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 collaborations, V. Skokov has determined the location of the Yang-Lee edge singularity in the O(N) model using the functional renormalization group method. This can be applied to the QCD phase diagram to determine the radius of convergence of the fugacity expansion and hence the location of the QCD critical point 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 has worked on various aspects of the CGC and their phenomenological consequences. In particular, he has calculated the multiplicity and transverse momentum dependence of the elliptic flow parameter v_2 in proton-nucleus (pA) collisions in the dense-dilute framework of CGC. Together with M. Li, he has also computed the first saturation corrections in pA collisions by solving the real-time classical Yang-Mills equation. Y. Mehtar-Tani and R. Boussarie have proposed a novel formulation of the gluon transverse momentum dependent (TMD) distribution which captures the leading logarithms in both the Bjorken and Regge limits.

(3) Jet and 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 has pushed the calculation of jet quenching to higher precision, now up to next-to-next-to-leading order (NNLO) in the opacity expansion. Together with collaborators, he has made concrete prediction of the nuclear modification factor at the LHC based on the state-of-the-art theory of jet quenching. Y. Hatta and collaborators calculated the impact of soft gluon resummation on the azimuthal angular correlation of jets. It has been shown that angular correlations of perturbative origin are numerically significant. They could obscure the primordial correlation due to the nontrivial parton distribution such as the linearly polarized gluon distribution. Y. Hatta and T. Ueda has calculated the gap survival probability in dijet production in proton-proton collisions at the LHC, resumming the nonglobal logarithms without any approximation to the number of colors.

(4) Origin of proton mass

Understanding the origin of proton mass is one of the most important goals of the future Electron-Ion Collider. Y. Hatta and R. Boussarie has developed an OPE-based approach to calculate the cross section of near-threshold electro-production of heavy quarkonia at large photon virtuality. The impact of the gluon condensate, related to the proton mass via the trace anomaly, has been estimated. D. Kharzeev argued that the cross section is dominated by the form factor of the trace of the energy momentum tensor. Based on this, he has extracted the nucleon "mass radius" from the recent experimental data on J/psi production from the Jefferson laboratory. Y. Hatta and Y. Zhao have introduced a parton distribution function associated with the gluon condensate and performed a one-loop calculation with a special attention to the possible zero mode.

(5) Hydrodynamical simulation of heavy-ion collisions

C. Shen has developed a comprehensive dynamical platform to simulate the evolution of fireballs created in heavy-ion collisions based on numerical codes for the viscous hydrodynamic equation. This can be applied to RHIC experiments with a wide range in center-of-mass energy, from the top energy (200 GeV per nucleon) to very low energy (7 GeV per nucleon) relevant to the ongoing Beam Energy Scan II experiment (BES II). This allows him to extract the shear viscosity from the input equation of state and the experimental data on particle multiplicity, *etc*. C. Shen has also studied various aspects of heavy-ion collisions such as Lambda polarization, deutron production and signals of vortex formation.

(6) Quantum information & computing

RBRC theorists also work on quantum computing and quantum information science. Y. Kikuchi discussed how to recover damaged information from Hawking radiation in Hayden-Preskill thought experiment. D. Kharzeev, Y. Kikuchi, and K. Ikeda have studied the real-time dynamics of the topological susceptibility near the critical point of massive Schwinger model and observed a sharp maximum due to critical fluctuations. Their spin Hamiltonian formulation is suitable for future digital quantum simulations.

(7) Beyond the standard model physics in low and high energy nuclear physics

Together with collaborators, J. de Vries has explored possible manifestations of physics beyond the Standard Mode (BSM) in low energy nuclear physics such as neutrinoless double beta decays and the nucleon electric dipole moment. In particular, his group has presented a first estimate of the complete amplitude of neutrinoless double beta decay including a contact term necessary for renormalization in chiral effective theory. J. de Vries also studied the prospect to discover sterile neutrinos at the LHC in the framework of neutrino-extended Standard Model Effective Field Theory.

(8) New connection between the nucleon electric dipole moment and QCD spin physics

One of the plausible operators to induce an electric dipole moment (EDM) in nucleons is the Weinberg operator which is a dimension-6, purely gluonic operator. Y. Hatta has found a novel relation between the nucleon matrix element of the Weinberg operator and certain twist-4 corrections in polarized Deep Inelastic Scattering (DIS) experiment. Based on this observation, he has made a numerical estimate of the EDM which turned out to be smaller than a previous estimate based on the QCD sum rule.

Members

Group Leader

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RBRC Researchers

Jordy DE VRIES
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Hiromichi NISHIMURA (Keio Univ.)
Yuya TANIZAKI (North Carolina State Univ.)

List of Publications & Presentations

Publications

[Original Papers]

R. Boussarie and Y. Hatta, "QCD analysis of near-threshold quarkonium leptoproduction at large photon virtualities," Phys. Rev. D **101**, 114004 (2020).

Y. Hatta and Y. Zhao, "Parton distribution function for the gluon condensate," Phys. Rev. D **102**, 034004 (2020).

Y. Hatta, "CP-odd gluonic operators in QCD spin physics," Phys. Rev. D **102**, 094004 (2020).

Y. Hatta, B. Xiao, F. Yuan, and J. Zhou, "Anisotropy in dijet production in exclusive and inclusive processes," Phys. Rev. Lett. **126**, 142001 (2021).

Y. Hatta and T. Ueda, "Non-global logarithms in hadron collisions at $N_c = 3$," Nucl. Phys. B **962**, 115273 (2021).

Y. Hatta, "Nucleon electric dipole moment from polarized deep inelastic scattering," Phys. Lett. B **814**, 136126 (2021).

Y. Hatta and M. Strikman, "ϕ-meson leptoproduction near threshold and the strangeness D-term," Phys. Lett. B **817**, 136295 (2021).

N. Bao and Y. Kikuchi, "Hayden-Preskill decoding from noisy Hawking radiation," J. High Energy Phys. **2021**, 17 (2021).

K. Ikeda, D. Kharzeev, and Y. Kikuchi, "Real-time dynamics of Chern-Simons fluctuations near a critical point," Phys. Rev. D **103**, L071502 (2021).

L. Gao, S. Kaushik, D. Kharzeev, and E. Philip, "Chiral kinetic theory of anomalous transport induced by torsion," arXiv.2010.07123 [cond-mat], (2020).

D. Kharzeev, "The mass radius of the proton," arXiv.2102.00110 [hep-ph] (2021).

M. Buzzegoli and D. Kharzeev, "Anomalous gravitomagnetic moment and non-universality of the axial vortical effect at finite temperature," arXiv.2102.01676 [hep-th] (2021).

D. Kharzeev and E. Levin, "Deep inelastic scattering as a probe of entanglement: confronting experimental data," arXiv.2102.09773 [hep-ph] (2021).

R. Boussarie and Y. Mehtar-Tani, "A novel formulation of the unintegrated gluon distribution for DIS," arXiv.2006.14569 [hep-ph] (2020).

J. Barata, Y. Mehtar-Tani, and A. Soto-Ontoso, "Revisiting transverse momentum broadening in dense QCD media," arXiv.2009.13667 [hep-ph] (2020).

Y. Mehtar-Tani, D. Pablos, and K. Tywoniuk, "Cone size dependence of jet suppression in heavy-ion collisions," arXiv.2101.01742 [hep-ph] (2021).

R. Boussarie and Y. Mehtar-Tani, "Gauge invariance of transverse momentum dependent distributions at small-x," Phys. Rev. D **103**, 094012 (2021).

M. Li and V. Skokov, "First saturation correction in high energy proton-nucleus collisions: I. Time evolution of classical Yang-Mills fields beyond leading order," arXiv.2102.01594 (2021).

T. Altinoluk, N. Armesto, A. Kovner, M. Lublinsky, and V. Skokov, "Angular correlations in pA collisions from CGC: multiplicity and mean transverse momentum dependence of v_2," arXiv.2012.01810 [hep-ph] (2020).

A. Behtash, S. Kamata, M. Martinez, A. Schafer, and V. Skokov, "Transasymptotics and hydrodynamization of the Fokker-Planck equation for gluons," Phys. Rev. D **103**, 056010 (2021).

A. Dumitru and V. Skokov, "An incorrect pre-asymptotic RG flow of scattering amplitudes in QCD towards the unitarity limit," arXiv.2010.03015 [hep-ph] (2020).

A. Connelly, G. Johnson, F. Rennecke, and V. Skokov, "Universal location of the Yang-Lee edge singularity in O(N) theories," Phys. Rev. Lett. **125**, 19 (2020).

C. Cheng and C. Shen, "Exploring theoretical uncertainties in the hydrodynamic description of heavy-ion collisions," arXiv.2103.09848 [nucl-th] (2021).

W. Serenone, J. Barbon, D. Chinellato, M. Lisa, and C. Shen, "Lambda polarization from thermalized jet energy," arXiv.2102.11919 [hep-ph] (2021).

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W. Zhao, C. Shen, C. Ko, Q. Liu, and H. Song, "Beam-energy dependence of the production of light nuclei in Au + Au collisions," Phys. Rev. C **102**, 044912 (2020).

D. Oliinychenko, C. Shen, and V. Koch, "Deuteron production in AuAu collisions at $\sqrt{s}$ = 7–200 GeV via pion catalysis," Phys. Rev. C **103**, 034913 (2021).

G. Giacalone, B. Schenke, and C. Shen, "Observable signature of initial state momentum anisotropies in nuclear collisions," Phys. Rev. Lett. **125**, 192391 (2020).

B. Schenke, C. Shen, and P. Tribedy, "Running the gamut of high energy nuclear collisions," Phys. Rev. C **102**, 044905 (2020).

B. Schenke, C. Shen, and D. Teaney, "Transverse momentum fluctuations and their correlation with elliptic flow in nuclear collision," Phys. Rev. C **102**, 034905 (2020).

V. Cirigliano, W. Dekens, J. de Vries, M. Hferichter, and E. Mereghetti, "Towards complete leading-order predictions for neutrinoless double β decay," Phys. Rev. Lett. **126**, 172002 (2021).

J. de Vries, H. Dreiner, J. Gunther, Z. Wang, and G. Zhou, "Long-lived sterile neutrinos at the LHC in effective field theory," J. High Energy Phys. **2021**, 148 (2021).

J. de Vries, A. Gnech, and S. Shain, "Renormalization of CP-violating nuclear forces," Phys. Rev. C **103**, L012501 (2021).

V. Cirigliano, W. Dekens, J. de Vries, M. Hoferichter, and E. Mereghetti, "Determining the leading-rder contact term in neutrinoless double beta decay," arXiv.2102.03371 [nucl-th] (2021).

[Review Articles]

D. Kharzeev and J. Liao, "Chiral magnetic effect reveals the topology of gauge fields in heavy-ion collisions," Nat. Rev. Phys. **3**, 55 (2021).

A. Monnai, B. Schenke, and C. Shen, "QCD equation of state at finite chemical potentials for relativistic nuclear collisions," Int. J. Mod. Phys. A **36**, 2130007 (2021).

C. Shen and L. Yan, "Recent development of hydrodynamic modeling in heavy-ion collisions," Nucl. Sci. Tech. **31**, 122 (2020).

Presentations

[International Conferences/Workshops]

Y. Hatta (invited), "Use of Wigner/GTMD at the EIC," Jet Observables at the Electron-Ion Collider, RIKEN BNL Center Workshop, BNL, July 27–29, 2020.

Y. Hatta (invited), "QCD Wigner distribution," QCD with Electron-Ion Collider, IIT, Bombay, India, January 4–7, 2020.

Y. Hatta (invited), "Quarkonium photo- and lepto-production near threshold," 3rd Proton Mass Workshop, Argonne National Lab, January 14–16, 2021.

Y. Hatta (invited), "Quarkonium production near threshold," Open Questions in Photon-Induced Interactions, CFNS Workshop, April 26–28, 2021.

D. Kharzeev (invited), "Chirality: a theoretical overview," Chirality and Criticality Workshop, INT, Seattle, May 11–22, 2020.

D. Kharzeev (invited), "The Chiral Qubit: quantum computing with Dirac/Weyl semimetals," APS Users Meeting, ANL, August 27–28, 2020.

D. Kharzeev (invited), "Mass radius of the proton," Deep Inelastic Scattering Conference, Stony Brook, April 12–16, 2021.

D. Kharzeev (invited), "Semiclassical description of chiral anomaly with real and synthetic gauge fields," Gravity and Emergent Gauge Fields Workshop, ITP Mainz, April 12–23, 2021.

C. Shen (invited), "Dynamical modeling of the collectivity in pO and OO collisions," Opportunities of OO and pO Collisions at the LHC,

CERN, Febuary 5, 2021.

V. Skokov (invited), "Universality driven analytic structure of QCD crossover," International Workshop "FunQCD: from first principles to effective theories," March 29–April1, 2021.

V. Skokov (invited), "Universality driven analytic structure of QCD crossover," XXXII International (online) Workshop on High Energy Physics, "Hot problems of strong interactions," November 9–13, 2020.

V. Skokov (invited), "Saturation corrections to dilute-dense particle production in the color glass condensate," RHIC&AGS User's Group Meeting, October 22, 2020.

V. Skokov (invited), "Universality driven analytic structure of QCD crossover: radius of convergence in baryon chemical potential," Rice University & University of Illinois at Urbana-Champaign, June 15, 2020.

Y. Kikuchi, "Real-time chiral dynamics from a digital quantum simulation," The 2020 Fall Meeting of the Division of Nuclear Physics of the American Physical Society, October 29–November 1, 2020.

[Seminars]

Y. Hatta, "QCD trace anomaly and proton mass problem," University of Kentucky, October 20, 2020.

Y. Hatta, "Two topics in QCD spin," Kyoto University, November 20, 2020.

Y. Hatta, "Probing the Wigner distribution at the electron-ion collider," Tata Institute of Fundamental Research, July 23, 2020.

D. Kharzeev, "Chiral magnetic effect: from quarks to quantum computers," INT Colloquium, March 18, 2021.

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

C. Shen, "Dynamical modeling of the initial energy-momentum and baryon charge distributions for heavy-ion collisions," LBL HIT Seminar, March 2, 2021.

C. Shen, "Multi-messenger heavy-ion physics," Invited Physics Colloquium, ASU Theoretical Physics Colloquium, March 31, 2021.

C. Shen, "Observable signature of initial state momentum anisotropies in nuclear collisions," Nuclear Seminar, the ALICE Collaboration, December 8, 2020.

C. Shen, "Dynamical modeling of relativistic heavy-ion collision at beam energy scan energies," The 4th RHIC-BES Theory and Experiment Online Seminar, August 25, 2020.