

Subnuclear System Research Division
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 experiment 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. This has significant implications for the future tomographic study of the nucleon through the generalized parton distributions (GPDs).

(2) Gravitational form factors in holographic QCD

Y. Hatta and collaborators computed one of the gravitational form factors, the so-called D-term, in holographic QCD using the Sakai-Sugimoto model. This is the first computation of the gravitational form factors in top-down holographic QCD. They found that the D-term exhibits the phenomenon of glueball dominance, similar to the vector meson dominance of the electromagnetic form factors.

(3) Small- x behavior of the GPD $Eg(x)$

Y. Hatta and a collaborator derived, for the first time, the small- x evolution equation for the gluon GPD $Eg(x)$. It has been shown that, despite its association with nucleon helicity-flip processes, $Eg(x)$ grows rapidly with decreasing x in exactly the same way as the BFKL Pomeron.

(4) Lee-Yang edge singularity

V. Skokov and collaborators employ the functional renormalization group approach at next-to-leading order of the derivative expansion to refine their earlier findings for the universal location of the Yang-Lee edge singularity in classic O(N) universality classes. To this date, it is the most precise determination of the Yang-Lee edge singularity.

(5) CGC for ultraperipheral nuclear collisions

V. Skokov and collaborators provided the first calculation of two-gluon production at mid-rapidity in ultra-peripheral collisions in the Color Glass Condensate framework. To estimate systematic uncertainty associated with poor understanding of the wave function of the nearly real photon, they consider two diametrically different models: the dilute quark-antiquark dipole approximation and a vector meson, in which color charge density is approximated by McLerran-Venugopalan model.

(6) Simulating the tiniest fluids in 3 + 1 dimensions

Employing a dynamical initial state model coupled to (3 + 1)D viscous relativistic hydrodynamics, C. Shen and collaborators explored the rapidity dependence of anisotropic flow in the Relativistic Heavy-Ion Collider (RHIC) small system scan at 200 GeV center of mass energy [6]. They demonstrate that approximately 50% of the p_T -differential triangular flow difference between the measurements by the STAR and PHENIX Collaborations can be explained by the use of reference flow vectors from different rapidity regions. This emphasizes the importance of longitudinal flow decorrelation for anisotropic flow measurements in asymmetric nuclear collisions and the need for (3 + 1)D simulations.

(7) Multi-scale imaging of nuclei geometry at high energy

C. Shen and collaborators showed that the failure to describe the v_2 ratio in central UU and AuAu collisions at RHIC was due to inappropriate treatments of well-deformed nuclei in modeling the initial conditions of the QGP [8]. With rigorous input from Skyrme density functional calculations, they show that correcting nuclear deformations in hydrodynamic simulations restores agreement with BNL RHIC data. This brings consistency to the results of nuclear experiments across energy scales and demonstrates the impact of the hexadecapole deformation of Uranium nucleus on high-energy collisions.

(8) Renormalization of jet quenching parameter

Y. Mehtar-Tani and collaborators demonstrated that the leading quantum corrections to parton energy loss can be resummed and incorporated through a renormalization of the jet quenching parameter, while still preserving the classical tree-level framework. The renormalized jet quenching now depends on the length of the medium, owing to non-local quantum effects, resulting in a weakly non-Markovian dynamics. Based on this theory result, they developed a systematic approach with significant implications for jet quenching phenomenology.

Members**Group Leader**

Yoshitaka HATTA

RBRC Researchers

Yacine MEHTAR-TANI

Chun SHEN

Vladimir SKOKOV

Bhattacharya SHOHINI

List of Publications & Presentations**Publications****[Original Papers]**

- Y. Hatta, B. Xiao, and F. Yuan, "Semi-inclusive diffractive deep inelastic scattering at small- x ," *Phys. Rev. D* **106**, 094015 (2022).
- M. Fujita, Y. Hatta, S. Sugimoto, and T. Ueda, "Nucleon D-term in holographic quantum chromodynamics," *Prog. Theor. Exp. Phys.* **2022**, 093B06 (2022).
- Y. Hatta and J. Zhou, "Small- x evolution of the gluon GPD E_g ," *Phys. Rev. Lett.* **129**, 25 (2022).
- S. Bhattacharya, Y. Hatta, and W. Vogelsang, "Chiral and trace anomalies in deeply virtual Compton scattering," *Phys. Rev. D* **107**, 014026 (2023).
- A. Kumar *et al.* [JETSCAPE], "Inclusive jet and hadron suppression in a multistage approach," *Phys. Rev. C* **107**, 034911 (2023).
- K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, and C. Shen, "Unveiling the dynamics of nucleosynthesis in relativistic heavy-ion collisions," *arXiv:2207.12532*.
- W. Fan *et al.* [JETSCAPE], "Multiscale evolution of charmed particles in a nuclear medium," *Phys. Rev. C* **107**, 054901 (2023).
- H. Alalawi, J. Boyd, C. Shen, and M. Strickland, "Impact of fluctuating initial conditions on bottomonium suppression in 5.02 TeV heavy-ion collisions," *Phys. Rev. C* **107**, L031901 (2023).
- 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," *arXiv:2211.16408*.
- W. Zhao, S. Ryu, C. Shen, and B. Schenke, "3D structure of anisotropic flow in small collision systems at energies available at the BNL Relativistic Heavy Ion Collider," *Phys. Rev. C* **107**, 014904 (2023).
- Y. Tachibana *et al.* [JETSCAPE], "Hard jet substructure in a multi-stage approach," *arXiv:2301.02485*.
- W. Ryssens, G. Giacalone, B. Schenke, and C. Shen, "Evidence of hexadecapole deformation in uranium-238 at the relativistic heavy ion collider," accepted by *Phys. Rev. Lett.*, *arXiv:2302.13617*.
- H. Mäntysaari, B. Schenke, C. Shen, and W. Zhao, "Multi-scale imaging of nuclear deformation at the electron ion collider," *arXiv:2303.04866*.
- T. Schaefer and V. Skokov, "Dynamics of non-Gaussian fluctuations in model A," *Phys. Rev. D* **106**, 014006 (2022).
- H. Duan, A. Kovner, and V. V. Skokov, "CGC for ultra-peripheral Pb + Pb collisions at the Large Hadron Collider: a more realistic calculation," *J. High Energy Phys.* **12**, 077 (2022).
- G. Johnson, F. Rennecke, and V. V. Skokov, "Universal location of Yang-Lee edge singularity in classic O(N) universality classes," *arXiv:2211.00710*.
- H. Duan, A. Kovner, and V. V. Skokov, "Classical entanglement and entropy," *arXiv:2301.05735*.
- P. Caucal and Y. Mehtar-Tani, "Universality aspects of quantum corrections to transverse momentum broadening in QCD media," *J. High Energy Phys.* **09**, 023 (2022).
- P. Caucal and Y. Mehtar-Tani, "Transverse momentum broadening from NLL BFKL to all orders in pQCD," *arXiv:2209.08900*.
- Y. Mehtar-Tani, S. Schlichting, and I. Soudi, "Jet thermalization in QCD kinetic theory," *arXiv:2209.10569*.

[Proceedings]

- Y. Hatta, "Nucleon EDM from polarized DIS," *JPS Conf. Proc.* **37**, 020601 (2022).
- S. Benic, Y. Hatta, A. Kaushik, and H. Li, "A novel contribution to single spin asymmetries in SIDIS at two loops," *JPS Conf. Proc.* **37**, 020203 (2022).
- S. Bhattacharya, K. Cichy, M. Constantinou, J. Dodson, X. Gao, A. Metz, S. Mukherjee, A. Scapellato, F. Steffens, and Y. Zhao, "GPDs in asymmetric frames," *PoS Lattice* **2022**, 095 (2023).
- H. Mäntysaari, B. Schenke, C. Shen, and W. Zhao, "Bayesian inference of the fluctuating proton shape in DIS and hadronic collisions," *Acta Phys. Polon. Supp.* **16**, 33 (2023).

- V. Vovchenko, V. Koch, and C. Shen, “Proton number cumulants and correlation functions from hydrodynamics and the QCD phase diagram,” *Acta Phys. Polon. Supp.* **16**, 83 (2023).
- C. Shen, W. Zhao, and B. Schenke, “Collectivity in ultra-peripheral heavy-ion collisions,” *EPJ Web Conf.* **276**, 01002 (2023).
- Y. Tachibana, C. Shen *et al.* [JETSCAPE], “Comprehensive study of multi-scale jet-medium interaction,” arXiv:2212.12188.

Presentations

[International Conferences/Workshops]

- Y. Hatta (invited), “EIC science: ep reactions,” Town hall meeting on hot & cold QCD, USA (MIT), September 20–22, 2022.
- Y. Hatta (invited), “Nucleon D-term in the Sakai-Sugimoto model,” INT Workshop on Origin of the Visible Universe: Unraveling the Proton Mass, USA (University of Washington), June 13–17, 2022.
- Y. Hatta (invited), “Experimental observables to access GTMDs,” Towards improved hadron femtography with hard exclusive reactions, USA (Virginia Tech University), July 18–22, 2022.
- Y. Hatta (invited), “Nucleon EDM and polarized DIS,” QCD evolution, University of Virginia, May 9–13, 2022.
- Y. Hatta (invited), “Azimuthal angular correlation of jets from soft gluon radiation,” RBRC workshop on predictions for sPHENIX, USA (BNL), July 20–22, 2022.
- S. Bhattacharya (invited), “Hunting for gluon orbital angular momentum at the EIC,” XXIX Cracow Epiphany Conference on Physics at the EIC and Future Facilities, Cracow, Poland, January 18, 2023.
- S. Bhattacharya (invited), “Chiral and trace anomalies in DVCS,” CFNS Meetings, USA (Stony Brook University), March 10, 2023.
- C. Shen (selected contributed talk), “Collectivity and baryon junctions in ultra-peripheral heavy-ion collisions,” the 20th International Conference on Strangeness in Quark Matter, June 14, 2022.
- C. Shen (invited), “Going beyond flow: Did we hit the precision wall?,” First CMS Heavy-Ion Workshop, August 8, 2022.
- C. Shen (invited), “Multi-messenger heavy-ion physics with JETSCAPE,” 13th International workshop on Multiple Partonic Interactions at LHC, November 15, 2022.
- C. Shen (invited), “3D modeling of the RHIC isobar collisions,” Intersection of Nuclear Structure and High-energy Nuclear Collisions, February 17, 2023.
- C. Shen (invited), “Illuminating early-stage dynamics of heavy-ion collisions through photons at RHIC BES energies,” 11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collision, March 29, 2023.
- Y. Mehtar-Tani (invited), “Quantum induced anomalous diffusion in QCD matter,” Jet Quenching In The Quark-Gluon Plasma workshop, ECT*, Trento, June 13–17, 2022.
- Y. Mehtar-Tani (invited), “Transverse momentum broadening from NLL BFKL to all orders in pQCD,” Resummation Evolution Factorization, October 31–November 4, 2022.
- Y. Mehtar-Tani (invited), “Jet energy loss and heavy flavor, Heavy Flavours from small to large systems,” Institut Pascal Program, Orsay, France (Paris-Saclay University), October 3–21, 2022.
- Y. Mehtar-Tani (invited), “Transverse momentum broadening from NLL BFKL to all orders in pQCD,” 13th international workshop on Multiple Partonic Interactions at the LHC, Madrid, Spain, November 14–18, 2022.

[Domestic Conference/Workshop]

- Y. Hatta (invited), “Nucleon gravitational form factors in holographic QCD,” Third International Workshop on the Extension Project for the J-PARC, Hadron experimental facility, Japan (J-PARC), March 14–16, 2023.

[Seminars]

- Y. Hatta, “QCD spin physics at the EIC,” Heavy-ion tea seminar, USA (Lawrence Berkeley National Laboratory), October 14, 2022.
- Y. Hatta, “Chiral and trace anomalies in DVCS,” Stony Brook, USA, November 2, 2022.
- Y. Hatta, “Azimuthal angular asymmetry of soft gluons in jet production, USA (Yale University), April 28, 2022.
- Y. Hatta, “Near-threshold quarkonium production and the nucleon gravitational form factors,” CFNS seminar, USA (Stony Brook University), August 25, 2022.
- S. Bhattacharya, “Primary observables to access orbital angular momentum of partons,” Nuclear Physics Seminar, USA (University of Illinois Urbana-Champaign), February 13, 2023.
- S. Bhattacharya, “Computing PDFs and GPDs in Lattice QCD: Recent Progress,” Center for Nuclear Theory seminar, USA (Stony Brook University), February 22, 2023.
- C. Shen, “Longitudinal dynamics and particle production in relativistic nuclear collisions,” RBRC seminar, July 7, 2022.
- C. Shen, “Flowing through the nuclear phase diagram at the highest temperatures and densities,” Physics colloquium at Wayne State University, October 6, 2022.
- C. Shen, “3D modeling of the collective behaviors in relativistic heavy-ion collision,” Nuclear Seminar at HENPIC-EVO, December 22, 2022.
- C. Shen, “3D modeling of the collective behaviors in relativistic heavy-ion collisions,” Nuclear Seminar at Iowa State University, February 23, 2023.
- Y. Mehtar-Tani, “The hottest matter under the microscope: probing the quark gluon plasma at colliders,” BNL lecture, Upton (BNL), December 14, 2022.
- Y. Mehtar-Tani, “Quantum induced anomalous diffusion in QCD matter,” Teilchentee seminar at ITP, Heidelberg, Germany (Heidelberg)

University), June 2, 2022.

Y. Mehtar-Tani, “3D-structure of the proton: from partons to strong fields,” UCLA Nuclear Physics Group, Los Angeles, CA (UCLA), September 15, 2022.

Press Release

S. Bhattacharya, R. Boussarie, and Y. Hatta, “Theorists propose a novel way to measure gluons’ orbital motion,” DOE highlights, November 10, 2022.

Awards

C. Shen, 2023 Outstanding Junior Faculty Award, Wayne State Academy of Scholars, <https://academy.wayne.edu/junior-award>.

V. Skokov, LeRoy and Elva Martin Award for Teaching Excellence (NCSU).