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) Heavy Ion Collisions, QCD phase diagram
(2) Perturbative Quantum Chromo-Dynamics (QCD)
(3) Nucleon structure, mass and spin

3. Summary of Research Activity

(1) Chiral and trace anomalies in Deeply Virtual Compton Scattering

Y. Hatta, S. Bhattacharya and a collaborator discovered novel 'anomaly poles' in QCD Compton scattering. These are poles $1/t$ in momentum transfer t in off-forward scattering and are manifestations of the underlying QCD chiral and trace anomalies. Their work provides novel perspectives on the generalized parton distributions (GPDs) important for the tomographic study of the nucleon.

(2) Gravitational form factors of atomic nuclei

Y. Hatta and collaborators computed the gravitational form factors of various nuclei in the Skyrme model. They computed the D-term form factors, mass radius, scalar radius, tensor radius as well as the pressure distribution of these nuclei. Interestingly, the pressure in the core region of nuclei is found to be negative, suggesting a different mechanism to achieve stability compared to nucleons.

(3) Viscosities of the Baryon-Rich Quark-Gluon Plasma from Beam Energy Scan Data

C. Shen and collaborators perform the first Bayesian analysis of the RHIC Beam Energy Scan data using event-by-event (3 + 1)D multi-stage hybrid simulations. This work marked the first milestone of quantitative constraining the Quark-Gluon Plasma properties at finite baryon density.

(4) Multi-scale Imaging of Nuclear Deformation at the Electron-Ion Collider

C. Shen and collaborators demonstrate that exclusive vector meson production at high energy is sensitive to the geometric deformation of the target nucleus at multiple length scales within the Color Glass Condensate framework. This work shows that $|t|$-differential diffractive vector meson production could become a powerful tool, enabling the most direct measurements of nuclear structure at different length scales, ranging from nuclear deformation at low $|t|$ to nucleon- and subnucleon-size scales at higher $|t|$.

(5) Unveiling the dynamics of nucleosynthesis in relativistic heavy-ion collisions

C. Shen and collaborators develop a comprehensive kinetic approach to study the effects of hadronic re-scatterings, such as $\pi\mathrm{NN} \leftrightarrow \pi d$ and $\pi\mathrm{NNN} \leftrightarrow \pi + {}^3\mathrm{H}({}^3\mathrm{He})$, on d, ${}^3\mathrm{H}$, and ${}^3\mathrm{He}$ production in these collisions. This advancement helps resolve the overestimation of triton production in the statistical hadronization model and provides the evidence for hadronic re-scattering effects on nucleosynthesis in relativistic heavy-ion collisions.

(6) Energy loss of a fast moving parton in Gribov-Zwanziger plasma:

M. Kurian and collaborators employed the Gribov-Zwanziger prescription for the first time in the analysis of parton energy loss in the QCD medium. Their findings demonstrate that the momentum evolution of energetic partons is profoundly influenced by non-perturbative effects, which in turn significantly impact the phenomenological quantities related to energy loss.

(7) Open charm phenomenology with a multi-stage approach to relativistic heavy-ion collisions:

M. Kurian and collaborators investigated the phenomenological aspects of heavy quarks in the context of relativistic heavy-ion collisions. Utilizing for the first time IP-Glasma fluctuating initial states and hydrodynamics tuned to a global Bayesian analysis, they showed that the observables associated with heavy flavor are strongly influenced by the fluctuating initial state and bulk evolution.

(8) Probing quark orbital angular momentum at EIC and EicC:

S. Bhattacharya and collaborators proposed to extract quark orbital angular momentum (OAM) through exclusive $\pi 0$ production in electron-(longitudinally-polarized) proton collisions. Their analysis demonstrated that the $\sin 2\phi$ azimuthal angular correlation between the transverse momentum of the scattered electron and the recoil proton is a sensitive probe of quark OAM. This study aims to pave the way for the first measurement of quark OAM in relation to the Jaffe-Manohar spin sum rule.

(9) Generalized Parton Distributions from Lattice QCD with Asymmetric Momentum Transfer: Axial-vector case:

S. Bhattacharya and collaborators introduced a novel approach involving the adoption of a Lorentz covariant parameterization for the matrix elements, introducing Lorentz-invariant amplitudes. This approach allowed for the proposal of an alternative definition of quasi-GPDs, ensuring frame independence and potentially reducing power corrections in matching to light-cone GPDs. They employed this parameterization to compute the axial-vector GPD for the first time from an asymmetric frame at zero skewness.

(10) Breakdown of collinear factorization in the exclusive photoproduction of a $\pi\gamma$ pair

J. Schoenleber and collaborators studied the exclusive photoproduction of a $\pi\gamma$ pair with large invariant mass, which is sensitive to the exchange of either two quarks or two gluons in the t-channel. It is shown that the process involving two-gluon exchanges does not factorize in the Bjorken limit at the leading twist. This can be explicitly demonstrated by the fact that there exist diagrams, which contribute at the leading twist, for which Glauber gluons remain trapped.

(11) Renormalons and power corrections in pseudo- and quasi-GPDs

High-order behavior of the perturbative expansion for short-distance observables in QCD is intimately related to the contributions of small momenta in the corresponding Feynman diagrams and this correspondence provides one with a useful tool to investigate power suppressed nonperturbative corrections. Schoenleber and collaborators used this technique to study the structure of power corrections to parton quasi- and pseudo-GPDs which are used in lattice calculations of generalized parton distributions. As the main result, the functional dependence of the leading power corrections to quasi(pseudo)-GPDs on x variable for nonzero skewedness parameter is predicted.

Members

Group Leader

Yoshitaka HATTA

RBRC Researchers

Manu KURIAN
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Vladimir SKOKOV

List of Publications & Presentations

Publications

[Original Papers]

S. Bhattacharya, Y. Hatta, and W. Vogelsang, "Chiral and trace anomalies in deeply virtual Compton scattering," Phys. Rev. D **107**, 014026 (2023).

A. Martin-Caro, M. Huidobro, and Y. Hatta, "Gravitational form factors of nuclei in the Skyrme model," Phys. Rev. D **108**, 034014 (2023).

Y. Hatta, "Accessing the gravitational form factors of the nucleon and nuclei through a massive graviton," Phys. Rev. D **109**, L051502 (2024).

A. Martin-Caro, M. Huidobro, and Y. Hatta, "Nuclear mass radius and pressure in the Skyrme model," arXiv:2312.12984.

S. Benic, Y. Hatta, A. Kaushik, and H. Li, "Perturbative QCD contribution to transverse single spin asymmetries in the Drell-Yan process and SIDIS," Phys. Rev. D **109**, 074038 (2024).

Y. Hatta and F. Yuan, "Angular dependence in transverse momentum dependent diffractive parton distributions at small-x," Phys. Lett. B. **854**, 138738 (2024).

K. J. Sun, R. Wang, C. Ko, Y. Ma, and C. Shen, "Unveiling the dynamics of little-bang nucleosynthesis," Nat. Commun. **15**, 1074 (2024).

C. Shen, B. Schenke, and W. Zhao, "Viscosities of the baryon-rich quark-gluon plasma from beam energy scan datan," Phys. Rev. Lett. **132**, 072301 (2024).

H. Mantysaari, F. Salazar, B. Schenke, C. Shen, and W. Zhao, "Effects of nuclear structure and quantum interference on diffractive vector meson production in ultraperipheral nuclear collisions," Phys. Rev. C **109**, 024908 (2024).

V. H. Ribeiro, D. Dobrigkeit Chinellato, M. A. Lisa, W. Matioli Serenone, C. Shen, J. Takahashi *et al*., "Λ polarization from vortex rings as the medium response for jet thermalization," Phys. Rev. C **109**, 014905 (2024).

L. Du, C. Shen, S. Jeon, and C. Gale, "Probing initial baryon stopping and equation of state with rapidity-dependent directed flow of identified particles," Phys. Rev. C **108**, L041901 (2023).

P. Achenbach *et al*., "The present and future of QCD," Nucl. Phys. A **1047**, 122874 (2024).

A. Sorensen *et al*., "Dense nuclear matter equation of state from heavy-ion collisions," Prog. Part. Nucl. Phys. **134**, 104080 (2024).

JETSCAPE Collaboration, "Multiscale evolution of charmed particles in a nuclear medium," Phys. Rev. C **107**, 054901 (2023).

J. Noronha, B. Schenke, C. Shen, and W. Zhao, "Progress and challenges in small systems," arXiv: 2401.09208.

JETSCAPE Collaboration, "A new metric improving Bayesian calibration of a multistage approach studying hadron and inclusive jet suppression," arXiv: 2307.09641.

M. Debnath, R. Ghosh, M. Y. Jamal, M. Kurian, and J. Prakash, "Energy loss of a fast moving parton in Gribov-Zwanziger plasma," Phys. Rev. D **109**, L011503 (2024).

M. Singh, M. Kurian, S. Jeon, and C. Gale, "Open charm phenomenology with a multi-stage approach to relativistic heavy-ion collisions," Phys. Rev. C **108**, 054901 (2023).

R. Ghosh, M. Y. Jamal, and M. Kurian, "Impact of chiral asymmetry and magnetic field on passage of an energetic test parton in a QCD medium," Phys. Rev. D **108**, 054035 (2023).

S. K. Singh, M. Kurian, and V. Chandra, "Revisting shear stress tensor evolution: Non-resistive magnetohydrodynamics with momentum-dependent relaxation time," arXiv:2403.13160.

A. Dumitru, A. Kovner, and V. Skokov, "Entanglement entropy of the proton in coordinate space," Phys. Rev. D **108**, 014014 (2023).

A. Kovner, M. Li, and V. Skokov, "Probing gluon Bose correlations in nuclear wave function in deep inelastic scattering," Phys. Rev. D **107**, 114032, (2023).

A. Kovner, M. Lublinsky, V. Skokov, and Z. Zhao, "Not all that is β_0 is β-function: the DGLAP resummation and the running coupling in NLO JIMWLK," arXiv:2308.15545.

S. Bhattacharya, D. Zheng, and J. Zhou, "Accessing the gluon GTMD $F_{1,4}$ in exclusive π^0 production in *ep* collisions," Phys Rev D. **109**, 096029, (2024).

S. Bhattacharya, K. Cichy, M. Constantinou, X. Gao, A. Metz, J. Miller, S. Mukherjee, P. Petreczky, F. Steffens, and Y. Zhao, "Moments of proton GPDs from the OPE of nonlocal quark bilinears up to NNLO," Phys. Rev. D **108**, 014507 (2023).

S. Bhattacharya, K. Cichy, M. Constantinou, J. Dodson, A. Metz, A. Scapellato, and F. Steffens, "Chiral-even axial twist-3 GPDs of the proton from lattice QCD," Phys. Rev. D **108**, 054501 (2023).

S. Bhattacharya, K. Cichy, M. Constantinou, X. Gao, A. Metz, J. Miller, S. Mukherjee, P. Petreczky, F. Steffens, and Y. Zhao, "Generalized parton distributions from lattice QCD with asymmetric momentum transfer: Axial-vector case," Phys. Rev. D **109**, 034508 (2023).

S. Bhattacharya, D. Zheng, and J. Zhou, "Probing quark orbital angular momentum at EIC and EicC," arXiv:2312.01309.

S. Nabeebaccus, J. Schoenleber, L. Szymanowski, and S. Wallon, "Breakdown of collinear factorization in the exclusive photoproduction of a pion-photon pair with large invariant mass," arXiv:2311.09146.

V. M. Braun, M. Koller, and J. Schoenleber, "Renormalons and power corrections in pseudo- and quasi-GPDs," Phys. Rev. D **109**, 074510 (2024).

[Proceedings]

S. Bhattacharya, R. Boussarie, and Y. Hatta, "Probing the gluon orbital angular momentum at the EIC," Acta Phys. Polon. Supp. **7**, A16, 2023.

S. Bhattacharya, Y. Hatta, and W. Vogelsang, "Unraveling anomalies in Deeply Virtual Compton Scattering," in DIS 2023, arXiv.2308.15377.

B. Schenke, H. Mantysaari, F. Salazar, C. Shen, and W. Zhao, "Vector meson production in ultraperipheral heavy ion collisions," arXiv:2404.10833.

H. Mantysaari, F. Salazar, B. Schenke, C. Shen, and W. Zhao, "Probing nuclear structure at the Electron-Ion Collider and in ultra-peripheral nuclear collisions," in 30th International Conference on Ultrarelativstic Nucleus-Nucleus Collisions, 12, 2023, arXiv: 2312.07467.

L. Du, C. Shen, S. Jeon, and C. Gale, "Constraints on initial baryon stopping and equation of state from directed flow," in 30th International Conference on Ultrarelativstic Nucleus-Nucleus Collisions, 12, 2023, arXiv:2312.06468.

S. Ryu, B. Schenke, C. Shen, and W. Zhao, "The role of longitudinal decorrelations for measurements of anisotropic flow in small collision systems," arXiv:2312.12595.

G. Pihan, A. Monnai, B. Schenke, and C. Shen, "Tracing baryon and electric charge transport in isobar collisions," in 30th International Conference on Ultrarelativstic Nucleus-Nucleus Collisions, arXiv: 2312.12376.

C. Shen, B. Schenke, and W. Zhao, "The effects of pseudorapidity-dependent observables on (3 + 1)D Bayesian Inference of relativistic heavy-ion collisions," in 30th International Conference on Ultrarelativstic Nucleus-Nucleus Collisions, arXiv: 2312.09325.

C. Shen, A. Noble, J.-F. Paquet, B. Schenke, and C. Gale, "Illuminating early-stage dynamics of heavy-ion collisions through photons at RHIC BES energies," PoS (HardProbes2023), 042 (2024).

J. Miller, S. Bhattacharya, K. Cichy, M. Constantinou, X. Gao, A. Metz, S. Mukherjee, P. Petreczky, F. Steffens, and Y. Zhao, "Proton Helicity GPDs from Lattice QCD," arXiv.2403.05282.

N. Nurminen, S. Bhattacharya, W. Chomicki, M. Constantinou, A. Metz, and F. Steffens, "Unveiling generalized parton distributions through the pseudo-distribution approach," arXiv:2311.18502.

L. J. Naik, V. Sreekanth, M. Kurian, and V. Chandra, "Chromo-turbulent fields and lepton pain production from collisional hot QCD medium," Proc. Indian Natl. Sci. Acad. 1–5, 2024.

M. Kurian, M. Singh, S. Jeon, and C. Gale, "Heavy flavor transport and observables in heavy-ion collisions within the MARTINI+MUSIC framework," arXiv:2312.14354.

Presentations

[International Conferences/Workshops]

Y. Hatta (invited), "GPDs at small-*x*," Color Glass Condensate at the Electron-Ion Collider, ECT*, Trento, Italy, May 15–19, 2023.

Y. Hatta (invited), "Chiral and trace anomalies in DVCS," Revestructure Workshop, Zagreb, Croatia, July 10–12, 2023.

Y. Hatta (invited), "Gravitational form factors," Symposium on Extreme Quantum Matter from Electron-Ion Collider to Tabletop Experiments, BNL, USA, August 31–September 2, 2023.

Y. Hatta (invited), "New topics in GPD," EIC-Asia Workshop, National Cheng-Kung University, Taiwan, January 29–31, 2024.

Y. Hatta (invited), "Spin physics at the EIC," INT Workshop 'Electroweak and Beyond the Standard Model Physics at the EIC,' University of Washington, USA, February 12–16, 2024.

C. Shen (invited), "Multi-scale imaging of nucleus and nucleon geometry at high energy," Shape Coexistence Workshop 2023, Guelph University, Canada, May 1, 2023.

C. Shen (invited), "Nuclear and nucleon structure impact on small-x evolution and rapidity dependence," Initial Stages 2023, Copenhagen, Denmark, June 21, 2023.

C. Shen (invited), "Applications of causality conditions in heavy-ion phenomenology," The Many Faces of Relativistic Fluid Dynamics, KITP, USA, June 27, 2023.

C. Shen (invited), "Modeling photon production in large and small systems," The EMMI RRTF, Heidelberg, Germany, July 26, 2023.

C. Shen (invited), "Theoretical modeling of fluid vorticity and spin polarization," APS/JPS DNP Meeting, Hawaii, USA, November 26, 2023.

M. Kurian (invited), "Probing QCD medium with heavy quark in relativistic heavy-ion collision," 4th Heavy Flavor Meet, Indian Institute of Technology, Goa, India, November 2–4, 2023.

V. Skokov (invited), "Rethinking running coupling in jimwlk", Workshop on overlap between QCD resummations," Centre Paul Langevin, Aussois, France, January 14–17, 2024.

S. Bhattacharya (invited), "Axial and trace anomalies in DVCS," EINN2023, Paphos, Cyprus, November 1, 2023.

S. Bhattacharya (invited), "Generalized parton distributions from lattice QCD," 1st CFNS Postdoc Meeting, CFNS, Stony Brook University, USA, October 19, 2023.

S. Bhattacharya (invited), "What are GPDs and how to access them on Lattice QCD?", SPIN 2023, Duke University, North Carolina, USA, September 29, 2023.

S. Bhattacharya (invited), "Imprints of chiral and trace anomalies in GPDs," Workshop: Precision QCD Predictions for ep Physics at the EIC, CFNS, Stony Brook University, USA, September 20, 2023.

S. Bhattacharya (invited), "Quark GPDs from non-symmetric frames," Lattice QCD and Probes of New Physics, Santa Fe, New Mexico, USA, August 8, 2023.

J. Schoenleber (invited), "Renormalons and power corrections to pseudo- and quasi-GPDs," RBRC Workshop on Generalized Parton Distributions for Nucleon Tomography in the EIC Era, Brookhaven National Laboratory, USA, January 2024.

[Seminars]

Y. Hatta, "Chiral and trace anomalies in DVCS," Lawrence Berkeley National Laboratory, August 15, 2023.

C. Shen, "Bayesian Inference of QGP properties and 3D dynamics of heavy-ion collisions in the RHIC Beam Energy Scan Program," online RHIC BES Seminar Series, October 24, 2023.

M. Kurian, "Heavy quarks-Charm & Bottom Quarks and its dynamics," Theory Group seminar, Arizona State University, USA, March 7, 2024.

M. Kurian, "Probing QCD medium with heavy quark dynamics," CFNS seminar, Stony Brook University, USA, July 26, 2023.

M. Kurian, "Probing QCD medium with heavy quark dynamics," RBRC seminar, BNL, USA, June 1, 2023.

S. Bhattacharya, "Uncovering anomalies in generalized parton distributions," University of Maryland, College Park, Maryland, USA, November 9, 2023.

S. Bhattacharya, "Generalized TMDs and GPDs: Recent advances," Lawrence Berkeley National Laboratory, California, USA, October 31, 2023.

S .Bhattacharya, "Manifestation of anomalies in deep virtual compton scattering," Jefferson Lab, Virginia, USA, April 10, 2023.

J. Schoenleber (invited), "The $x \to \xi$ region in processes involving GPDs," University of Maryland, USA, February, 2024.

J. Schoenleber (invited), "The $x \to \xi$ region in processes involving GPDs," Hybrid RBRC Seminar, BNL, USA, December, 2023.

Press Releases

B. Schenke and C. Shen, "Seeing the shape of atomic nuclei," DOE Highlights, November 2023.

S. Bhattacharya, "Calculations reveal high-resolution view of quarks inside Protons," BNL Newsroom, `https://www.bnl.gov/newsroom/news.php?a=121380`.

Award

V. Skokov, LeRoy and Elva Martin Award for Teaching Excellence, April, 2023.

Outreach Activity

S. Bhattacharya, "Empowering women to explore nuclear physics empowering women to explore nuclear physics," BNL Newsroom, `https://www.bnl.gov/newsroom/news.php?a=221624`.