RIKEN BNL Research Center
Computing Group

1. Abstract

The computing group founded in 2011 as a part of the RIKEN BNL Research Center established at Brookhaven National Laboratory in New York, USA, and dedicated to conduct researches and developments for large-scale physics computations important for high energy particle and nuclearphysics. The group was forked from the RBRC Theory Group.

The main mission of the group is to provide important numerical information that is indispensable for theoretical interpretation of experimental data from the first principle theories of particle and nuclear physics. Their primary area of research is lattice quantum chromodynamics (QCD), which describes the sub-atomic structures of hadrons, which allow the ab-initio investigation for strongly interacting quantum field theories beyond perturbative analysis.

The RBRC group and its collaborators have emphasized the necessity and importance of precision calculations, which will precisely check the current understandings of nature, and will have a potential to find a physics beyond the current standard model of fundamental physics. The first-principle studies also elucid intrecate nature of various phenomena in quantitive and unambiguous manners. We have therefore adopted techniques that aim to control and reduce any systematic errors. This approach has yielded many reliable results.

The areas of the major activities are R&D for high performance computing codes, developments for computing algorithms, and researches of particle, nuclear, and lattice theories. Since the inception of RBRC, many breakthroughs and pioneering works has carried out in computational forefronts. These are the use of the domain-wall fermions, which preserve chiral symmetry, a key symmetry for understanding dynamics of subnuclear elementary particle quark, the three generations of QCD devoted supercomputers and very efficient software library for lattice gauge theories, pioneering works for QCD calculation for Cabibbo-Kobayashi-Maskawa theory, QCD + QED simulation for isospin breaking, novel algorithms for statistical error reduction in general lattice calculation *etc.* The chiral quark simulation has been performed in a uncompromised setup at the physical up, down quark mass, the precision for many basic quantities reached to accuracy of sub-percent, and the group is working for further important and challenging calculations, such as the full and complete calculation of CP violating $K \to \pi\pi$ decays and ε'/ε, or hadronic contributions to muon's anomalous magnetic moment $g-2$.

Recent focus area is stusies of the nucleon's shape, structures, and the motion of quarks and gluon inside nucleon called parton distribution, which provide theoretical guidance to physics for sPHENIX and future Electron Ion Collider (EIC), Hyper Kamiokande, DUNE. Similar partonic contents inside photon is also computed. Closely related calculation has been carried out for electric dipole moment of nucleon related to the origin of the current matter rich universe (rather than anti-matter) and stability of universe, the proton decay. Towards finite density QCD, they also explored Quantum Computing for field theories. Applications of the Machine Learning (ML) and Artificial Intelligence (AI) for novel and more efficient ways to carry out lattice QCD calculations are among the new topics of the group.

2. Major Research Subjects

(1) Search for new law of physics through tests for Standard Model of particle and nuclear physics, especially in the framework of the Cabibbo-Kobayashi-Maskawa (CKM), hadronic contributions to the muon's anomalous magnetic moment $(g-2)$ for FNAL and J-PARC's experiments, as well as B physics at Belle II and LHCb
(2) Nuclear Physics and dynamics of QCD or related theories, including study for the structures of nucleons related to physics for sPHENIX, Electron Ion Collider (EIC or eRHIC), Hyper Kamiokande, T2K, DUNE, or the matter rich universe
(3) Theoretical and algorithmic development for lattice field theories, QCD machine (co-)design and software development
(4) Exploration for quantum computing for quantum field theories including the hadronic vacuum polarization contributions to muon $g-2$

3. Summary of Research Activity

Research activities during the current report period by RBRC members include various nulcleon formfactor and structure calculations, hadronic contributions to the anomalous magnetic moment $(g-2)_\mu$, kaon and B meson physics, and algorithm & software developments.

In April 2020, $(g-2)_\mu$ experiment collaboration at FNAL carried out a very precise measurement of precession rate of muons under magnetic field to 0.14 parts per million accuracy. This provides a very stringent test of the current understanding of elementary particle physics so called the Standard Model of particle physics. The strong interaction of quark and gluon is described by Quantum Chromo Dyanics (QCD) and is a dominant source of uncertainty in the theoretical prediction of $(g-2)_\mu$. Members of RBRC has been working on the two separate mode of QCD contributions, Hadronic Vacuum Polarization (HVP) and Hadronic Light-by-Light (HLbL). Following an update of HVP was reported in previous year for mid range energy (roughly a few hundreds of MeV) contribution, the group carried out the final total conribution for $(g-2)_\mu$ from entire energy region this year. The new full results will be published next year.

Photon Structure Function for sPHENIX and EIC is being explored. A new way to compute highly boosted hadron essential for parton distribution calculation on Lattice is investigated. FT-HMC with decimation of short-distance degrees of freedom is carried out for the efficient algorithm of Lattice QCD sampling. New renormalization of QCD operators, including the electro-weak four-quark operators, is developed.

Members

Group Leader
Taku IZUBUCHI

RBRC Researchers
Raza SUFIAN
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Special Postdoctoral Researcher
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Hiroshi OKI (Nara Women's Univ.)
Masaaki TOMII (Univ. of Connecticut)

List of Publications & Presentations

Publications

[Original Papers]

T. Blum *et al.* [RBC and UKQCD], "$\Delta I = 3/2$ and $\Delta I = 1/2$ channels of $K \to \pi\pi$ decay at the physical point with periodic boundary conditions," Phys. Rev. D **108**, 094517 (2023).

T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung, C. Lehner, and C. Tu, "Hadronic light-by-light contribution to the muon anomaly from lattice QCD with infinite volume QED at physical pion mass," [arXiv:2304.04423 [hep-lat]].

M. Bruno, D. Hoying, T. Izubuchi, C. Lehner, A. S. Meyer, and M. Tomii, "Isospin 0 and 2 two-pion scattering at physical pion mass using distillation with periodic boundary conditions in lattice QCD," [arXiv:2304.03313 [hep-lat]].

T. Blum *et al.* [RBC and UKQCD], "Isospin 0 and 2 two-pion scattering at physical pion mass using all-to-all propagators with periodic boundary conditions in lattice QCD," Phys. Rev. D **107**, 094512 (2023). [erratum: Phys. Rev. D **108**, 039902 (2023)].

T. Blum *et al.* [RBC and UKQCD], "Update of Euclidean windows of the hadronic vacuum polarization," Phys. Rev. D **108**, 054507 (2023).

R. G. Edwards, C. Egerer, N. Karthik, R. S. Sufian *et al.*, "Non-singlet quark helicity PDFs of the nucleon from pseudo-distributions," J. High Energy Phys. **2023**, 86 (2023).

T. Khan, T. Liu, and R. S. Sufian, "Gluon helicity distribution in the nucleon from lattice QCD and machine learning," Phys. Rev. D **108**, 074502 (2023).

J. Liang, R. S. Sufian, B. Wang, T. Draper, T. Khan, K. F. Liu, and Y. B. Yang, "Elastic and resonance structures of the nucleon from hadronic tensor in lattice QCD: implications for neutrino-nucleon scattering and hadron physics," arXiv:2311.04206.

T. Chowdhury, K. Yu, M. Shamim, M. Kabir, and R. S. Sufian, "Enhancing quantum utility: simulating large-scale quantum spin chains on superconducting quantum computers," arXiv:2312.12427 [quant-ph].

G. F. de Téramond, A. Paul, S. Brodsky, H. Dosch, A. Deur, T. Liu, and R. S. Sufian, "The strong coupling in the nonperturbative and near-perturbative regimes," arXiv:2403.16126 [hep-ph].

V. D. Burkert *et al.*, "Precision studies of QCD in the low energy domain of the EIC," Prog. Part. Nucl. Phys. **131**, 104032 (2023).

A. Bazavov, D. Bollweg, O. Kaczmarek, F. Karsch, S. Mukherjee *et al.*, "Charm degrees of freedom in hot matter from lattice QCD," Phys. Lett. B **850**, 138520 (2024).

D. Bollweg *et al.*, "Equation of state and speed of sound of (2 + 1)-flavor QCD in strangeness-neutral matter at nonvanishing net baryon-number density," Phys. Rev. D **108**, 1, 014510 (2023).

[Proceedings]

R. Abir *et al.*, "The case for an EIC theory alliance: Theoretical challenges of the EIC," arXiv:2305.14572 [hep-ph].

N. Matsumoto, R. C. Brower, and T. Izubuchi, "Decimation map in 2D for accelerating HMC," PoS **LATTICE2023**, 033 (2024).

F. He, M. Abramczyk, T. Blum, T. Izubuchi, H. Ohki, and S. Syritsyn, "The calculations of nucleon electric dipole moment using background field on lattice QCD," PoS **LATTICE2023**, 336 (2024).

M. Engelhardt, N. Hasan, T. Izubuchi, C. Kallidonis, S. Krieg, S. Meinel, J. Negele, A. Pochinsky, G. Silvi, and S. Syritsyn, "Transverse momentum-dependent parton distributions for longitudinally polarized nucleons from domain wall fermion calculations at the physical pion mass," PoS **LATTICE2022**, 103 (2023).

M. Fukuma, N. Matsumoto, and Y. Namekawa, "Applying the worldvolume hybrid Monte Carlo method to lattice field theories," PoS **LATTICE2022**, 011 (2023).

Presentations

[International Conferences/Workshops]

R. Sufian (invited), "EIC physics from lattice QCD: Origin of the nucleon spin and mass structures," EIC Workshop, University of Tokyo, May, 2024.

R. Sufian (invited), "Gluonic structure of the proton from lattice QCD," From Quarks and Gluons to the Internal Dynamics of Hadrons, Center for Frontiers in Nuclear Science, Stony Brook University, May, 2024.

R. Sufian (invited), "Impact of lattice QCD calculations on constraining gluon helicity distribution and nucleon's resonance structure," Nuclear Theory Seminar, University of Maryland, November, 2023.

R. Sufian (invited), "Applications to neutrino and hadronic physics," Temple University, Hadronic tensor in lattice QCD, September, 2023.

R. Sufian "Implications for neutrino-nucleon scattering," 40th Annual International Symposium on Lattice Field Theory, August, 2023.

R. Sufian (invited), "Investigating nucleon's elastic, resonance and DIS structures from hadronic tensor in Lattice QCD," Large Momentum Effective Field Theory, LaMET 2023, Regensburg, Germany, July, 2023.

R. Sufian (invited), "Polarized and unpolarized gluon distributions in the nucleon from Lattice QCD," RIKEN-BNL Research Center Seminar, May, 2023.

R. Sufian, "Gluon heliciity distribution in the nucleon from lattice QCD and machine learning," APS/DNP meeting, Minneapolis, April, 2023.

M. Tomii (invited), "Recent status of $K \to \pi\pi$ calculation by RBC/UKQCD with periodic boundary conditions," Workshop on 'Large-scale Lattice QCD Simulation and Application of Machine Learning,' Tsukuba, Japan, November 23–25, 2023.

M. Tomii (invited), "Calculation of $K \to \pi\pi$ decay matrix elements using periodic boundary conditions," Fundamental Science Joint Symposium 'Seika Soshutsu Kasoku,' Tokyo, Japan, December 18–20, 2023.

M. Tomii (invited), "Lattice calculation of $K \to \pi\pi$ matrix elements and ε' using periodic boundary conditions," Hiroshima University, December 6, 2023.

M. Tomii (invited), "Two-pion scattering & $K \to \pi\pi$ decay calculations with periodic boundaries," RIKEN R-CCS, January 12, 2024.

T. Izubuchi (plenary), "Tau hadronic decay input for Muon g-2," The 17th International Workshop on Tau Lepton Physics (TAU2023). University of Louisville, KY, December 4–8, 2023.