

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) Phase diagram of QCD

The major goal of RHIC heavy-ion program is to map out the QCD phase diagram at finite temperature and density. Together with a collaborator, V. Skokov has determined the precise location of the Yang-Lee edge singularity for the Ising universality class using the functional renormalization group method and the epsilon expansion. This can be applied to the QCD phase diagram to determine the location of the QCD critical point (which belongs to the Ising universality class) at finite chemical potential.

### (2) QCD at small $x$

The initial condition of heavy-ion collisions at RHIC is governed by the Color Glass Condensate (CGC) which is the universal form of matter in the high energy (small- $x$ ) limit of QCD. The RBRC scientists have made major contributions to this field, and the efforts continue to date. V. Skokov and collaborators showed that the Bose-Einstein correlation between two small- $x$  gluons in the saturated environment can be experimentally probed via three-jet production in Deep Inelastic scattering. He also continued a project with M. Li on the first saturation corrections in pA collisions. Y. Mehtar-Tani and R. Boussarie further developed their proposal for a new semi-classical approach to gluon-mediated DIS processes. They derived a factorization formula that involves a novel gluon transverse momentum dependent (TMD) distribution function and showed that both the DGLAP and Regge limits are recovered.

### (3) Jet quenching

Jets have become an important tool to uncover the transport properties of matter created in heavy-ion collisions and the nontrivial parton structure in the nucleon. These are important goals of the sPHENIX and EIC experiments. Y. Mehtar-Tani and collaborators showed that transverse momentum broadening of emergent partons in QCD media can be formulated as a super-diffusive process due to non-local quantum corrections. This yields anomalous system size dependence of momentum broadening. They also showed that the momentum broadening exhibits geometric scaling and heavy tails akin to Levy random walks.

### (4) Resummation for jet angular distribution

Y. Hatta and collaborators continued to study the impact of soft gluon resummation on the azimuthal angular correlation of jets. They calculated various types of angular correlation in lepton-jet production and inclusive dijet production in DIS, dijet production in pp collisions and lepton pair production in ultraperipheral collisions. They also studied the relative strengths of angular correlations from soft gluon resummation and the linearly polarized gluon distribution. It is shown that the former can overshadow the signal from the latter.

### (5) $gT(x)$ contribution to single spin asymmetry

Y. Hatta and collaborators calculated the purely perturbative contribution to transverse single spin asymmetry which first arises in two-loop perturbation theory. It has been believed for more than 40 years that such a contribution is negligible. However, they have demonstrated that at the future Electron-Ion Collider, it can be comparable to other sources of single spin asymmetry such as three-parton correlation functions.

### (6) Hydrodynamical simulation of heavy-ion collisions

C. Shen has developed a full 3+1-dimensional dynamical framework based on Glauber geometry with string deceleration + hydrodynamics + hadronic transport model. This model provides good predictions for particle production in pp, pA and AA collisions from GeV to TeV energy regions. It is an essential tool to quantify baryon stopping at the RHIC BES phase II and study the origin of collectivity in ultra-peripheral collisions at RHIC and LHC.

### (7) Signature of the gluon orbital angular momentum

Y. Hatta and collaborators proposed a novel observable for the experimental detection of the gluon orbital angular momentum that constitutes the proton spin sum rule. They proposed to study double spin asymmetry in diffractive dijet production in DIS. A concrete

numerical prediction is given for the kinematics of the Electron-Ion Collider.

## Members

### Group Leaders

Hideto EN'YO

Yoshitaka HATTA

### RBRC Researchers

Yacine MEHTAR-TANI  
Chun SHEN

Vladimir SKOKOV

### Visiting Scientists

Hirofumi NISHIMURA (Keio Univ.)

Yuya TANIZAKI (North Carolina State Univ.)

## List of Publications & Presentations

### Publications

#### [Original Papers]

- Y. Hatta, B. Xiao, F. Yuan, and J. Zhou, "Azimuthal angular asymmetry of soft gluon radiation in jet production," *Phys. Rev. D* **104**, 054037 (2021).
- S. Benic, Y. Hatta, A. Kaushik, and H. Li, " $gT(x)$  contribution to single spin asymmetries in SIDIS," *Phys. Rev. D* **104**, 094027 (2021).
- S. Bhattacharya, R. Boussarie, and Y. Hatta, "Signature of the gluon orbital angular momentum," *Phys. Rev. Lett.* **128**, 182002 (2022).
- S. Alzhirani, S. Ryu, and C. Shen, "Lambda spin polarization in event-by-event relativistic heavy-ion collisions," arXiv:2203.15718.
- D. Everett *et al.* [JETSCAPE Collaboration], "Role of bulk viscosity in deuteron production in ultrarelativistic nuclear collisions," arXiv:2203.08286.
- W. Zhao, C. Shen, and B. Schenke, "Collectivity in ultra-peripheral Pb+Pb collisions at the large hadron collider," arXiv:2203.06094.
- C. Shen and B. Schenke, "Longitudinal dynamics and particle production in relativistic nuclear collisions," arXiv:2203.04685.
- A. De, C. Shen, and J. Kapusta, "Stochastic hydrodynamics meets hydro-kinetics," arXiv:2203.02134.
- H. Mantysaari, B. Schenke, C. Shen, and W. Zhao, "Bayesian inference of the fluctuating proton shape," arXiv:2202.01998.
- K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, and C. Shen, "Relativistic kinetic approach to light nuclei production in high-energy nuclear collisions," arXiv:2106.12742.
- D. Oliinychenko and C. Shen, "Resonance production in PbPb collisions at 5.02 TeV via hydrodynamics and hadronic afterburner," arXiv:2105.07539.
- G. Giacalone, B. Schenke, and C. Shen, "Constraining the nucleon size with relativistic nuclear collisions," *Phys. Rev. Lett.* **128**, 042301 (2022).
- X. An *et al.*, "The BEST framework for the search for the QCD critical point and the chiral magnetic effect," *Nucl. Phys. A* **1017**, 122343 (2022).
- V. Vovchenko, V. Koch, and C. Shen, "Proton number cumulants and correlation functions in Au-Au collisions at  $\sqrt{s_{NN}} = 7.7$ -200 GeV from hydrodynamics," *Phys. Rev. C* **105**, 014904 (2022).
- C. Gale, J. F. Paquet, B. Schenke, and C. Shen, "Multimessenger heavy-ion collision physics," *Phys. Rev. C* **105**, 014909 (2022).
- S. Ryu, V. Jovic, and C. Shen, "Probing early-time longitudinal dynamics with the Lambda hyperon's spin polarization in relativistic heavy-ion collisions," *Phys. Rev. C* **104**, 054908 (2021).
- S. Wu, C. Shen, and H. Song, "Dynamically exploring the QCD matter at finite temperatures and densities: A short review," *Chin. Phys. Lett.* **38**, 081201 (2021).
- G. Giacalone and C. Shen, "Manipulating strong electromagnetic fields with the average transverse momentum of relativistic nuclear collisions," *Eur. Phys. J. A* **57**, 230 (2021).
- C. Chiu and C. Shen, "Exploring theoretical uncertainties in the hydrodynamic description of relativistic heavy-ion collisions," *Phys. Rev. C* **103**, 064901 (2021).
- W. M. Serenone, J. G. P. Barbon, D. D. Chinellato, M. A. Lisa, C. Shen, J. Takahashi, and G. Torrieri, "Lambda polarization from thermalized jet energy," *Phys. Lett. B* **820**, 136500 (2021).
- S. Cao *et al.* [JETSCAPE], "Determining the jet transport coefficient  $\hat{q}$  from inclusive hadron suppression measurements using Bayesian parameter estimation," *Phys. Rev. C* **104**, 024905 (2021).
- M. A. Lisa, J. G. P. Barbon, D. D. Chinellato, W. M. Serenone, C. Shen, J. Takahashi, and G. Torrieri, "Vortex rings from high energy central  $p$ +A collisions," *Phys. Rev. C* **104**, 011901 (2021).
- P. Caucal and Y. Mehtar-Tani, "Universality aspects of quantum corrections to transverse momentum broadening in QCD media," arXiv:2203.09407.
- R. Boussarie and Y. Mehtar-Tani, "Gluon-mediated inclusive deep inelastic scattering from regge to bjorken kinematics," arXiv:2112.01412.
- P. Caucal and Y. Mehtar-Tani, "Anomalous diffusion in QCD matter," arXiv:2109.12041.

- J. Barata, Y. Mehtar-Tani, A. Soto-Ontoso, and K. Tywoniuk, “Medium-induced radiative kernel with the Improved opacity expansion,” *J. High Energy Phys.* **09**, 153 (2021).
- Y. Mehtar-Tani, D. Pablos, and K. Tywoniuk, “Cone size dependence of jet suppression in heavy-ion collisions,” *Phys. Rev. Lett.* **127**, 252301 (2021).
- F. Rennecke and V. V. Skokov, “Universal location of Yang Lee edge singularity for a one-component field theory in  $1 \leq d \leq 4$ ,” arXiv:2203.16651.
- H. Duan, A. Kovner, and V. V. Skokov, “Gluon quasiparticles and the CGC density matrix,” *Phys. Rev. D* **105**, 056009 (2022).
- M. Li and V. V. Skokov, “First saturation correction in high energy proton-nucleus collisions. Part III. Ensemble averaging,” *J. High Energy Phys.* **01**, 160 (2022).
- S. Mukherjee, F. Rennecke, and V. V. Skokov, “Analytical structure of the equation of state at finite density: Resummation versus expansion in a low energy model,” *Phys. Rev. D* **105**, 014026 (2022).
- A. Kovner, M. Li, and V. V. Skokov, “Probing gluon bose correlations in deep inelastic scattering,” *Phys. Rev. Lett.* **128**, 182003 (2022).
- M. Li and V. V. Skokov, “First saturation correction in high energy proton-nucleus collisions. Part II. Single inclusive semi-hard gluon production,” *J. High Energy Phys.* **06**, 141 (2021).
- M. Li and V. V. Skokov, “First saturation correction in high energy proton-nucleus collisions. Part I. Time evolution of classical Yang-Mills fields beyond leading order,” *J. High Energy Phys.* **06**, 140 (2021).
- T. Altinoluk, N. Armesto, A. Kovner, M. Lublinsky, and V. V. Skokov, “Angular correlations in pA collisions from CGC: multiplicity and mean transverse momentum dependence of  $v_2$ ,” *Eur. Phys. J. C* **81**, 583 (2021).
- F. Oosterhof, J. de Vries, R. Timmermans, and U. van Kolck, “Nucleon decay in the deuteron,” *Phys. Lett. B* **820**, 136525 (2021).

### [Proceedings]

- D. Oliinychenko and C. Shen, “Resonance production in Pb+Pb collisions at 5.02 TeV,” *EPJ Web Conf.* **259**, 10008 (2022).
- V. Vovchenko, V. Koch, and C. Shen, “Net-particle number fluctuations in a hydrodynamic description of heavy-ion collisions,” *EPJ Web Conf.* **259**, 10011 (2022).
- S. Ryu, S. McDonald, C. Shen, S. Jeon, and C. Gale, “Medium response from mini-jets and in-medium hadronization in relativistic heavy ion collisions,” *Proc. Sci. HardProbes2020*, 160 (2021).
- C. Shen, “Dynamic modeling for heavy-ion collisions,” *EPJ Web Conf.* **259**, 02001 (2022).
- Y. Mehtar-Tani, “A novel formulation of the unintegrated gluon distribution for DIS,” Contribution to: DIS2021, arXiv:2110.02105.
- R. Boussarie and Y. Mehtar-Tani, “On gauge invariance of transverse momentum dependent distributions at small  $x$ ,” *Proc. Sci. HardProbes2020*, 182 (2021).

## Presentations

### [International Conferences/Workshops]

- Y. Hatta (invited), “Quarkonium production near threshold,” CFNS Workshop on Open Questions in Photon-Induced Interactions, Stony Brook, USA, April 26–28, 2021.
- Y. Hatta (invited), “Odderon measurements at the EIC,” Saturation and Diffraction at the LHC and the EIC, ECT\*, Italy, June 29–July 1, 2021.
- Y. Hatta (invited), “Connection observables with different terms contributing to the proton mass,” EICUG Summer Meeting, Remote Workshop, August 2–7, 2021.
- Y. Hatta (invited), “Parton orbital angular momentum,” QCD Structure of the Nucleon, University of Alcala, Spain, October 4–8, 2021.
- Y. Hatta (invited), “Resummation of nonglobal logarithms,” Simons Center Workshop on Particle Jets in Quantum Field Theory, Stony Brook, USA, March 21–25, 2022.
- C. Shen (invited), “Computational challenges and opportunities in multi-messenger heavy-ion physics,” OSG All-Hands Meeting 2022, March 14, 2022.
- C. Shen (invited), “Challenges of hydrodynamic modeling at FAIR and NICA energies,” The 3rd Workshop on Physics Performance Studies at FAIR and NICA, December 1, 2021.
- C. Shen (invited), “Dynamical modeling of high energy nuclear collisions,” The 8th Asian Triangle Heavy-Ion Conference, November 6, 2021.
- C. Shen (invited), “Local polarization from hydrodynamics,” The 6th International Conference on Chirality, Vorticity, and Magnetic Field in Heavy-Ion Collisions, November 2, 2021.
- C. Shen (invited), “Dynamical modeling for heavy-ion collisions,” Strangeness in Quark Matter 2021, May 18, 2021.
- Y. Mehtar-Tani (invited), “Universality aspects of quantum corrections to transverse momentum broadening,” Simons Center Workshop on Particle Jets in Quantum Field Theory, Stony Brook, USA, March 21–25, 2022.
- Y. Mehtar-Tani (invited), “Jet quenching and quantum applications,” MITP for the Youngsters event on “The Quantumness of Hard Probes,” Online, January 17–21, 2022.
- V. Skokov (invited), “Entropies and multiplicity distribution in DIS,” RBRC Workshop: Small- $x$  Physics in the EIC Era, Brookhaven National Laboratory, December 15–18, 2021.
- V. Skokov (invited), “Universality driven analytic structure of QCD crossover,” International Workshop, “FunQCD: from first principles to effective theories,” Online, March 29–April 1, 2021.

**[Domestic Conference/Workshop]**

Y. Hatta (invited), “Physics at EIC: Nucleon structure,” J. Polym. Sci. Symposium, Online, September 17, 2021.

**[Seminars]**

Y. Hatta, “Gravitational form factors of the proton,” Temple University, USA, November 15, 2021.

Y. Hatta, “Gravitational form factors of the proton,” Sun Yat-sen University, China, November 18, 2021.

Y. Hatta, “Two topics in QCD spin,” National Center for Nuclear Research, Poland, May 26, 2021.

Y. Hatta, “Azimuthal angular asymmetry of soft gluons in jet production,” University of Bergen, Norway, March 1, 2022.

C. Shen, “Longitudinal dynamics and particle production in relativistic nuclear collisions,” Wayne State PAN Seminar, February 4, 2022.

C. Shen, “Progress in dynamical modeling of heavy-ion collisions at high energy,” NBI Heavy-ion Seminar, September 16, 2021.

C. Shen, “Going with the flow—Explore the nuclear phase diagram at the highest temperatures and densities,” The Ohio State University, August 31, 2021.

C. Shen, “Probing early-time longitudinal dynamics with Lambda’s spin polarization,” Invited Nuclear Seminar, The BESTea Seminar, July 30, 2021.

Y. Mehtar-Tani, “Anomalous diffusion in QCD matter,” Nuclear Theory Group Seminar, McGill University, Canada, Online, December 7, 2021.

Y. Mehtar-Tani, “Wave Turbulence and anomalous diffusion in QCD matter,” Physics Colloquium, Tata Institute of Fundamental Research, India, Online, November 16, 2021.

Y. Mehtar-Tani, “Anomalous diffusion in QCD matter,” Heavy Ion Tea Seminar, LBNL, USA, Online, September 7, 2021.

Y. Mehtar-Tani, “Wave turbulence and anomalous diffusion of jets in the QGP,” ASU Theoretical Physics Colloquium, USA, Online, July 7, 2021.

Y. Mehtar-Tani, “The anatomy of jets in heavy ion collisions,” BNL Physics Colloquium, Online, June 22, 2021.

V. Skokov, “Analytic structure of QCD crossover,” Physics Department, Ben-Gurion University of the Negev, Israel, April 19, 2021.

**Award**

C. Shen, DOE early career award.