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.

The new $(g-2)_\mu$ 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 is now published this year.

Quantum computing on IBM quantum hardware: In three consecutive publications and preprints (Phys. Rev. Res. **6** (2024) 3, 033107, arXiv:2412.15180, arXiv:2503.18580), the group members have demonstrated determination of various properties of spin-chain systems, determination of entanglement entropy of black hole and strongly-correlated systems—extending one of the calculation to 100 qubits toward achieving the quantum advantage over classical ones in simulating quantum systems before the fault tolerance quantum era.

Glounic structure of the nucleon: In two recent publications (Phys. Rev. D **111**, no.7, 7 (2025) and Phys. Rev. D **111**, no.9, 094510 (2025)), the group members have presented the first theoretical step in identifying lattice QCD matrix elements necessary to determine and isolate all eight leading-twist gluon generalized parton distributions (GPDs) and demonstrated application of generative machine learning to facilitate determination of Parton distribution functions from lattice QCD.

Nucleon Structure from holographic light-front QCD: In two recent publications (Phys. Rev. Lett. **133**, no.18, 181901 (2024) and arXiv:2505.19545), the group members have presented analytic study of the strong coupling in the nonperturbative and near-perturbative regimes and extended the result to TeV scale by imposing rigorous renormalization-group results from asymptotically free gauge theories.

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

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Thomas BLUM (Univ. of Connecticut)
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List of Publications & Presentations

Publications

[Original Papers]

J. Schoenleber, R. S. Sufian, T. Izubuchi, and Y. B. Yang, "Gluon unpolarized, polarized, and transversity GPDs from lattice QCD: Lorentz-covariant parametrization," Phys. Rev. D **111**, no.9, 094510 (2025) doi:10.1103/PhysRevD.111.094510.

T. Blum (RBC and UKQCD) *et al.*, "Long-distance window of the hadronic vacuum polarization for the Muon $g - 2$," Phys. Rev. Lett. **134**, no.20, 201901 (2025) doi:10.1103/PhysRevLett.134.201901.

T. A. Chowdhury, T. Izubuchi, M. Kamruzzaman, N. Karthik, T. Khan, T. Liu, A. Paul, J. Schoenleber, and R. S. Sufian, "Polarized and unpolarized gluon PDFs: Generative machine learning applications for lattice QCD matrix elements at short distance and large momentum," Phys. Rev. D **111**, no.7, 7 (2025) doi:10.1103/PhysRevD.111.074509.

G. F. de Teramond, A. Paul, H. G. Dosch, S. J. Brodsky, A. Deur, T. Liu, and R. S. Sufian, "Asymptotic gauge symmetry and UV extension of the nonperturbative coupling in holographic QCD," [arXiv:2505.19545 [hep-ph]].

T. A. Chowdhury, K. Yu, and R. S. Sufian, "First measurement of entanglement dynamics in the SYK model using quantum computers," [arXiv:2503.18580 [quant-ph]].

T. A. Chowdhury, K. Yu, M. Asaduzzaman, and R. S. Sufian, "Capturing the page curve and entanglement dynamics of black holes in quantum computers," [arXiv:2412.15180 [quant-ph]].

J. Schoenleber, R. S. Sufian, T. Izubuchi, and Y. B. Yang, "Gluon unpolarized, polarized, and transversity GPDs from lattice QCD: Lorentz-covariant parametrization," Phys. Rev. D **111**, no.9, 094510 (2025) doi:10.1103/PhysRevD.111.094510.

G. F. de Téramond (HLFHS) *et al.*, "QCD running coupling in the nonperturbative and near-perturbative regimes," Phys. Rev. Lett. **133**, no.18, 181901 (2024) doi:10.1103/PhysRevLett.133.181901.

T. A. Chowdhury, K. Yu, M. A. Shamim, M. L. Kabir, and R. S. Sufian, "Enhancing quantum utility: Simulating large-scale quantum spin chains on superconducting quantum computers," Phys. Rev. Res. **6**, no.3, 3 (2024) doi:10.1103/PhysRevResearch.6.033107.

[Proceedings]

S. Yamamoto, P. Boyle, T. Izubuchi, L. Jin, C. Lehner, and N. Matsumoto, "Improvement in autocorrelation times measured by the master-field technique using field transformation HMC in 2+1 domain wall fermion simulations," PoS **LATTICE2024**, 034 (2025) doi:10.22323/1.466.0034 [arXiv:2502.05452 [hep-lat]].

M. Tomii (RBC and UKQCD), "$\Delta I = 1/2$ process of $K \to \pi\pi$ decay on multiple ensembles with periodic boundary conditions," PoS **LATTICE2024**, 232 (2025) doi:10.22323/1.466.0232.

Presentations

[International Conferences/Workshops]

R. Sufian (invited), "Massless particles and the structure of the visible universe," Physics Seminar, University of New Mexico, Albuquerque, New Mexico, April 2024.

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), "Inverse problems in lattice QCD calculations of hadron structures," Inverse Problems and Uncertainty Quantification in Nuclear Physics, Institute of Nuclear Theory, University of Washington, July 2024.

M. Tomii, "Delta I = 1/2 process of K->pipi decay on multiple ensembles with periodic boundary conditions," The 41st International Symposium on Lattice Field Theory (LATTICE2024), Liverpool, UK, July 28–August 3, 2024.

M. Tomii (Lead talk), "Lattice calculation of K->pipi decay and pipi scattering," The 11th International Workshop on Chiral Dynamics (CD 2024), Lead talk, Bochum, Germany, August 24–30, 2024.

M. Tomii, "Reconstruction of long-distance hadronic vacuum polarization from pipi scattering and its contribution to the muon $g-2$," JPS 79th AnnualMeeting, Sapporo, Japan, September 16–19, 2024.

M. Tomii (invited), "pipi scattering on the lattice and its applications," Nishinomiya-Yukawa symposium, Hadrons and Hadron Interactions in QCD (HHIQCD 2024), Kyoto, Japan, October 14–November 15, 2024.

R. Sufian (invited), "Page curve and entanglement dynamics of gluons & gluon GPDs from lattice QCD," University of Kentucky, December 2024.

R. Sufian, "Applications of ML in lattice QCD calculations of hadron physics," APS joint March meeting and April Meeting-global physics summit, March 2025.

M. Tomii (invited), "Hadronic vacuum polarization in the long distance window in lattice QCD," APS Global Summit, Joint March and April Meeting, Anaheim, USA, March 16–21, 2025.