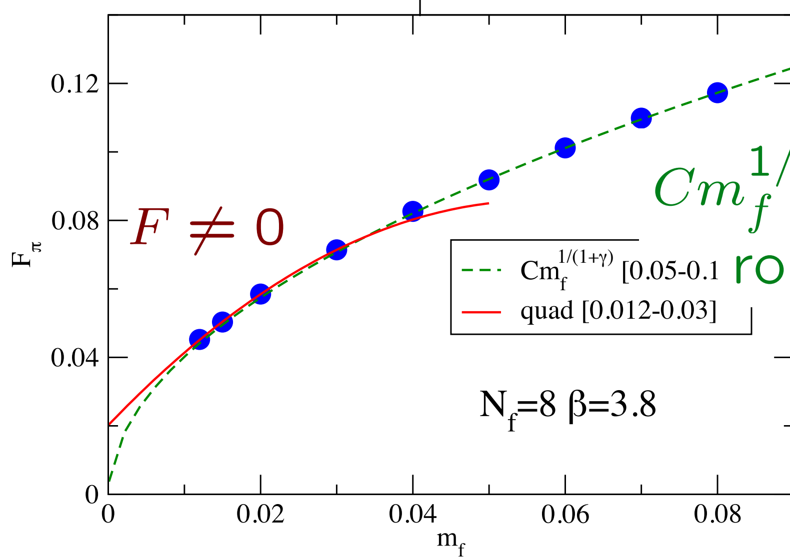

$F \neq 0$

$C m_f^{1/(1+\gamma)}$

rough estimate of γ

Recent study of LatKMI Collaboration

Search for candidate of walking technicolor

$N_f = 12$: PRD86(2012)054506; $N_f = 8$: PRD87(2013)094511 + updates

$N_f = 4$ QCD: Spontaneous chiral symmetry breaking

$N_f = 12$ QCD: Consistent with conformal phase

$N_f = 8$ QCD may be a candidate of Walking technicolor

- Spontaneous chiral symmetry breaking
  $F_\pi / m_\pi \to \infty$ and $F_\pi \neq 0$ towards $m_f \to 0$
- Slow running (walking) coupling in wide scale range
  Approximate hyperscaling in F_π
- Large anomalous mass dimension $\gamma^* \sim 1$ in walking region
  $\gamma = 0.6$–1.0: Hyperscaling-like behavior of m_π, F_π, m_ρ
- Light composite scalar $\Leftarrow$ Important to check!

Next: Flavor-singlet scalar in (approximate) conformal theory

Recent study of LatKMI Collaboration

Search for candidate of walking technicolor

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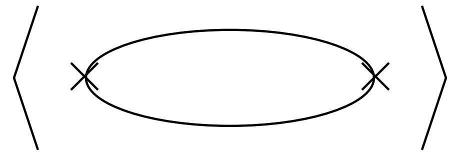
Next: Flavor-singlet scalar in (approximate) conformal theory

Composite flavor-singlet scalar

in $N_f = 12$ and 8 QCD

Difficulty of flavor-singlet scalar meson

- Flavor non-singlet scalar meson $S_{NS}(t) = \sum_{\vec{x}} \overline{\psi}_a(\vec{x},t)\psi_b(\vec{x},t)$ $(a \neq b)$

$\langle 0|S_{NS}(t)S^\dagger_{NS}(0)|0\rangle \quad =$  $= -C(t)$

c.f. m_π, F_π from non-singlet pseudoscalar

$O(100)$ configurations $\times$ $O(1)$ $D^{-1}[U](x,y)$

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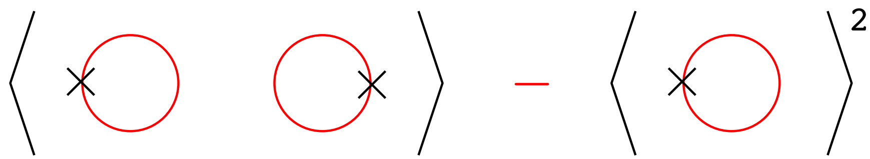
$\langle 0|S(t)S^\dagger(0)|0\rangle \quad = -C(t) + (N_f/4)D(t)$ (disconnected)

$D(t) =$ 

Much harder but essential for flavor-singlet

$O(10000)$ configurations $\times$ $O(100)$ $D^{-1}[U](x,x)$

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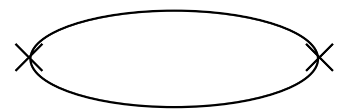
$$\langle 0|S_{NS}(t)S^\dagger_{NS}(0)|0\rangle \quad = \quad \Big\langle$$  $$\Big\rangle = -C(t)$$

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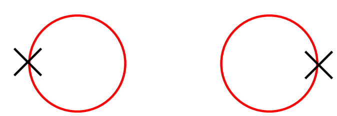
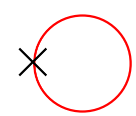
$$D(t) = \Big\langle$$  $$\Big\rangle - \Big\langle$$  $$\Big\rangle^2$$

Much harder but essential for flavor-singlet

$O(10000)$ configurations $\times$ $O(10)$ $D^{-1}[U](x,x)$

using noise reduction method

'97 Venkataraman and Kilcup

used in $N_f = 2+1$ η': Gregory *et al.*; $N_f = 12$ σ: Jin and Mawhinney

Composite flavor-singlet scalar in $N_f = 12$ QCD

Purpose of $N_f = 12$ QCD calculation

Why $N_f = 12$

- Investigated by many groups

  '08,'09 Appelquist *et al.*, '10 Deuzeman *et al.*, '10,'12 Hasenfratz,
  '11 Fodor *et al.*, '11 Appelquist *et al.*, '11 DeGrand, '11 Ogawa *et al.*,
  '12 Lin *et al.*, '12,'13 Iwasaki *et al.*, '12,'13 Itou, '12 Jin and Mawhinney, and $\cdots$

In our work PRD86(2012)054506 [Talk: Ohki (Thu.)]

consistent behavior with conformal phase

- A few studies of flavor-singlet scalar in conformal theory
  1. SU(2) Adjoint $N_f = 2$ glueball: '09 Del Debbio *et al.*
  2. SU(3) $N_f = 12$ meson: '12 Jin and Mawhinney

c.f. SU(3) $N_f = 12$ meson: '13 LH Collaboration

Purpouse of this work

Understand properties of flavor-singlet scalar in $N_f = 12$

regarded as pilot study of $N_f = 8$ theory

Flavor-singlet scalar in $N_f = 12$ QCD

PRL111(2013)162001

Simulation parameters

- $\beta = 4$ HISQ/Tree action
  calculation of m_σ
- Huge number of configurations
  measuring every 2 tarj.
- Four m_f on more than two volumes
- Noise reduction method with $N_r = 64$
- Local meson operator of $(1 \otimes 1)$

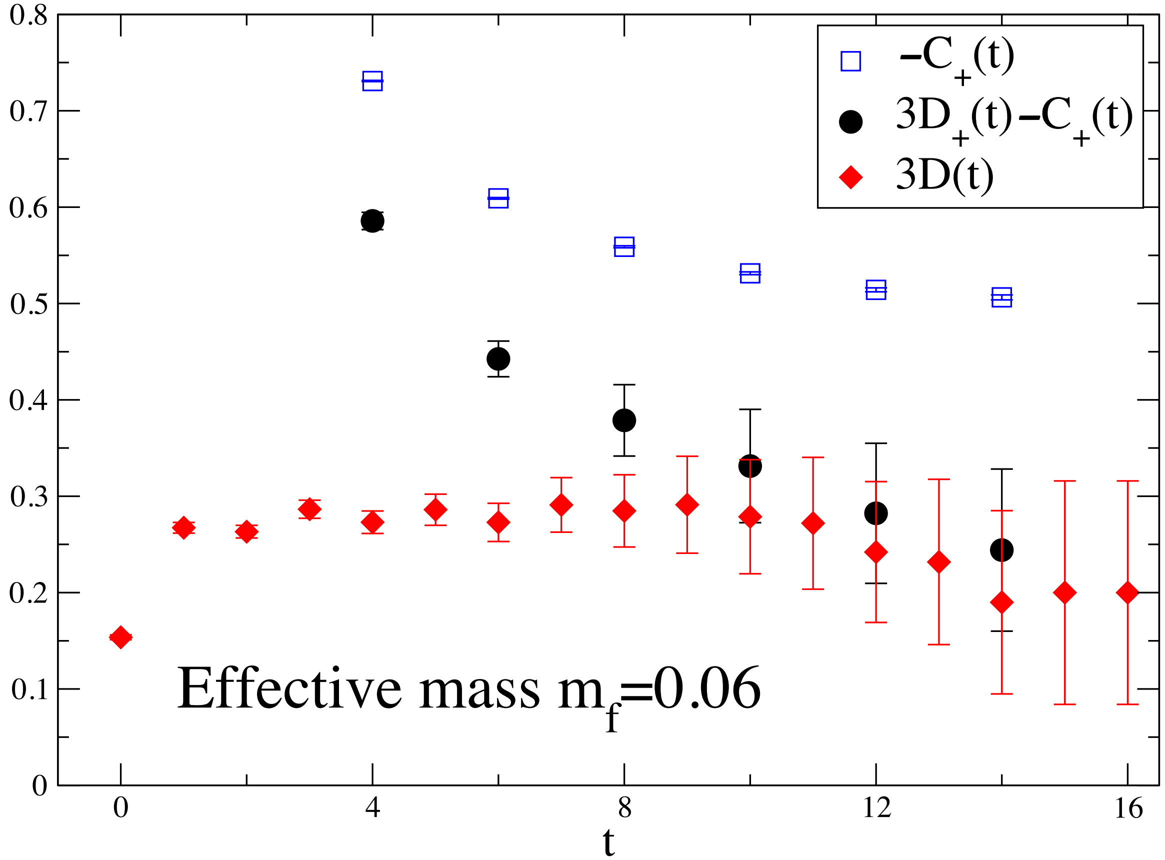
L, T	m_f	confs
24,32	0.05	11000
	0.06	14000
	0.08	15000
	0.10	9000
30,40	0.05	10000
	0.06	15000
	0.08	15000
	0.10	4000
36,48	0.05	5000
	0.06	6000

Machines: φ at KMI, CX400 at Kyushu Univ.

Effective mass in $N_f = 12$

PRL111(2013)162001

$m_f = 0.06, L = 24$ with $N_{\rm conf} = 14000$



Non-singlet scalar

a_0: $-C_+(t)$

Singlet scalar

σ: $3D_+(t) - C_+(t)$

$m_\sigma < m_{a_0}$

σ: $D(t)$

Consistent m_σ
with smaller error

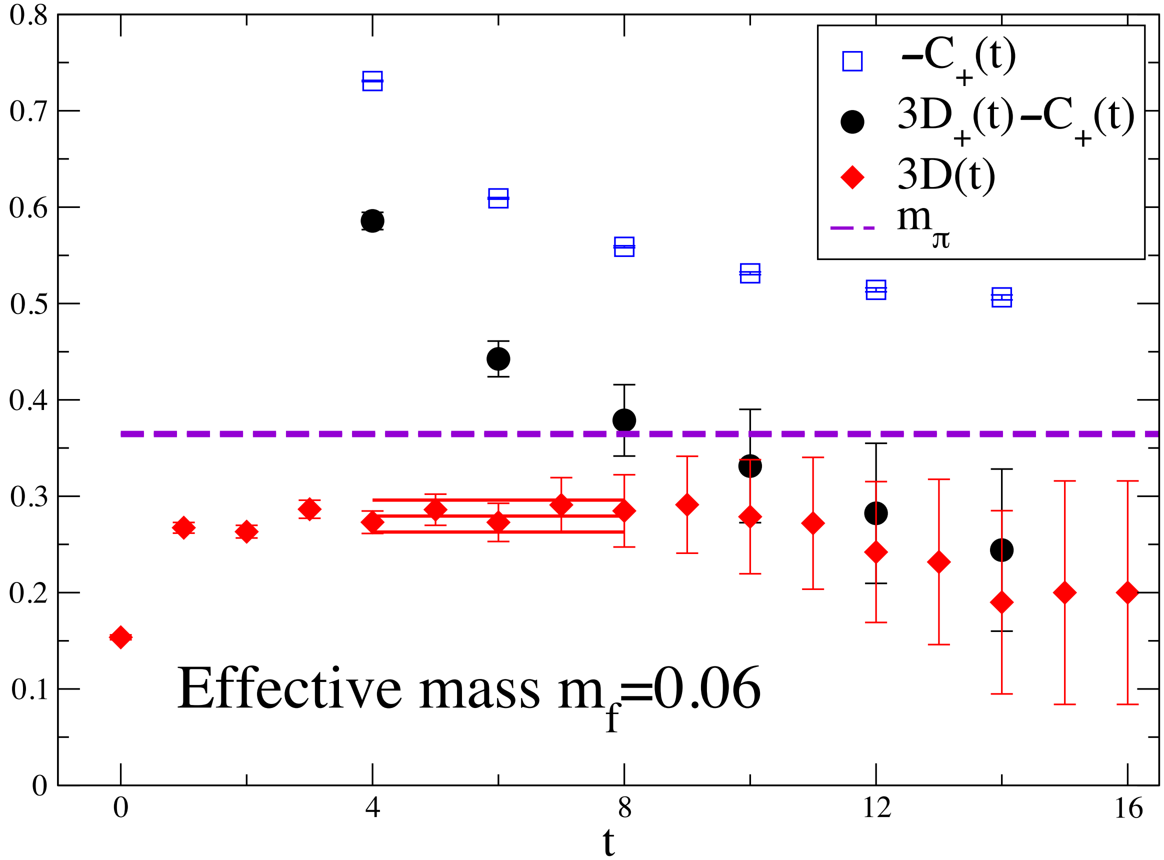
$$X_+(t) = 2X(t) + X(t+1) + X(t-1)$$

Good signal of m_σ from $D(t)$

Effective mass in $N_f = 12$

PRL111(2013)162001

$m_f = 0.06, L = 24$ with $N_{\text{conf}} = 14000$



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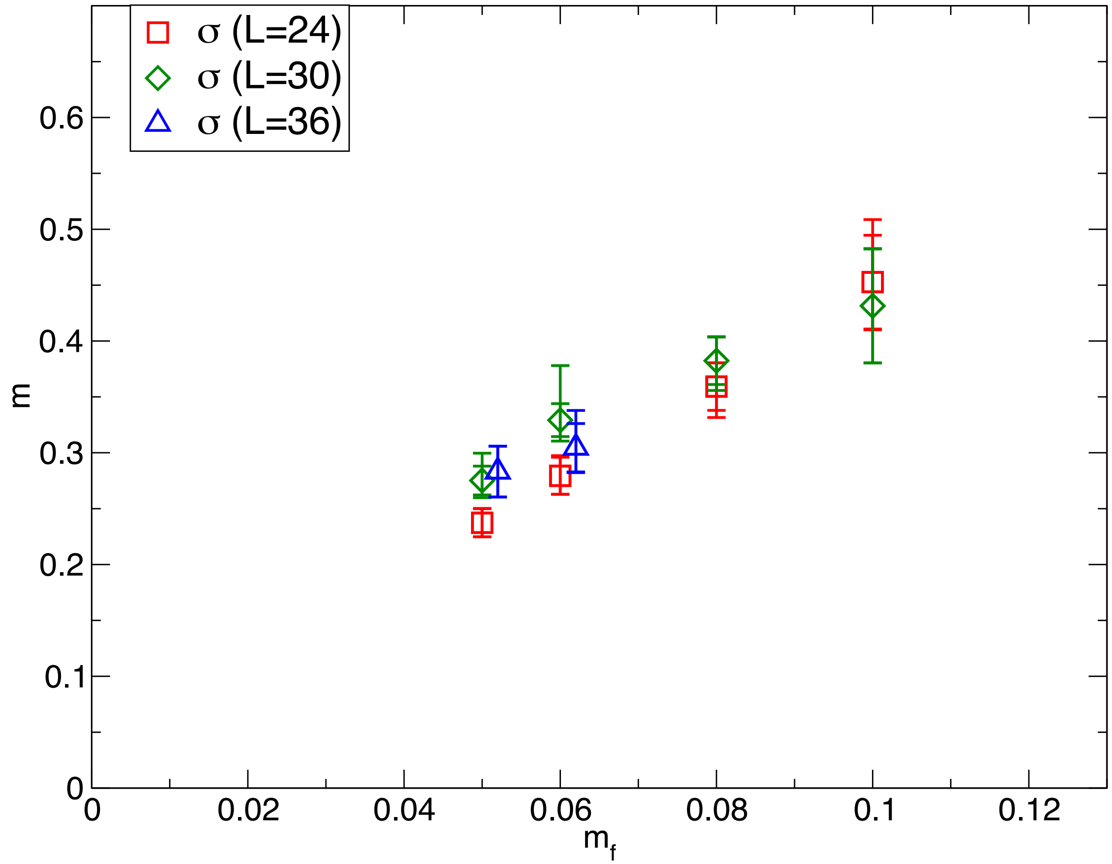
m_f dependence in $N_f = 12$

PRL111(2013)162001

m_σ from fit of $3D(t)$ with $t = 4$–8



Reasonable signals with almost 10% statistical error

Systematic error from fit range dependence of m_σ

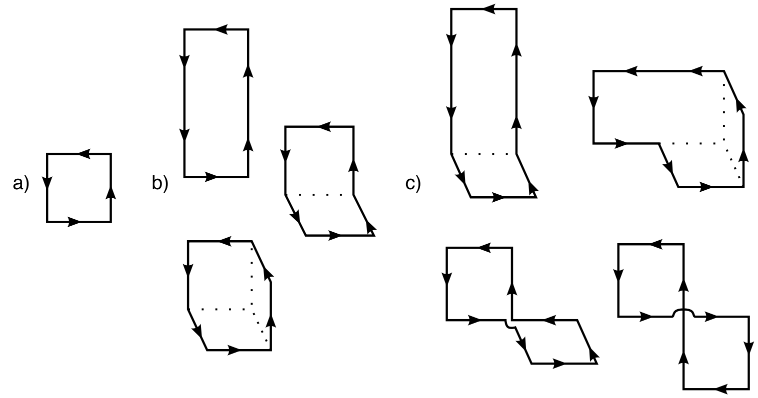
Finite volume effect under control $\leftarrow$ 2 larger volumes agree

Flavor-singlet state from Glueball operator

[Poster: Rinaldi]

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 $\rightarrow$ Huge statistical noise

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

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

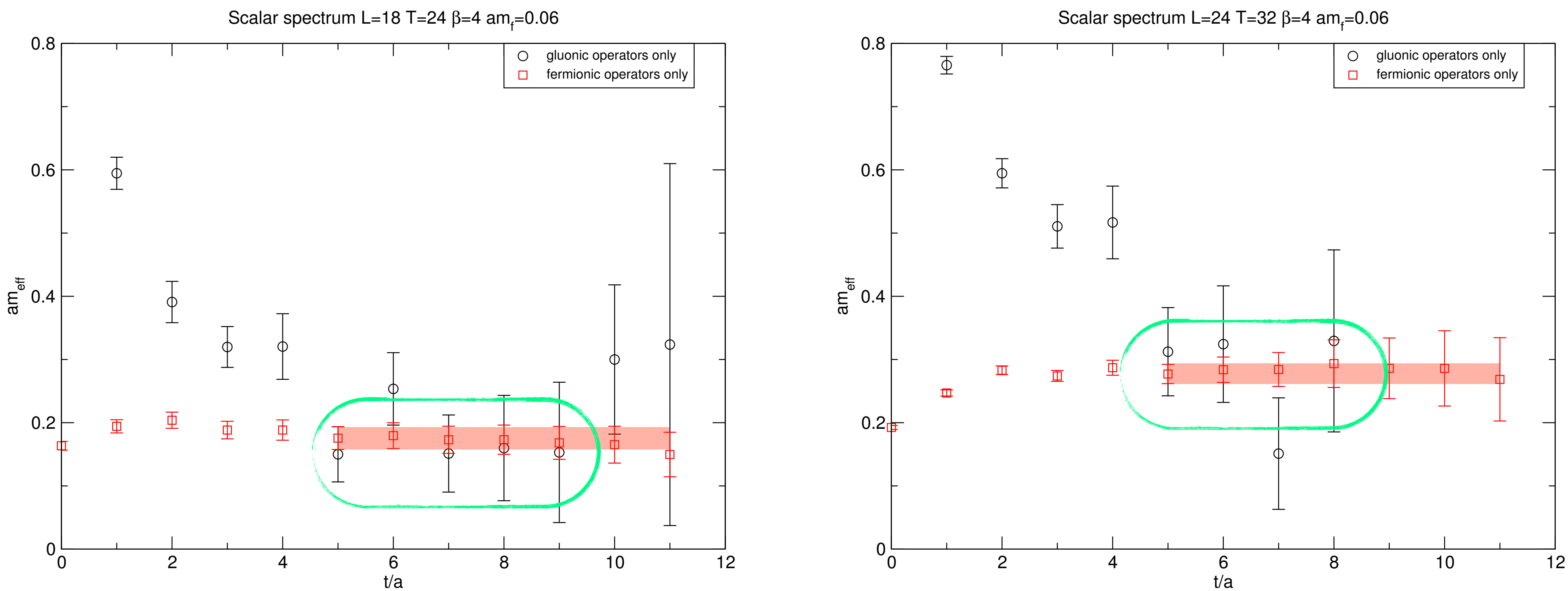
Same m_σ is obtained from meson and glueball correlators, in principle.

$\rightarrow$ Reliability test of result

Comparison of effective mass in $N_f = 12$

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

Glueball correlator and meson $D(t)$



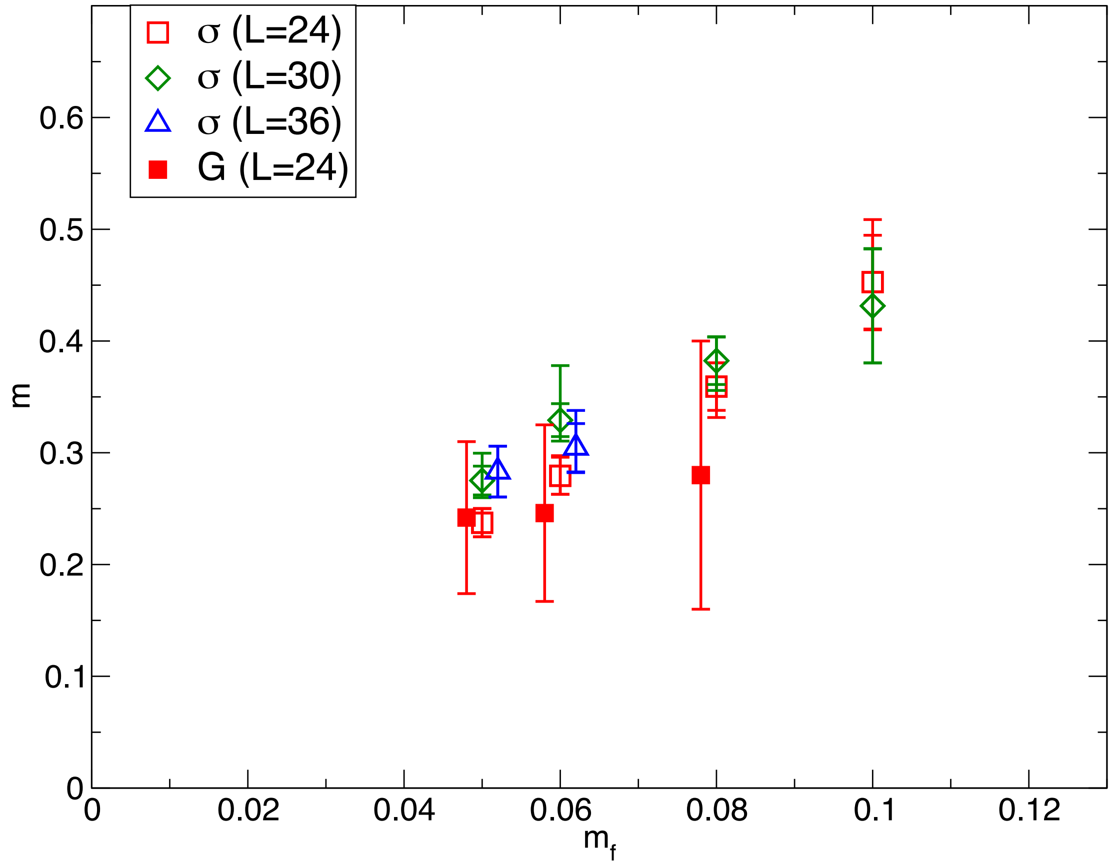
Larger error in glueball correlator

Reasonably consistent in large t

m_f dependence in $N_f = 12$

PRL111(2013)162001

m_σ from fit of $3D(t)$ with $t = 4$–8



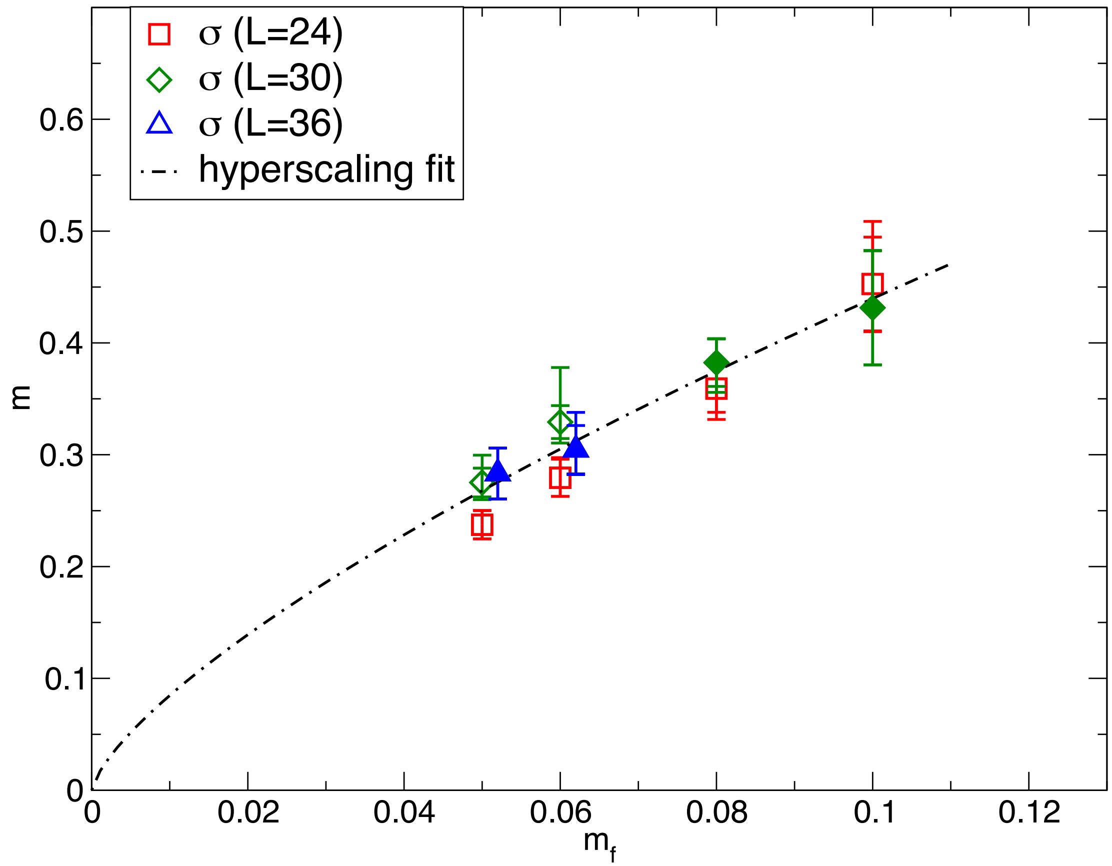
Consistent mass from glueball operator calculation

$\rightarrow$ show only meson results in the following pages

m_f dependence in $N_f = 12$

PRL111(2013)162001

m_σ from fit of $3D(t)$ with $t = 4$–8



Hyperscaling test with fixed γ using larget volume at each m_f

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

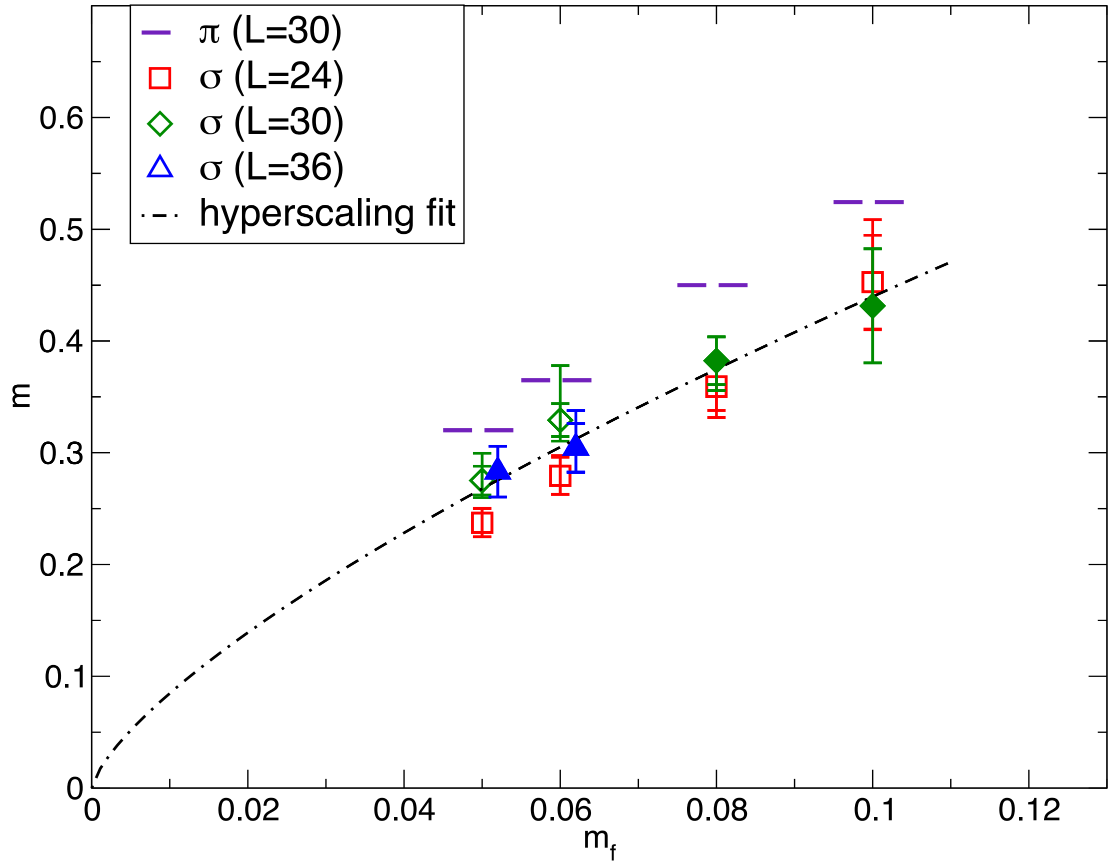
PRD86(2012)054506

Consistent hyperscaling as m_π

m_f dependence in $N_f = 12$

PRL111(2013)162001

m_σ from fit of $3D(t)$ with $t = 4$–8

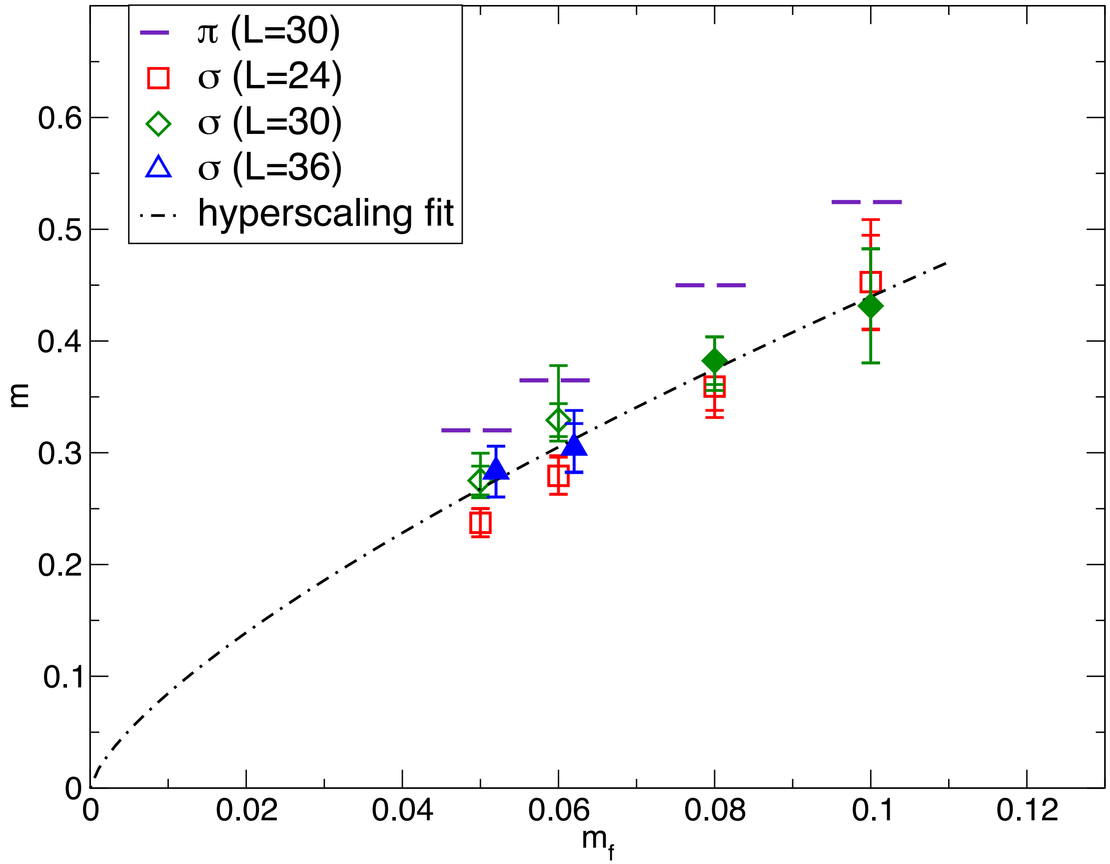


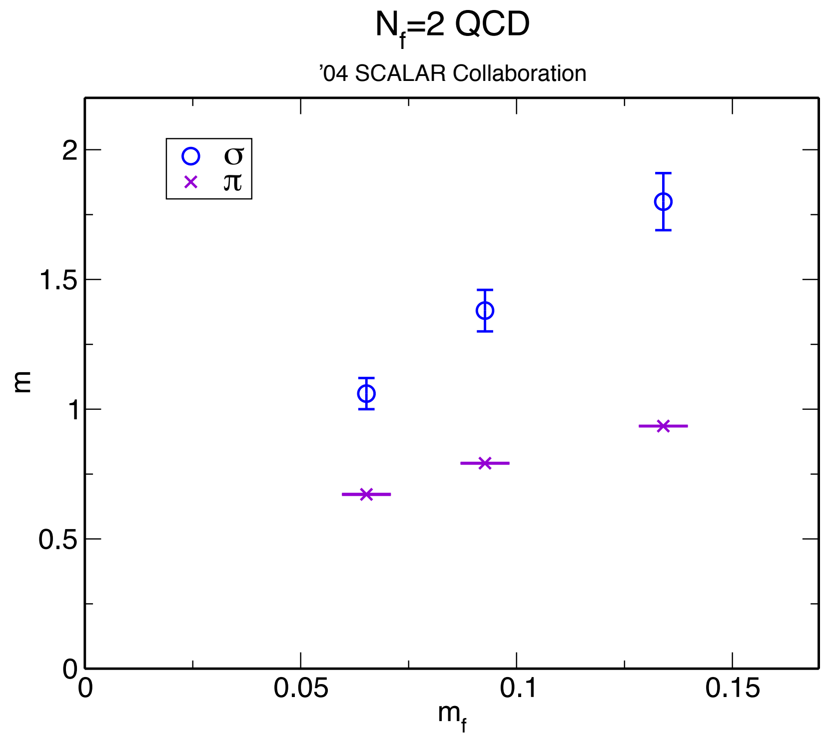
Lighter than π in all m_f

m_f dependence in $N_f = 12$

PRL111(2013)162001

m_σ from fit of $3D(t)$ with $t = 4$–8





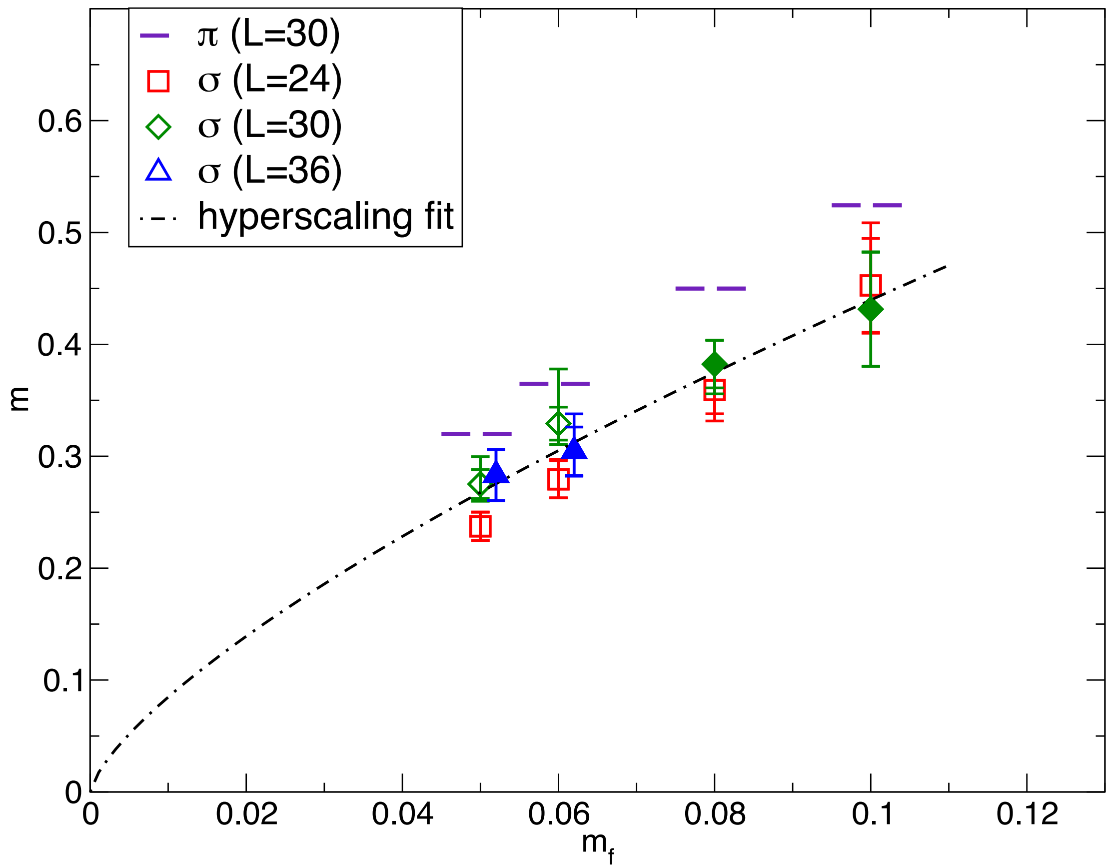
Lighter than π in all m_f

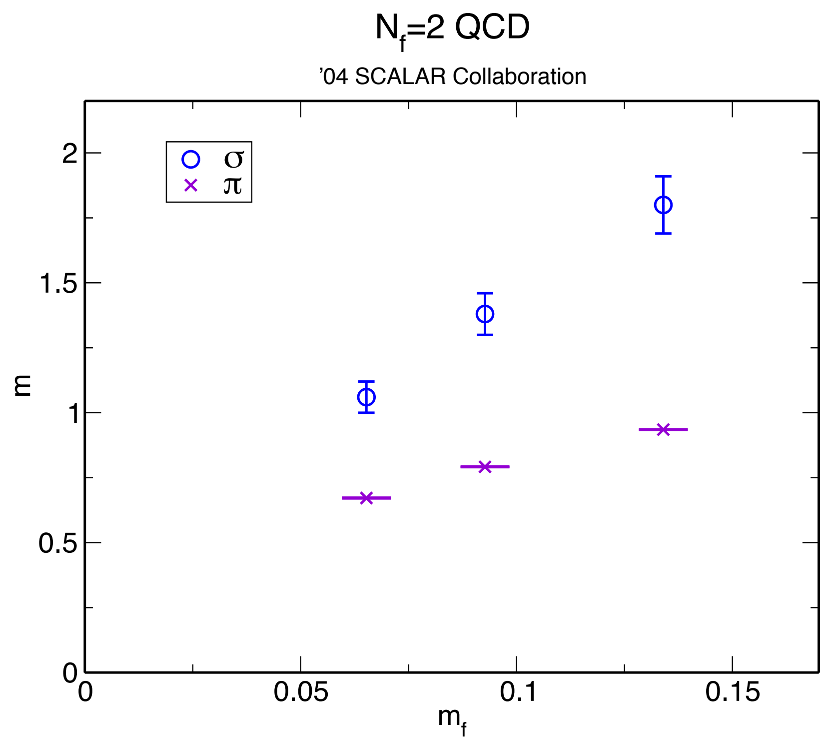
Much different from usual QCD

m_f dependence in $N_f = 12$

PRL111(2013)162001

m_σ from fit of $3D(t)$ with $t = 4$–8





$\boxed{\text{Conformal symmetry may make } \sigma \text{ light}}$

Encouranging for observing light scalar

in approximate conformal theory

Composite flavor-singlet scalar in $N_f = 8$ QCD

Flavor-singlet scalar in $N_f = 8$ QCD

$N_f = 8$ QCD may be candidate of walking theory; PRD87(2013)094511

[Talk: Nagai (Thu.)]

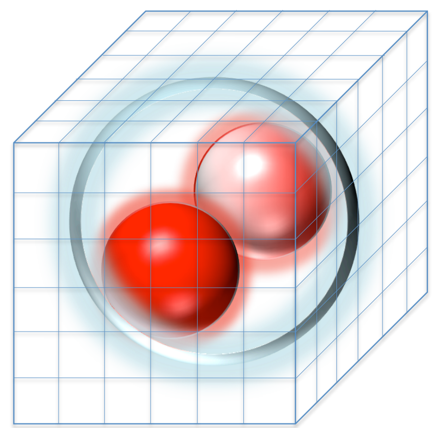
If flavor-singlet scalar is light

$\rightarrow$ Possibility of composite Higgs (technidilaton)

Required conditon to explain $m_{\mathrm{Higgs}}/v_{\mathrm{EW}} \sim 0.5$

$$m_\sigma/F \sim 1 \text{ in } m_f = 0 \text{ limit}$$

c.f. usual QCD $m_\sigma/F \sim$ 4–5



Purpose

1. Different from usual QCD?
2. Estimate m_σ/F in $m_f = 0$ limit

Flavor-singlet scalar in $N_f = 8$ QCD

report of preliminary results arXiv:1309.0711

Maybe candidate of walking theory; PRD87(2013)094511

Simulation parameters

- $\beta = 3.8$ HISQ/Tree action
  calculation of m_σ
- Huge number of configurations
  measuring every 2 tarj.
- Five m_f with three volumes
- Noise reduction method with $N_r = 64$
- Local meson operator of $(1 \otimes 1)$

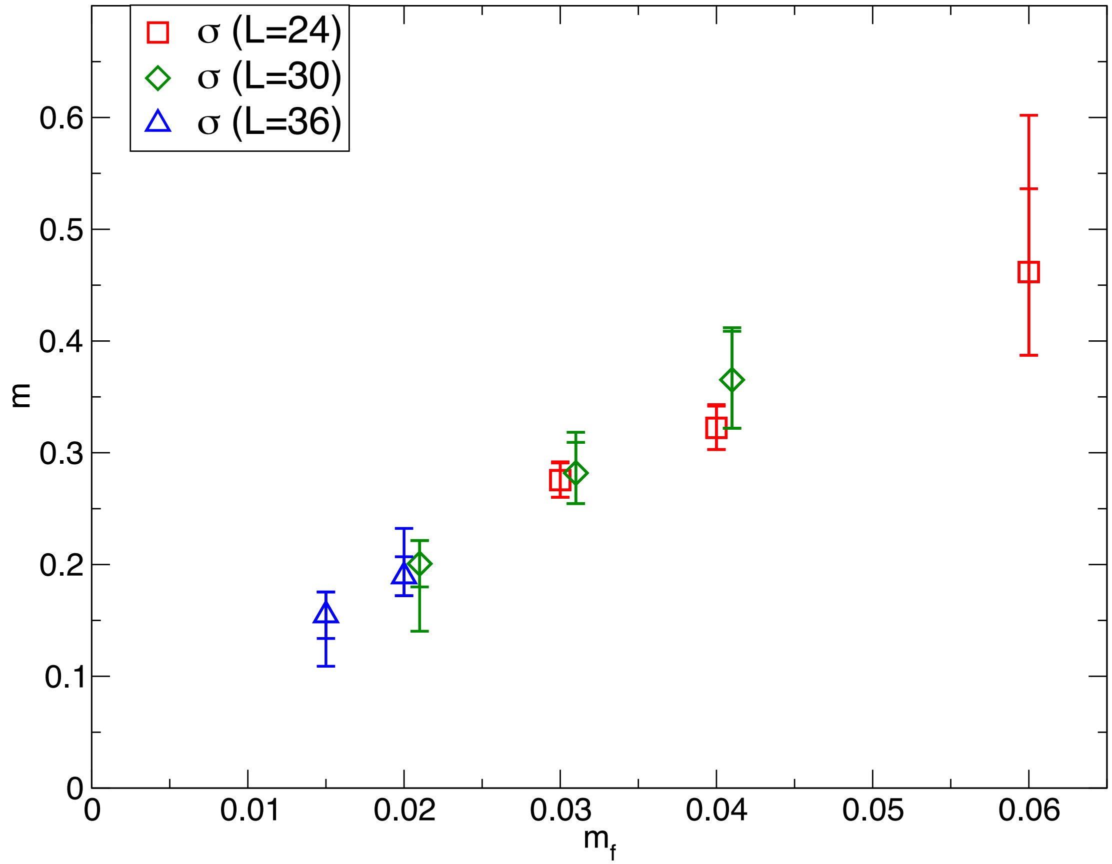
L, T	m_f	confs
24,32	0.03	36000
	0.04	50000
	0.06	18000
30,40	0.02	8000
	0.03	16500
	0.04	12900
36,48	0.02	5000
	0.015	3200

All results are preliminary.

Machines: φ at KMI, CX400 at Nagoya Univ.,
CX400 and HA8000 at Kyushu Univ.

m_f dependence in $N_f = 8$

m_σ from fit of $2D(t)$ with $t = 6$–11



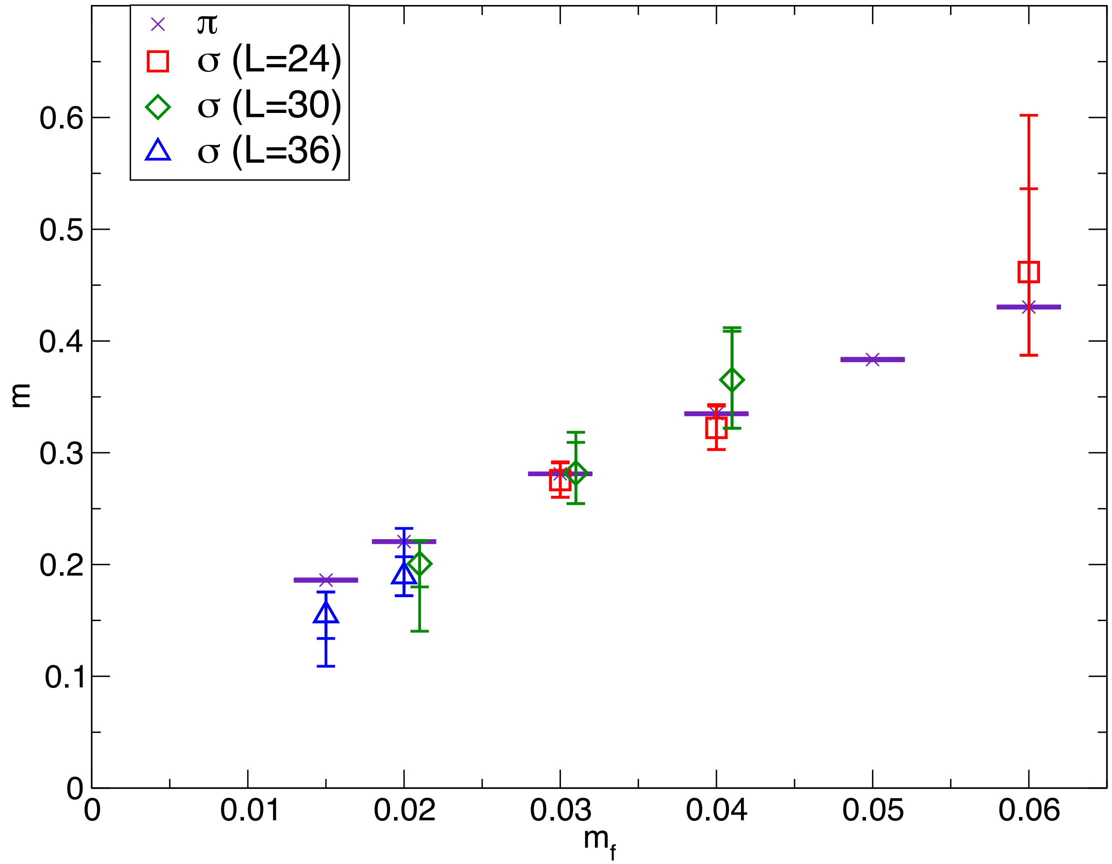
Reasonable signals with statistical error $< 20\%$

Systematic error from fit range dependence of m_σ

Finite volume effect seems under control

m_f dependence in $N_f = 8$

m_σ from fit of $2D(t)$ with $t = 6$–11



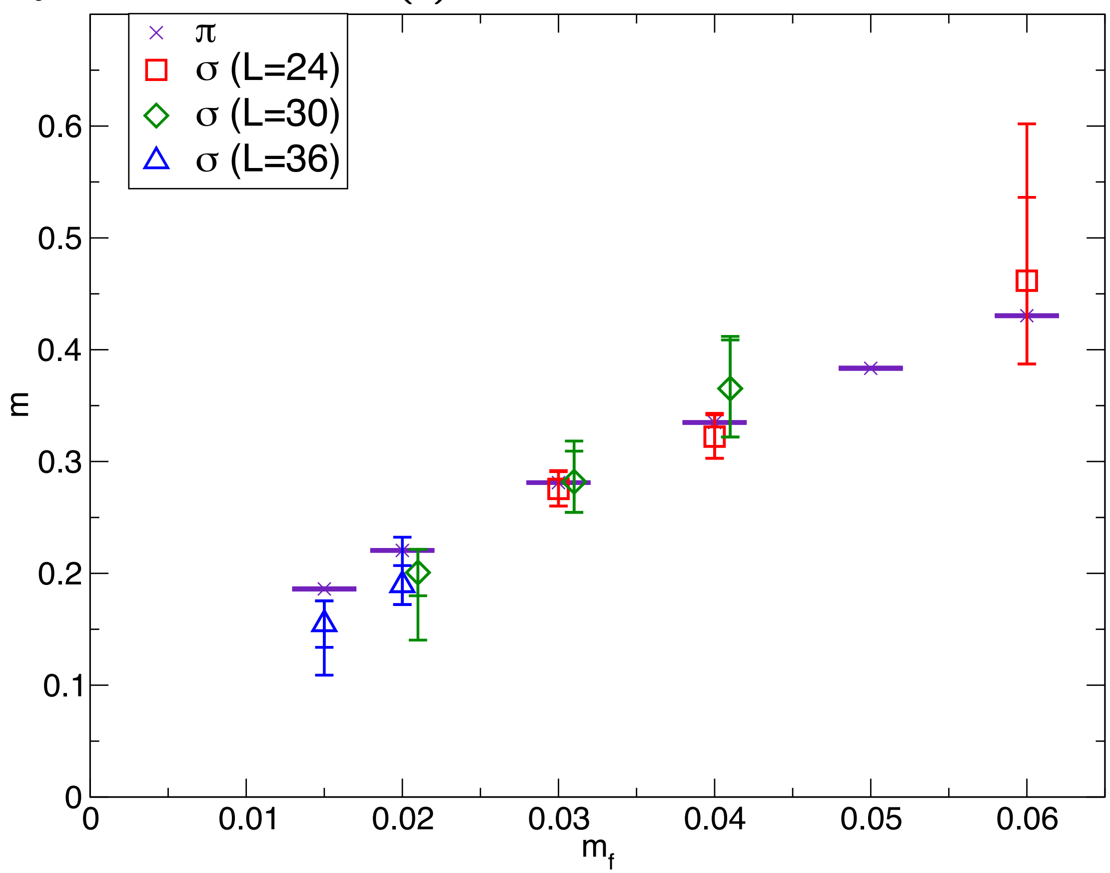
Reasonable signals with statistical error $< 20\%$

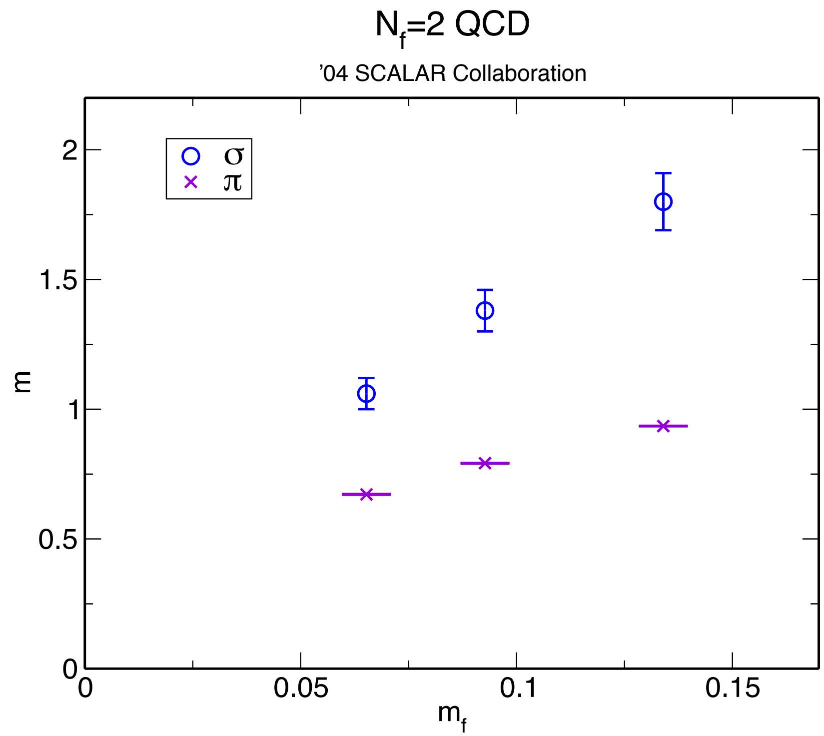
Systematic error from fit range dependence of m_σ

$m_\sigma \sim m_\pi$ in all m_f

m_f dependence in $N_f = 8$

m_σ from fit of $2D(t)$ with $t = 6$–11



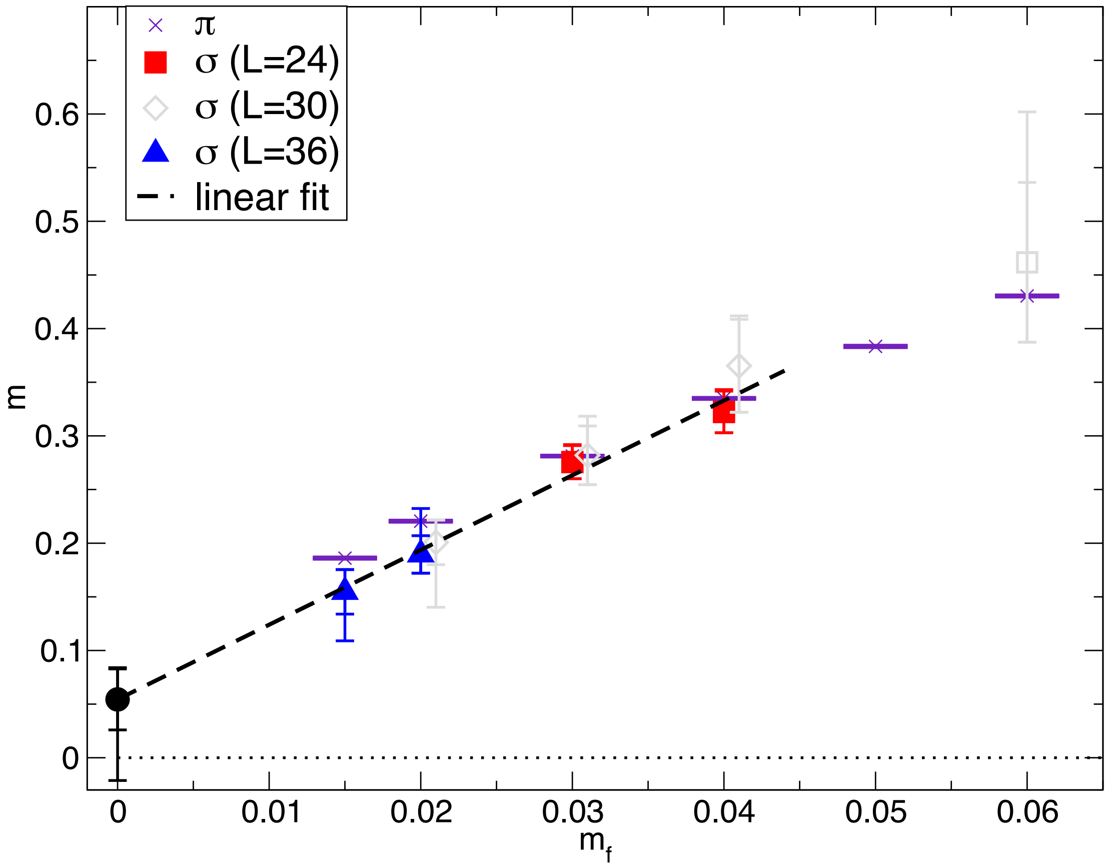


Reasonable signals with statistical error $< 20\%$

Systematic error from fit range dependence of m_σ

$m_\sigma \sim m_\pi$ in all m_f, much different from $N_f = 2$ QCD

Chiral extrapolation (1) in $N_f = 8$



$$m_\sigma = m_0 + Am_f\colon\ m_0 = 0.054(28)\left({}^{8}_{70}\right) \rightarrow \frac{m_\sigma}{F/\sqrt{2}} = 3.8(2.0)\left({}^{1.4}_{5.0}\right)$$

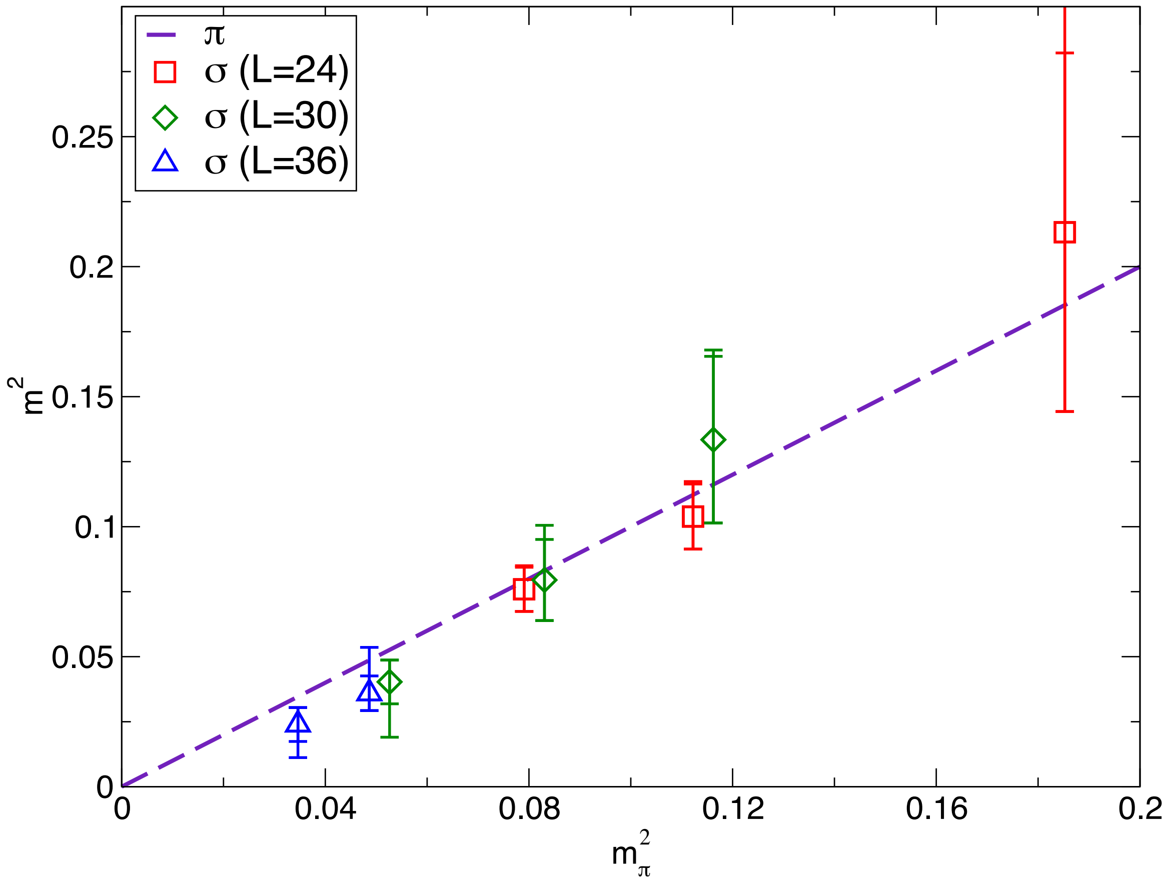
$F = 0.0202(13)\left({}^{54}_{67}\right)$ updated from PRD87(2013)094511

$F_\pi/\sqrt{2} = 93$ MeV in usual QCD

Chiral extrapolation (2) in $N_f = 8$

ChPT with scale symmetry breaking '13 Matsuzaki and Yamawaki

$$m_\sigma^2 = m_0^2 + C \cdot m_\pi^2 + (\text{chiral log of } m_\pi)$$

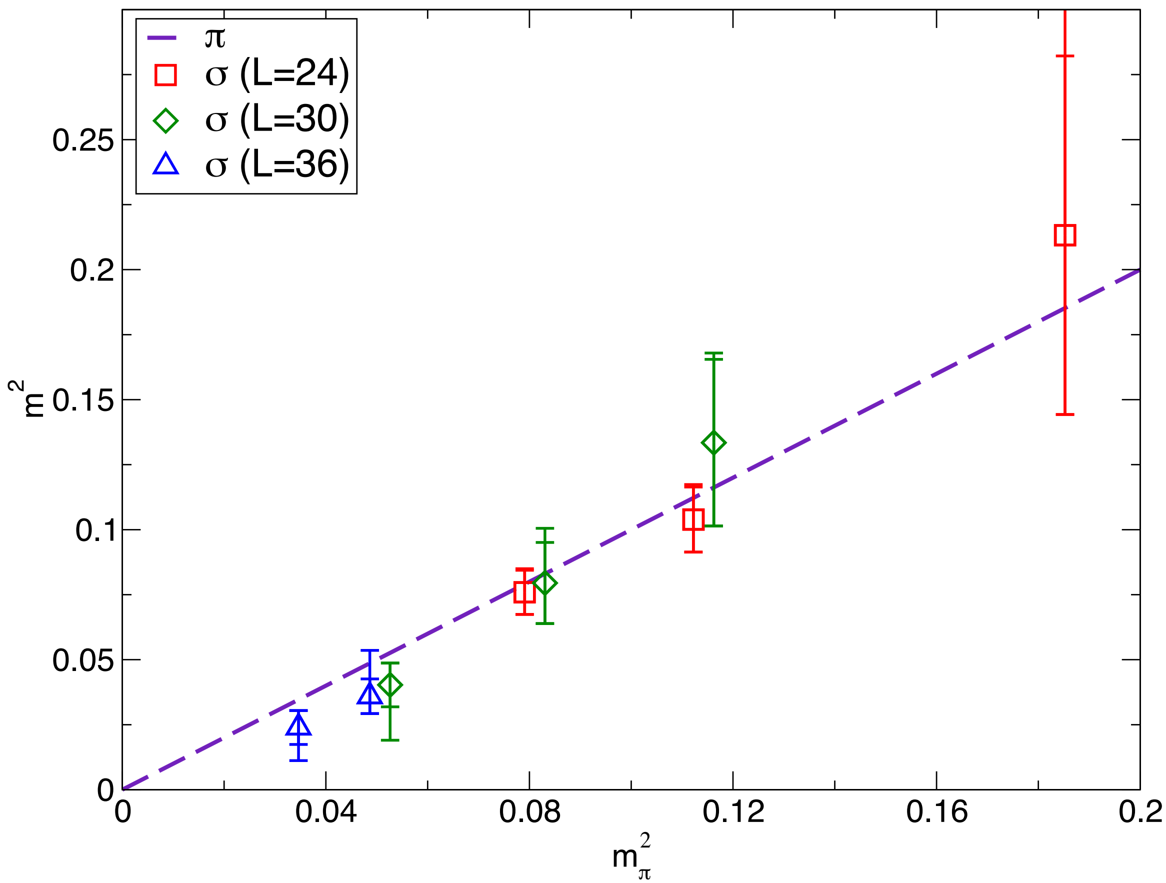


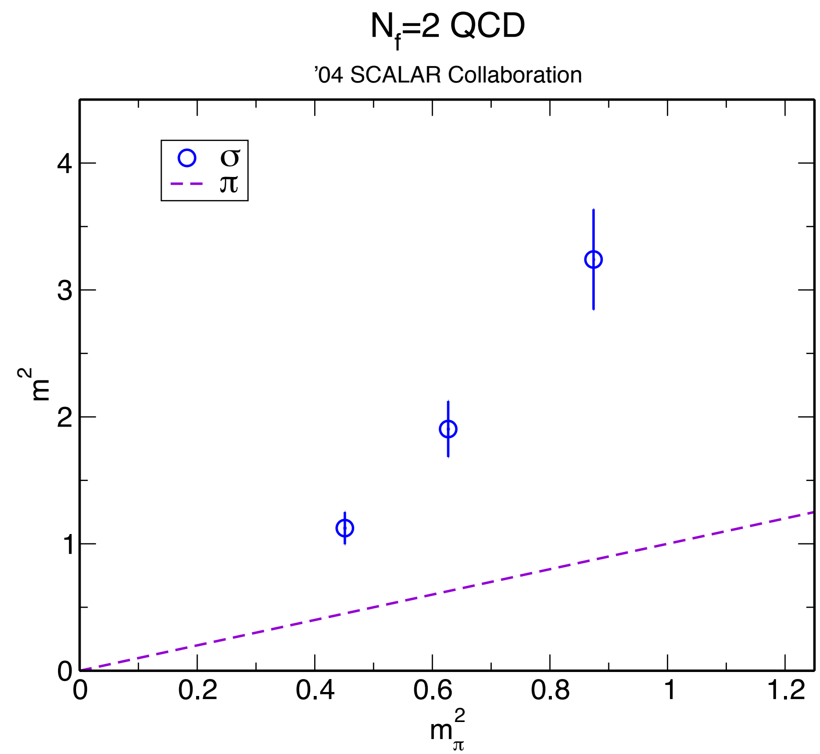
$m_\sigma \sim m_\pi \to C \sim 1$

Chiral extrapolation (2) in $N_f = 8$

ChPT with scale symmetry breaking '13 Matsuzaki and Yamawaki

$$m_\sigma^2 = m_0^2 + C \cdot m_\pi^2 + (\text{chiral log of } m_\pi)$$



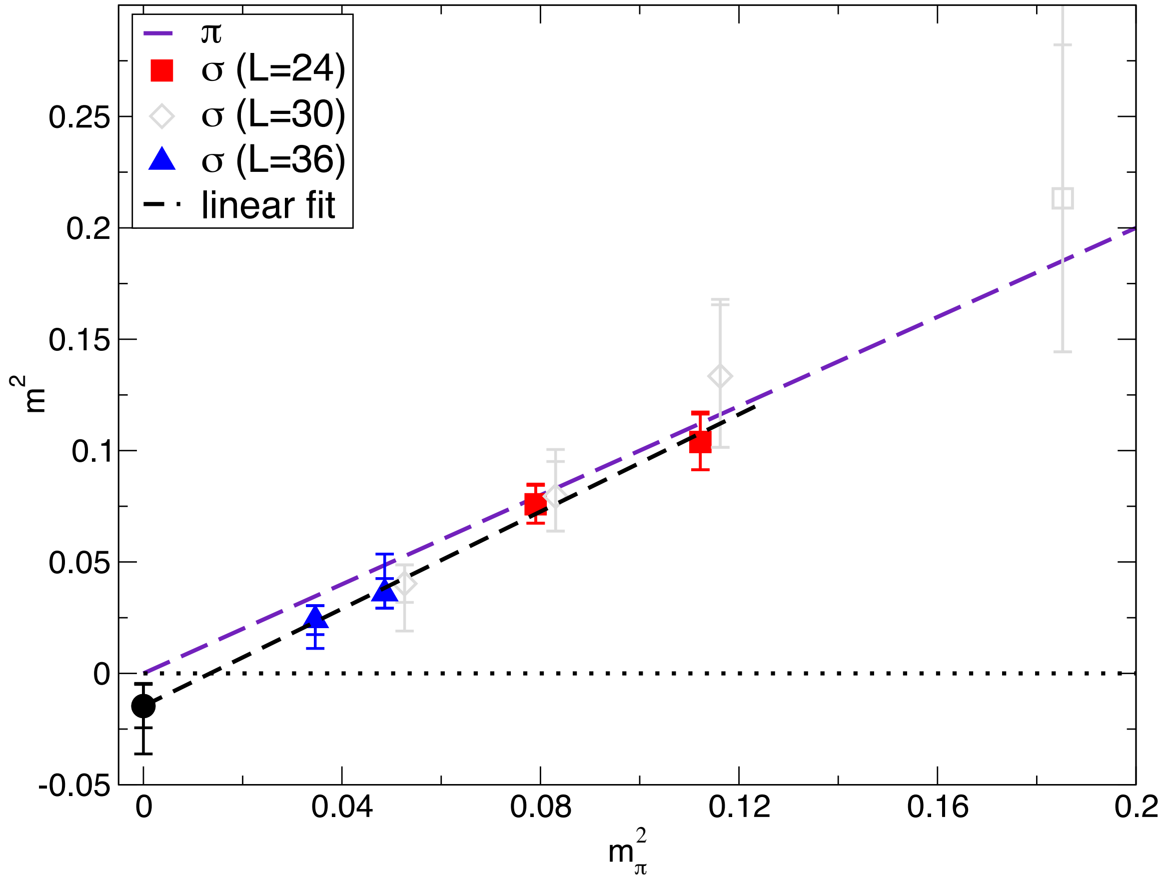


$m_\sigma \sim m_\pi \to C \sim 1$: different from $N_f = 2$ QCD

Chiral extrapolation (2) in $N_f = 8$

ChPT with scale symmetry breaking '13 Matsuzaki and Yamawaki

$$m_\sigma^2 = m_0^2 + C \cdot m_\pi^2 + (\text{chiral log of } m_\pi)$$



$m_0^2 < 0$: data not in $m_\sigma > m_\pi$ region

Need to check $m_\sigma > m_\pi$ at smaller m_f as in usual QCD

Comparison of m_σ in $N_f = 8$ with m_{Higgs}

$F/\sqrt{2} = 123$ GeV; One-family model (four-doublet fermions)

- Simple linear fit

$$\frac{m_\sigma}{F/\sqrt{2}} = 3.8(2.0)(^{1.4}_{5.0})$$

consistent with $m_{\text{Higgs}} = 125$ GeV $\sim F/\sqrt{2}$ within lower error

- ChPT with spontaneous scale symmetry breaking

$$m_\sigma^2 = -0.015(10)(^{3}_{19})$$

consistent with $m_{\text{Higgs}}^2 \sim F^2/2$ within 1.6 standard deviations

- Several other fits, *e.g.*, $m_\sigma^2/(F_\pi/\sqrt{2})^2 = d_0 + d_1 m_\pi^2$

reasonably consistent results with above

Possibility to reproduce m_{Higgs}

Summary

Flavor-singlet scalar is important in walking technicolor theory.

Difficult due to huge noise in lattice simulation

$\Rightarrow$ Noise reduction method and large $N_{\rm conf}$ $O(10000)$

Results of $N_f = 12$ QCD (consistent behaviors with conformal phase)

- $m_\sigma < m_\pi$; much different from small N_f QCD
- Conformal symmetry may make σ light

Results of $N_f = 8$ QCD (maybe candidate of walking technicolor)

- $m_\sigma \sim m_\pi$; much different from small N_f QCD
- Might be reflection of approximate conformal symmetry
- Need more data at smaller m_f for reliable chiral extrapolation
- Several fit results suggest

Possibility of light composite scalar $\to$ $m_{\rm Higgs} \sim v_{EW}$

(technidilaton)