Chapter 6

Field Theory Research Team

6.1 Members

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6.2 Overview of Research Activities

Field theory research team performs researches related with the numerical computation of quantum field theory (QFT) in elementary particle and nuclear physics. The quantum field theory is the framework of quantum theory combined with Einstein's special relativity to describe the physical properties of elementary particles. The standard model (SM) of particle physics, which is scripted with QFT, represents the state-of-the-art understanding of the most basic physical law of the elements of matters in this world. This almost perfect law of nature is still incomplete in several reasoning: it does not explain the origin of dark matter; it does not explain the spectrum of elementary particles; it is not natural that highest energy scale in SM is seventeenth order of magnitude lower the Plank scale; etc. These motivate searches of new physics in various theoretical and experimental directions. Among these precision tests of SM and seeking answers of these questions in extensions of SM require precise information of the quantum chromo dynamics (QCD) which governs the strong interaction in SM. The involved QCD dynamics cannot be solved by hand. Computational approach with lattice QCD, discretized version of the QCD on the continuous space-time, is powerful and most effective. After the first lattice QCD simulation about 40 years ago, its technique has become sophisticated and matured to date by tremendous efforts. Realistic simulations with various parameters tuned as in the nature are becoming possible by use of supercomputer like K using a conventional version of the lattice QCD formulation. The required precision to many interesting quantities for the test of the standard model, however, has not been reached yet. In this situation, the breakthrough could be obtained by using methods which are ideal but computationally demanding. We believe using the next generation supercomputers like Fugaku with related developments makes this happen.

To maximize the power of the next generation supercomputers, multifaceted improvements are needed. First, algorithmic development for simulation technique and analysis of the large data set will be more than useful. Second, given the idea in algorithms, efficiency in the future HPC environment need to be maximized. The team conducts researches in such directions.

6.3 Research Results and Achievements

6.3.1 Lattice QCD codes and algorithms

Algorithm and code development of Lattice QCD (LQCD) for the supercomputer Fugaku is one of the most important missions of the team. The QCD Wide SIMD (QWS) Library is produced in the Flagship 2020 Project and open for public at github [40]. QWS provides libraries for most demanding numerical efforts in the Wilson fermion simulations. Namely the linear solvers for Wilson types are supported. The QWS library would be the most effective for those to simulate fermions in QCD on Fugaku. It has achieved [25+]× speed up compared with the K supercomputer for the target application Wilson fermion solver.

In the particle physics applications, domain-wall fermions (DWFs), a most efficient chiral fermion formulation to date, are the promising framework for the Fugaku era. DWFs are variants of the Wilson fermions. It is a five dimensional Wilson fermion with a spacial boundary condition imposed in the fifth direction, which effectively makes domain walls in the both ends of the fifth direction. The four-dimensional physical degree of freedom is projected out from the wall positions. Each four-dimensional slice of the DWF at a fixed fifth dimensional position is a four dimensional Wilson fermion. The 5D DWF is superficially a connection of many 4D Wilson fermions. We may use QWS for numerical manipulations for 4D Wilson part where the most of the computational cycles are concentrated.

To make full use of QWS, LQCD package from which QWS is called is needed. The LQCD packages Bridge++ and Grid are the candidates for the use of DWF applications. Test and development of Grid is underway mainly using Intel Skylake processors at this stage through HPCI on Ito subsystem-A at Kyushu University and RIKEN Hokusai Big Waterfall, taking the finite temperature QCD with three degenerate quark flavors as a test case.

With relatively small size simulations for three degenerate quark flavors, a global search has been started as code and algorithm test. A pseudo-critical behavior in the susceptibility of plaquette (simplest observable in the gauge theory) has been fond, which will be tested with changing parameters in future study.

One of the QCD package with Japanese initiative is Bridge++. Hybrid Monte Carlo for two-flavor QCD with domain-wall fermion algorithm is implemented in Bridge++ and tested at K-supercomputer. Tuning of the parameters of the molecular dynamics was done and realistic test runs were performed by taking the parameter set corresponding to those near the finite temperature transition but a bit above that. This code development appears to be successful. The knowledge acquired here for 2-flavor will be combined with the knowledge of the Grid development for 3-flavors and will be used for the development for 2+1-flavor simulations planned for the supercomputer Fugaku.

Large volume QCD simulations for Fugaku may suffer from extra slowing down. Multigrid algorithm is a promising method if implemented in efficient way. Applying it to domain-wall fermions may require special treatment as the physical light degree of freedom is not realized as simple as that of the Wilson fermion. First step to this direction is examined and is reported in the meeting of the Japan Physical Society [34] as well as in workshops [22][24].

A good pseudo random number generator for parallel computers are useful for LQCD computation and beyond that. Mersenne twister, which is one of this sort, is taken and its parameter set was searched for on K-supercomputer. The project, started with tuning of the program for this parameter mining, resulted finding about 180 million parameter sets.

Our team together with the Programming Environment Research Team organized an international workshop on the QCD coding for Fugaku [1], calling related developers to participate. There knowledge and ideas acquired by domestic and international developers were shared, which encourages further research and development for the successful use of Fugaku for LQCD.

HPC-Phys workshops [2] are domestic meeting aiming to encourage exchanging ideas for high-performance computing especially research and developments for large scale numerical simulations in fundamental physics. This workshop in series are supported by the priority issue No. 9 to be tackled by the supercomputer Fugaku through the Joint Institute for Computational Fundamental Science (JICFuS). This year one of these workshops is held at R-CCS, and the other at Waseda University, organized by our team members together with the members in JICFuS. We plan to continue this activity taking main role of the organization in the future as well.

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[1] https://www.r-ccs.riken.jp/labs/ftrt/FugakuQCD.html

[2] https://hpc-phys.kek.jp/

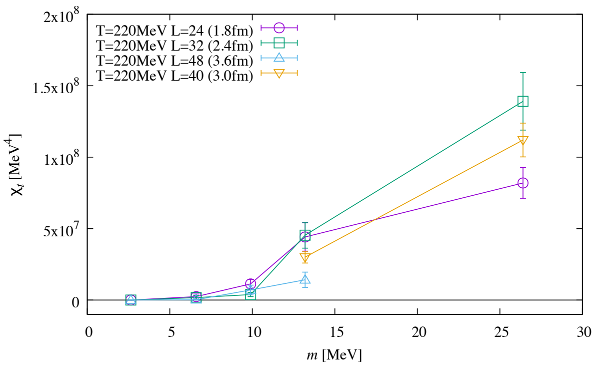

Figure 6.1: Preliminary result of the topological susceptibility as a function of ud-quark mass m for QCD with two dynamical quarks at system temperature about T=220 MeV from JLQCD collaboration with a support of the priority issue 9 to be tackled by the supercomputer Fugaku. Use of a chiral fermion makes it possible to unambiguous definition of the topological charge, thus, of its susceptibility as well. Existence of the phase transition or cross-over around m=10 MeV is implied. Figure is reproduced from Ref. [14].

6.3.2 Finite Temperature QCD with domain wall fermions

99% of the mass of the visible universe (and our body as well) is made of the energy dynamically generated by QCD interaction. The underlying mechanism of mass generation is the chiral symmetry breaking (Nambu-Goldstone mechanism): the chiral symmetry is spontaneously broken in the present universe. One can think of what happens if we unwind the history of the universe and with the temperature high enough, then the chiral symmetry should recover. If there has been a phase transition or just a crossover is a prime question whose answer would have had great influence on the history of the universe and the fate of the matters inside that. Furthermore, understanding the nature of the transition is necessary to judge the fate of one of the promising dark matter scenarios.

There is a long history of the research of QCD at finite temperature theoretically and experimentally. For theory side, as the strong coupling QCD is the target, numerical computation with lattice QCD is most useful. Because the target physics question is an involved interplay of the symmetry and its spontaneous breaking, we need the formulation which respects the symmetry in the first place. The lattice formulation which preserves exact "chiral symmetry", thus being called as chiral fermions, is in our hands. However, it requires tremendous computational effort compared to the conventional lattice formulations, such as Wilson or staggered fermions, which respects only a part of the full chiral symmetry or does not at all. On the supercomputer Fugaku, we aim to conduct computations using chiral fermions and by that we can get rid of the compromises which we were not able to.

Along this line we employ domain-wall fermions as a practically best implementation of the chiral fermions to date. While ultimately the 2+1 flavor simulation, where lightest three quarks (up, down and strange flavors) enter, needs to be performed, we perform simulations of 2-flavor (without strange quark) QCD as a benchmark to the 2+1 flavor simulation. This is an approximation to 2+1 flavor world and actually known to be a very good approximation for low temperature systems. It is also expected to share crucial dynamical properties for finite temperatures near phase transition as well. This study is done in the JLQCD collaboration with a support of the priority issue No. 9 to be tackled by the supercomputer Fugaku to bridge to the 2+1 flavor simulations. Figure 6.1 shows a preliminary result of the topological susceptibility as a function of ud-quark mass m at temperature about $T = 220$ MeV, which is our main target temperature and is 20-30% higher than the critical temperature expected for the chiral transition at mass-less limit. A sudden growth observed for $m > 10$ MeV suggests a rapid transition. As there is no monotonic dependence on the volume, this is likely to be a crossover.

This quantity is related to the axial $U(1)$ anomaly. The axial $U(1)$ symmetry is intact in QCD at classical level, but, broken by quantum anomaly. There is a long history of debate as to whether this symmetry is effectively recovers above phase transition temperature. Chiral symmetric treatment of lattice QCD would provide the final answer to this question. Fig. 6.2 shows a preliminary results of the axial $U(1)$ susceptibility, a measure of the breaking of axial $U(1)$ symmetry, as a function of ud-quark mass m. Vanishing susceptibility in the $m \to 0$ limit suggests the recovery of the symmetry at this temperature.

The fate of the axial $U(1)$ symmetry is closely related to possible extended symmetries of the meson sector

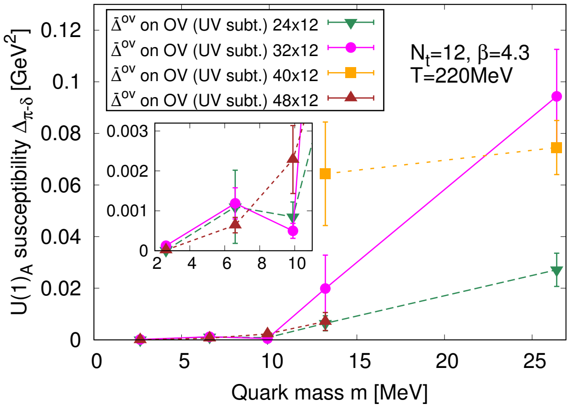

Figure 6.2: Preliminary result of the $U(1)_A$ susceptibility as a function of ud-quark mass m for QCD with two dynamical quarks at system temperature about T=220 MeV. Existence of the phase transition or cross-over around m=10 MeV is implied. Figure is reproduced from Ref. [14]

in finite temperature. The meson correlation functions in spacial distance is examined using the chiral fermions in the temperature range above the critical temperature of the chiral phase transition. It has been found that the chiral-spin symmetry $SU(2)_{CS}$ and further larger $SU(4)$ symmetry are approximately recovered in the temperature range of T $220 - 500$ MeV [3][9]. This is taken as an indication of suppressed chromomagnetic interactions in QCD and systems at these temperatures are effectively described with color singlet object composed of the chirally symmetric quarks bound by the chromoelectric interaction of QCD. This new finding is made possible with the use of chiral fermions, and shows the power of using methods with large numerical cost but without compromise.

6.3.3 Proton decay matrix elements

Proton decay is a smoking gun evidence of new physics beyond the standard model of particle physics. It naturally takes place in grand unified theories (GUTs) which unifies the known forces in the nature except gravity. Ongoing experiments such as SuperKamiokande as well as the ones in preparation: HyperKamiokande in Japan, DUNE in USA and JUNO in China are aiming to detect the proton decay in deep underground as one of the core missions. Even without the signal of the decay, the lower bound of the proton lifetime will be prolonged with continuous operation of the experiments. That could impose severe constraint on the GUT models (ultimately leading to the way to finding the unique single theory of everything), provided that the proton decay matrix elements are determined in good precision. The underlying theory for the matrix elements is the quantum chromo dynamics, QCD, which describes the strong interaction among quarks, building blocks of proton. For the quantitative treatment for matrix elements, numerical computation using lattice QCD defined on the discrete space-time is only way in our hands.

For long the numerical simulation of lattice QCD with physical value of light quark masses has not been possible due to its demanding computational cost. As such, extrapolations from simulations with unphysically heavy quark masses were performed. Use of K and other equivalent high performance computers and continuous improvement of the algorithms made it possible to now simulate QCD on top of the physical quark mass point. To cope with smaller quark mass, a larger volume needs to be used to control the finite volume error. Ever growing volume provides new room of improvement of the algorithm. All mode averaging (AMA), which one of our team member developed, is a promising new direction for accelerating the simulation for larger volumes. For most of the quantities calculated from QCD, the quark matrix inversion is the most computationally demanding part of the algorithm. The AMA framework guides the way to mix the exact low mode eigenvectors and many sloppy conjugate gradient solver with relaxed convergence criteria to minimize the computational cost for given precision using the covariance property of the matrix. This test is done using the Wilson fermion environment, with an outlook of using it to future chiral fermion simulations.

Using K at R-CCS and Hokusai BigWaterFall at Information System Division of RIKEN we have been testing the effectiveness of AMA technique using the gauge field configurations generated by PACS collaboration using a Wilson fermion formulation. With the success of the use of AMA for the low energy constants (LECs) of proton decay matrix elements which has been achieved last year, we pushed forward to compute the form factors at the physical kinematics this year. The form factors of proton decay has more direct relation to the proton lifetime. But the computational effort needed to achieve the same precision with the LECs is almost an order of magnitude larger. Despite the cost the computation appears to be successful thanks to AMA. Figure 6.3 (a) shows the ratio as function of the position t of the baryon number violating operator with proton and pion interpolating field with distance $t_s = 18$, 20 and 24, for three different momentum injections (shown in different panels) to pion near the kinematics of physical process. The value for the form factor extracted from the plateau fit to them are plotted as a function of the squared momentum transfer in Fig. 6.3 (b). There three data points with open circle come from the three panels in (a). The cyan band is showing the results obtained with a long chiral extrapolation. Our new results with smaller error bar was made possible to utilize the physical pion mass, which does not require the chiral extrapolation, with larger computational effort with the help of AMA. The new result at the physical kinematics appears to be consistent with the old one within two standard deviations, which suggests that there is no surprise in the chiral extrapolation which could have lead to far small value thus prolongs the proton lifetime as suggested in a model estimate.

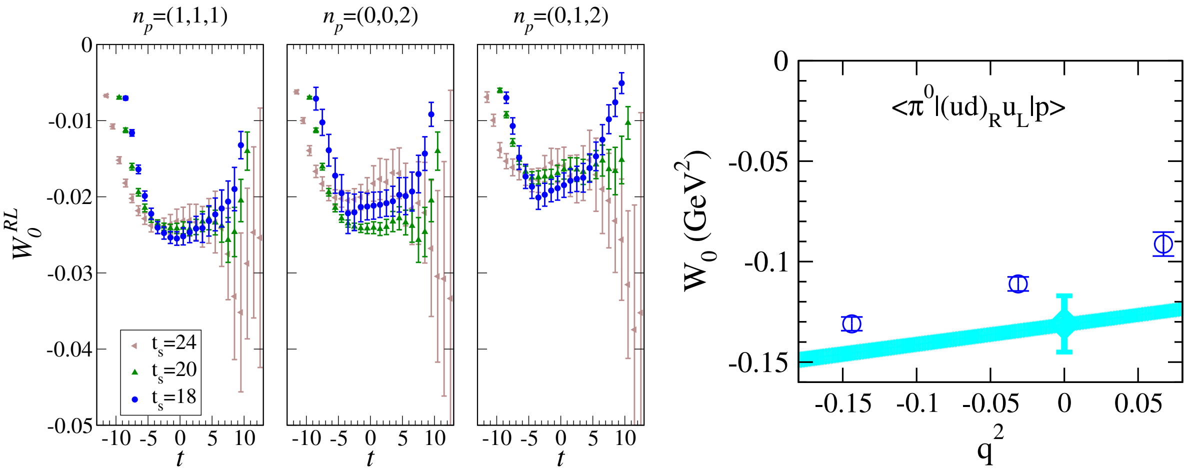

Figure 6.3: (a) (left panel) Relevant form factor of the $p \to \pi^0$ decay with $\mathcal{O}^I = \epsilon_{ijk}(u^{iT} C P_R d^j) P_L u^k$ in lattice units as a function of operator position t. (b) (right panel) $W_0(q^2)$ for the same process (open symbol) compared against the chiral extrapolated results of domain-wall fermions shown as a cyan band. The figures are reproduced from Ref. [20].

6.3.4 Miscellaneous LQCD developments

There are LQCD related publications reported by members of the team with external collaborations. These works does not use K-computer, but, serve as possible seeds for future high performance computing on supercomputer Fugaku and beyond that.

Yoshifumi Nakamura reported on works using Wilson fermions for QED and isospin breaking effects on the baryon spectrum [1][4], for the role of flavor symmetry on the hadronic matrix elements [2], and for system size effect on the vector meson and baryons [4]. A work for the single flavor optimization of the LQCD simulation algorithm was reported in [13]. He also worked on the tensor renormalization group as alternative algorithm to conventional Monte-Carlo, which have been reported in [11] and [12].

Issaku Kanamori reported on the application of the chiral random matrix model for two-color QCD [6], a toy-model but sharing several important properties with the real QCD. He also has published a work [7] on the numerical stochastic perturbation theory applied to the twisted Eguchi-Kawai model, a promising effective model for QCD in the limit of large number of colors.

The flavour lattice averaging group (FLAG) is establishing efforts to average LQCD results relevant to the phenomenological applications in particle physics and to provide them to community use. Yasumichi Aoki is taking a part of the activity and published the fourth edition "FLAG Review 2019" [8].

Our former member Eigo Shintani had been working on the hadronic vacuum polarization contribution to the muon $g-2$ in a big volume at physical point. This is done in collaboration with PACS Collaboration and published this year [10].

6.4 Schedule and Future Plan

The chiral fermion simulations of lattice QCD for the supercomputer Fugaku will eventually use 2+1 flavor (including the strange quark) physical point for heavy flavor physics targeting B mesons and the other precision tests of the standard model (SM). The same setting will also be used to explore the phase diagram of QCD at finite temperature which could end up simulating lighter quarks than physical. The Fugaku implementation of the existing algorithms are being developed this year and will further be extended to several LQCD packages in the coming years. Extended simulations to finer lattice, larger volume, and lighter quarks from the current ones, which would be the next stage on Fugaku as well as the post-Fugaku machines benefit from speedup with algorithmic development and tuning. There existing speedup techniques such as AMA or multigrid algorithm may serve as improvements. Developments in the methods beyond the conventional Monte-Carlo based on the molecular dynamics may find its use in the future simulations.

6.4.1 Algorithm and code development for the chiral fermion simulation in QCD for Fugaku

The chiral fermion simulations of two-flavor QCD uses Grid, the code set developed mainly by Edinburgh University. We are working on extending this to 2+1 flavor case. Through the co-design works for the supercomputer Fugaku involving members of our team, we foresee obstacles of simple extension of the Grid code set. The co-design software team is developing their version of Wilson fermion solvers, which can be used as main building blocks to simulate chiral fermions, too. A possible international collaboration with developers of Grid, which became one of the international standards, on the optimization for the supercomputer Fugaku, could benefit both sides and potential international users. The large volume and light quark simulations are computationally challenging. The AMA technique, being developed and tested seriously this year, will be useful. Independent of this technique, implementing and accelerating Multi-Grid algorithm would be a promising direction. In the lattice simulations, parameters not directly related with the physical setting, like the AMA and multi-grid specific ones or like tunable parameters in the hybrid Monte-Carlo potentially provide large rooms of improvement. There, optimizations assisted with deep learning could bring a significant speed up.

6.4.2 QCD phase diagram with chiral fermion simulations

As a test bed of new code development and new algorithms the degenerate three flavor simulation of QCD using chiral fermions can be used. The simulation is simpler than physical, non-degenerate, 2+1 flavor simulation, thus good for tests with situation close to the final target. But, it is also interesting on its own physical perspective. The phase diagram with respect to the change of the degenerate quark mass is one of the important boundary of 2+1 flavor QCD phase diagram. Recent results reported using conventional fermions suffer from huge discretization error. Use of the chiral fermions, thus being able to simulate with correct counting of the light degree of freedom, is expected to solve this problem. We started an experimental simulations with small size on existing HPC resources. Towards realistic simulations with larger volume and lighter quark mass, Fugaku-scale supercomputer is needed. Tests of the algorithm and codes for Fugaku will be immediate aim in the coming year. The knowledge acquired through these studies provide a base of the simulation of more challenging 2+1 flavor, where we would find further rooms for development on the algorithms and codes.

6.4.3 Collaboration on physics applications

We have a close collaboration with the priority issue No. 9 to be tackled by the supercomputer Fugaku. This project will be extended to the new “Program for Promoting Researches on the Supercomputer Fugaku” (Simulation for basic science: from fundamental laws of particles to creation of nuclei) next year. It will be continued for three years. We will start preparing the simulation on Fugaku in the first year and full scale simulations will be performed in the FY 2021 and 2022. Through this collaboration, we aim to maximize the scientific output of the issues for intensity frontier subjects including flavor physics, as well as for the QCD phase by cutting edge developments.

6.5 Publications

6.5.1 Articles/Journal

[1] CSSM/QCDSF/UKQCD Collaboration: Z.R. Kordov, R. Horsley, Y. Nakamura, H. Perlt, P.E.L. Rakow, G. Schierholz, H. Stüben, R.D. Young, J.M. Zanotti, “Electromagnetic contribution to $\Sigma - \Lambda$ mixing using lattice QCD+QED”, Phys.Rev. D101 (2020) no.3, 034517.

[2] J.M. Bickerton, R. Horsley, Y. Nakamura, H. Perlt, D. Pleiter, P.E.L. Rakow, G. Schierholz, H. Stüben, R.D. Young, J.M. Zanotti, “Patterns of flavor symmetry breaking in hadron matrix elements involving u, d, and s quarks”, Phys.Rev. D100 (2019) no.11, 114516.

[3] C. Rohrhofer, Y. Aoki, L.Ya. Glozman, S. Hashimoto, “Chiral-spin symmetry of the meson spectral function above T_c”, Phys.Lett. B802 (2020) 135245.

[4] PACS Collaboration: K.I. Ishikawa, N. Ishizuka, Y. Kuramashi, Y. Nakamura, Y. Namekawa, E. Shintani, Y. Taniguchi, N. Ukita, T. Yamazaki, T. Yoshié, “Finite size effect on vector meson and baryon sectors in 2+1 flavor QCD at the physical point”, Phys.Rev. D100 (2019) no.9, 094502.

[5] CSSM and QCDSF and UKQCD Collaborations: Z. Koumi, Y. Nakamura, H. Perlt, D. Pleiter, P.E.L. Rakow, G. Schierholz, A. Schiller, H. Stüben, R.D. Young, J.M. Zanotti, “Isospin splittings in the decuplet baryon spectrum from dynamical QCD+QED” J. Phys. G46 (2019) 11.

[6] Hiroyuki Fuji, Issaku Kanamori, Shinsuke M. Nishigaki, “Janossy densities for chiral random matrix ensembles and their applications to two-color QCD”, JHEP 1908 (2019) 053.

[7] Antonio González-Arroyo, Issaku Kanamori, Ken-Ichi Ishikawa, Kanata Miyahana, Masanori Okawa, Ryoichiro Ueno, “Numerical stochastic perturbation theory applied to the twisted Eguchi-Kawai model”, JHEP 1906 (2019) 127.

[8] Flavour Lattice Averaging Group: S. Aoki, Y. Aoki, D. Bečirević, T. Blum, G. Colangelo, S. Collins, M. Della Morte, P. Dimopoulos, S. Dürr, H. Fukaya, M. Golterman, Steven Gottlieb, R. Gupta, S. Hashimoto, U.M. Heller, G. Herdoiza, R. Horsley, A. Jüttner, T. Kaneko, C.-J.D. Lin, E. Lunghi, R. Mawhinney, A. Nicholson, T. Onogi, C. Pena, A. Portelli, A. Ramos, S.R. Sharpe, J.N. Simone, S. Simula, R. Sommer, R. Van De Water, A. Vladikas, U. Wenger, H. Wittig, “FLAG Review 2019”, Eur.Phys.J. C80 (2020) no.2, 113.

[9] C. Rohrhofer, Y. Aoki, G. Cossu, H. Fukaya, C. Gattringer, L.Ya. Glozman, S. Hashimoto, C.B. Lang, S. Prelovsek, “Symmetries of spatial meson correlators in high temperature QCD”, Phys.Rev. D100 (2019) no.1, 014502.

[10] PACS Collaboration: Eigo Shintani, Yoshinobu Kuramashi, “Hadronic vacuum polarization contribution to the muon $g-2$ with 2+1 flavor lattice QCD on a larger than (10 fm)^4 lattice at the physical point”, Phys.Rev. D100 (2019) no.3, 034517.

[11] Daisuke Kadoh, Yoshinobu Kuramashi, Yoshifumi Nakamura, Ryo Sakai, Shinji Takeda , Yusuke Yoshimura, “Tensor network analysis of critical coupling in two dimensional ϕ^4 theory”, JHEP 1905 (2019) 184.

[12] Yoshifumi Nakamura, Hideaki Oba, Shinji Takeda, “Tensor Renormalization Group Algorithms with a Projective Truncation Method”, Phys.Rev. B99 (2019) no.15, 155101.

[13] Taylor Haar, Waseem Kamleh, James Zanotti, Yoshifumi Nakamura, “Single flavour optimisations to Hybrid Monte Carlo”, Comput.Phys.Commun. 238 (2019) 111-123.

6.5.2 Conference Papers

[14] Kei Suzuki, Sinya Aoki, Yasumichi Aoki, Guido Cossu, Hidenori Fukaya, Shoji Hashimoto, “Axial U(1) symmetry, topology, and Dirac spectra at high temperature in $N_f = 2$ lattice QCD”, PoS CD2018 (2019) 085.

[15] E. Shintani, Y. Kuramashi, “Analysis of systematic error in hadronic vacuum polarization contribution to muon $g-2$”, PoS LATTICE2018 (2019) 060.

[16] JLQCD Collaboration: Kei Suzuki, Sinya Aoki, Yasumichi Aoki, Guido Cossu, Hidenori Fukaya, Shoji Hashimoto, “Axial U(1) symmetry and Dirac spectra in high-temperature phase of $N_f = 2$ lattice QCD”, PoS LATTICE2018 (2018) 152.

[17] Hiroshi Ohno, Yoshinobu Kuramashi, Yoshifumi Nakamura, Shinji Takeda, “Continuum extrapolation of the critical endpoint in 4-flavor QCD with Wilson-Clover fermions” PoS LATTICE2018 (2018) 174.

[18] Ryo Sakai, Daisuke Kadoh, Yoshinobu Kuramashi, Yoshifumi Nakamura, Shinji Takeda, Yusuke Yoshimura, “Tensor network study of two dimensional lattice ϕ^4 theory”, PoS LATTICE2018 (2018) 232.

[19] Sophie Hollitt, Roger Horsley, Paul D. Jackson, Yoshifumi Nakamura, Holger Perlt, Paul E.L. Rakow , Gerrit Schierholz, A. Schiller, Hinnerk Stüben, Ross D. Young, James M. Zanotti, “Control of SU(3) symmetry

breaking effects in calculations of B meson decay constant", PoS LATTICE2018 (2018) 268.

6.5.3 Posters

[20] Y. Aoki, Y. Kuramashi, E. Shintani, N. Tsukamoto, "Proton decay matrix elements with physical quark masses", The 37th International Symposium on Lattice Field Theory (Lattice 2019) (June 16-21, 2019, Wuhan, China).

[21] Y. Aoki, Y. Kuramashi, E. Shintani, N. Tsukamoto, "Proton decay matrix elements with physical quark masses", Fugaku QCD coding workshop (Dec. 12-13, 2019, Kobe, Japan).

[22] I. Kanamori, "Multigrid Solver with Bridge++ Code Set", Fugaku QCD coding workshop (Dec. 12-13, 2019, Kobe, Japan).

[23] Y. Aoki, Y. Kuramashi, E. Shintani, N. Tsukamoto, "Proton decay matrix elements with physical quark masses", シミュレーションによる宇宙の基本法則と進化の解明に向けて (QUCS 2019) (Dec. 16-19, 2019, Kyoto, Japan).

[24] I. Kanamori, "Multigrid Solver with Bridge++ Code Set", シミュレーションによる宇宙の基本法則と進化の解明に向けて (QUCS 2019) (Dec. 16-19, 2019, Kyoto, Japan).

[25] I. Kanamori, "Neighboring Communication with uTofu for LQCD Application", The 2nd R-CCS International Symposium (Feb. 17-18, 2020, Kobe, Japan).

[26] Y. Nakamura, "Nature of the finite temperature phase transition for three flavor QCD", The 2nd R-CCS international symposium (Feb. 17-18, 2020, Kobe, Japan).

[27] Y. Nakamura, "QCD Wide SIMD Library (QWS) for Fugaku", The 2nd R-CCS international symposium (Feb. 17-18, 2020, Kobe, Japan).

6.5.4 Invited Talks

[28] Y. Nakamura, "Phase diagram of finite temperature phase transition of QCD", 2019 Autumn Meeting of Physical Society of Japan (Sep. 17-20, 2019, Yamagata, Japan).

[29] Y. Nakamura, "Towards computing the standard model of particle physics by tensor renormalization group", Tensor Network States: Algorithms and Applications (TNSAA) 2019-2020 (Dec, 4-6, 2019, National Cheng-Chi University, Taipei, Taiwan).

6.5.5 Oral Talks

[30] Y. Nakamura, Y. Kuramashi, H. Ohno, S. Takeda, "Critical endpoints of the finite temperature QCD", International Molecule-type Workshop, "Frontiers in Lattice QCD and related topics" (April 15-26, 2019 YITP Yukawa Institute for Theoretical Physics, Kyoto University, Japan).

[31] C.- J. D. Lin, I. Kanamori, "chiral condensate and susceptibility of SU(2) $n_f = 8$ naive staggered system", The 37th International Symposium on Lattice Field Theory (Lattice 2019) (June 16-21, 2019, Wuhan, China).

[32] Y. Nakamura, Y. Kuramashi, H. Ohno, S. Takeda, "Critical endpoint in the continuum limit and critical endline at $N_t = 6$ of the finite temperature phase transition of QCD with clover fermions", The 37th International Symposium on Lattice Field Theory (Lattice 2019) (June 16-21, 2019, Wuhan, China).

[33] Y. Aoki, "Proton decay matrix elements with physical quark masses", 2019 Autumn Meeting of Physical Society of Japan (Sep. 17-20, 2019, Yamagata, Japan).

[34] I. Kanamori, H. Matsufuru, "Implementation of multigrid solver for domainwall fermion with the common code Bridge++", 2019 Autumn Meeting of Physical Society of Japan (Sep. 17-20, 2019, Yamagata, Japan).

[35] Y. Aoki, "Toward Fugaku: Symmetries to be Unfolded", R-CCS Cafe (Oct. 7, 2019, Kobe, Japan).

[36] I. Kanamori, "Linear solvers in LQCD application", R-CCS Cafe (Nov. 25, 2019, Kobe, Japan).

[37] Y. Nakamura, "QCD Wide SIMD Library (QWS) for Fugaku", Fugaku QCD coding workshop (Dec. 12-13, 2019, Kobe, Japan).

[38] I. Kanamori, "Communication with Double Buffering" Fugaku QCD coding workshop (Dec. 12-13, 2019, Kobe, Japan).

[39] C.- J. D. Lin, I. Kanamori, "About bulk phase transition of SU(2) $n_f = 8$ fundamental unimproved staggered fermion", 75th Annual Meeting, The Physical Society of Japan (Mar. 16-19, 2020, Nagoya, Japan).

6.5.6 Software

[40] Y. Nakamura, Y. Mukai, K.-I. Ishikawa, I. Kanamori, "QCD Wide SIMD Library (QWS)", `https://github.com/RIKEN-LQCD/qws`