NC STATE UNIVERSITY

Department of Physics

421 Riddick Hall Campus Box 8202 Raleigh, NC 27695-8202 TEL (919) 515-2521 FAX (919) 515-6538

Vladimir Skokov, Ph.D.
Assistant Professor
Department of Physics
North Carolina State University
E-mail: vskokov@ncsu.edu

To whom it may concern,

I am delighted to be able to write this letter in support of Haowu Duan's application. Haowu Duan joined my group in the fall of 2018. Right from the first email, he told me that he wanted to work on something specific — an intersection of high energy/nuclear physics and quantum information. His research excellence is reflected by three publications, single-authored refereed conference proceedings, and multiple papers in preparation. In all these publications, Haowu played the leading role in all research aspects inducing analytical and numerical calculations. Haowu is scheduled to graduate in Summer of 2023.

Haowu is an extraordinary researcher who finds pleasure in doing theoretical work, taking on new projects, learning new skills, and performing what would constitute to others tedious analytical and numerical computations. His preparation and technical skills are excellent. On the one hand, as a collaborator and a team member, he is invaluable: Haowu considers things critically and does not shy away from contradicting senior co-authors. On the other hand, Haowu is very strong in performing research independently. In a few years, he will be ready to start applying for faculty jobs and execute his research direction easily. Moreover, Haowu is an excellent mentor, as demonstrated by his interaction with my first-year graduate students, whom Haowu regularly meets to direct their learning in Quantum Field Theory and QCD at high energy.

Below I elaborate more on Haowu's research and mentoring skills.

Haowu came into my group with a specific goal to work on the intersection of high energy/nuclear physics and quantum information. His initiative in this direction led to the publication of two papers (both in Phys. Rev. D) titled "Entanglement, partial set of measurements, and diagonality of the density matrix in the parton model" and "Gluon quasiparticles and the CGC density matrix". In these papers, in the Color Glass Condensate model, we discuss the relevance of the entanglement entropy to the measurements in high-energy hadronic collisions. Performing quite technical analytic calculations Haowu was able to derive the density matrix for small x gluons in coherent and in the particle number basis. For the latter, we demonstrated the presence of the off-diagonal components, often omitted in the discussion of the parton model density matrix, as they do not affect experimental observables. However, the off-diagonal components contribute to entanglement entropy. By performing numerical simulations, Haowu explicitly demonstrated the significance of the off-diagonal components. In the follow-up paper, we studied the entanglement entropy in the Color Glass Condensate. Haowu was able to explicitly construct Bogoliubov transformation for small-x gluon creation/annihilation operators and thus demonstrate that there exists such a basis in which the density matrix is diagonal and, most significantly, has a Boltzmann form. We found that the behavior of the corresponding quasi-particle distribution is thermal in the semi-hard momentum range.

In the most recent paper (submitted to JHEP), "CGC for Ultra-Peripheral Pb+Pb Collisions at the Large Hadron Collider: a more realistic calculation", Haowu performed very tedious and technical calculations of double-gluon production for Deep Inelastic Scattering and UltraPeripheral Collisions within the Color Glass Condensate effective theory. Previous calculations by Jalilian-Marian and Kovchegov were performed within the limit of a large number of colors (N_c). Our goal was to extract azimuthal anisotropy, which necessitates going beyond the large N_c limit. The resulting analytic expressions were then numerically evaluated. By working on this paper, Haowu demonstrated not only his ability to perform complex theoretical derivations but also his prowess in numerics and utilizing parallel computing at NCSU's High-Performance Cluster. Without any external input, Haowu was able to construct a workflow for a very non-trivial numerical problem and to figure out the data management between different sub-programs of his code.

For all the projects, Haowu kept extremely detailed LaTeX notes which were easy to follow and reproduce. His numeric codes are published on GitHub and are freely available to everyone. Whenever he had a problem, Haowu would reach out and communicate. For me, in all aspects of conducting research, Haowu was more of a collaborator rather than an advisee.

Haowu is well versed in Light Cone perturbations theory, high energy evolution equations (including DGLAP, BFKL, BK and JIMWLK), lattice methods for gauge theories, and functional renormalization group approach. Haowu has worked with Schwinger-Keldysh formalism and real-time quantum field theory.

Haowu participated in multiple international conferences and workshops. He presented many talks and published single-author refereed conference proceedings. Haowu participated in multiple Summer Schools and assimilated a lot of material, as documented by his seminar presentations after school. He collaborated with a postdoc in my group, and they are finishing the paper without any senior researchers as co-authors.

Besides performing excellent research, Haowu is mentoring two second-year graduate students in my group. He is training the students in Quantum Field Theory and high-energy QCD for colliders. Haowu is always respectful to students; he is able to find time in his busy schedule of TAing, finalizing his thesis, and working on multiple research projects. The students had only praise for Haowu's availability and willingness to help.

Summary
I have had great pleasure working with Haowu. His passion for research is infectious; his skills are outstanding. Without any doubt, Haowu will strengthen any research group.

Sincerely,
Vladimir Skokov,
Assistant Professor of Physics

April 5, 2023