RIKEN BNL Research Center
Theory Group

1. Abstract

The efforts of the RBRC theory group are concentrated on the major topics of interest in High Energy Nuclear Physics, in particular, the physics explored by the RHIC and the future Electron-Ion Collider experiments at Brookhaven National Laboratory (BNL). This includes: understanding of the Quark-Gluon Plasma (QGP); the nature of dense quark matter; the initial state in high energy collisions, the Color Glass Condensate and its evolution to QGP through a Glasma; QCD spin physics; physics relevant to the future Electron-Ion Collider at BNL.

2. Major Research Subjects

(1) Nucleon structure and tomography, mass and spin
(2) Gluon saturation at small-x
(3) Perturbative and nonperturvative methods in Quantum Chromo-Dynamics (QCD)

3. Summary of Research Activity

(1) Spin-orbit entanglement at small-x

Y. Hatta and collaborators unveiled a novel emergent properties of quarks and gluons at small-x. The helicity and orbital angular momentum of individual partons are maximally entangled in a quantum mechanical sense. Y. Hatta and another collaborator generalized this observation to arbitrary values of x for gluons.

(2) Twist analysis of the spin-orbit correlation in QCD

Y. Hatta and J. Schoenleber derived exact relations between the spin-orbit correlations of quarks and gluons and twist-two and twist-three generalized parton distributions. Based on this result, they derived a novel momentum sum rule which is the momentum version of the Jaffe-Manohar sum rule.

(3) Nonlocal chiral anomaly and generalized parton distribution

Y. Hatta, J. Schoenleber, and a collaborator established the nonlocal generalization of the QCD chiral anomaly along the light-cone. Using this relation, they derived novel relations between generalized parton distributions of different twists.

(4) Near-threshold vector meson production and the gravitational form factors

Y. Hatta and J. Schoenleber and collaborators studied the near-threshold production of the ϕ-meson off the nucleon and established its connection to the nucleon gravitational form factors to next-to-leading order in QCD. They also studied ϕ and J/ψ production near threshold in Sullivan process and made connection to the pion gravitational form factors.

(5) Target fragmentation region in DIS

F. Salazar and a collaborator derived the first factorized expression for single-inclusive jet production in the target fragmentation region of Deep Inelastic Scattering at small Bjorken-x. They focused on the differential cross-section for longitudinally polarized photons and show that it is not suppressed by $P_\perp/Q$ and it admits a leading-power expansion in terms of novel transverse momentum dependent (TMD) quark and gluon jet fracture functions, which they compute explicitly in the Color Glass Condensate effective theory. Their results establish a new avenue to explore gluon saturation in the target fragmentation region.

(6) Quark TMD at small-x

F. Salazar, and collaborators demonstrated that several back-to-back dijet production processes in dilute-dense collisions at small x can be factorized in terms of universal sea quark transverse momentum dependent distributions (TMDs) which we compute explicitly in the Color Glass Condensate effective theory. They showed that all relevant sea quark TMDs emerge from two fundamental building blocks—the SIDIS/Drell-Yan sea quark operator and the quark-antiquark dipole correlator—whose universal structure depends on the color flow of the process. They pave the way for incorporating sea quark effects in small-x phenomenology.

(7) All order factorization for virtual Compton scattering at next- to-leading power

J. Schoenleber and a collaborator established the conjectured all-order factorization theorem for DVCS at next-to- leading power in terms of twist-3 GPDs using soft-collinear effective theory (SCET). They have repro- duced the known leading order coefficient functions using the systematic SCET approach. Furthermore, they have found a new "end-point like" contribution—which was previously unknown in the literature—that formally appears at that power accuracy. A phenomenological analysis of this contribution requires further study and is left to future work.

(8) Evidence of collinear factorization breaking due to collinear-to- soft Glauber exchanges for a $2 \to 3$ exclusive process at leading twist

J. Schoenleber and collaborators studied the factorization breaking due to Glauber modes in certain $2 \to 3$ exclusive processes that have recently been proposed to study the x-dependence of GPDs. They have rigorously proven that for a certain leading power topology involving the gluon GPD a loop momentum is trapped in the Glauber region and that this results in an endpoint divergence in the naive factorization formula.

(9) Polarized and unpolarized gluon PDFs: Generative machine learning applications for lattice QCD matrix elements at short distance and large momentum

In the calculation of parton distributions from lattice QCD using Large momentum effective theory/short distance factorization the main bottleneck when it comes to precision are the $O(1/P_z)$ power corrections that are necessarily large, because the lattice calculation becomes unfeasible at $P_z > 2$ GeV. J. Schoenleber and collaborators have proposed and implemented a new strategy based on generative machine learning to circumvent this problem.

(10) Threshold resummation for double-deeply virtual Compton scat- tering

J. Schoenleber has derived a refactorization theorem of the coefficient function for double-deeply virtual Compton scattering (DDVCS), which can be used to resum threshold logarithms to all orders. This was also used as a cross check for the exact two-loop calculation of that function that became available at the same time.

(11) Gluon Unpolarized, Polarized, and Transversity GPDs from Lattice QCD: Lorentz-Covariant Parametrization

J. Schoenleber and collaborators have constructed a Lorentz covariant parametrization for the off-forward hadronic matrix elements of the space-like separated bilocal gluon operator, which was previously not achieved. This allows one to identify projections of the operator onto each of the eight leading twist gluon GPDs. The work presents the first step in providing the first calculation of the gluon GPDs on the lattice.

(12) θ-term in the Schwinger model

H. Kanno and his collaborators studied two-flavor Schwinger model by a numerical method called tensor renormalization group method. They studied theta dependence of the free energy with exact periodicity of the theta parameter.

(13) Second-order relativistic viscous magnetohydrodynamics

M. Kurian and collaborators developed a second-order relativistic viscous magnetohydrodynamics (MHD) framework from kinetic theory with a modified collision kernel. They thoroughly examine shear stress tensor evolution equations and associated transport coefficients with particle momentum-dependent relaxation time.

Members

Group Leader

Yoshitaka HATTA

RBRC Researchers

Farid SALAZAR

Jakob SCHOENLEBER

SPDRs

Manu KURIAN

Hayato KANNO

List of Publications & Presentations

Publications

[Original Papers]

Y. Hatta and J. Schoenleber, "Sullivan process near threshold and the pion gravitational form factors," 2502.12061.

Y. Hatta, H. Klest, K. Passek-K, and J. Schoenleber, "Deeply Virtual ϕ-meson production near threshold," 2501.12343, PTEP in press.

S. Bhattacharya, Y. Hatta, and J. Schoenleber, "Nonlocal chiral anomaly and generalized parton distributions," Phys. Rev. D **111**, 014013 (2025).

Y. Hatta and J. Montgomery, "Maximally entangled gluons for any x," Phys. Rev. D **111**, 014024 (2025).

Y. Hatta and J. Schoenleber, "Twist analysis of the spin-orbit correlation in QCD," J. High Energy Phys. **09**, 154 (2024).

S. Bhattacharya, R. Boussarie, and Y. Hatta, "Spin-orbit entanglement in the Color Glass Condensate," Phys. Lett. B **859**, 139134 (2024).

S. Bhattacharya, R. Boussarie, and Y. Hatta, "Exploring orbital angular momentum and spin-orbit correlation for gluons at Electron-Ion Collider," Phys. Rev. D **111**, 034019 (2024).

P. Caucal and F. Salazar, "Transverse momentum dependent factorisation in the target fragmentation region at small x," 2502.02634.

P. Caucal, M. Guerrero Morales, E. Iancu, F. Salazar, and F. Yuan, "Unveiling the sea: universality of the transverse momentum dependent quark distributions at small x," 2503.16162.

J. Schoenleber and R. Szafron, "All order factorization for virtual Compton scattering at next-to-leading power," J. High Energy Phys. **11**, 031 (2024).

S. Nabeebaccus, J. Schoenleber, L. Szymanowski, and S. Wallon, "Evidence of collinear factorization breaking due to collinear-to-soft Glauber exchanges for a $2 \to 3$ exclusive process at leading twist," 2409.16067.

T. A. Chowdhury, T. Izubuchi, M. Kamruzzaman, N. Karthik, T. Khan, T. Liu, A. Paul, J. Schoen-leber, 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**, 074509 (2025).

J. Schoenleber, "Threshold resummation for double-deeply virtual Compton scattering," J. High Energy Phys. **01**, 142 (2025).

J. Schoenleber, R. S. Sufian, T. Izubuchi, and Y. -B. Yang, "Gluon Unpolarized, Polarized, and Transversity GPDs from Lattice QCD: Lorentz-Covariant Parametrization (Part I)," 2412.14110.

S. K. Singh, M. Kurian, and V. Chandra, "Revisting shear stress tensor evolution: Non-resistive magnetohydrodynamics with momentum-dependent relaxation time," Phys. Rev. D **110**, 014004 (2024).

H. Kanno, S. Akiyama, K. Murakami, and S. Takeda, "Grassmann Tensor Renormalization Group for $N_f = 2$ massive Schwinger model with a theta term," 2412.08959.

[Proceedings]

C. Gale, S. Jeon, M. Kurian. B. Schenke, and M. Singh, "Simulating charm quarks in IP-glasma initial stage and quark-gluon plasma: A hybrid approach for charm quark phenomenology," EPJ Web Conf. **316**, 04018 (2025).

A. Sheik, M. Kurian, S. K. Das, V. Chandra, B. K. Nandi, and S. Dash, "Heavy quark transport coefficients in a viscous QCD medium with collisional and radiative processes," Springer Proc. Phys. **304**, 1174 (2024).

H. Kanno, S. Akiyama, K. Murakami, and S. Takeda, "Grassmann tensor renormalization group for two-flavor massive schwinger model with a theta term," PoS LATTICE2024 (2025), 368.

Presentations

[International Conferences/Workshops]

Y. Hatta (invited), "Quark and gluon spin-orbit correlations," CFNS workshop 'From quarks and gluons to the internal dynamics of hadrons,' Stony Brook University, New York, USA, May 15–17, 2024.

Y. Hatta (invited), "Quark and gluon spin-orbit correlations," ECT* workshop 'Beyond-eikonal methods in high energy scattering,' Trento, Italy, May 20–24, 2024.

Y. Hatta (invited), "Introduction to the electron-ion collider: theory," Nuclear and Particle Physics at the EIC, Tokyo University, May 28–30, 2024.

Y. Hatta (invited), "Gravitational form factors at the EIC," Holography, QCD and the EIC, SUNY Old Westbury, May 29–30, 2024.

Y. Hatta (invited), "Theory overview: Nucleon and nuclei E/M and gravitational form factors," DNP meeting, Boston, October 7–10, 2024.

Y. Hatta (invited), "Diffractive dijet and diffractive SIDIS processes at the EIC," DNP Meeting, Boston, October 7–10, 2024.

Y. Hatta (invited), "Spin-orbit correlation in QCD," Next generation perturbative QCD for hadron structure, Mainz institute for theoretical physics, Germany, October 21–31, 2024.

F. Salazar (invited), "Mining for gluon saturation at the Electron-Ion Collider," CFNS workshop 'ePIC/EIC Early Science,' Stony Brook University, New York, USA, April 24, 2025.

F. Salazar (plenary), "Latest developments in high-energy QCD to understand the initial state in heavy-ion collisions," Quark Matter Conference, Goethe University Frankfurt, Frankfurt, Germany, April 11, 2025.

F. Salazar (invited), "CGC meets NRQCD for EIC," Physics Opportunities at an Electron-Ion Collider Conference, Florida International University, Florida, USA, February 28, 2025.

F. Salazar (invited), "CGC meets NRQCD for EIC," CFNS workshop 'Cold Nuclear Matter Effects: from the LHC to the EIC,' Stony Brook University, New York, USA, January 14, 2025.

J. Schoenleber (invited), "Threshold resummation for virtual Compton scattering," CFNS workshop 'From quarks and gluons to the internal dynamics of hadrons,' Stony Brook University, New York, USA, May 15–17, 2024.

J. Schoenleber (invited), "All order factorization for virtual Compton scattering at next-to-leading power," CFNS workshop 'Precision QCD predictions for ep Physics at the EIC (3rd edition),' Stony Brook University, New York, USA, September 23–27, 2024.

J. Schoenleber, "All order factorization for virtual Compton scattering at next-to-leading power," EFT and Multi-Loop Methods for Advancing Precision in Collider and Gravitational Wave Physics, Technical University Munich, Munich, Germany, October 7–31, 2024.

J. Schoenleber, "Deeply virtual ϕ-meson production near threshold," Physics Opportunities at the Electron-Ion Collider XI, Florida International University, Miami, USA, February 24–28, 2024.

M. Kurian, "Simulating Charm Quarks in IP-Glasma Initial Stage and Quark-Gluon Plasma: A Hybrid Approach for charm quark phenomenology," 21st International Conference on Strangness in Quark Matter (SQM 2024), Strasbourg, France, June 3–7, 2024.

H. Kanno (invited) "Grassmann tensor renormalization group for two-flavor massive Schwinger model with a theta term," PCTS-Simons Collaboration Confinement and QCD Strings, Princeton Center for Theoretical Science, Princeton University, USA, November 10–12, 2024.

H. Kanno, "Grassmann Tensor Renormalization Group for two-flavor massive Schwinger model with a theta term," Lattice 2024, Liverpool University, UK, July 28–August 3, 2024.

H. Kanno, "Grassmann Tensor Renormalization Group for two-flavor massive Schwinger model with a theta term," Strings and Fields, Kyoto University, Japan, August 5–9, 2024.

H. Kanno, "Grassmann Tensor Renormalization Group for two-flavor massive Schwinger model with a theta term," Progress of Particle Physics, Kyoto University, Japan, August 19–23, 2024.

H. Kanno, "Grassmann Tensor Renormalization Group for two-flavor massive Schwinger model with a theta term," Japan Physical Society annual meeting, Hokkaido University, Japan, September 16–19, 2024.

[Seminars]

Y. Hatta, "Spin-orbit entanglement in QCD," CFNS Seminar, Stony Brook University, USA, August 22, 2024.

F. Salazar, "Searching for a universal limit of all nuclear matter: Mining for gluon saturation at colliders," Nuclear Theory seminar, University of Maryland, Maryland, USA, March 23, 2025.

F. Salazar, "Searching for a universal limit of all nuclear matter: Mining for gluon saturation at colliders," PAN Seminar, Wayne State University, Michigan, USA, February 14, 2025.

F. Salazar, "Unveiling the sea: Identifying quark distributions in the color glass condensate," RBRC Seminar, Brookhaven National Laboratory, New York, USA, February 6, 2025.

J. Schoenleber, "All order factorization for virtual Compton scattering at next-to-leading power," Stony Brook University, New York, USA, November 14, 2024.

M. Kurian, "Exploring the strongly interacting nuclear matter with heavy quark phenomenology," Indian Institute of Technology Dhanbad, India, July 22, 2024.

H. Kanno, S. Akiyama, K. Murakami, and S. Takeda, "Grassmann Tensor Renormalization Group for two-flavor massive Schwinger model with a theta term," RBRC seminar, Brookhaven National Laboratory, USA, December 5, 2024.

Awards

Y. Hatta, BNL Science and technology award, 2024.

Outreach Activities

F. Salazar, Panelist at Career/Graduate Panel at Florida International University, March 20, 2025