Chapter 6

Field Theory Research Team

6.1 Members

Yoshinobu Kuramashi (Team Leader)

Yoshifumi Nakamura (Research Scientist)

Hiroya Suno (Research Scientist, Joint Position with the Nishina Center for Accelerator-based Research)

Eigo Shintani (Research Scientist)

Yuya Shimizu (Postdoctoral Researcher)

Ken-Ichi Ishikawa (Visiting Scientist, Hiroshima University)

Shoichi Sasaki (Visiting Scientist, Tohoku University)

Takeshi Yamazaki (Visiting Scientist, University of Tsukuba)

Shinji Takeda (Visiting Scientist, Kanazawa University)

6.2 Research Activities

Our research field is physics of elementary particles and nuclei, which tries to answer questions in history of mankind: what is the smallest component of matter and what is the most fundamental interactions? This research subject is related to the early universe and the nucleosynthesis through Big Bang cosmology. Another important aspect is quantum properties, which play an essential role in the world of elementary particles and nuclei as well as in the material physics at the atomic or molecular level. We investigate nonperturbative properties of elementary particles and nuclei through numerical simulations with the use of lattice QCD (Quantum ChromoDynamics). The research is performed in collaboration with applied mathematicians, who are experts in developing and improving algorithms, and computer scientists responsible for research and development of software and hardware systems.

Lattice QCD is one of the most advanced case in quantum sciences: interactions between quarks, which are elementary particles known to date, are described by QCD formulated with the quantum field theory. We currently focus on two research subjects: (1) QCD at finite temperature and finite density. We try to understand the early universe and the inside of neutron star by investigating the phase structure and the equation of state. (2) First principle calculation of nucleon form factors. Proton and neutron, which are called nucleon, consist of three quarks. We investigate their internal structure and low energy properties by the measurement of various form factors.

Successful numerical simulations heavily depend on an increase of computer performance by improving algorithms and computational techniques. However, we now face a tough problem that the trend of computer architecture becomes large-scale hierarchical parallel structures consisting of tens of thousands of nodes which individually have increasing number of cores in CPU and arithmetic accelerators with even higher degree of parallelism: we need to develop a new type of algorithms and computational techniques, which should be different from the conventional ones, to achieve better computer performance. For optimized use of K computer

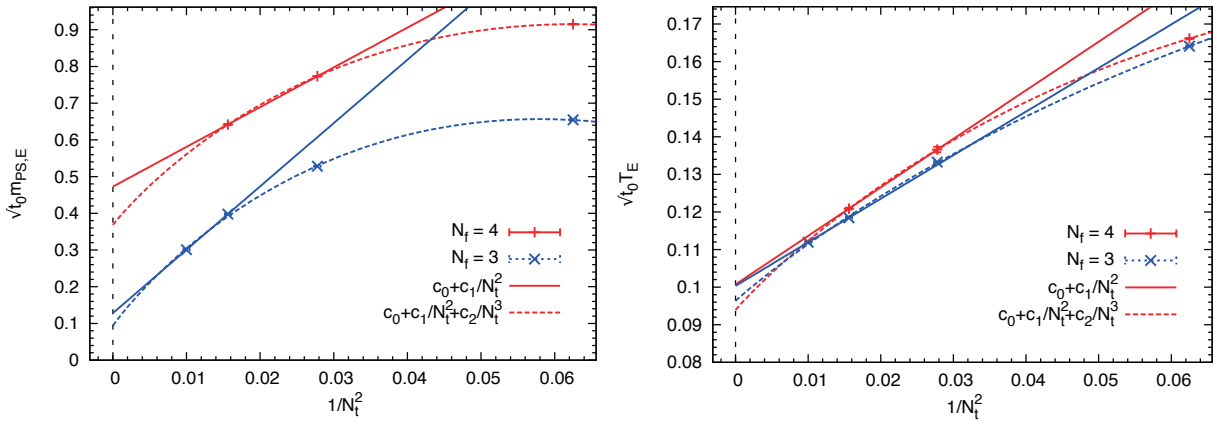

Figure 6.1: Continuum extrapolation of the critical point $\sqrt{t_0}m_{\rm PS,E}$ (left) and $\sqrt{t_0}T_{\rm E}$ (right) with $\sqrt{t_0}$ the Wilson flow scale. Red and blue symbols denote 4 and 3 flavor cases, respectively.

our research team aims at (1) developing a Monte Carlo algorithm to simulate physical system with negative weight effectively and (2) improving iterative methods to solve large system of linear equations. These technical development and improvement are carried out in the research of physics of elementary particles and nuclei based on lattice QCD.

6.2.1 QCD at finite temperature and finite density

Establishing the QCD phase diagram spanned by the temperature T and the quark chemical potential μ in a quantitative way is an important task of lattice QCD. We have been working on tracing the critical end line in the parameter space of temperature, chemical potential and quark masses in 4, 3 and 2+1 flavor QCD using the $O(a)$-improved Wilson quark action and the Iwasaki gauge action. We have determined the critical end point at zero chemical potential $\mu = 0$ in 3 flavor case. Our strategy is to identify at which temperature the Kurtosis of physical observable at the transition point on several different spatial volumes intersects. This method is based on the property of opposite spatial volume dependence of the Kurtosis at the transition point between the first order phase transition side and the crossover one. We have carried out a systematic study of the critical end point changing the temporal lattice size from $N_t = 4$ to 10 in 3 flavor case, which corresponds to change the lattice spacing. In Fig. 6.1 (left and right panels) we show the continuum extrapolation of the critical pseudoscalar meson mass $m_{\rm PS,E}$ and the critical temperature $T_{\rm E}$ normalized by $\sqrt{t_0}$, where $\sqrt{t_0}$ denotes the Wilson flow scale. We also make the same study in 4 flavor case for comparison. We observe that the critical temperature seems to follow the $O(a^2)$ scaling property both in 3 mad 4 flavor cases. On the other hand, $\sqrt{t_0}m_{\rm PS,E}$ shows significantly large scaling violation and its continuum extrapolation gives different values for 3 and 4 flavor cases: rather close to zero for the former and sufficiently deviated from zero for the latter. The origin of the difference between 3 and 4 flavor cases and ,especially, whether $m_{\rm PS,E}$ in 3 flavor case may vanish in the continuum limit are intriguing theoretical issues. Currently we are performing a simulation at finer lattice spacing to investigate the possibility that $m_{\rm PS,E}$ may vanish in the continuum limit.

6.2.2 Nucleon form factors

Nucleon form factors are good probes to investigate the internal structure of the nucleon which is a bound state of quarks. Study of their properties requires nonperturbative method and much effort has been devoted to calculate them with lattice QCD since 1980's. Unfortunately, the current situation is that we are still struggling for reproducing the well-established experimental results, e.g., the electric charge radius and the axial vector coupling. This means that we have not yet achieved proper treatment of a single hadron in lattice QCD calculation. The left panel of Fig. 6.2 shows a summary plot of the electric charge radius calculated with lattice QCD as of 2014. We focus on two major systematic uncertainties in the current lattice QCD simulations: one is heavier quark masses than the physical values and the other is finite spatial volume effects. In order to get rid of them we have carried out calculation of the nucleon form factors on a $(10.8\ {\rm fm})^4$ lattice at the physical point in 2+1 flavor QCD. Thanks to the large spatial volume we can get access to small momentum transfer region up to $q^2 = 0.013\ {\rm GeV}^2$. The right panel of Fig. 6.2 plots our results for the electric charge radius, whose

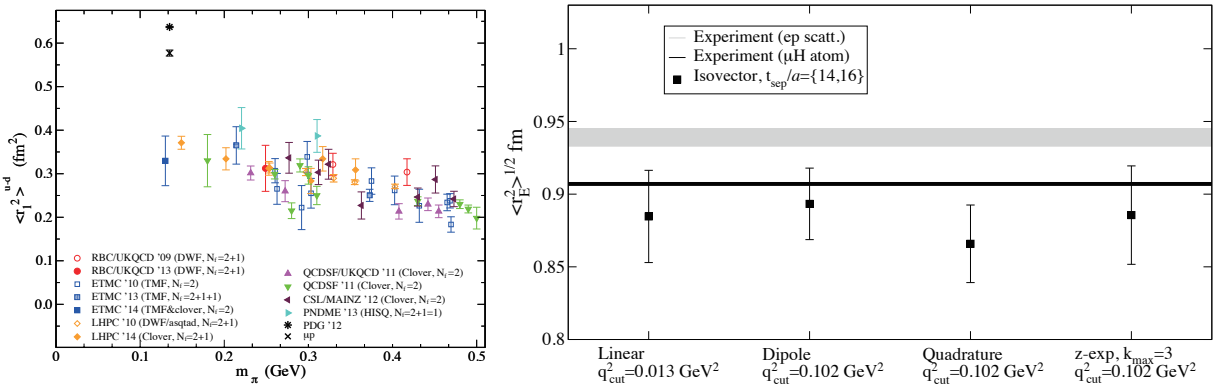

Figure 6.2: Summary plot of lattice QCD results for electric charge radius presented in the international conference of "Lattice 2014" (left) and our result on a $(10.8\ \mathrm{fm})^4$ lattice at the physical point in 2+1 flavor QCD (right). Experimental results for *e-p* scattering and muonic hydrogen spectroscopy are represented by "$*$" and "$\times$" symbols in the left panel and gray and black horizontal bands in the right panel.

four data represent four types of analyses to extract the electric charge radius from the form factor. Comparing the left and right panels in Fig. 6.2 our results show a remarkable improvement. We are now trying further reduction of the magnitude of the error.

6.2.3 Tensor network scheme in path-integral formalism

The Monte Carlo simulation of lattice gauge theory is quite powerful to study nonperturbative phenomena of particle physics. However, when the action has an imaginary component like the θ term, it suffers from the numerical sign problem, which is failure of importance sampling techniques. The effect of the θ term on the non-Abelian gauge theory, especially quantum chromodynamics (QCD), is important, because it is related to a famous unsolved problem, "strong CP problem". The difficulty is also shared with the finite density lattice QCD. So development of effective techniques to solve or by-pass the sign problem leads to a lot of progress in the study of the QCD phase diagram at finite temperature and density. The tensor network scheme is a promising theoretical and computational framework to overcome these difficulties. So far we have developed the Grassmann version of the tensor renormalization group (GTRG) algorithm in the tensor network scheme, which allows us to deal with the Grassmann variables directly. The GTRG algorithm was successfully applied to the analysis of the phase structure of one-flavor lattice Schwinger model (2D QED) with and without the θ term showing that the algorithm is free from the sign problem and the computational cost is comparable to the bosonic case thanks to the direct manipulation of the Grassmann variables. This was the first successful application of the tensor network scheme to a Euclidean lattice gauge theory including the relativistic fermions in path-integral formalism. Toward the final target of 4D QCD we are currently working on three research subjects in the tensor network scheme: (i) non-Abelian gauge theories, (ii) higher dimensional (3D or 4D) models, and (iii) development of computational techniques for physical observables. In 2017 we have succeeded in applying the tensor network scheme to three dimensional finite temperature Z_2 gauge theory. The left panel of Fig. 6.3 shows the N_σ dependence of the specific heat as a function of $1/\beta$ at $N_\tau = 3$, where N_σ and N_τ denote the spatial and temporal extent of the lattice, respectively, and $1/\beta$ is proportional to temperature. We observe the clear peak structure at all the values of N_σ and the peak height $C_{\max}(N_\sigma)$ grows as N_σ increases. We can determine the critical exponent ν from the finite size scaling behavior of the peak position $\beta_c(N_\sigma)$. In the right panel of Fig. 6.3 we plot the N_σ dependence of $\beta_c(N_\sigma)$ at $N_\tau = 3$. The solid curve represents the fit result obtained with the fit function of $\beta_c(N_\sigma) = \beta_c(\infty) + BN_\sigma^{1/\nu}$ for $N_\sigma \in [512, 4096]$, which gives $\beta_c(\infty) = 0.711150(4)$ and $\nu = 0.99(4)$. The value of the critical exponent is consistent with $\nu = 1$ in the universality class of the two dimensional Ising model as expected by the Svetitsky-Yaffe conjecture. Next step may be an application of the tensor network scheme to non-commutative gauge theories.

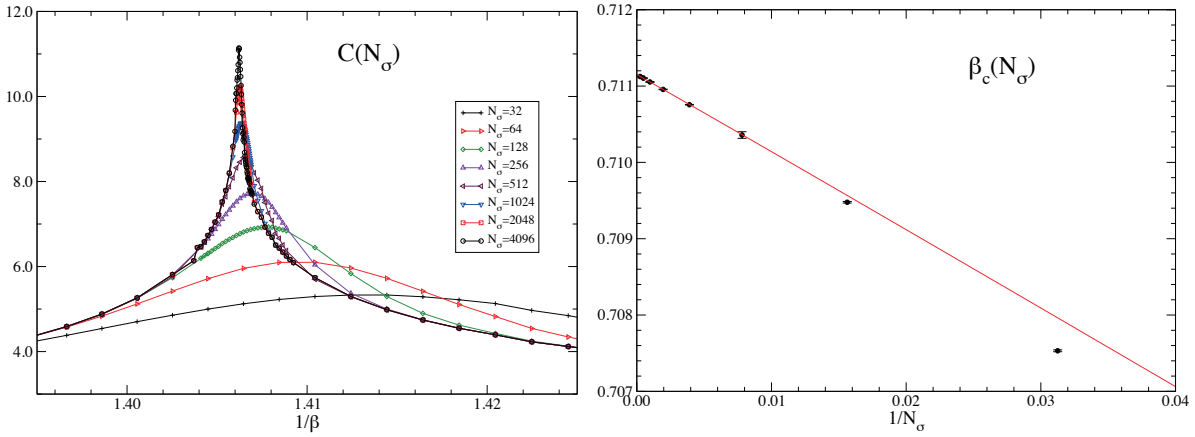

Figure 6.3: N_σ dependence of specific heat as a function of $1/\beta$ (left) and scaling property of $\beta_c(N_\sigma)$ (right).

6.3 Schedule and Future Plan

6.3.1 QCD at finite temperature and finite density

We are performing a systematic study of the critical end point in 4 flavor QCD in comparison with 3 flavor case. We also investigates whether or not $m_{\mathrm{PS,E}}$ in 3 flavor QCD vanishes in the continuum limit.

6.3.2 Nucleon form factors

We are trying to reduce the statistical error of the nucleon form factors on a $(10.8\ \mathrm{fm})^4$ lattice at the physical point. After that we plan to investigate the cutoff effect.

6.3.3 Tensor network scheme in path-integral formalism

As stated above, there are three important subjects in research and development of tensor network scheme in path-integral formalism: (i) non-Abelian gauge theories, (ii) higher dimensional (3D or 4D) models, and (iii) development of computational techniques for physical observables. Future research keeps to follow these three directions.

6.4 Publications

6.4.1 Articles

[1] Takeshi Yamazaki and Yoshinobu Kuramashi, "Relation between scattering amplitude and Bethe-Salpeter wave function in quantum field theory", Phys. Rev. D 96 (2017) ref. 114511.

[2] Xiao-Yong Jin, Yoshinobu Kuramashi, Yoshifumi Nakamura, Shinji Takeda and Akira Ukawa, "Critical point phase transition for finite temperature 3-flavor QCD with non-perturbatively $O(a)$-improved Wilson fermions at $N_t = 10$", Phys. Rev. D 96 (2017) ref. 034523.

[3] Yuya Shmizu and Yoshinobu Kuramashi, "Berezinskii-Kosterlitz-Thouless transition in lattice Schwinger model with one-flavor of Wilson fermion", Phys. Rev. D 97 (2018) ref. 034502.

[4] Daisuke Kadoh, Yoshinobu Kuramashi, Yoshifumi Nakamura, Ryo Sakai, Shinji Takeda and Yusuke Yoshimura, "Tensor network formulation for two-dimensional lattice $N = 1$ Wess-Zumino model", JHEP 1803 (2018) ref. 141.

[5] Yusuke Yoshimura, Yoshinobu Kuramashi, Yoshifumi Nakamura, Ryo Sakai and Shinji Takeda, "Calculation of fermionic Green functions with Grassmann higher-order tensor renormalization group", Phys. Rev. D 97 (2018) ref. 034502.

[6] Taisuke Boku, Ken-Ichi Ishikawa, Yoshinobu Kuramashi and Lawrence Meadows, "Mixed precision solver scalable to 16000 MPI processes for lattice quantum chromodynamics simulations on the Oakforest-PACS system", arXiv:1709.08785 [physics.comp-ph].

[7] Yasumichi Aoki, Taku Izubuchi, Eigo Shintani and Amarjit Soni, "Improved lattice computation of proton decay matrix elements", Phys. Rev. D 96 (2017) ref. 014506.

[8] V. G. Bornyakov et al., "Flavour breaking effects in the pseudoscalar meson decay constants", Phys. Lett. B767 (2017) p. 366.

[9] T. Haar et al., "Applying polynomial filtering to mass preconditioned Hybrid Monte Carlo", Comput. Phys. Commun. 215 (2017) p. 113.

[10] A. J. Chambers et al., "Nucleon structure functions from lattice operatorproduct expansion", Phys. Rev. Lett. 118 (2017) ref. 242001.

[11] A. J. Chambers et al., "Electromagnetic form factors at large momenta from lattice QCD", Phys. Rev. D 96 (2017) ref. 114509 .

[12] R. Sakai, S. Takeda and Y. Yoshimura, "Higher order tensor renormalization group for relativistic fermion systems", Prog. Theor. Exp. Phys. (2017) 063B07.

6.4.2 Conference Papers

[13] Natsuki Tsukamoto, Ken-Ichi Ishikawa, Yoshinobu Kuramashi, Shoichi Sasaki, and Takeshi Yamazaki for PACS Collaboration, "Nucleon structure from 2+1 flavor lattice QCD near the physical point", EPJ Web Conf., 175 (2018) ref. 06007.

[14] Taku Izubuchi, Yoshinobu Kuramashi, Christoph Lehner and Eigo Shintani, "Lattice study of finite volume effect in HVP for muon g-2", EPJ Web Conf. 175 (2018) ref. 06020.

[15] Renwick Hudspith, Randy Lewis, Kim Matlman and Eigo Shintani, "α_s from the hadronic vacuum polarisation", EPJ Web Conf. 175 (2018) ref. 10006.

[16] Xiao-Yong Jin, Yoshinobu Kuramashi, Yoshifumi Nakamura, Shinji Takeda and Akira Ukawa, "Continuum extrapolation of critical point for finite temperature QCD with $N_f = 3$", arXiv:1710.08057 [hep-lat].

[17] R. Sakai, D. Kadoh, Y. Kuramashi, Y. Nakamura, S. Takeda, and Y. Yoshimura, "Application of tensor network method to two-dimensional lattice $N = 1$ Wess-Zumino model", EPJ Web Conf. 175 (2018) ref. 11019.

[18] Takeshi Yamazaki, Ken-Ichi Ishikawa, Yoshinobu Kuramashi for PACS Collaboration, "Comparison of different source calculations in two-nucleon channel at large quark mass", EPJ Web Conf., 175 (2018) ref. 05019.

[19] S. Takizawa et al., "A scalable multi-granular data model for data parallel workflows", HPC ASIA 2018, Proceedings of the International Conference on High Performance Computing in Asia-Pacific Region (2018) p. 251-260.

6.4.3 Invited talks

[20] Yoshinobu Kuramashi, "Lattice QCD approach to proton puzzle", 2018 Annual (73th) Metteing of the Physical Society of Japan, Tokyo University of Science, Noda, Japan, March 22-25, 2018.

[21] Eigo Shintani, "Lattice QCD study of nucleon EDM", RCNP Workshop on Fundamental Physics Using Neutrons and Atoms, RCNP, Osaka, Japan, July 4-5, 2017.

[22] Eigo Shintani, "Lattice study of finite size effect in the leading order of hadronic contribution to muon $g-2$", First Workshop of the Muon g-2 Theory Initiative, Q Center, Chicago, USA, June 3-6, 2017.

[23] Eigo Shintani, "Lattice calculation of matrix element on proton decay", International Workshop on Baryon & Lepton Number Violation 2017, Case Western University, Cleveland, Ohio, USA, May 15-18, 2017.

[24] Takeshi Yamazaki, "Binding energy of light nucleus from lattice QCD", QCD Downunder 2017, Novotel Cairns Oasis Resort, Australia, July 10-14, 2017.

[25] Takeshi Yamazaki, "Study of nucleon structure from lattice QCD", The Forth Project Report Meeting of the HPCI System Including K computer, KOKUYO Hall, Tokyo, Japan, November 2, 2017.

[26] Takeshi Yamazaki, "Relation between scattering amplitude and Bethe-Salpeter wave function in quantum field theory", Multi-Hadron Systems from Lattice QCD, University of Washington, Seattle, USA, February 5-9, 2018.

[27] Takeshi Yamazaki, "A new calculation method of scattering phase shift with Bethe-Salpeter wave function in lattice QCD", 2018 Annual (73th) Metteing of the Physical Society of Japan, Tokyo University of Science, Noda, Japan, March 22-25, 2018.

[28] Sinji Takeda, "Tensor networks in particle physics", Tensor Networks 2017, AICS, Kobe, Japan, August 3, 2017.

6.4.4 Posters and Presentations

[29] Yoshinobu Kuramashi for PACS Collaboration, "A large scale simulation of 2+1 flavor lattice QCD", The 35th International Symposium on lattice field theory (Lattice 2017), Palacio de Congresos de Granada, Spain, June 19-24, 2017.

[30] Eigo Shintani, "Lattice study of finite volume effect in HVP for muon $g-2$", The 35th International Symposium on lattice field theory (Lattice 2017), Palacio de Congresos de Granada, Spain, June 19-24, 2017.

[31] Takeshi Yamazaki, Ken-ichi Ishikawa, Yoshinobu Kuramashi for PACS Collaboration, "Comparison of different source calculations in two-nucleon channel at large quark mass", The 35th International Symposium on lattice field theory (Lattice 2017), Palacio de Congresos de Granada, Spain, June 19-24, 2017.

[32] S. Takeda, "Cost reduction of tensor renormalization group algorithm by projective truncation technique", 2018 Annual (73th) Metteing of the Physical Society of Japan, Tokyo University of Science, Noda, Japan, March 22-25, 2018.

[33] S. Takeda, "Continuum extrapolation of critical point for finite temperature QCD with $N_f = 3$", The 35th International Symposium on lattice field theory (Lattice 2017), Palacio de Congresos de Granada, Spain, June 19-24, 2017.