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Lattice study of flavor-singlet scalar in large-N_f QCD

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We present the results for the mass of the flavor-singlet scalar meson in $N_f = 8$ QCD, where we found signals of walking theory in our previous work, from the lattice calculation using the Highly Improved Staggered Quark action. It is found that the flavor-singlet scalar is as light as Nambu-Goldstone pseudoscalar in this theory. Since this property is similar to $N_f = 12$ QCD, where we found consistent behavior with conformal theory, it can be regarded as a signal of approximate scale symmetry in this theory. Thus, the light scalar may be a technidilaton, a pseudo Nambu-Goldstone boson of the approximate scale symmetry in walking technicolor. We discuss the possibility that such a light scalar meson can be regarded as a composite Higgs with mass 125 GeV.

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1. Introduction

The walking technicolor model is an attractive candidate to explain the origin of electroweak symmetry breaking, whose features are approximate scale invariance and a large anomalous dimension, $\gamma_m \approx 1$ [1] (see also similar works [2, 3, 4]). Such a theory is expected to have a light composite flavor-singlet scalar boson, the "technidilaton" [1], emerging as a pseudo Nambu-Goldstone (NG) boson of the spontaneously broken approximate scale symmetry, which may allow a composite description of the Higgs boson as light as 125 GeV [5, 6]. To test this scenario, it is important to study the flavor-singlet scalar state in candidate theories of walking technicolor from first-principle lattice gauge theory calculations. One of the most popular candidates for walking technicolor theories is QCD with a large number of (massless) flavors (N_f) in the fundamental representation. For the past few years, we have studied the SU(3) gauge theory with $N_f = 4, 8, 12$, and 16, in a common lattice setup [7, 8, 9], and found that the response of the composite spectra to mass deformation in $N_f = 12$ QCD is consistent with that of a conformal theory [7], and $N_f = 8$ QCD might be a candidate for a walking technicolor theory [8].

In $N_f = 12$ QCD we observed [9, 10] a flavor-singlet scalar meson (σ) lighter than the "pion" having the quantum numbers corresponding to the NG pion (π) in the broken phase. This novel phenomena is also confirmed by a subsequent work by LH collaboration [11] using a different lattice action. Such a light scalar meson in $N_f = 12$ QCD would not be a composite Higgs associated with spontaneous symmetry breaking. However, its presence strongly suggests that a walking theory would have a similar light scalar meson, because the walking theory should have similar properties to the conformal theory due to the approximate scale symmetry, even though the source of the scale symmetry breaking is different between conformal and walking theories. The former originates from the explicit breaking mass m_f only, and the latter from m_f and the dynamically generated fermion mass, m_D, arising from the spontaneous chiral symmetry breaking.

In this work, we calculate the mass of the flavor-singlet scalar fermionic bound state in $N_f = 8$ QCD, and observe σ as light as π, similarly to $N_f = 12$ QCD. Since $N_f = 8$ QCD is expected to be a walking technicolor theory, the flavor-singlet scalar in this theory can be a candidate for the composite Higgs (technidilaton) with a 125 GeV mass. All the results in this report are published in Ref. [12].

2. Simulation parameters

We carry out simulations in an SU(3) gauge theory with eight fundamental fermions using two degenerate staggered fermion species with bare fermion mass m_f. Each species has four fermion degrees of freedom, called tastes. We use a tree-level Symanzik gauge action and the Highly Improved Staggered Quark (HISQ) [13] action without tadpole improvement or mass correction in the Naik term [14]. The flavor symmetry breaking of this action is highly suppressed in QCD [14]. It is also true in our $N_f = 8$ QCD simulations, where the breaking is almost negligible in the meson masses [8]. At the same bare coupling $\beta \equiv 6/g^2 = 3.8$ as in our previous work [8], we calculate the mass of the flavor-singlet scalar (m_σ) at five fermion masses, $m_f = 0.015, 0.02, 0.03, 0.04$, and 0.06, to investigate the m_f dependence of m_σ. We use four volumes of spatial extent $L = 18, 24, 30$, and 36, with fixed aspect ratio $T/L = 4/3$. We generate the gauge configurations between 6400 and

100000 trajectories with $\tau = 1$ depending on the simulation parameters with the standard hybrid Monte Carlo algorithm. We use the MILC code version 7 [15] with some modifications to suit our needs, such as Hasenbusch mass preconditioning [16] to reduce the computational cost. The measurements are performed every 2 trajectories. The statistical error of m_σ is estimated by the jackknife method, with a bin size of 200 trajectories to eliminate autocorrelation sufficiently.

Since the composite Higgs should be associated with the electroweak symmetry breaking, it must be predominantly a bound state of technifermions carrying electroweak charges, but not of technigluons having no electroweak charges (up to some mixings between them). Thus, we focus only on fermion bilinear operator. For the measurement of m_σ we use the local bilinear operator of the $(\mathbf{1}\otimes\mathbf{1})$ staggered spin-taste structure, which has $J^{PC} = 0^{++}$ quantum numbers, defined as $\mathscr{O}_\mathrm{S}(t) = \sum_{i=1}^{2}\sum_{\vec{x}}\overline{\chi}_i(\vec{x},t)\chi_i(\vec{x},t)$, where the index i runs through different staggered fermion species. The full correlator of the operator is given by the connected $C(t)$ and also vacuum-subtracted disconnected $D(t)$ correlators, $\langle \mathscr{O}_\mathrm{S}(t)\mathscr{O}_\mathrm{S}^\dagger(0)\rangle \propto 2D(t) - C(t)$, where the factor in front of $D(t)$ comes from the number of species. To reduce the rather large statistical noise of $D(t)$, as in the $N_f =$ 12 QCD calculation [9], we utilize a method [17], which has been employed in the literature [17, 18, 19, 20], with 64 random sources spread in spacetime and color spaces. Since $2D(t)$ contains a contribution from σ [9], and gives an earlier plateau than $2D(t) - C(t)$ [12], we determine m_σ by a single cosh fit of $2D(t)$ in the region $t = 6$–11, assuming only σ propagating in this region. In order to estimate the systematic error coming from the fixed fit range, we carry out another fit in a region at larger t than the fixed one, with the same number of data points [12].

3. Results

Figure 1 presents our main result, m_σ as function of m_f compared to m_π. We find a clear signal that σ is as light as π for all the fermion masses we simulate. This property is distinctly different from the one in usual QCD, where m_σ is clearly larger than m_π [21, 22], while it is similar to the one in $N_f = 12$ QCD, as observed in our previous study [9]. Thus, this might be regarded as a reflection of the approximate scale symmetry in this theory, no matter whether the main scale symmetry breaking in the far infrared comes from m_f or m_D. The figure also shows that our simulation region is far from the heavy fermion limit, because the vector meson mass obtained from the $(\gamma_i\gamma_4\otimes\xi_i\xi_4)$ operator, denoted by ρ(PV) in Fig. 1, is clearly larger than m_π.

Although the accuracy of our data is not enough to make a clear conclusion for a chiral extrapolation, we shall report some results below. In order to estimate m_σ in the chiral limit, we shall use the lightest three data with the smallest error at each m_f, i.e., the two data on $L = 36$ and the lightest data on $L = 24$, in the following analyses. The validity of ChPT is intact even when the light σ comparable with π is involved in the chirally broken phase: the systematic power counting rule as a generalization of ChPT including σ as a dilaton was established in Ref. [23] ("dilaton ChPT (DChPT)") including a computation of the chiral log effects. At the leading order we have $m_\pi^2 = 4m_f\langle\bar{\psi}\psi\rangle/F^2$ (Gell-Mann-Oakes-Renner relation) and

$$m_\sigma^2 = d_0 + d_1 m_\pi^2, \tag{3.1}$$

where $d_0 = m_\sigma^2|_{m_f=0}$ and $d_1 = (3-\gamma_m)(1+\gamma_m)/4\cdot(N_f F^2)/F_\sigma^2$, with γ_m being the mass anomalous dimension in the walking region, and F and F_σ being the decay constants of π and σ, respectively,

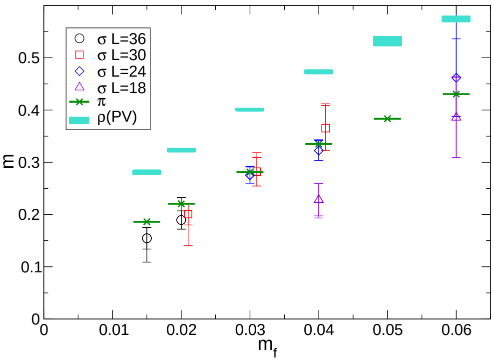

Figure 1: Mass of the flavor-singlet scalar m_σ compared to the mass of NG pion m_π as a function of the fermion mass m_f. Outer error represents the statistical and systematic uncertainties added in quadrature, while inner error is only statistical. Square symbols are slightly shifted for clarity. Shaded region indicates the mass of the vector meson with one standard deviation.

in the chiral limit. The value of F from our data is estimated as $F = 0.0202(13)(^{54}_{67})$, which is updated from the value in the previous paper [8] using more statistics and a new data at smaller m_f. We use the normalization of $F/\sqrt{2} = 93$ MeV for π at physical m_π in the usual QCD. In the following fit, we ignore higher order terms, including chiral log. We plot m_σ^2 as a function of m_π^2 in Fig. 2. The extrapolation to the chiral limit based on Eq. 3.1 gives a reasonable $\chi^2/\mathrm{d.o.f.} = 0.27$, with a tiny value in the chiral limit, $d_0 = -0.019(13)(^{3}_{20})$ where the first and second errors are statistical and systematic, respectively. It agrees with zero with 1.4 standard deviation and shows a consistency with the NG nature of σ. Although errors are large at this moment, it is very encouraging for obtaining a light technidilaton to be identified with a composite Higgs with mass 125 GeV, with the value very close to $F/\sqrt{2} \simeq 123$ GeV of the one-family model with 4 weak-doublets, i.e., $N_f = 8$, because $d_0 \sim F^2/2 \sim 0.0002$ in this case.

From the value of d_1, we can read F_σ, because the factor $(3-\gamma_m)(1+\gamma_m)/4$ is close to unity when we use $\gamma_m = 0.6$–1.0 [8]. The value of F_σ is important to make a prediction of the couplings of the Higgs boson from the walking technicolor theory. From the obtained slope $d_1 = 1.18(24)(^{35}_{7})$, we estimate F_σ as $F_\sigma \sim \sqrt{N_f}F$, in curious coincidence with the holographic estimate [24] and the linear sigma model. Note that the property $d_1 \sim 1$ is another feature different from usual QCD, where a much larger slope was observed for $m_\pi > 670$ MeV in $N_f = 2$ case [21].

With our statistics we can also fit the data with an empirical form, $m_\sigma = c_0 + c_1 m_f$, consistent with Eq. 3.1 up to higher order corrections, where we obtain $c_0 = 0.029(39)(^{8}_{72})$ as plotted in Fig. 3, which corresponds to the ratio $m_\sigma/(F/\sqrt{2}) = 2.0(2.7)(_{5.1}^{8})$. Several other fits, such as a linear m_π^2 fit of m_σ^2/F_π^2, are carried out, and they give reasonably consistent ratios with the one from c_0. All the fit results suggest a possibility to reproduce the Higgs boson mass within the large errors.

4. Conclusion

We have calculated the mass of the flavor-singlet scalar in $N_f = 8$ QCD, and found a flavor-singlet scalar as light as the NG pion. This property is much different from the usual QCD, but similar to $N_f = 12$ QCD as seen in our previous study [9]. Thus, this is considered to be a reflection of approximate conformality in this theory, whose signal was seen in our spectrum study [8]. We

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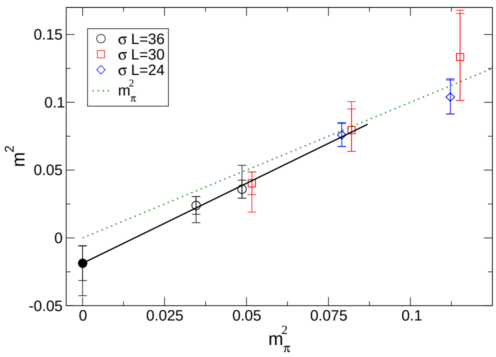

Figure 2: Chiral extrapolation of m_σ^2 as a function of m_π^2 by the DChPT fit in Eq. 3.1 is plotted by solid line and full circle. Description of symbols and errors are in caption of Fig. 1. Dotted line denotes $m_\sigma^2 = m_\pi^2$.

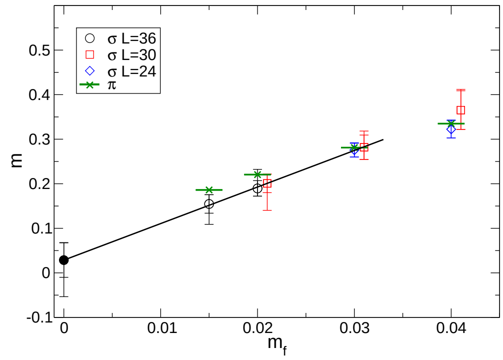

Figure 3: Chiral extrapolation of m_σ as a linear function of m_f is plotted by solid line and full circle. Description of symbols and errors are in caption of Fig. 1.

have extrapolated our m_σ data to the chiral limit with several fitting forms. If we chose the one-family model to set the scale, all the fit results suggest a possibility to reproduce the Higgs boson mass of 125 GeV, even though the results have large errors.

An important future task is a more accurate estimation of m_σ in the chiral limit. To do this, we would need the statistics accumulated further to reduce errors, and several data points in smaller fermion mass region for a stable extrapolation. Another important future direction is to observe $m_\pi < m_\sigma$ in a much smaller mass region than the current data, which is a signal of spontaneous chiral symmetry breaking. If the signal was clearly observed, the chiral extrapolations would be improved, in particular the dilaton ChPT fit would give a positive value of m_σ^2 in the chiral limit.

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