

A light composite scalar in eight-flavor QCD on the lattice

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In search for a composite Higgs boson (techni-dilaton) in the walking technicolor, we present our preliminary results on the first observation of a light flavor-singlet scalar in a candidate theory for the walking technicolor, the $N_f = 8$ QCD, which was found in our previous paper to have spontaneous chiral symmetry breaking together with remnants of the conformality. Based on simulations with the HISQ-type action on several lattice sizes with various fermion masses, we find evidence of a flavor-singlet scalar meson with mass comparable to that of the Nambu-Goldstone pion in both the small fermion-mass region, where chiral perturbation theory works, and the intermediate fermion-mass region where the hyperscaling relation holds. We further discuss its chiral limit extrapolation in comparison with other states studied in our previous paper: the scalar has a mass much smaller than that of the vector meson, which is compared to the Nambu-Goldstone pion having a vanishing mass in that limit.

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1. Introduction

Recently a Higgs boson with mass around 125 GeV was discovered at LHC. While it is consistent with the one in the Standard model (SM), there still exists a possibility that it is a composite particle in an underlying strongly coupled gauge theory. One such example is the techni-dilaton predicted as a naturally light fermionic bound state in the walking technicolor having approximate scale symmetry and a large anomalous dimension $\gamma_m \sim 1$ [1]. A composite Higgs as the techni-dilaton is a pseudo Nambu-Goldstone (NG) boson of the spontaneously broken approximate scale symmetry and is shown to be phenomenologically consistent with the current LHC data [2]. Thus the most urgent theoretical task to test the walking technicolor would be to check whether or not such a light flavor-singlet scalar bound state exists using first-principle calculations on the lattice. (For reviews on the lattice studies in search for candidates for the walking technicolor see [3].)

Actually, in a previous work [4], we observed a flavor-singlet fermionic scalar meson (σ) lighter than the "pion" (corresponding to the NG pion in the broken phase) in the $N_f = 12$ QCD, which was studied by us in another paper on the same setting [5] and was consistent with a conformal theory. Since the conformal theory should have no bound state ("unparticle") at the exact chiral limit, the light bound states are only possible in the presence of the fermion mass m_f in such a way that it produces the confining forces (blowing-up coupling) in the infrared region below the fermion mass scale. A light scalar in such theory would not be regarded as a composite Higgs boson. Nevertheless the walking theory should have a similar light scalar bound state in a similar conformal dynamics, with the role of m_f replaced by the dynamically generated mass of the fermion.

In this paper we indeed observe a light flavor-singlet scalar σ in the $N_f = 8$ QCD, which was shown to be a good candidate for the walking technicolor in our previous work [6]. The σ we observe could be a first evidence of a candidate for the composite Higgs as a techni-dilaton on the lattice. As in $N_f = 12$ QCD [4], we extract the m_σ from the correlation function of the 0^{++} fermion bilinear operator, which consists of both connected and (vacuum subtracted) disconnected contributions. We find that the σ is as light as the NG pion similarly to $N_f = 12$ QCD [4]. As suggested by our previous work [6] on other quantities, an approximate hyperscaling behavior is also expected for the m_σ in the relatively heavier m_f region, while near the chiral limit where the spontaneous chiral breaking effects become dominant, the m_σ should be described by a polynomial function as a perturbation of m_f . We then discuss the chiral limit extrapolation of m_σ in a way consistent with the chiral perturbation theory.

In the next section, we explain the simulation setup and the methods for the flavor-singlet scalar measurement. In Section 3, we show the results on the correlation functions, the m_σ as a function of m_f . In Section 4, we summarize our results and discuss the implications of light scalar in the chiral limit for a composite Higgs scenario. All the results shown here are preliminary.

2. Lattice setup

The gauge configurations for SU(3) gauge theory with eight fundamental fermions are generated by the HMC algorithm with tree-level Symanzik gauge action and HISQ (highly improved staggered quark) action without tadpole improvement and mass correction in the Naik term. By

using two degenerate staggered fermion species, we carry out simulations on three different lattice volumes ($V = L^3$) $L = 18, 24$, and 30 , with fixed aspect ratio $T/L = 4/3$ at a single lattice spacing ($\beta \equiv 6/g^2 = 3.8$) for five different fermion masses ($m_f = 0.02, 0.04, 0.06, 0.08, 0.10$). For each parameter, we accumulate more than 5000 trajectories, and perform measurements every 2 trajectories. Such a number of configurations allows us to obtain a reasonable signal of m_σ . The statistical error is estimated by the standard jackknife method with bin size of more than 100 trajectories.

For the measurement of the flavor-singlet scalar, we use the following local staggered fermion bilinear operator

$$O_S(t) = \sum_i \sum_x \bar{\chi}_i(x, t) \chi_i(x, t), \quad (2.1)$$

where i denotes the staggered fermion species, $i = 1, 2$. Using this operator we measure the two-point correlation function $\langle O_S(t) O_S(0) \rangle \propto 2D(t) - C(t)$, where $C(t)$ and $D(t)$ are the connected and the vacuum subtracted disconnected correlators, respectively. The factor 2 in front of $D(t)$ is due to the number of species. For the calculation of $D(t)$, which is essential to estimate the σ correlator, we need to calculate the inverse of the Dirac operator for all the space-time points (x, t) . In order to reduce the computational cost of the inversion, we use the stochastic estimator with noise vectors for space-time and color. The large fluctuation coming from random noise can be efficiently reduced by employing the noise reduction technique for staggered fermions [7, 8], which was already applied in previous studies, for example, the calculation of the flavor-singlet pseudo-scalar [8, 9], the chiral condensate [10], and also the σ in $N_f = 12$ QCD [11, 4]. The chosen number of noise vectors for each gauge configuration is 64 to sufficiently suppress the fluctuation of random noise compared to gauge fluctuation. We tested the calculation method in the $N_f = 12$ QCD case as reported in Ref. [4].

In the staggered fermion formulation, the scalar operator in Eq.(2.1) overlaps not only with the σ , but also with the pseudo-scalar state ($\pi_{\overline{SC}}$), which is the staggered parity partner of σ and has the staggered spin-taste structure ($\gamma_4 \gamma_5 \otimes \xi_4 \xi_5$). In order to reduce the contribution from the parity partner we use the projection $C_+(t) \equiv 2C(t) + C(t+1) + C(t-1)$ at even t . The full correlator $2D_+(t) - C_+(t)$ in the large t region behaves as

$$2D_+(t) - C_+(t) = A_\sigma(t), \quad (2.2)$$

where $A_H(t) = A_H(e^{-m_H t} + e^{-m_H(T-t)})$. The connected correlator $C_+(t)$ in the large t region can be regarded as $A_{a_0}(t)$ where a_0 is the flavor non-singlet scalar state. Thus, the asymptotic behavior of $2D_+(t)$ is given by

$$2D_+(t) = A_\sigma(t) + A_{a_0}(t). \quad (2.3)$$

This means that both $2D_+(t) - C_+(t)$ and $2D_+(t)$ can be used to extract m_σ from their ground state masses, if $m_\sigma < m_{a_0}$. We will discuss this point later. Another projection $C_-(t) \equiv 2C(t) - C(t+1) - C(t-1)$ at even t is also used to obtain the π_{SC} state, which is the parity partner of a_0 .

3. Result

Figure 1 shows a typical result of $-C(t)$ and $2D(t)$ for $L = 30$, $m_f = 0.02$. As shown in the figure, we can obtain a good signal for $2D(t)$ thanks to a large statistics and the noise reduction

technique. In the large t region, $2D(t)$ behaves as a smooth function of t . This result indicates that the taste symmetry breaking effects on the parity partner are small [4] thanks to utilizing the HISQ-type action. The smallness of the taste symmetry breaking was also observed in other meson masses in our previous work [6].

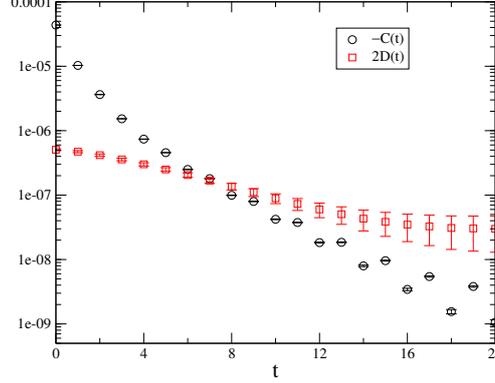


Figure 1: Connected $-C(t)$ and disconnected $2D(t)$ correlators for $L = 30$, $m_f = 0.02$.

The left panel of Fig. 2 shows all the parity-projected correlators constructed from the $C(t)$ and $D(t)$ for $L = 30$, $m_f = 0.02$. We see that the full correlator $2D_+(t) - C_+(t)$ at large t is dominated by $2D_+(t)$. Accordingly, the effective mass obtained from $2D_+(t)$ becomes consistent with that obtained from $2D_+(t) - C_+(t)$ as shown in the right panel of Fig. 2. This property allows us to evaluate the flavor-singlet scalar mass from the correlator $2D_+(t)$. The advantage of using $2D_+(t)$ is that the plateau appears at small t owing to the cancellation between the a_0 and the contamination from excited states of the σ . The plateau of $2D_+(t)$ enables us to determine the effective mass with relatively smaller statistical error. We fit $2D_+(t)$ with a single cosh form in the range $t_{min} = 6$ and $t_{max} = T/2$ to obtain m_σ for all the values of m_f . Comparing this with the rest of spectrum, we find that the σ is not heavier than π_{SC} , whose effective mass corresponds to the one of $C_-(t)$ in the right panel of Fig. 2. As for the a_0 corresponding to $-C_+(t)$, the result would suggest $m_{a_0} > m_\sigma$, as we expected, although we do not obtain a good effective mass plateau in our lattice volume.

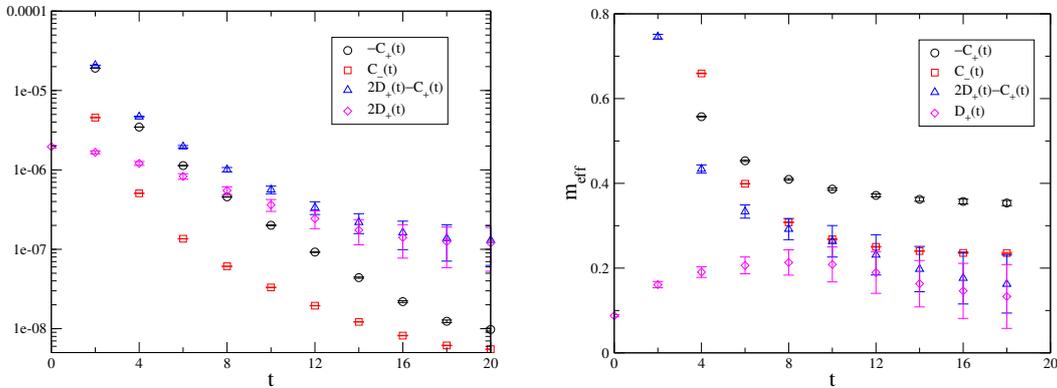


Figure 2: Parity-projected correlators for the different channels constructed from $C(t)$ and $D(t)$ (Left), and their effective masses (Right) for $L = 30$, $m_f = 0.02$.

The left panel of Fig. 3 presents fit results of the m_σ as a function of m_f for each volume,

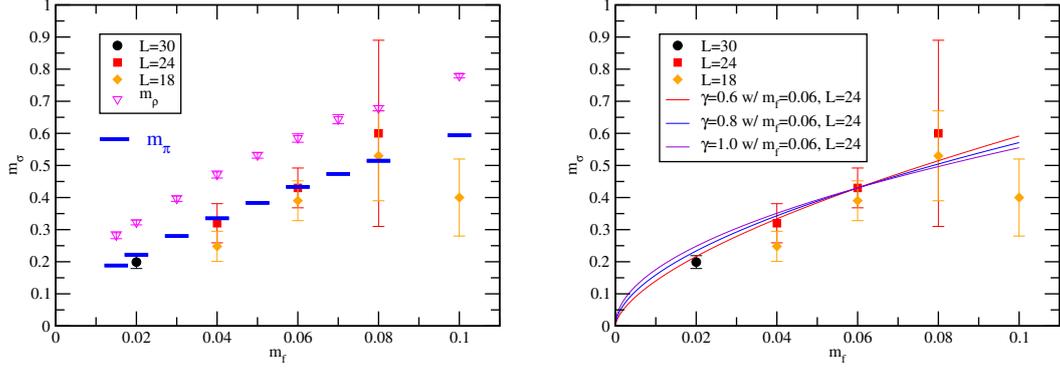


Figure 3: (Left) Flavor-singlet scalar mass m_σ as a function of m_f for each volume. The errors are only statistical. For comparison also plotted are m_π and m_ρ observed in Ref. [6]. (Right) Comparison of the m_σ data with the hyperscaling curve(s) for the value(s) of γ observed in Ref. [6] (see text), with the absolute value normalized to the data at $L = 24, m_f = 0.06$.

together with other masses m_π and m_ρ taken from Ref. [6]. The errors are only statistical. The two results on the different volumes $L = 18$ and 24 at $m_f = 0.04$ are consistent within the statistical error, so that we expect finite size effects to be small at heavier m_f . It is remarkable that all the m_σ results at the measured m_f are comparable to m_π . This feature is different from that of ordinary QCD with small N_f , and similar to the one observed in $N_f = 12$ QCD [4]. It is also to be noted that m_σ is much smaller than m_ρ .

Since we observed an approximate hyperscaling relation of other physical quantities for relatively heavy $m_f, m_f \geq 0.05$, interpreted as a remnant of conformality in our previous study [6], we also expect it for σ in this region. We plot the hyperscaling curves $m_\sigma = C(m_f)^{1/(1+\gamma)}$ in the right panel of Fig. 3, where $\gamma = 0.6, 0.8$ and 1.0 are values of m_π, m_ρ and F_π , respectively, observed in Ref. [6], and the value of C is matched to the σ data at $m_f = 0.06, L = 24$. The data are roughly consistent with the hyperscaling relation with $\gamma = 0.6 - 1.0$ within the errors.

On the other hand, the small m_f region, $m_f \leq 0.04$, was shown to be consistent with the spontaneous chiral symmetry breaking [6]. We have seen in Fig. 3 that σ is much lighter than ρ , and is as light as π all the way down to the small m_f region well described by the chiral perturbation theory, at least in the present data. This would imply a light composite scalar in the chiral limit in the walking theory.

4. Summary and Discussion

We have observed for the first time a light flavor-singlet scalar meson in the $N_f = 8$ QCD, which was shown to be a good candidate for the walking technicolor theory in our previous study. The observed mass is as light as the one of π in the simulation parameters region. Measuring disconnected correlator was critical to the achievement. Our results are encouraging in search for the walking technicolor in view of the 125 GeV Higgs at LHC.

Although our results are very preliminary and the statistical error is large, we discuss the chiral limit extrapolation of m_σ . As we observed in the previous paper [6], other physical quantities in the small m_f region are described by the chiral perturbation theory fit. In Fig. 4 we plot the results

of ChPT-like fits of m_π and m_ρ with the range $0.015 \leq m_f \leq 0.04$ (4 data) using the following fit functions [6],

$$m_\pi^2 = c_1^\pi m_f + c_2^\pi m_f^2, \quad m_\rho = c_0^\rho + c_1^\rho m_f + c_2^\rho m_f^2. \quad (4.1)$$

From the data in this region, we try to estimate the m_σ in the chiral limit. Note that σ in the chiral limit can be a bound state only in the presence of fermion mass dynamically generated by the chiral symmetry breaking, which breaks scale symmetry explicitly as well as spontaneously. Hence its chiral limit mass should not be zero in the same way as ρ , so that the chiral fit should have the same functional form as that of ρ . We carry out the chiral extrapolation with just the lightest two points on $L \geq 24$ and hence use the linear fit,

$$m_\sigma = c_0^\sigma + c_1^\sigma m_f. \quad (4.2)$$

The fit result is shown in Fig. 4. The value in the chiral limit reads $m_\sigma = 0.08(7)$. Then we have

$$\frac{m_\sigma}{m_\rho} = 0.5(5), \quad \frac{m_\sigma}{F_\pi/\sqrt{2}} = 4(4), \quad (4.3)$$

in the chiral limit ($F_\pi/\sqrt{2}$ corresponds to $f_\pi = 93 \text{ MeV}$ in the real-life QCD). Note that in a typical walking technicolor model, the one-family (four-weak-doublets) model with $N_f = 8$, we have $F_\pi/\sqrt{2} \simeq 123 \text{ GeV}$. Within the error our results accommodate the 125 GeV Higgs boson.

Here we note another possible signature of the walking behavior to be observed on the lattice data. As we mentioned above, when the chiral symmetry is spontaneously broken, the chiral limit of m_σ should be non-zero due to the very presence of the dynamically generated mass of the fermion, while m_π should go to zero as a NG boson for the same reason (non-zero dynamical mass). Hence, if $m_\sigma < m_\pi$ for larger m_f as in our data, the chiral extrapolation of m_σ and m_π must be crossing to $m_\sigma > m_\pi$ at a certain smaller m_f . This never occurs in the conformal phase, since all the masses should obey the hyperscaling relations, and the ratio of m_σ/m_π becomes a constant towards the chiral limit. Therefore, the observation of such a crossing phenomenon could be another signal of a walking theory. This will occur in much smaller m_f region than in the present calculation, as seen from our rough chiral extrapolation in Fig. 4. In order to directly check the crossing on the lattice, we will need simulations at even smaller fermion masses and larger volumes.

Besides increasing statistics and obtaining more accurate m_σ results in future, we shall construct a flavor-singlet scalar operator by gluonic operators (glueball) to check a consistency between the ground state masses extracted from different operators, as was studied in the $N_f = 12$ QCD [4, 12]. We also would need to investigate lattice discretization effects in this theory.

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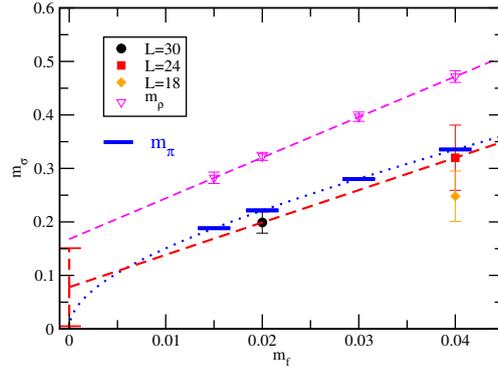


Figure 4: Fit result of the chiral extrapolation for m_σ . For comparison, other spectra of m_π and m_ρ and their chiral fits in Ref. [6] are also shown.

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