Flavor-singlet scalar in large N_f QCD

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(LatKMI Collaboration)

KMI Topics @ KMI, April 10, 2013

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1. Introduction

Discovery of "Higgs" particle @ LHC

$m_H \sim 126$ GeV

Still we have lots of things to understand, such as

- Property of "Higgs" particle
  elementary
- Mechanism of electroweak symmetry breaking
  $\langle H \rangle \neq 0$
- Gauge hierarchy problem
  fine tuning of m_H

Standard Model

Beyond Standard Model: SUSY, Little Higgs, Technicolor, $\cdots$

1. Introduction

Discovery of "Higgs" particle @ LHC
$m_H \sim 126$ GeV

Still we have lots of things to understand, such as

- Property of "Higgs" particle
  elementary | composite
- Mechanism of electroweak symmetry breaking
  $\langle H \rangle \neq 0$ | VEV from dynamics
- Gauge hierarchy problem
  fine tuning of m_H | no fine tuning

Standard Model | Technicolor: strongly coupled theory

Beyond Standard Model: SUSY, Little Higgs, Technicolor, $\cdots$

Technicolor

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

N_f, representation of fermions, N_{TC} not determined

$F^{\text{TC}}, \langle \overline{Q}Q \rangle \neq 0 \to$ similar to QCD

$$F^{\text{TC}} = O(250) \text{ GeV} \to F_\pi^{\text{QCD}} = 93 \text{ MeV}$$

But, Technicolor $\neq$ scale up of QCD

• FCNC vs quark mass

Inconsistency of constraints

FCNC ($K^0 - \overline{K}^0$ mixing) $\Longleftrightarrow$ large quark mass $m_t = O(100)$ GeV

• Small Higgs mass

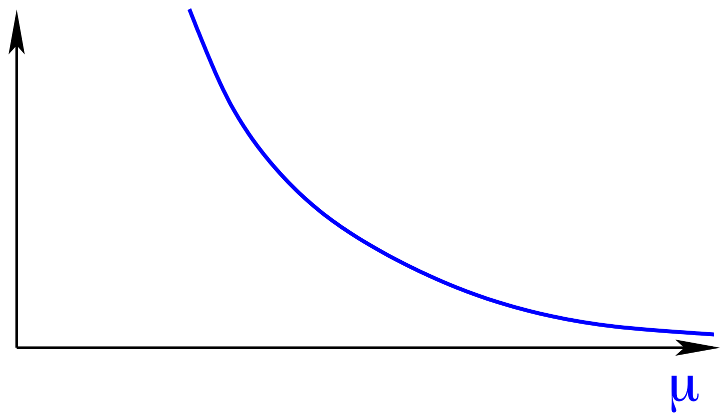
$$\frac{m_{\text{Higgs}}}{F^{\text{TC}}} \lesssim 1 \Longleftrightarrow \frac{m^{\text{QCD}}_{f_0(500)}}{F_\pi} = 4 \sim 6$$

Walking Technicolor

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

- Spontaneous chiral symmetry breaking
- Slow running (walking) coupling in wide scale range
- Large anomalous mass dimension $\gamma^* \sim 1$ in walking region
- Composite, light scalar state

Not



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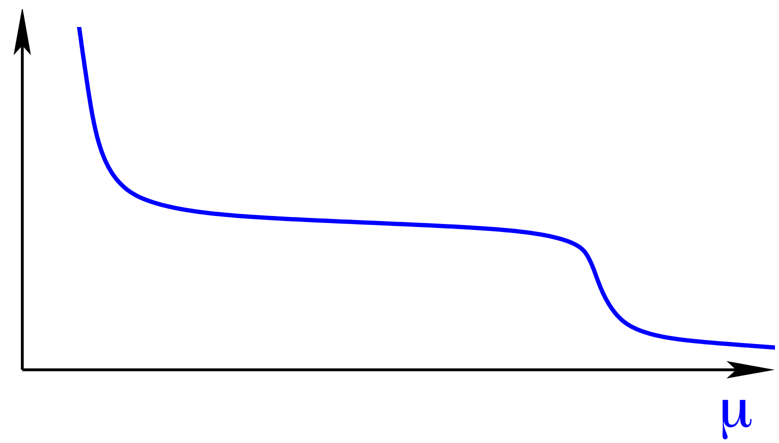


Quark mass enhanced by renormalization of $\langle \overline{Q} Q \rangle$

$$\text{WTC: } \left(\frac{\mu}{\mu_{\text{TC}}}\right)^{\gamma^*} \Longleftrightarrow \text{TC: } 1 + \gamma(g) \log\left(\frac{\mu}{\mu_{\text{TC}}}\right)$$

Candidate of walking technicolor

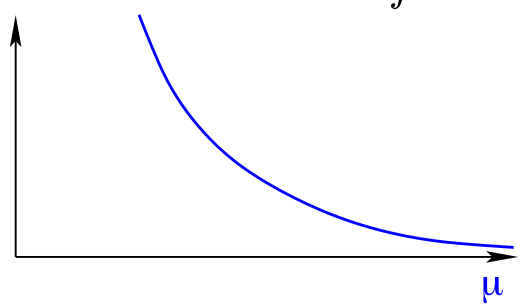
SU(3) gauge theory with N_f massless fermions

- Spontaneous chiral symmetry breaking

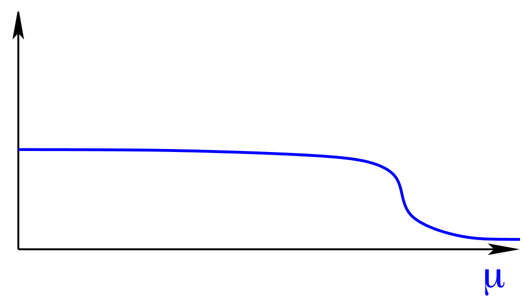
  Small $N_f = 0,\ 2,\ 2{+}1,\ 3,\ 2{+}1{+}1 \leftarrow$ lattice QCD

- Slow running (walking) coupling in wide scale range

  $\rightarrow$ No running in $9 \leq N_f \leq 16$ (2-loop perturbation)



Small N_f



Large $N_f \leq 16$

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

- Composite, light scalar state

Candidate of walking technicolor

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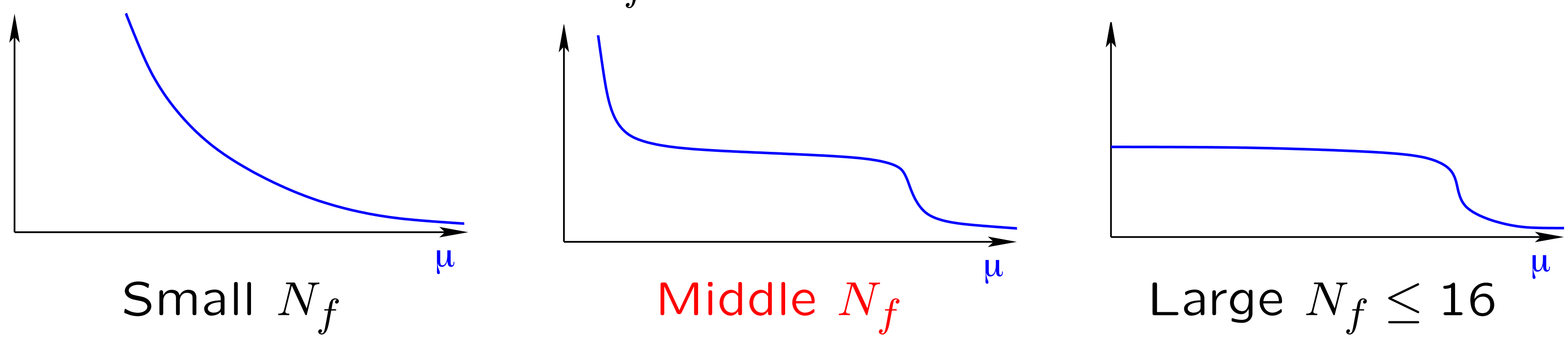

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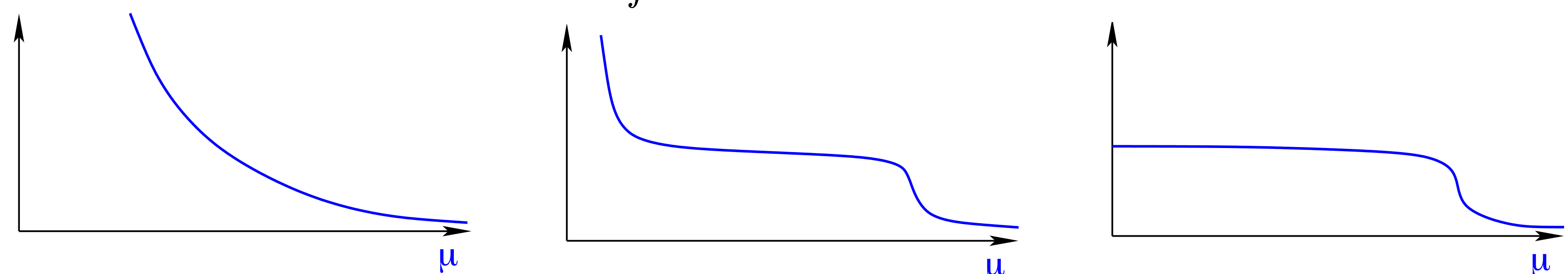

Small N_f Middle N_f Large $N_f \leq 16$

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

  $\gamma = 1$ in $N_f \sim 12$ by Schwinger-Dyson equation

- Composite, light scalar state

  Nambu-Goldstone boson of scale invariance (Dilaton)

Candidate of walking technicolor

- Spontaneous chiral symmetry breaking
- Slow running (walking) coupling in wide scale range
- Large anomalous mass dimension $\gamma^* \sim 1$ in walking region
- Composite, light scalar state

Question: Such theory really exists?

Nonperturbative calculation is important.

$\rightarrow$ numerical calculation with lattice gauge theory

Candidate of walking technicolor

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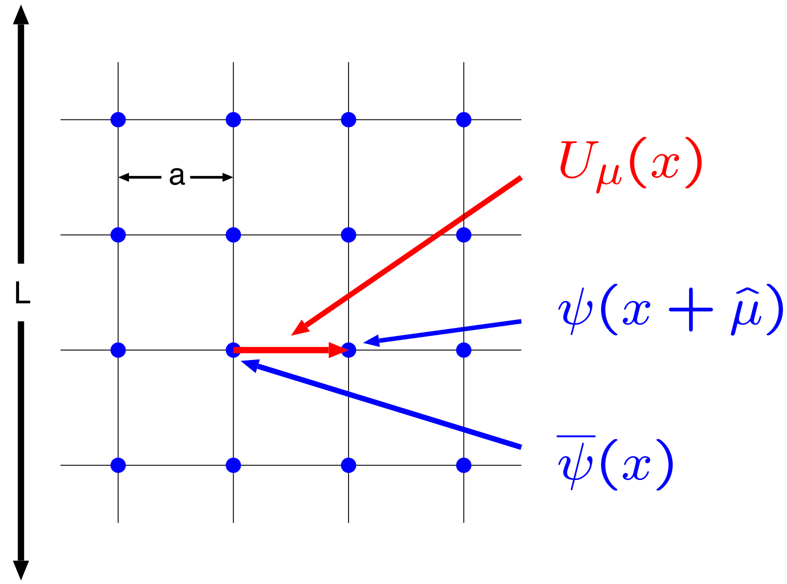
Lattice gauge theory



Lattice spacing a

Momentum cutoff: $|p| \leq \pi/a$

4-dim. Spacetime $= L^3 \times T$

Fermion $\psi(x)$: on site

Gauge $U_\mu(x)$: link between sites

Nonperturbative calculation by Monte Carlo simulation

$$\langle \mathcal{O}(\overline{\psi}, \psi, U) \rangle = \int \mathcal{D}U \text{Prob}[U] \mathcal{O}(\overline{\psi}, \psi, U) = \frac{1}{N_{\text{conf}}} \sum_{i}^{N_{\text{conf}}} \mathcal{O}(D^{-1}[U_i], U_i)$$

$$+\delta\left(1/\sqrt{N_{\text{conf}}}\right)$$

$\text{Prob}[U] \propto \int \mathcal{D}\overline{\psi}\mathcal{D}\psi\, e^{N_f \overline{\psi} D[U]\psi - S_g[U]}$, Grassmann integral: $\psi\overline{\psi} \to D^{-1}[U]$

Most of all computational cost

$D[U] : (L^3 \cdot T \cdot N_{\text{color}} \cdot N_{\text{dirac}}) \times (L^3 \cdot T \cdot N_{\text{color}} \cdot N_{\text{dirac}})$ matrix

Lattice gauge theory

2-point function; $P(t) = \sum_{\vec{x}} \overline{\psi}(\vec{x},t)\gamma_5\psi(\vec{x},t)$, $J^P = 0^-$

$$\begin{aligned} \langle 0|P(t)P^\dagger(0)|0\rangle &= \sum_i \langle 0|P|\pi_i\rangle\langle\pi_i|P^\dagger|0\rangle e^{-m_{\pi_i}t} \\ &\xrightarrow{t\gg 1} |\langle 0|P(0)|\pi_0\rangle|^2 e^{-m_{\pi_0}t} \end{aligned}$$

$\to m_{\pi_0}$ and F_{π_0} from $|\langle 0|P(0)|\pi_0\rangle|$

$|\pi_i\rangle$: i-th state with same quantum numbers as operator P

same m_{π_0} obtained

if different operator P' has same quantum numbers as P

$$\langle 0|P'(t)(P')^\dagger(0)|0\rangle \xrightarrow{t\gg 1} |\langle 0|P'(0)|\pi_0\rangle|^2 e^{-m_{\pi_0}t}$$

But $|\langle 0|P(0)|\pi_0\rangle| \neq |\langle 0|P'(0)|\pi_0\rangle|$

call 0th state of pseudoscalar $\to \pi$ in all N_f

Purpose of our project

Systematic investigation of N_f dependence

SU(3) gauge theory with N_f (massless) fermions

$$N_f = 0, 4, 8, 12, 16$$

- Search for candidate of walking technicolor

  Mearsure m_{meson}, F_π, $\langle\overline{\psi}\psi\rangle$ c.f. $g^2(\mu), \gamma_m$ from $Z_m(\mu)$

- If candidate exists, property of theory

  Scalar state in (approximate) conformal theory

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

- $\beta \equiv 6/g^2 \to$ lattice spacing a
- $L, T \sim O(10)$
- $m_f \neq 0 \to$ 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	$18^3 \times 24$–$36^3 \times 48$	0.015–0.016
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.

Recent study of LatKMI Collaboration

Search for candidate of walking technicolor

PRD86(2012)054506; arXiv:1302.6859

chiral broken → walking → conformal increasing N_f

Signal of phase

- Chiral broken phase

  Simulations at $m_f \neq 0$

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

- Conformal phase

Simulations at $m_f \neq 0$: scale invariance breaking → confinement phase

Hyperscaling with anomalous dimension γ^* at small m_f

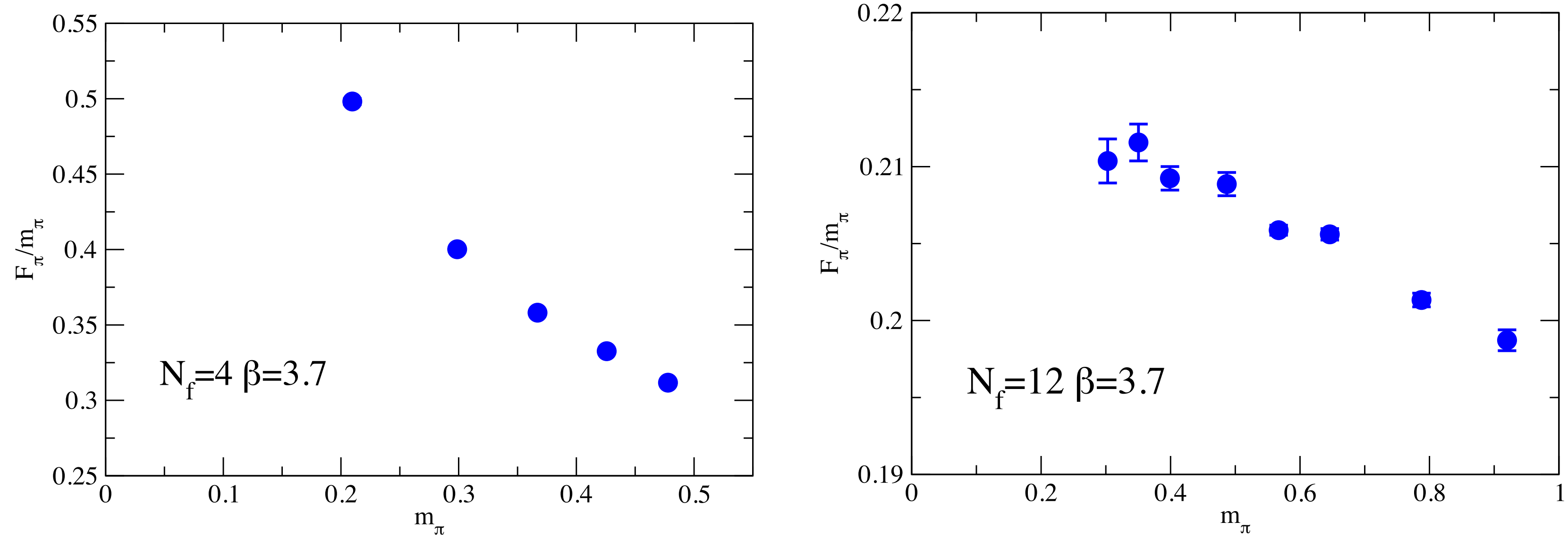
$$m_H = C_H \; m_f^{1/(1+\gamma^*)}$$
$$F_\pi = C_F \; m_f^{1/(1+\gamma^*)} \quad \Rightarrow \frac{F_\pi}{m_\pi} \xrightarrow{m_\pi \to 0} \text{constant}$$

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

Recent study of LatKMI Collaboration

$N_f = 12$: PRD86(2012)054506; $N_f = 8$: arXiv:1302.6859

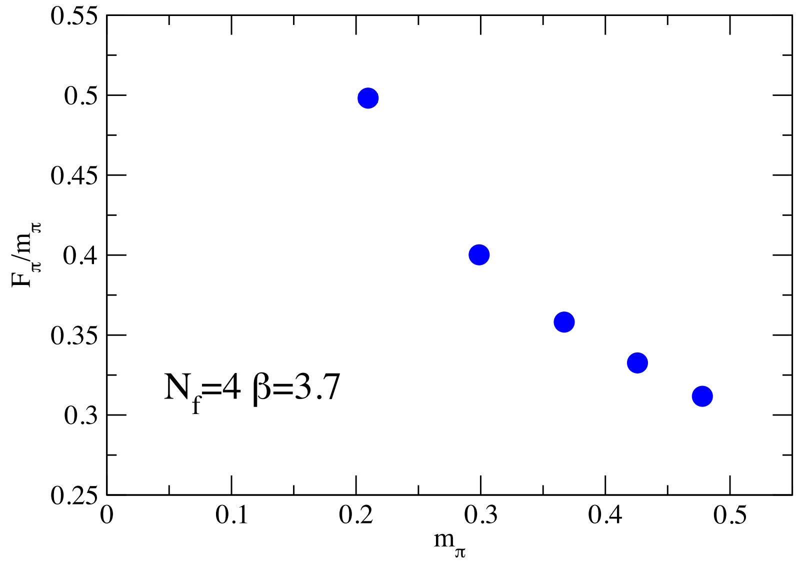
$F_\pi/m_\pi \to \infty$ $\qquad$ $F_\pi/m_\pi \to$ constant



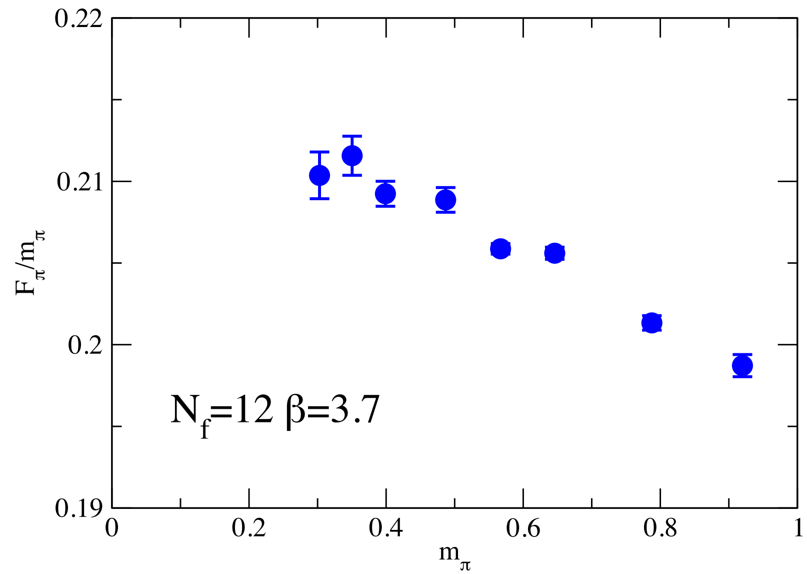
Recent study of LatKMI Collaboration

$N_f = 12$: PRD86(2012)054506; $N_f = 8$: arXiv:1302.6859

Chiral broken



Conformal



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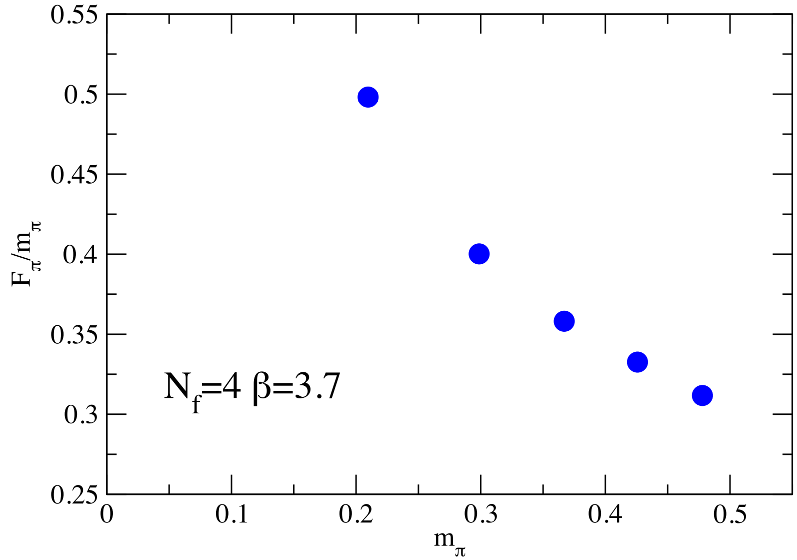

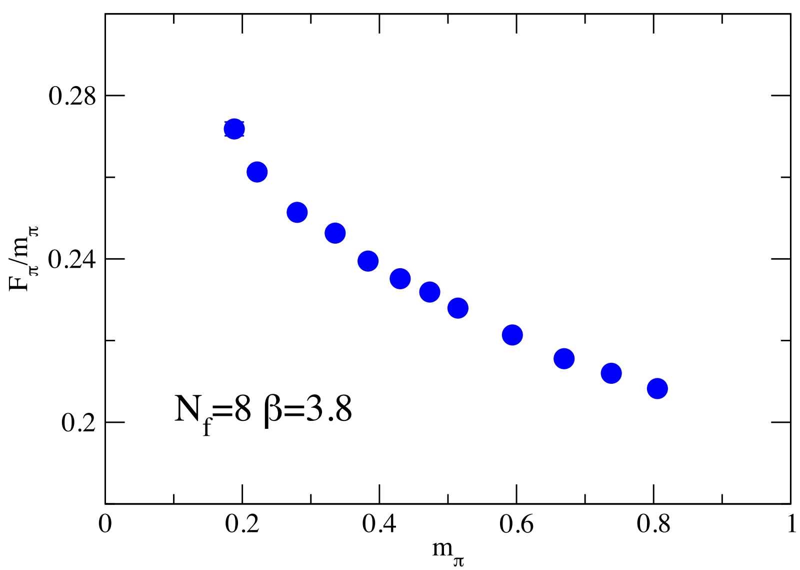

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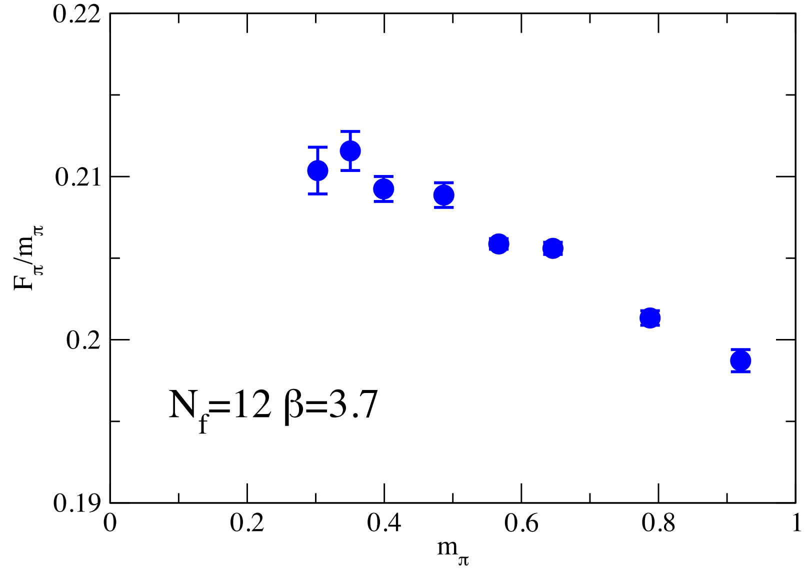
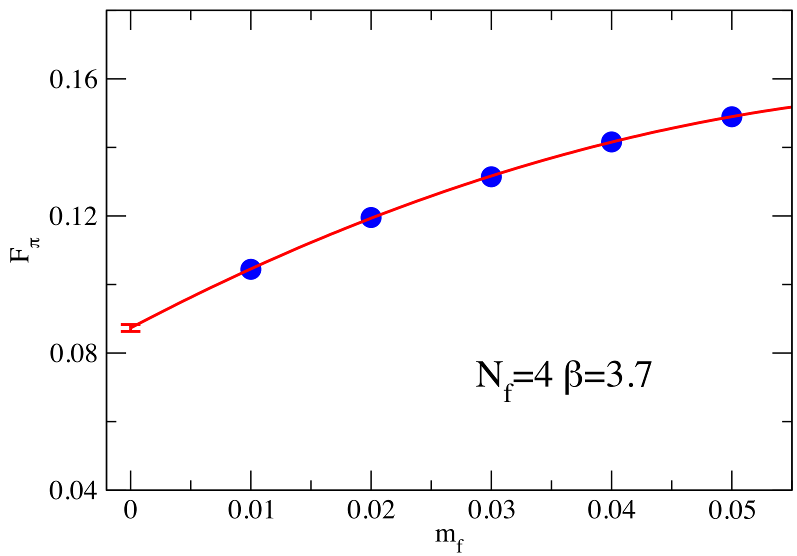


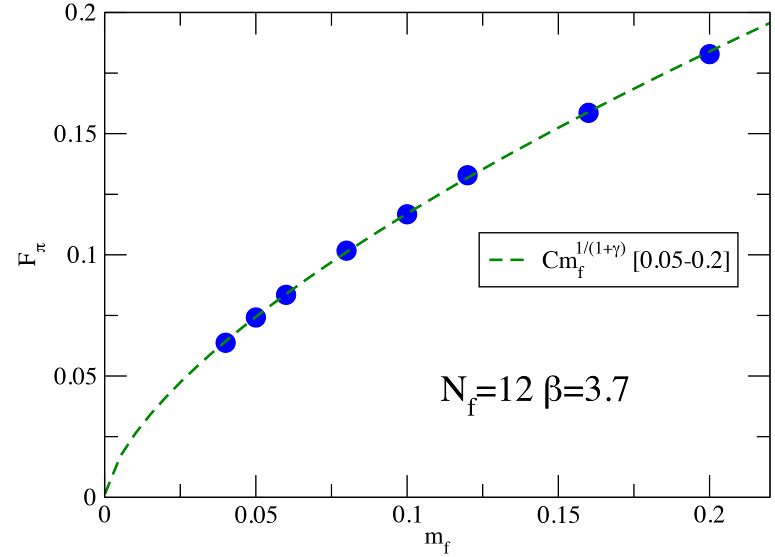
Recent study of LatKMI Collaboration

PRD86(2012)054506; arXiv:1302.6859

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



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



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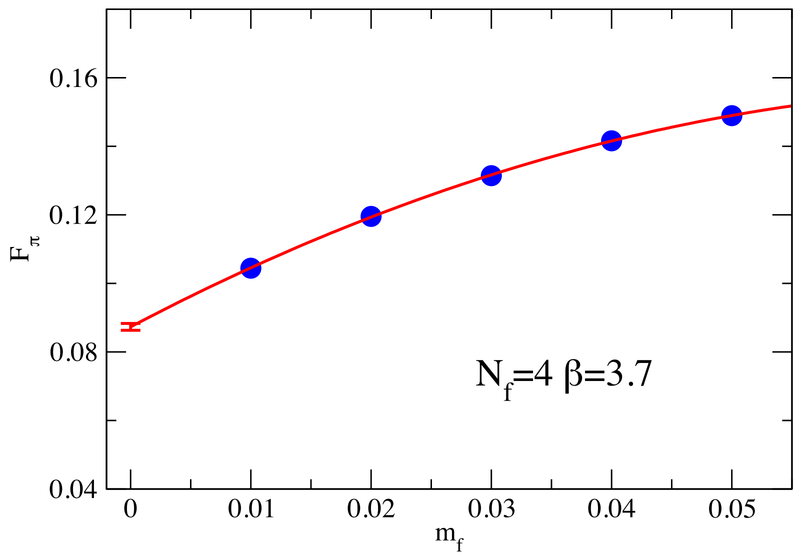
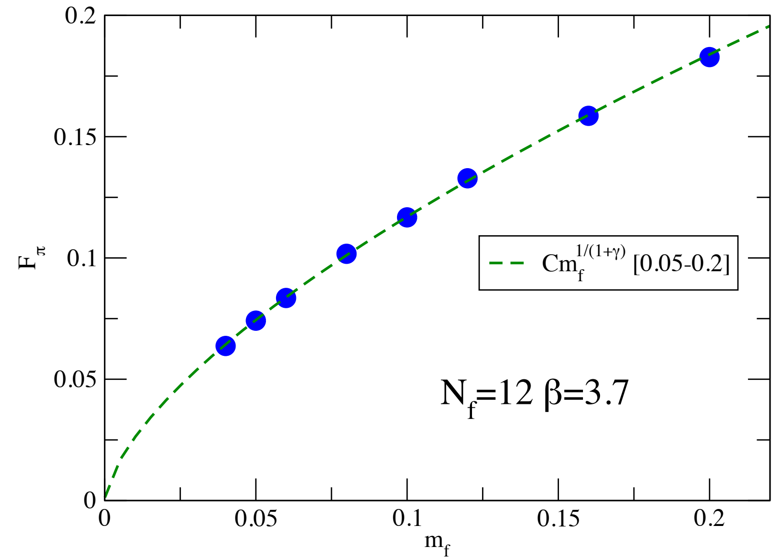
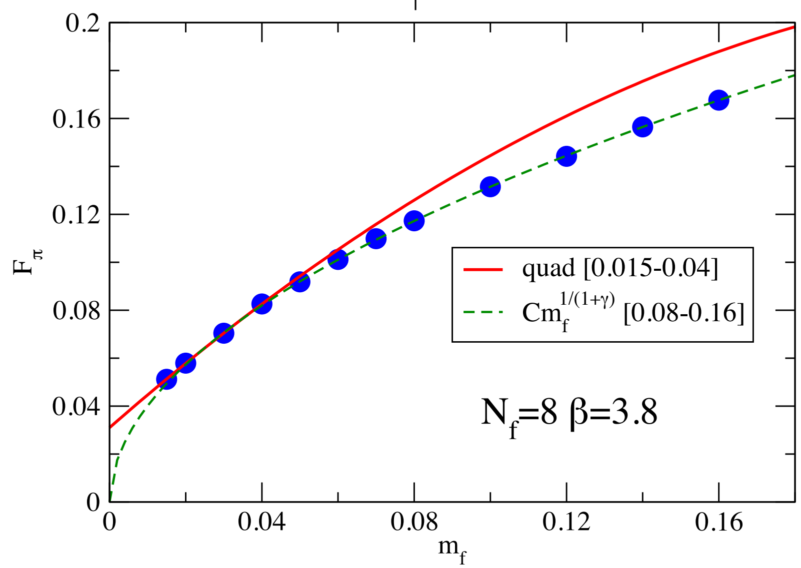


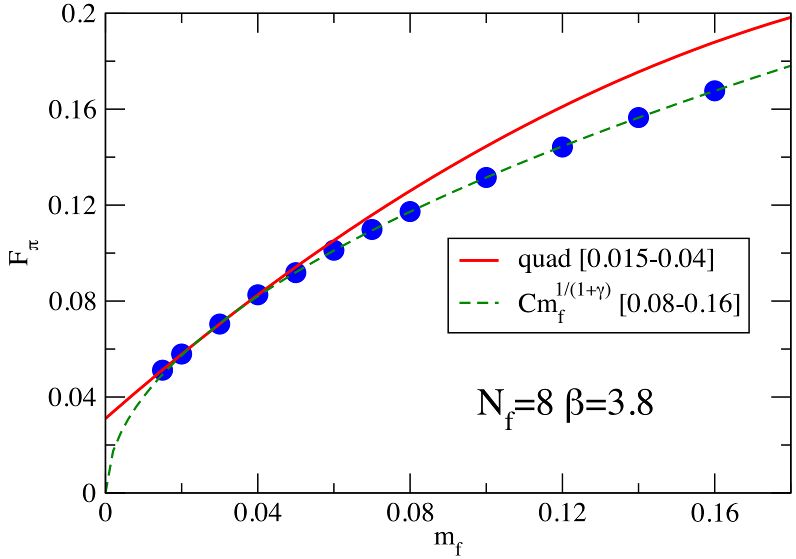


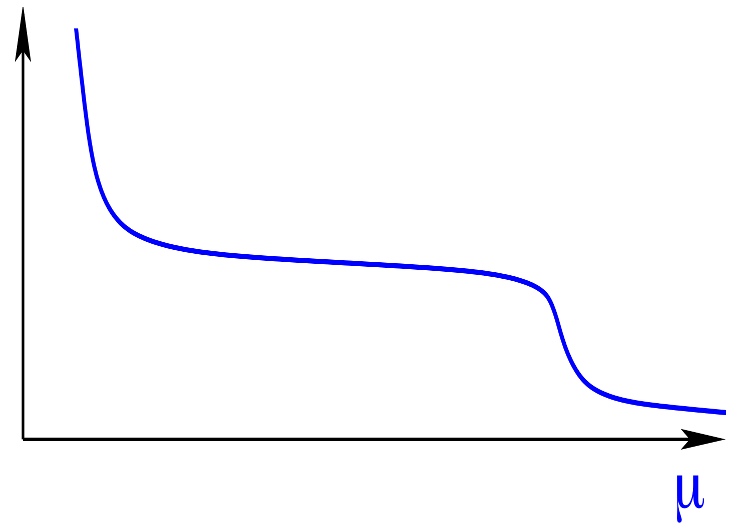


Recent study of LatKMI Collaboration

PRD86(2012)054506; arXiv:1302.6859

Possible explanation through walking coupling



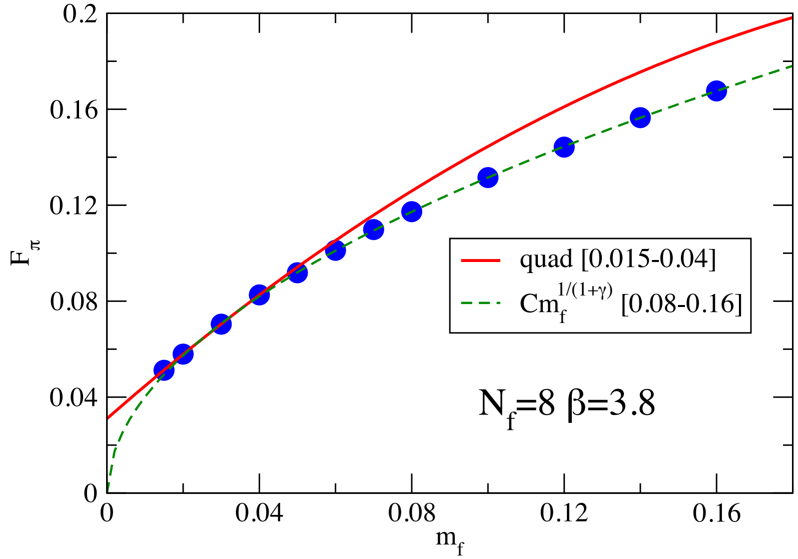


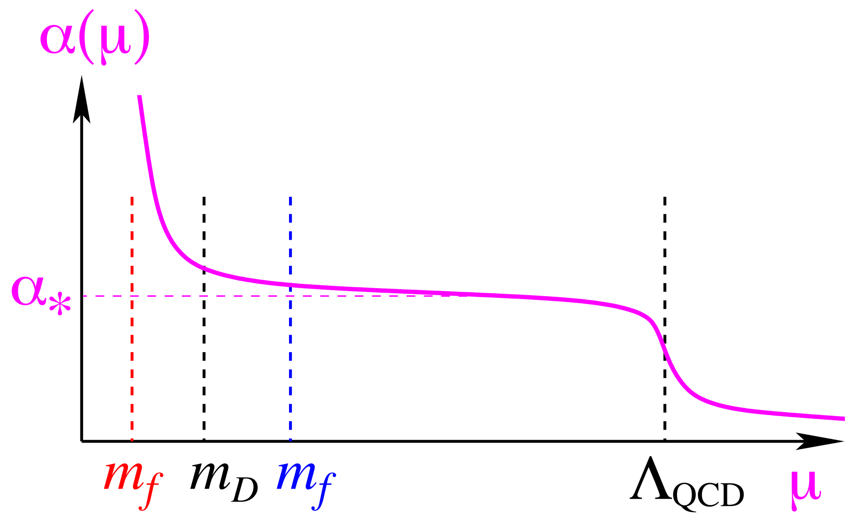
If $N_f = 8$ QCD has walking coupling ...

Recent study of LatKMI Collaboration

PRD86(2012)054506; arXiv:1302.6859

Possible explanation through walking coupling





m_f is regarded as IR scale cutoff of system.

Large $m_f \gg m_D$

Confine system at m_f

Not care spontaneous chiral symmetry breaking

$\rightarrow$ same as conformal system with large m_f

Small $m_f \lesssim m_D$

Contain spontaneous chiral symmetry breaking effect

Dual nature maybe signal of walking coupling

Recent study of LatKMI Collaboration

Search for candidate of walking technicolor

PRD86(2012)054506; arXiv:1302.6859

$N_f = 4$ QCD: Spontaneous chiral symmetry breaking

$N_f = 12$ QCD: Consistent with conformal phase

$N_f = 8$ QCD seems to have

- Spontaneous chiral symmetry breaking
  $F_\pi \neq 0$ in $m_f \to 0$
- Slow running (walking) coupling in wide scale range
  Dual nature of F_π and if explanation is true
- Large anomalous mass dimension $\gamma^* \sim 1$ in walking region
  if explanation is true, $\gamma = 0.62$–0.97 from larger m_f
- Composite, light scalar state $\Leftarrow$ Important to check!

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

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Flavor-singlet scalar

in (approximate) conformal theory

All results are preliminary.

Previous study of flavor-singlet scalar meson

$N_f \leq 2+1$ QCD

1. McNeile and Micheal; PRD63(2001)114503
2. Kunihiro *et al.* (SCALAR); NPPS119(2003)275
3. Hart *et. al.*; PRD74(2006)114504
4. Bernard *et. al.*; PRD76(2007)094504
5. Prelovsek and Mohler; PRD79(2009)014503
6. Prelovsek *et al.*; PRD82(2010)094507
7. Fu; JHEP07(2012)142
8. Cossu *et al.* (JLQCD); PoS(Lattice 2012)197

Only one study in large N_f QCD, but
$N_f = 12$ QCD at unphysical phase

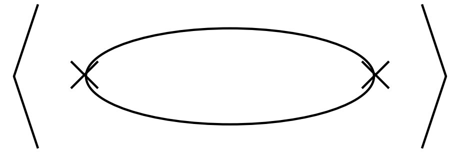
Jin and Mawhinney; PoS(Lattice 2011)066

No realistic calculation in large N_f QCD

Difficulty

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

$$\langle 0|S_{NS}(t)S_{NS}^{\dagger}(0)|0\rangle \quad =$$



$$= -C(t)$$

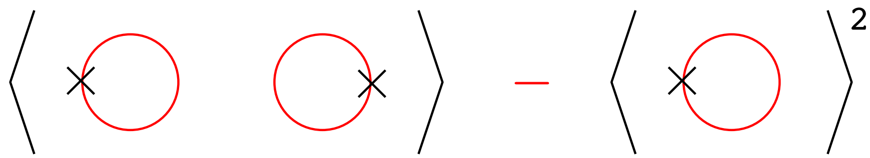
c.f. m_π, F_π from nonsinglet pseudoscalar

$$O(100) \text{ configuration} \times O(1) \; D^{-1}[U](x,y) = \psi(x)\overline{\psi}(y)$$

- Flavor-singlet scalar meson $S(t) = \sum_{\vec{x}} \overline{\psi}_a(\vec{x},t)\psi_a(\vec{x},t)$

$$\langle 0|S(t)S^{\dagger}(0)|0\rangle \quad = -C(t) + D(t) \text{ (disconnected)}$$

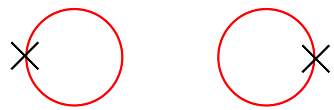
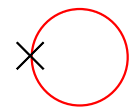
$$D(t) =$$

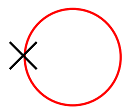


Essential for flavor-singlet but much harder

Difficulty

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

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

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

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

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

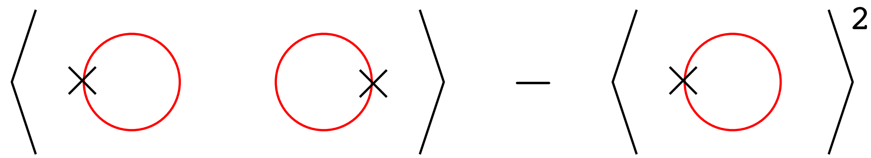
2. $\langle$Large + small$\rangle - \langle$Large$\rangle = \langle$small$\rangle$ + (stat. error)

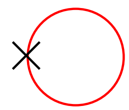
$\langle$small$\rangle$: $\exp(-m_\sigma t)$; stat. error: independent of t

Huge calculation cost necessary

Difficulty

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

$D(t) =$ 

1.  $= \psi(x)\overline{\psi}(x) = D^{-1}[U](x,x)$ 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

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

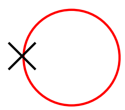
Reduce calculation cost and use huge N_{conf}

Calculation method

Random source propagator

$$\phi_i(x,t) = \sum_{x_0,t_0} D^{-1}\xi_i(x_0,t_0), \qquad \lim_{N_r\to\infty}\frac{1}{N_r}\sum_{i=1}^{N_r}\left[\xi_i^\dagger(x,t)\xi_i(x_0,t_0)\right] = \delta_{x,x_0}\delta_{t,t_0}$$

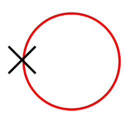
Simple method



$$= \frac{1}{N_r}\sum_{i=1}^{N_r}\left[\sum_x \xi_i^\dagger(x,t)\phi_i(x,t)\right]$$

Noise reduction method in staggered action

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



$$= \frac{1}{N_r}\sum_{i=1}^{N_r}\left[m_f\sum_x \phi_i^\dagger(x,t)\phi_i(x,t)\right] \to m_f \times (\pi \text{ correlator})$$

Regarded as integrated Ward-Takahashi identity $(a \neq b, m_a = m_b)$

$$\overline{\psi}_a\psi_a(x_0,t_0) = m_a\sum_{x,t}\overline{\psi}_a\gamma_5\psi_b(x,t)\overline{\psi}_b\gamma_5\psi_a(x_0,t_0)$$

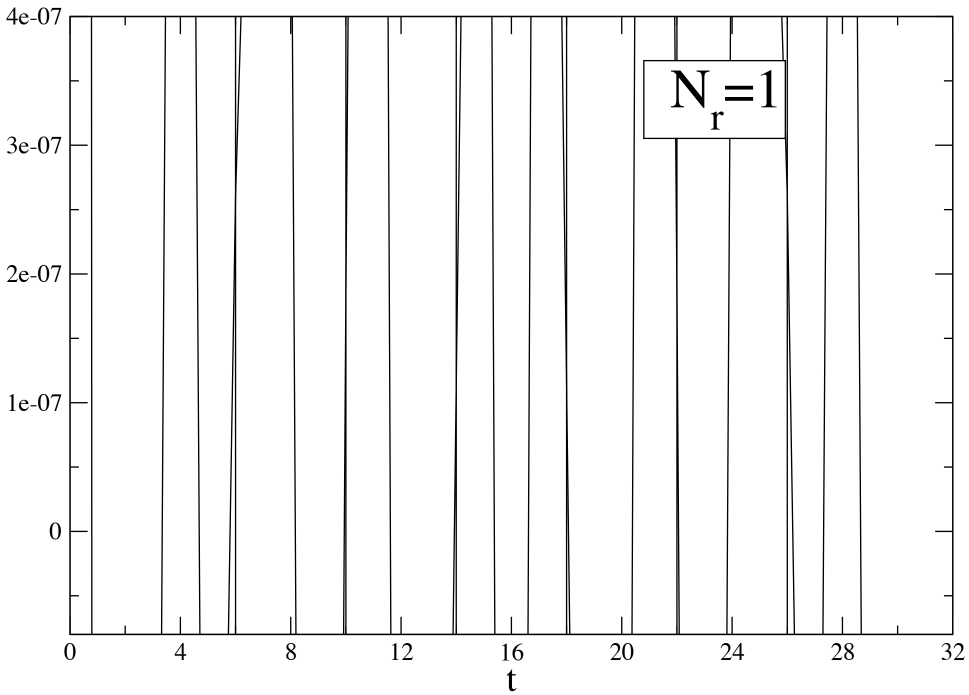
Jin and Mawhinney, $N_f = 12$ σ; Gregory *et al.*, $N_f = 2+1$ η'

Comparison with two methods

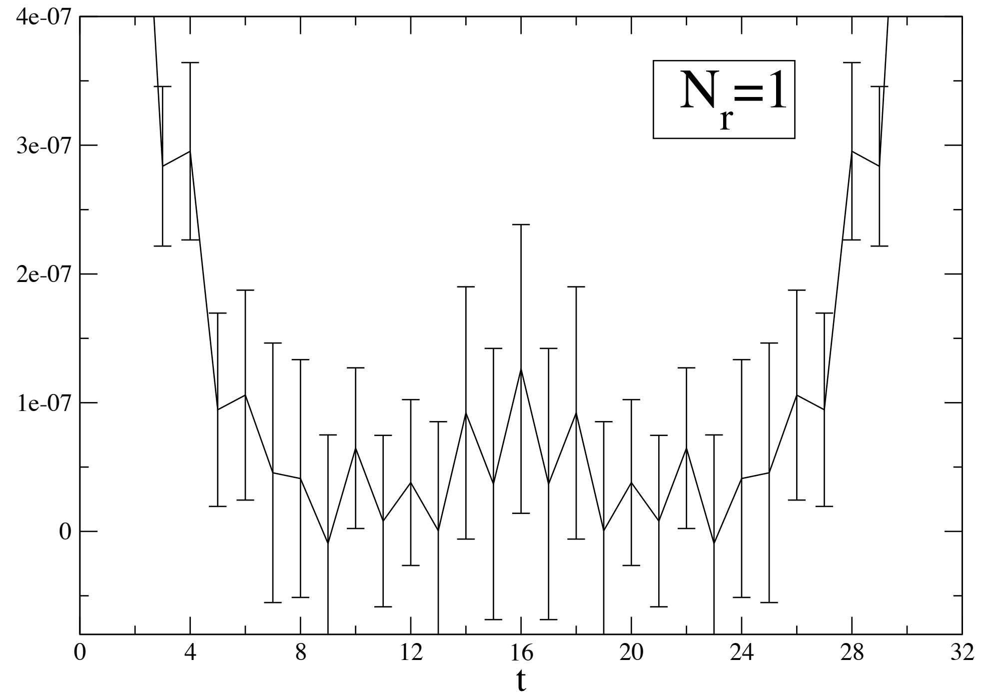
20 configuraions in $N_f = 12$ QCD with $m_f = 0.06$, $24^3 \times 32$, $\beta = 4$

N_r dependence of $D(t)$

Simple method



Noise reduction method



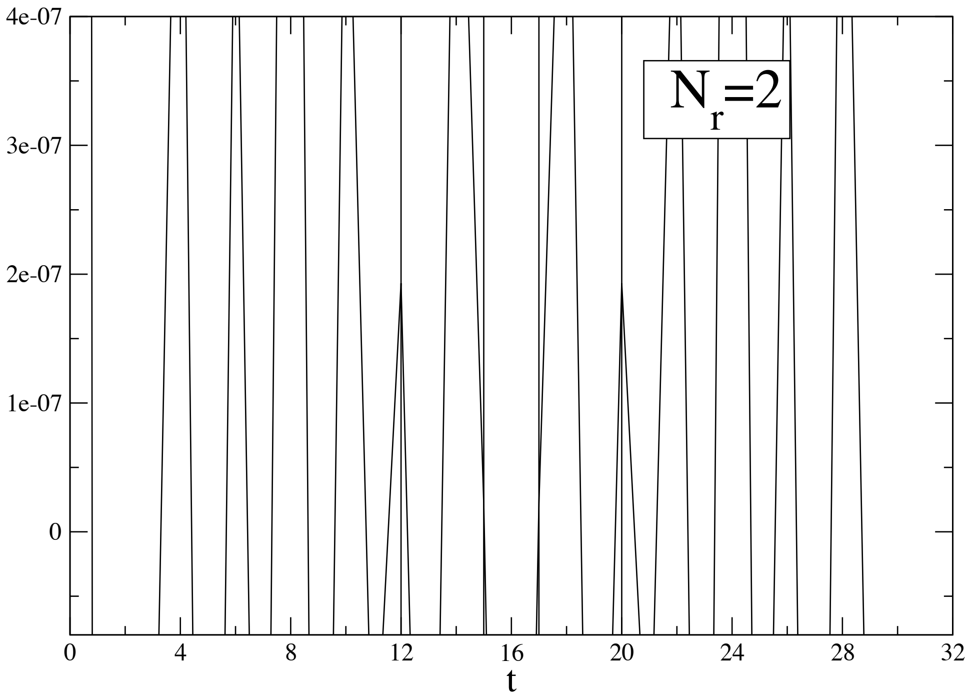
How many N_r is necessary for convergence?

Comparison with two methods

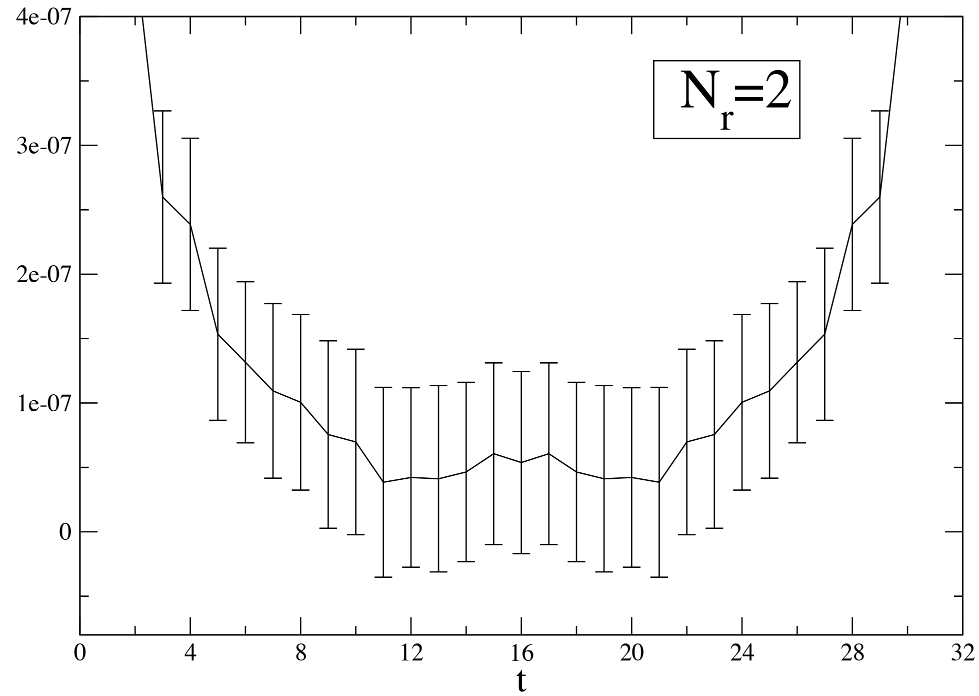
20 configuraions in $N_f = 12$ QCD with $m_f = 0.06$, $24^3 \times 32$, $\beta = 4$

N_r dependence of $D(t)$

Simple method



Noise reduction method

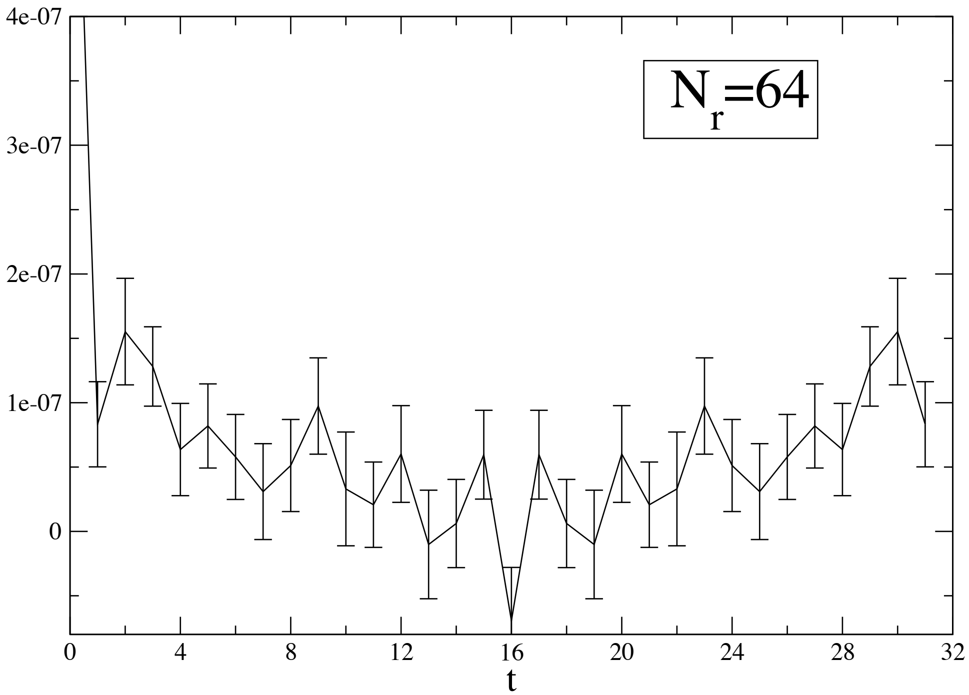


Comparison with two methods

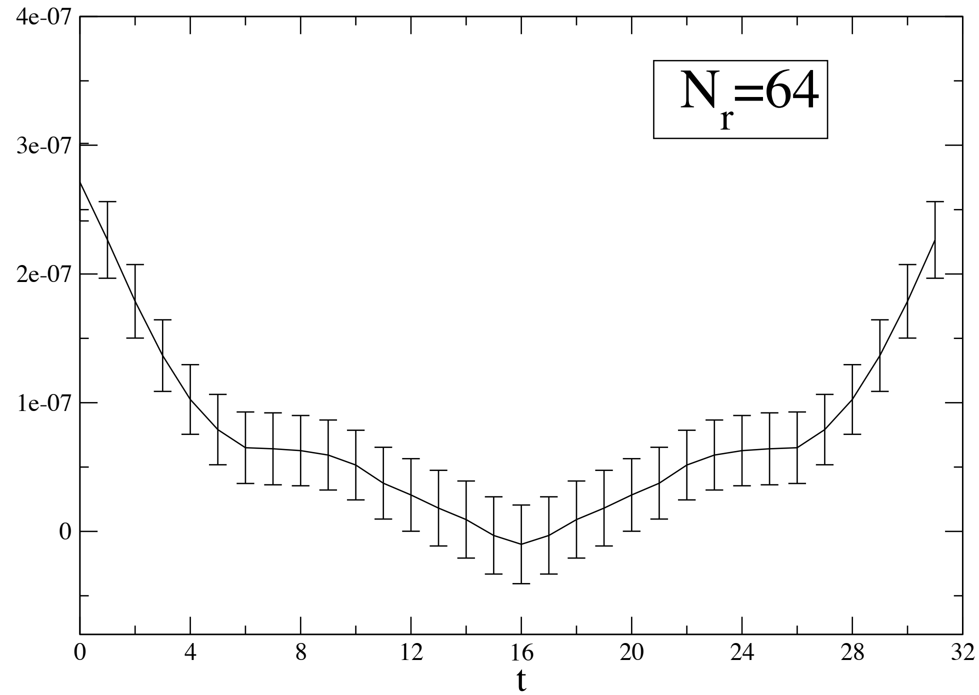
20 configuraions in $N_f = 12$ QCD with $m_f = 0.06$, $24^3 \times 32$, $\beta = 4$

N_r dependence of $D(t)$

Simple method



Noise reduction method



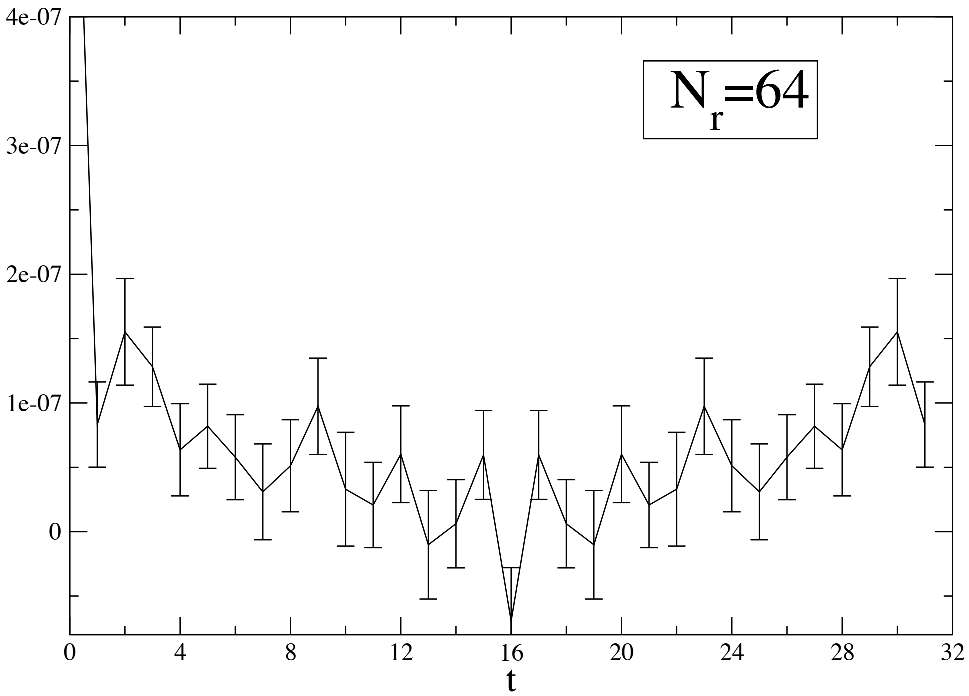
Convegence in Reduction method with $N_r = 64$

Comparison with two methods

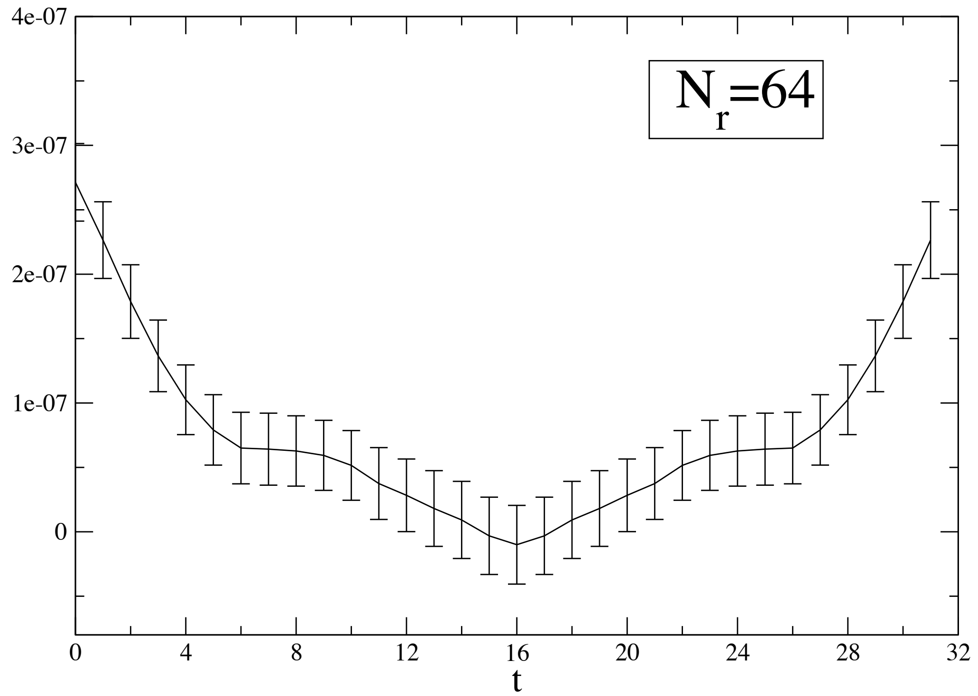
20 configuraions in $N_f = 12$ QCD with $m_f = 0.06$, $24^3 \times 32$, $\beta = 4$

N_r dependence of $D(t)$

Simple method



Noise reduction method

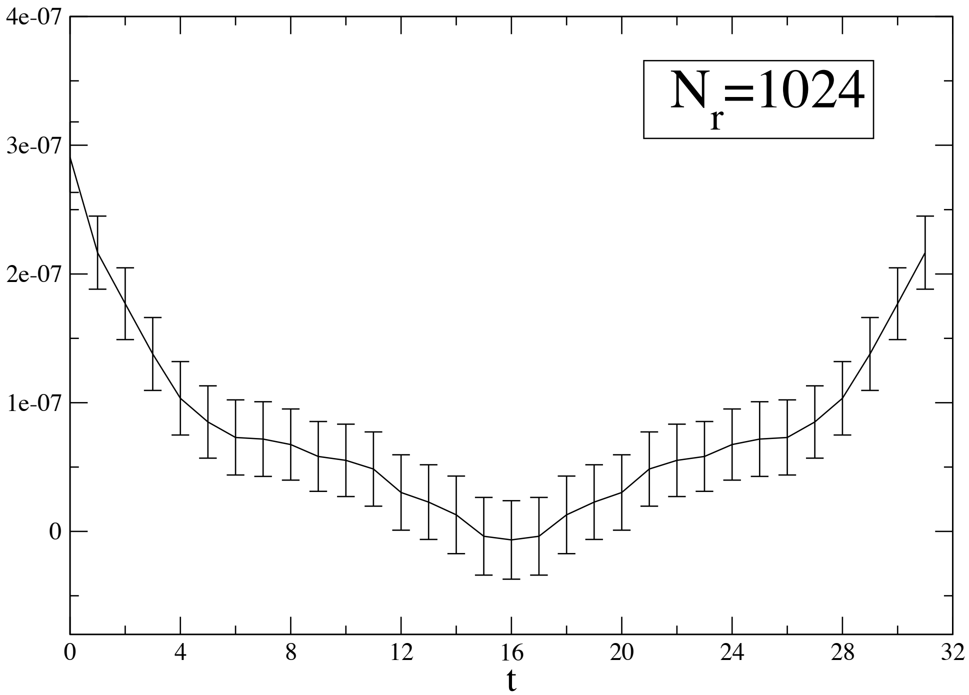


Comparison with two methods

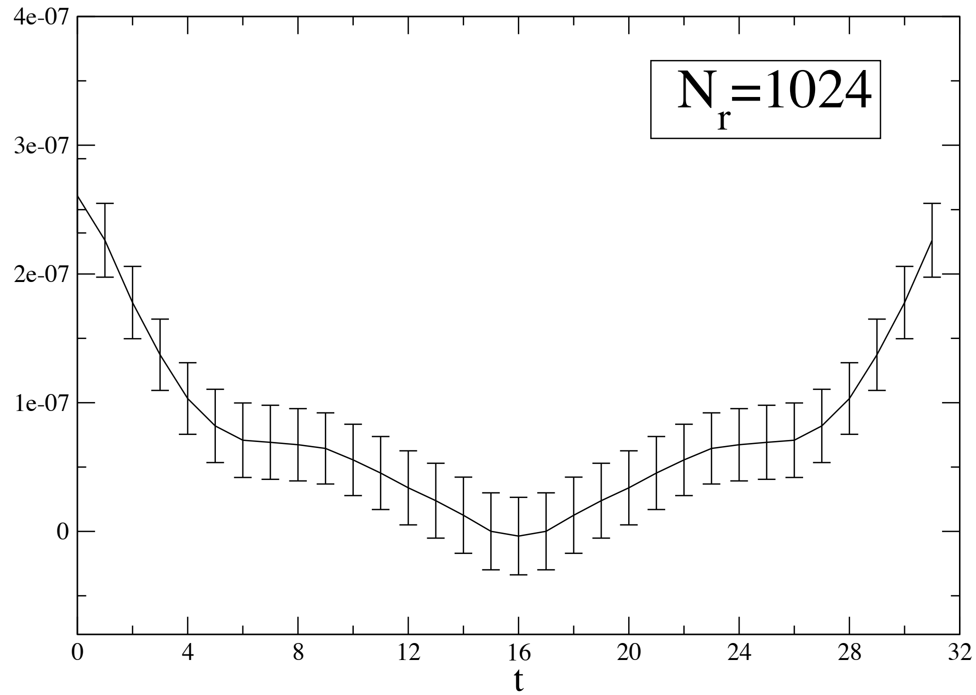
20 configuraions in $N_f = 12$ QCD with $m_f = 0.06$, $24^3 \times 32$, $\beta = 4$

N_r dependence of $D(t)$

Simple method



Noise reduction method



Reduction method is $\sim$ 10 times efficient.

$N_f = 12$ QCD (Preliminary)

Consistent with conformal phase (LatKMI; PRD86(2012)054506)

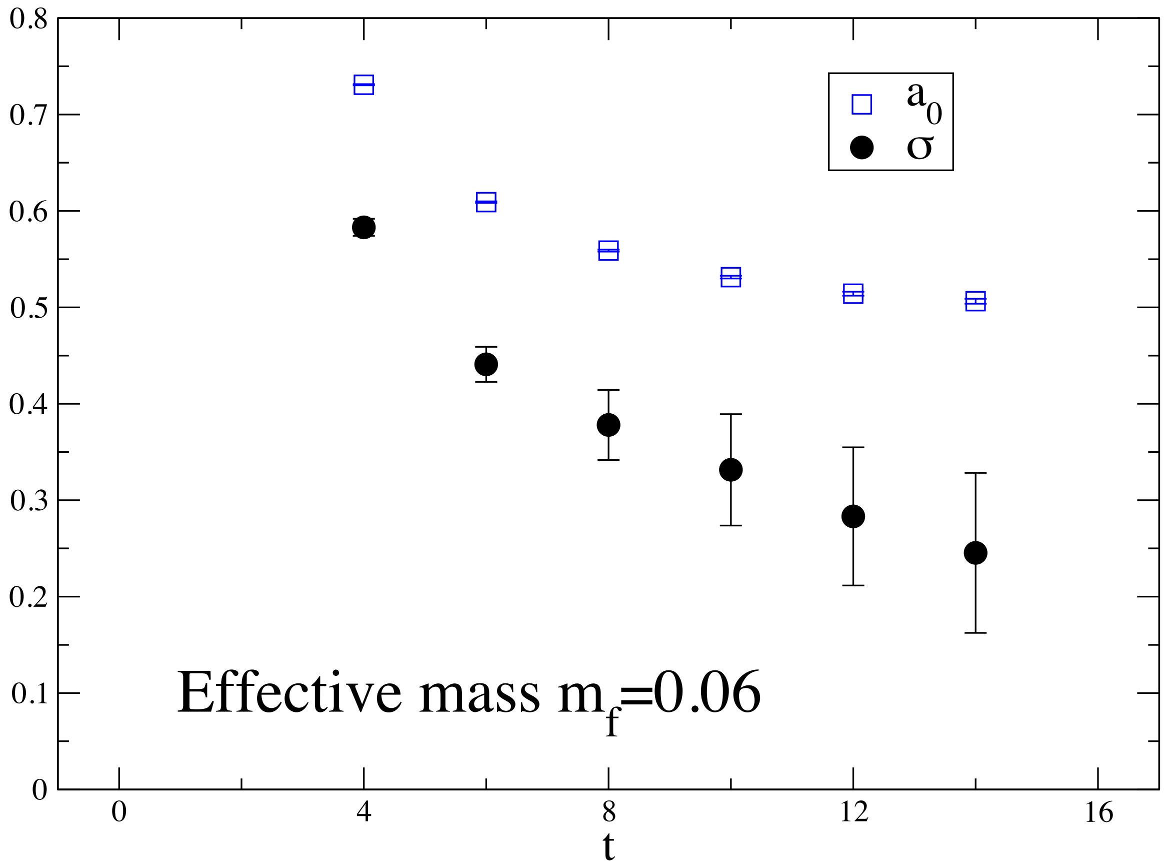
Simulation parameters

- $\beta = 4$
- Noise reduction method with $N_r = 64$
- $O(10^3 \sim 10^4)$ configuration at each m_f and L, T

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

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

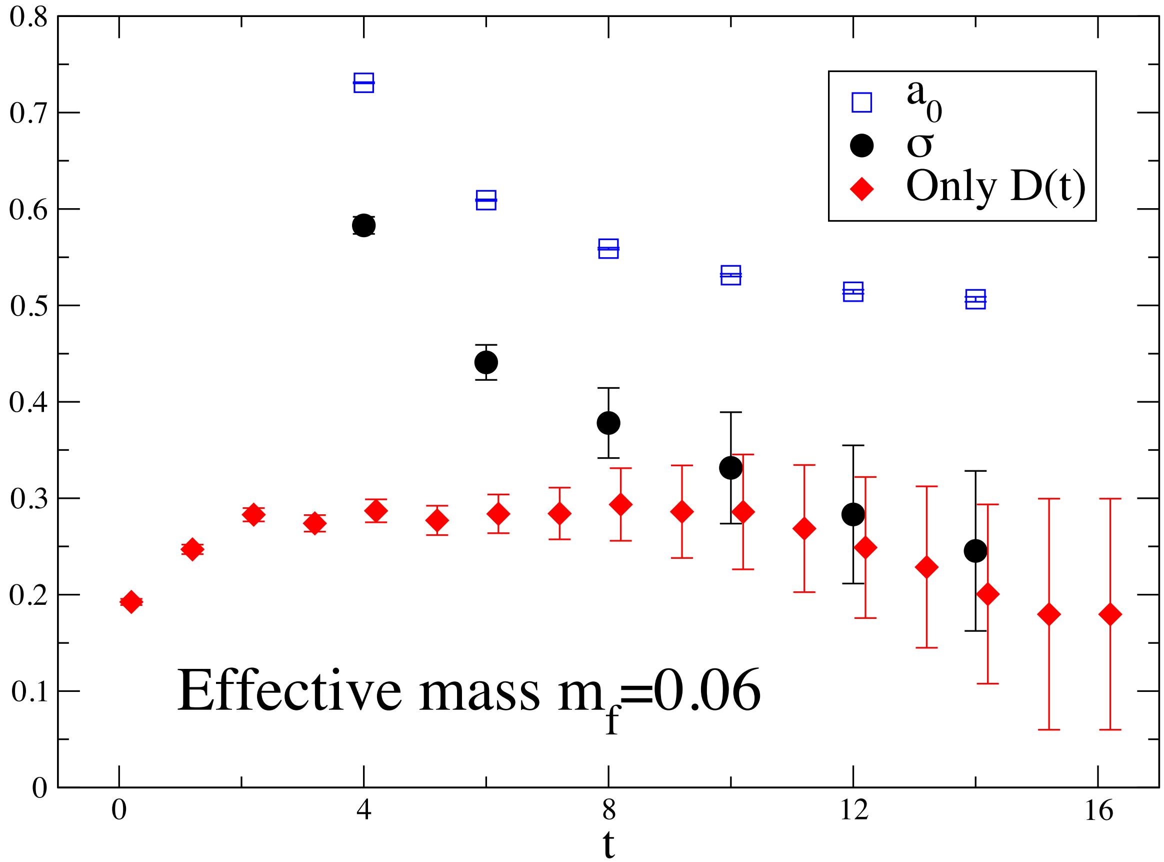
σ: $D_+(2t) - C_+(2t)$

$m_\sigma < m_{a_0}$

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

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

σ: $D_+(2t) - C_+(2t)$

$m_\sigma < m_{a_0}$

Only $D(t)$

Consistent m_σ

Smaller error

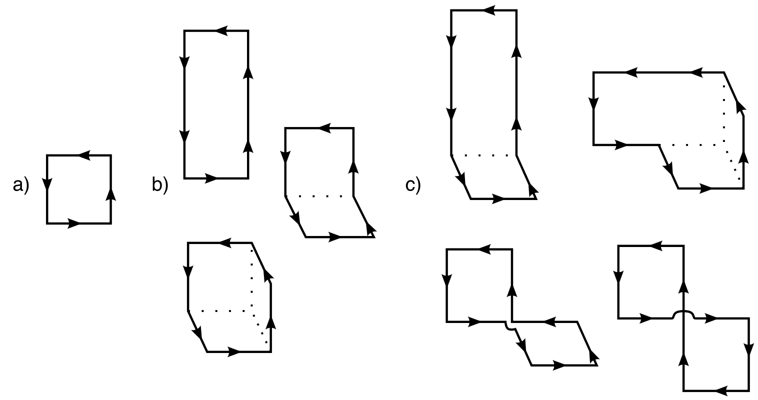
$$X_+(2t) = 2X(2t) + X(2t+1) + X(2t-1)$$

Good signal of m_σ from $D(t)$

Flavor-singlet state from Glueball operator

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.

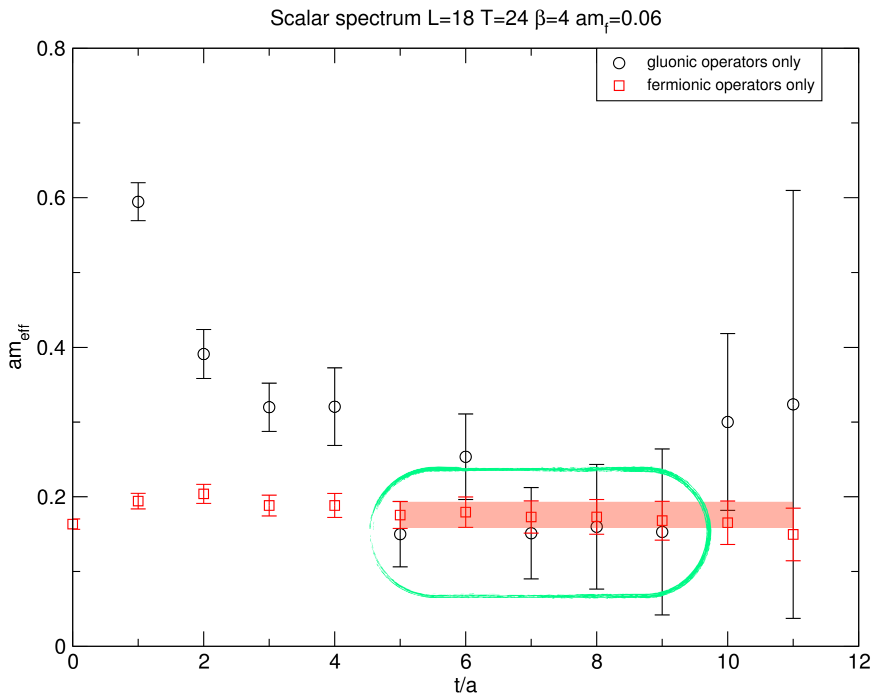
$\rightarrow$ Reliability check of result, but never done before

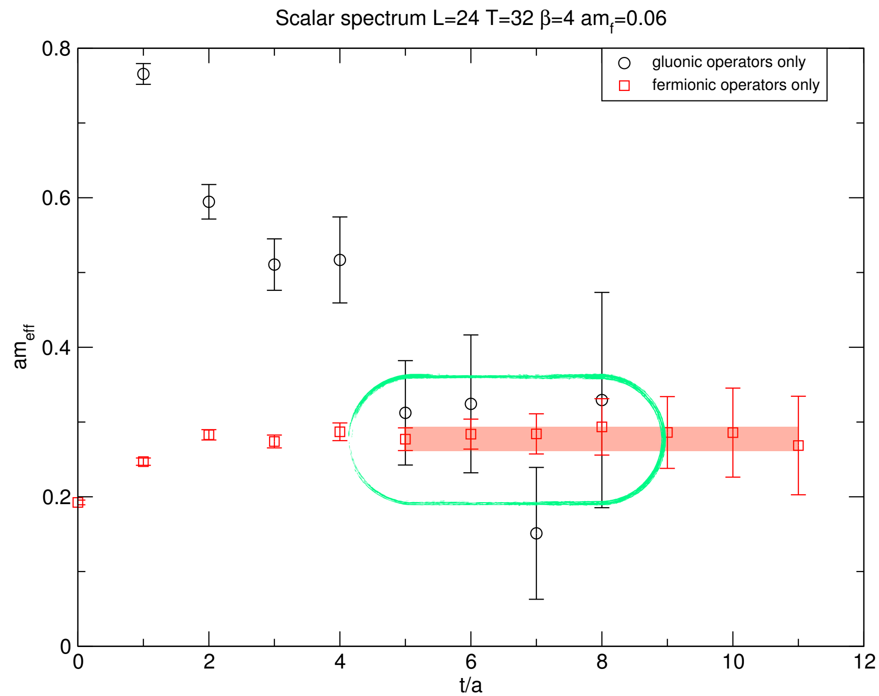
Comparison of effective mass in $N_f = 12$

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





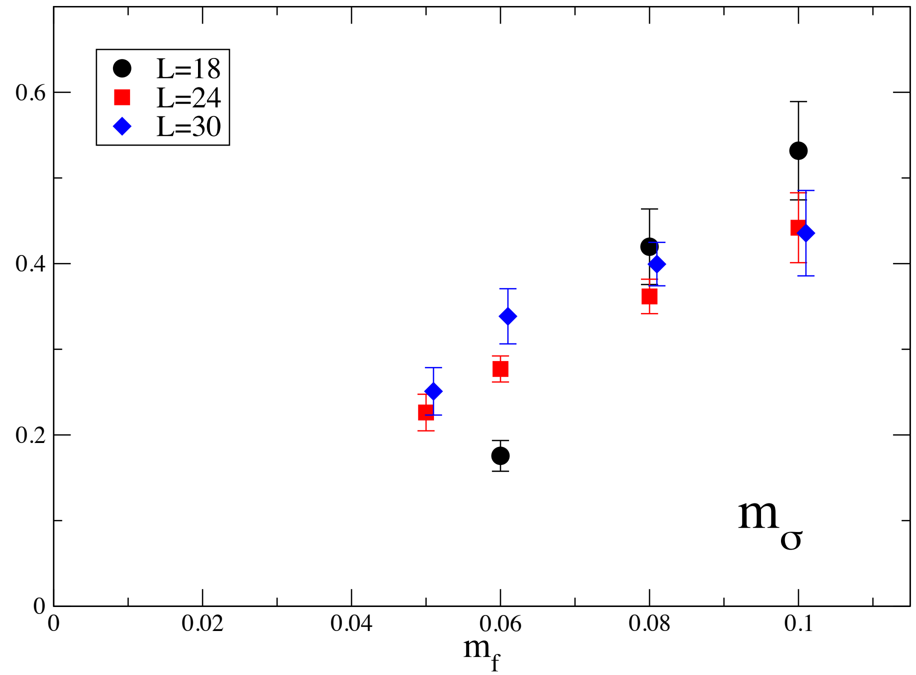
Larger error in glueball correlator

Reasonably consistent in large t

$\rightarrow$ show only meson results

m_f dependence in $N_f = 12$ (Preliminary)

m_σ from effective mass of $D(t)$ at $t = 5$

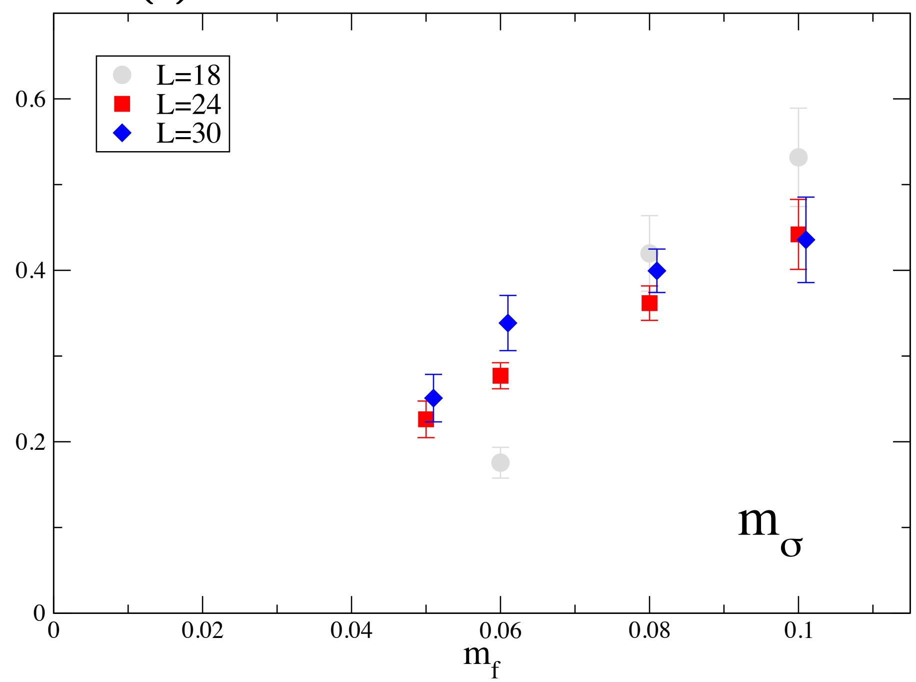


Clear m_f dependence

Large finite volume effect at only $m_f = 0.06$, $L = 18$

m_f dependence in $N_f = 12$ (Preliminary)

m_σ from effective mass of $D(t)$ at $t = 5$

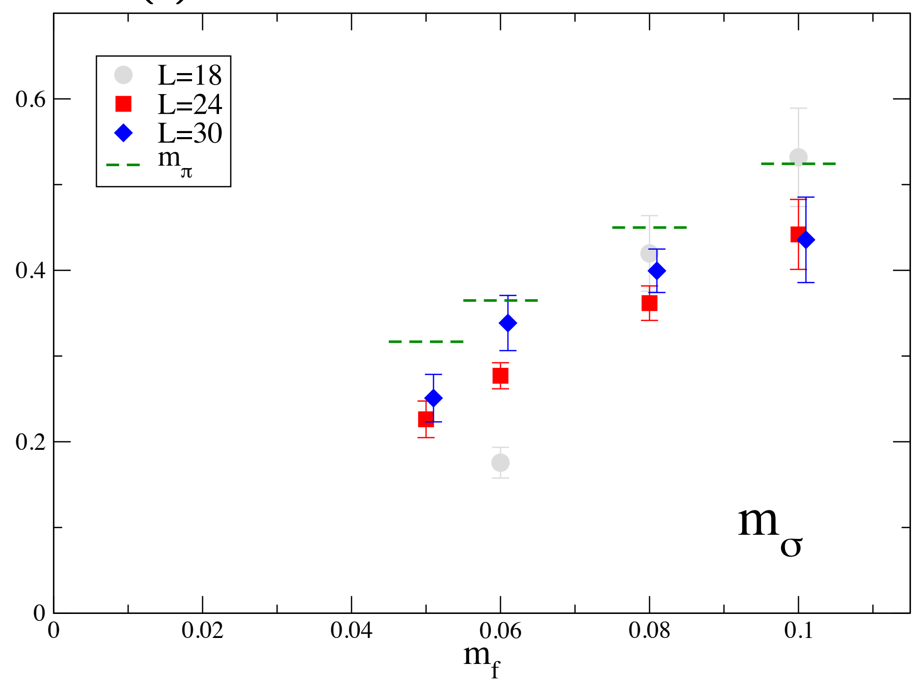


Flavor-singlet scalar is relatively light?

Hyperscaling is seen as in m_π?

m_f dependence in $N_f = 12$ (Preliminary)

m_σ from effective mass of $D(t)$ at $t = 5$



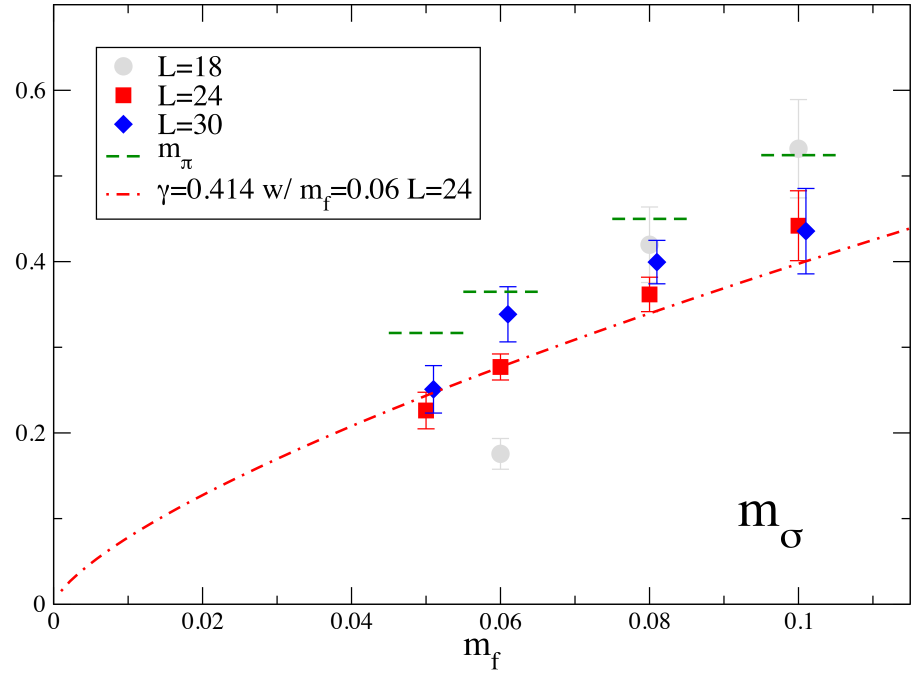
Flavor-singlet scalar is relatively light?

Lighter than π

Hyperscaling is seen as in m_π?

m_f dependence in $N_f = 12$ (Preliminary)

m_σ from effective mass of $D(t)$ at $t = 5$



Flavor-singlet scalar is relatively light?

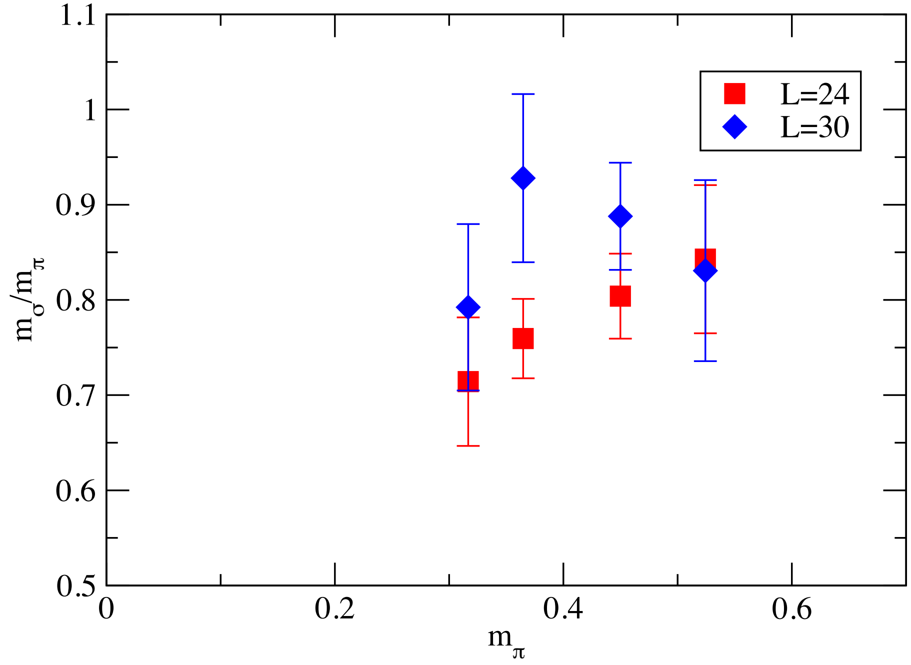
Lighter than π

Hyperscaling is seen as in m_π?

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

m_f dependence in $N_f = 12$ (Preliminary)

m_σ from effective mass of $D(t)$ at $t = 5$



Flavor-singlet scalar is relatively light?

Lighter than π

Hyperscaling is seen as in m_π?

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

Not inconsistent with hyperscaling

$N_f = 8$ QCD (Preliminary)

Chiral broken phase and might be walking theory

LatKMI; arXiv:1302.6859

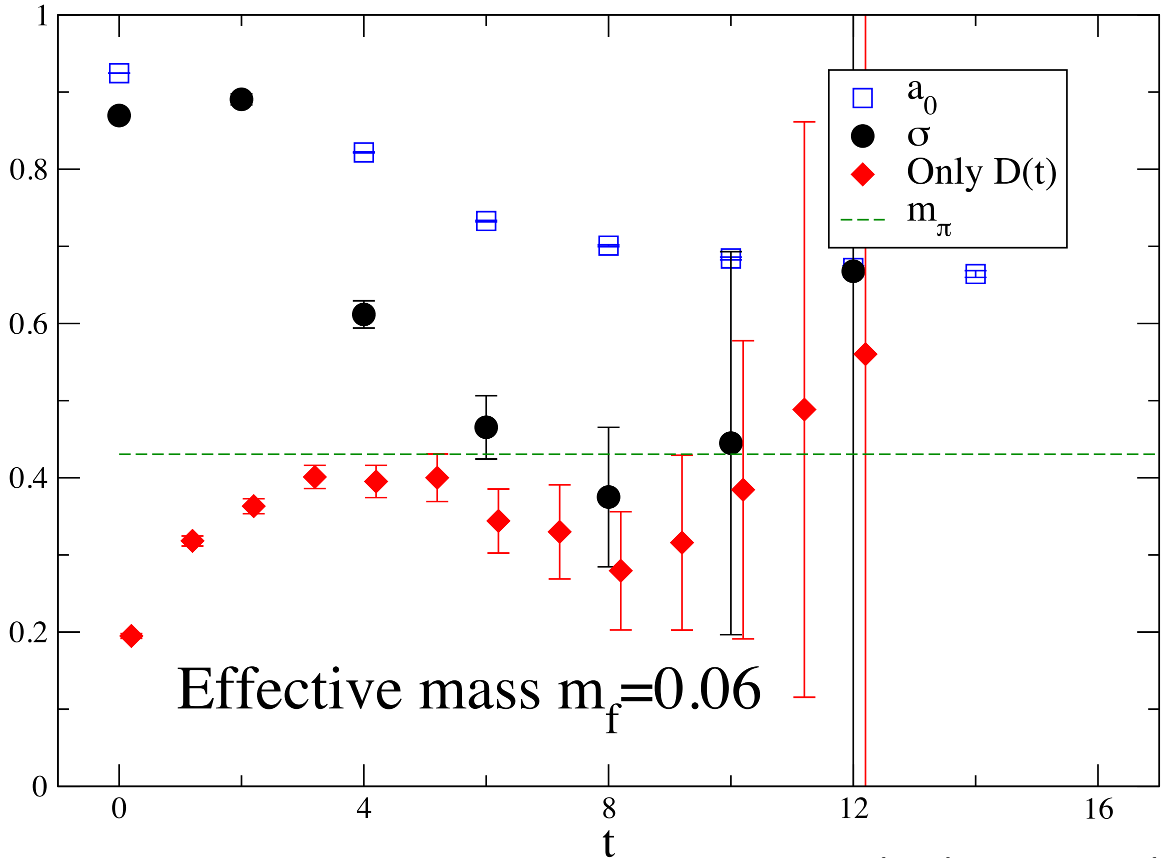
Simulation parameters

- $\beta = 3.8$
- Noise reduction method with $N_r = 64$
- Only one parameter

L, T	m_f	confs
24,32	0.06	7600

Effective mass in $N_f = 8$ (More 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

σ: $D_+(2t) - C_+(2t)$

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

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

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

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

Important to study m_f dependence and if $m_\sigma \sim F_\pi$ in $m_f \to 0$

Summary

Important to study flavor-singlet scalar for walking technicolor model

if $m_\sigma \sim F_\pi$

Flavor-singlet scalar is difficult due to huge noise in lattice simulation.

Noise reduction method and Huge N_{conf}

Preliminary results of $N_f = 12$ QCD (comformal phase)

- Consistent m_σ from meson and glueball correlators
- $m_\sigma < m_\pi$; much different from small N_f QCD
- Not inconsistent with hyperscaling

More preliminary results of $N_f = 8$ QCD (might be walking theory)

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

Encouraging results

Discussion

Why flavor-singlet scalar calculation is possible?

- Nice noise reduction methods
- Huge N_{conf}
- Small $m_\sigma \to$ slow exp. dump of correlator
- Small $O(a^2)$ error $\leftarrow$ improved action, etc.

Future perspectives

- $N_f = 8$ QCD; Important to check $m_\sigma \sim F_\pi$ in $m_f \to 0$
- Decay constant f_σ; probably possible at present
- Coupling?, scattering amplitude?; much difficult