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Lattice Study of SU(3) Gauge Theory with Four Fundamental Fermions

Yasumichi Aoki^a, Tatsumi Aoyama^a, Ed Bennett^b, Masafumi Kurachi^c, Toshihide Maskawa^a,
Kohtaroh Miura^d, Kei-ichi Nngai^a, Hiroshi Ohki^e, Enrico Rinaldi^f, Akihiro Shibata^g,
Koichi Yamawaki^h and Takeshi Yamazaki^h

(LatKMI Collaboration)

^a*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya 464-8602, Japan*

^b*Department of Physics, Swansea University, Singleton Park, Swansea SA2 8PP, UK*

^c*Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*

^d*Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

^e*Centre de Physique Théorique(CPT), Aix-Marseille University, Campus de Luminy, Case 907, 163 Avenue de Luminy, 13288 Marseille cedex 9, France*

^f*RIKEN/BNL Research Center, Brookhaven National Laboratory, Upton, NY, 11973, USA*

^g*Lawrence Livermore National Laboratory, Livermore, California, 94550, USA*

^h*Computing Research Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*

ⁱ*Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan*

LatKMI Collaboration has been studying SU(3) gauge theories with large numbers of fermion flavors, N_f . Here, we report results of lattice simulations for SU(3) gauge theory with four fundamental fermions. We first show fermion mass dependence of F_π , $\langle\bar{q}q\rangle$, M_π , M_ρ and chiral extrapolations of them, showing the evidence of chiral symmetry breaking. Then, we show preliminary result of the measurement of the mass of the flavor-singlet scalar bound state.

Keywords: Lattice gauge theory, Large N_f QCD, Walking technicolor.

1. Introduction

As a part of the project of studying large N_f QCD, the LatKMI Collaboration has been studying the SU(3) gauge theory with four fundamental fermions (four-flavor QCD). The main purpose of studying four-flavor QCD is to provide a qualitative comparison to $N_f = 8, 12, 16$ QCD; however, a quantitative comparison to real-world QCD is also interesting. To make such comparisons more meaningful, it is desirable to use the same kind of lattice action consistently, so that qualitative difference of different theories are less affected by artifacts of lattice discretization. Here, we adopt the highly-improved staggered quark action with the tree-level Symanzik gauge action (HISQ/tree), which is exactly the same as the setup for our simulations for SU(3) gauge theories with $N_f = 8, 12$ and 16 fundamental fermions¹⁻³. In the next section, we show the fermion mass dependence of F_π , $\langle\bar{q}q\rangle$, M_π , M_ρ and chiral extrapolations of them. In section 3, preliminary result of the measurement

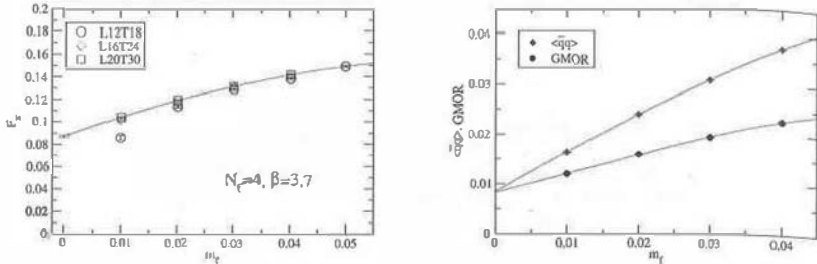


Fig. 1. The decay constant of the NG boson, F_π , (left panel) and the chiral condensation, $\langle \bar{q}q \rangle$, (right panel) as functions of m_f for $N_f = 4$, $\beta = 3.7$. On the right panel, only the largest volume data is plotted. The chiral condensate estimated by using the GMOR relation is also plotted in the right panel. All the curves appearing in figures are obtained by fitting the quadratic function to the largest volume data.

of the mass of the flavor-singlet scalar bound state will be reported.

2. Chiral property and the vector meson mass

For our study of four-flavor QCD, we generated gauge configurations for $\beta = 3.7$ with three volumes, $(L, T) = (12, 18)$, $(16, 24)$, $(20, 30)$, and four or five bare mass parameter, m_f , in the range of $0.01 \leq m_f \leq 0.05$ depending on the volume.

In Fig. 1, we show the decay constant of the Nambu–Goldstone (NG) boson, F_π , and the chiral condensation, $\langle \bar{q}q \rangle$, as functions of m_f . Quadratic fits of F_π and $\langle \bar{q}q \rangle$ show a non-zero value in the chiral limit, which can be considered as evidence for four-flavor QCD being in the chirally broken phase. As a consistency check, we also calculated the chiral condensate by using the GMOR relation, which is shown in the plot of $\langle \bar{q}q \rangle$. From the figure, we can see that the value of the chiral condensate obtained from the GMOR relation agrees with that of $\langle \bar{q}q \rangle$ in the chiral limit.

In the left panel of Fig. 2, we show the plot of the mass-squared (m_π^2) of the NG boson obtained from our simulations as a function of m_f . m_π^2 can be fitted well by a linear ansatz; if the quadratic term is allowed, its coefficient is small. This is consistent with predictions from chiral perturbation theory.

The right panel of Fig. 2 shows the ratio of the mass of the vector meson, M_ρ , to F_π for various values of m_f . The curve in the figure is the quadratic fit to the data of the largest volume, from which we can see the value of the ratio in the chiral limit being $M_\rho/F_\pi \simeq 6$. This value is very close to the ratio in the real-world QCD, $775 \text{ MeV}/130 \text{ MeV} \simeq 6$. In this sense, though the number of light fermion flavors is slightly larger than that in the real-world QCD, the two theories are very similar as far as the mass of the vector meson is concerned.

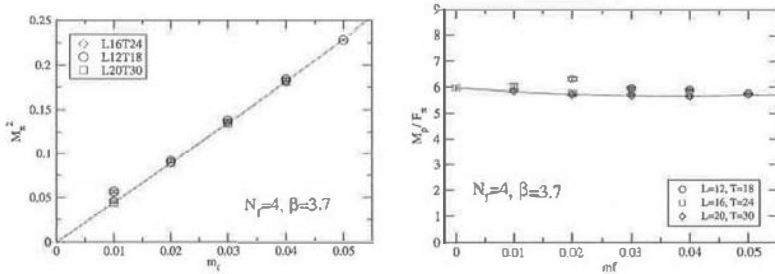


Fig. 2. Left: Mass-squared of the NG boson as a function of m_f . Quadratic fit to the largest volume data is also shown. Right: The ratio of the mass of the vector meson, M_ρ , to F_π for various values of m_f . Quadratic fit to the largest volume data is also shown.

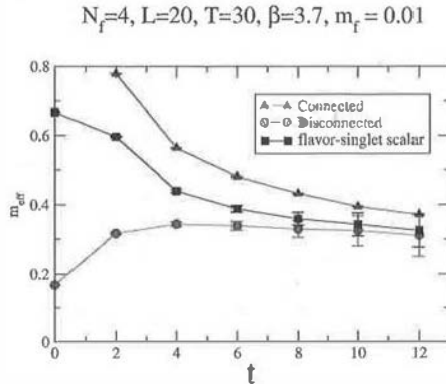


Fig. 3. The effective mass plot of the flavor-singlet scalar for $L = 20, T = 30, m_f = 0.01$. The (black) square symbols represent effective mass calculated from the full scalar correlator, while (blue) triangle and (red) circle symbols represent those obtained from the connected and disconnected correlators, respectively.

3. Flavor-singlet scalar bound state

The flavor-singlet scalar meson is very interesting object both in large N_f QCD and in real-world QCD. In the former case, it could be related to the 126 GeV Higgs boson discovered at the LHC, while for the latter case, it is related to the σ meson. We calculate the flavor-singlet scalar correlator to extract the bound state mass by using the same technique we adopted for $N_f = 8$ and 12 QCD. (See Refs. ^{4,5} for details.) The preliminary effective mass plot $L = 20, T = 30, m_f = 0.01$ is shown in Fig. 3. The plateau is observed in the disconnected channel, and the mass extracted from it is about 0.3, which is heavier than the pseudo NG boson ($M_\pi \sim 0.2$) in the

same parameter. This is quite different from $N_f = 8$ and 12 QCD, in which it was shown that the mass of the flavor-singlet scalar bound state is comparable to or smaller than the pseudo NG boson^{4,5}.

4. Summary

In this report, we showed our lattice simulation results for four-flavor QCD, which was performed by using the HISQ action with the tree-level Symanzik gauge action. It was shown that the theory is in the chiral symmetry breaking phase, and the ratio of M_ρ to F_π in the chiral limit is quite close to that of real-world QCD. Preliminary results for flavor-singlet bound state mass were also shown, and the qualitative difference between four-flavor QCD and (near-)conformal theories such as $N_f = 8$ and 12 QCD was pointed out. More detailed analysis with higher statistics and similar investigation in multiple mass parameter would help to understand the physical interpretation of the result, which will be pursued in the future.

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