Quantum Chromodynamics at extreme gluon densities

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Proposing Organization: North Carolina State University

Principal Investigator: Vladimir Skokov
Physics Department, College of Sciences
North Carolina State University
Raleigh, NC 27695
Phone: …
Email: vskokov@ncsu.edu

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1 Introduction

Title: Quantum Chromodynamics at extreme gluon densities

Lead Institution: North Carolina State University

Principal Investigator: Vladimir Skokov

Abstract: Scattering processes and soft/semi-hard particle production in high-energy hadron-hadron and lepton-hadron collisions are largely defined by the small Bjorken x component of the hadron(s) wave-function. These collisions provide access to kinematic regions in nucleons and nuclei where parton densities are extremely high and dominated by gluons. In contrast to well-understood dilute QCD dynamics at small distance scales, high gluon density QCD is an intrinsically new, nonlinear regime forbidding usual perturbative treatment. Nevertheless due to the formation of a semi-hard scale, the so-called saturation momentum, the theory is calculable semi-analytically using weak coupling, but non-perturbative techniques. This proposal aims to develop a unifying quantitative framework for describing novel aspects of small-x physics in hadron-hadron, lepton-hadron, and Ultra Peripheral A-A collisions.

This work is especially relevant to experiments at Relativistic Heavy Ion Collider (BNL), the Large Hadron Collider (CERN) and a future Electron-Ion Collider (BNL and JLab).

Summary of Proposed Work: The main objectives are

- Build a unified framework for a systematic first-principle description of multiparticle production and multiparticle correlations at small x in various colliding systems (p-p/A, e-p/A and ultra peripheral p/A-A). The critical steps include:
  - Deriving complete analytic results for the first-saturation correction in projectile gluon density for single inclusive and double inclusive gluon production in the classical approximation for asymmetric collisions (e.g. proton-nucleus collisions);
  - Theoretical development of a reweighting technique enabling an access to the high multiplicity tail of hadronic wave-function/particle production;
  - Proper account for small x evolution in order to restore the three-dimensional snapshot of multiparticle production in collisions and to elicit the dependence on the collision energy;
  - Making the source code(s) performing numerical lattice simulations for multiparticle production publicly available.

  Potential Impact: These first-principle quantitative studies of the initial state effects in hadronic collisions may lead to a potential shift of paradigm in our understanding of particle production and, specifically, the origin of collectivity in hadronic collisins. Additionally, on this stage of the EIC R&D program, quantitative predictions for the observables sensitive to gluon saturation or to various gluon distribution functions (e.g. the linearly polarized gluon distribution in an unpolarized hadron) in the relevant energy range may influence yet flexible design of EIC detectors by providing an optimal kinematic range for performing corresponding measurements.

- Quantitatively study momentum entanglement in hadronic wave function. Derive small x evolution for the full density matrix including the off-diagonal components in the basis of valence charge density. Extract small x evolution of the associated entanglement entropy. Identify potential experimental observables.

Potential impact: Quantum entanglement is a universal phenomenon underlying the behavior of quantum systems of diverse nature. The concept does not rely on small coupling methods and thus may facilitate extension of evolution equations for entanglement entropy to an arbitrary value of the strong coupling.

- Provide a cohesive picture of the role of quantum statistics at small x. Study associated effects in gluon and quark production. Compute the initial state background contribution to the Chiral Magnetic Effect (CME).

  Potential impact: Experimental data collected by CMS (LHC) collaboration in p-A collisions challenges the conventional picture of the flow-driven CME background established in A-A collisions. The initial state correlations may explain the observed discrepancy.

List of Personal:

1. Faculty: Vladimir Skokov (PI)
2. Postdoctoral Fellows: to be hired
3. Graduate students: Haowu Duan, Gregory Johson

2 Narrative Introduction

The 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan "Reaching for the Horizon" outlined the key fundamental questions:

> *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?*
>
> *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*
>
> *Where does the saturation of gluon densities set in?*

under one overarching theme

"How does subatomic matter organize itself and what phenomena emerge?".

The scientific urge to answer these questions lead the NSAC to recommend EIC as the "highest priority for new facility construction following the completion of FRIB". In mid 2018, this recommendation was supported by the National Academy of Science which concluded "that the science questions regarding the building blocks of matter are compelling and that an EIC is essential to answering these questions." However, this can only be achieved with appropriate theoretical support and development of new theoretical tools built upon first-principle approaches to the theory of strong interactions. This proposal seeks funding for building such a tool with a broader application range which includes also high energy hadron-hadron collisions and ultra peripheral collisions of proton-nucleus and nucleus-nucleus.

Besides the EIC physics, the successful implementation of the proposal will have a significant impact on understanding the results of other planned or on-going experimental programs at the large facilities in the U.S. (RHIC, CEBAF) and Europe (CERN).

2.1 Motivation

The two decades worth of experimental measurements at RHIC and, then, the LHC have provided many unexpected results, including strong evidence for the formation of a strongly coupled plasma of quarks and gluons in heavy-ion collisions at high energy [1–4]. This plasma demonstrated properties of a nearly perfect fluid; this fact facilitated a theoretical description of the collisions dynamics in the framework of hydrodynamics starting just about 1 fm/c after the heavy-ion impact [4–6].

The success of the hydrodynamic description, however, cannot be complete without a detailed understanding of the initial non-equilibrium state. The properties of this state go beyond the range of applicability of hydrodynamics and are little known; the evolution of this state towards equilibrated thermal nearly perfect liquid is not well understood. One dominant mechanism describing the initial phase is based on the saturation framework, also widely known as the Color Glass Condensate [7–9]. According to the framework, the high energy particle production and scattering processes are dominated by the classical gluon fields providing a background for systematic weak-coupling computation of quantum correction on top of it.

Under laboratory conditions, collisions of heavy-ions create probably the most optimal environment for probing quark-gluon plasma near equilibrium, but at the same time they are poorly suited to study the initial state particle production. This is because most of the observables in heavy-ion collisions are sensitive not only to initial state, but also to final sate interactions. However, to uniquely map the transport properties of the plasma, it is critical to extract information about the initial state in collisions where the final state is better understood and the initial state is expected to play the dominant role. This necessitates probing a nucleus and a nucleon with the smallest projectiles: proton and ultimately electron. Theoretically, a controlled, first principle description of such collisions (p-p, p-A, e-A) is not as complex as A-A collisions and at high energy can be performed in a common quantitative framework: the saturation framework. Later on, the results of the framework may be transferred to describe the initial state of A-A collisions.

One example of a similar strategy was realized recently in Refs. [10–12] where the saturation motivated model (IP-SAT, see Ref. [13]) for e-p collisions was used to constrain the shape fluctuations of the proton wave function by studying coherent and incoherent diffractive vector meson production at HERA. The proton shape fluctuations may have a direct impact on properties of the matter created in A-A collisions from the initial state in peripheral to ultra central collisions.

Theoretical analysis of future experimental data from an Electron-Ion Collider will definitely make a greater impact on our understanding of the dynamics in p-p, p-A and A-A collisions. The reverse is also partially true as the data collected in p-p and p-A collisions currently drive an active development of the first principle approaches to high energy QCD physics. Additionally p-p and p-A collisions allow us to probe a different phase space of high energy QCD, complementing future EIC coverage, and thus better constraining the applicability range of our frameworks.

Before an EIC comes into operation, ultra peripheral collisions (UPC) of p-A and A-A provide a unique opportunity to further sharpen theoretical methods. It is clear that many smoking-gun signals of new QCD dynamics at high energy will be measured with rather high statistics by collecting UPC data at the LHC and RHIC. Additionally, researchers at the LHC seriously consider future physics opportunities for studying high-density QCD with UPC in ions and proton beams. This is why it is crucial to have a common approach to a wide energy or Bjorken x range; in saturation framework the energy dependence is captured by the small-x renromalization group evolution equations. A modern pinnacle of performing numerical analysis of the small-x evolution is based on the leading order JIMWLK (Jalilian-Marian–Iancu–McLerran–Weigert–Leonidov–Kovner) equation [14–17] which resums powers of $\alpha_s \log x^{-1}$ and extends the applicability range of BK (Balitsky-Kovchev) equation [18–21] to finite number of colors N_c. It has not yet been fully utilized to describe gluon production, while it paves a way for reducing model dependence towards a first-principle framework.

The number of unresolved theoretical issues complemented by a number of quite puzzling and unexplained features of experimental data (see below and Secs. 3, 4 and 5) and the need for the development of new theoretical tools to EIC physics require to solidify our understanding of small x dynamics, to develop first-principle based event generators and, finally, to explore new approaches and ideas.

Cristallizing the above, there are four major motivational themes which drive our interest:

Theme 1: To differentiate initial state effects from final state dynamics of strongly coupled quark-gluon plasma. Multiparticle production and correlations are cannonical measurements for a) the formation of the strongly coupled plasma, see e.g. Refs. [4, 5]; b) the Chiral Magnetic Effect [22], the novel transport mechanism due to QCD quantum axial anomaly; c) higher order cumulants of proton fluctuations as a signature of a critical point or first-order phase transition [23]. For all of these items in the list, it is important to disentangle the initial state contribution from the genuine final state effects in near-equilibrium quark-gluon plasma. Quantifying the role of the initial state will further strengthen the discovery potential for all these key measurements and improve the chances of establishing these novel phenomena.

Theme 2: To find a better, simpler description of complex problems in hadron structure and high energy QCD. At small x or at high energy, the number of gluons grows rapidly; intuitively, it is reasonable to expect that an effective, statistical description of some if not all observables can be feasible and accurate. There are already known examples where statistical analogy was implemented and offered fresh insights on complex problems: – treatment of high-energy evolution as a reaction-diffusion process in statistical physics [24–26], – parametrization of parton distribution functions motivated by quantum statistics distributions [27–29], – establishing the dominance of Bose enhancement in high multiplicity events [30], – entropy of small x gluons in hadronic wave function and its relation to multiplicity and entropy of produced hadrons in the final state [31–35].

Along these lines, one may hypothesize that small x evolution may be generalized beyond a weakly coupled regime through the universal notion of the entanglement entropy. It could be also possible that strict bounds on the entanglement entropy [36, 37] may lead to a resolution of the QCD unitarity problem at high energy.

Additionally, recently established set of dualities between the vertices of the infra-red triangle [38–40] may also bring better understanding of particle production in near classical regime.

Theme 3: Describe puzzling features of the data. There are puzzling features of the data that may potentially be described with the saturation/CGC formalism; these include: – long-range rapidity correlations and apparent collectivity in p-p and p-A collisions [41–44], – baryon-baryon anti-correlation in p-p collisions [45], – re-emergence of the Cronin peak in multiplicity biased p-A collisions at high energy [46] , – strong correlations between soft-hard particle production in p-p and p-A collisions [47, 48].

Theme 4: Rigorous theoretical predictions on gluon saturation dynamics in experimental observables at a future EIC. An EIC has a strong discovery potential for a novel QCD phase. Theoretical development and in particular predictions based on saturation dynamics are required to claim the discovery.

The success of this project is defined by delivering the following key results

- Developing a systematic framework for particle production at small x. Making the associated source code(s) performing numerical simulations available online. This item is an integral part of the proposal; it was pointed out on multiple occasions that there are no publicly available small x codes or they are not well documented.
- Derivation of the small-x evolution equations for the off-diagonal components of the density matrix in the basis of the valence charge density. Derivation of the small-x evolution equations for the momentum entanglement entropy and seeking for universal features allowing to a potential extension to arbitrary coupling.
- Providing a detailed and cohesive picture of the role of quantum statistics at small x. Ultimately establishing a connection to the Kulish-Fadeev formalism, the color memory effect, and BMS (Bondi-Metzner-Sachs) symmetry and their consequences at small x. Publishing a detailed review on the role of quantum statistics crystallizing synergy of the results obtained by the PI and other researchers.

3 Proposed Research: Multiparticle production and correlations at small x in p-p/A and e-A collisions

3.1 Background

Below we discuss the essential background material and motivations for major goals of the proposed research on this topic.

Particle production in classical approximation

To review the current theoretical status of particle production in the saturation/CGC formalism, let us first consider the single inclusive gluon production cross section. Suppressing impact parameter dependence (see Ref. [49] for more details), the production cross section can be written as [50, 51]

$$\frac{dN}{d^2k\, d^2b\, d^2B} = \frac{1}{\alpha_s} f\left(\frac{Q_{sp}^2}{k^2}, \frac{Q_{sA}^2}{k^2}\right), \tag{1}$$

where Q_{sp} and Q_{sA} are the saturation momenta for the projectile and target, α_s is the strong coupling constant, B is the impact parameter between the projectile nuclei or nucleon and target nucleus, b is the transverse position of the gluon. The function f was only studied numerically [52–55]. Analytically tractable is only its expansion in either one of the arguments. In the *dilute-dense* approximation valid for asymmetric collisions, one assumes that the projectile is a dilute object, $\frac{Q_{sp}^2}{k^2} \lesssim 1$ which facilitates the expansion of the production cross section in this parameter

$$\frac{dN}{d^2k\, d^2b\, d^2B} = \frac{1}{\alpha_s}\left[\frac{Q_{sp}^2}{k^2} f_1\left(\frac{Q_{sA}^2}{k^2}\right) + \left(\frac{Q_{sp}^2}{k^2}\right)^2 f_2\left(\frac{Q_{sA}^2}{k^2}\right) + \dots\right]. \tag{2}$$

The function f_1 is known analytically [56, 57]. At this order the number of produced gluons for given projectile and target configurations is given by

$$\left.\frac{dN}{d^2k\, dy}\right|_{\rho_\mathrm{p},\rho_\mathrm{t}} = \frac{2g^2}{(2\pi)^3}\int \frac{d^2q}{(2\pi)^2}\frac{d^2q'}{(2\pi)^2}\Gamma(\vec{k}_\perp,\vec{q}_\perp,\vec{q}\,'_\perp)\rho_\mathrm{p}^a(-\vec{q}\,'_\perp)\left[U^\dagger(\vec{k}_\perp-\vec{q}\,'_\perp)U(\vec{k}_\perp-\vec{q}_\perp)\right]_{ab}\rho_\mathrm{p}^b(\vec{q}_\perp), \tag{3}$$

where $\Gamma(\vec{k}_\perp,\vec{q}_\perp,\vec{q}\,'_\perp)$ is the square of Lipatov vertex, see Ref. [30] for details. Here ρ_p is a given configuration of the color charged density in the projectile, and U is the eikonal scattering matrix – the adjoint Wilson line – for scattering of a single gluon on the target. The target Wilson lines depend on the target color sources, ρ_t.

Functions $f_2, f_3, \dots$ are not known analytically at present. Here we want to explain what we mean by analytical results, as e.g. f_i may still involve rather complicated momentum integrals of Wilson lines of the target field, see e.g. Eq. (3). Getting to a number, often requires using f_i to conduct numerical lattice simulations. This is why in what follow we often refer to this as semi-analytical approach. In contrast to numerical Classical Yang-Mills (CYM) calculations, f_i require neither numerical solution for the proper time dependence nor numerical implementation of LSZ (projection of gluon field time evolution to asymptotic particle states). Also the advantage of this semi-analytic approach is that, in contrast to numerical CYM, the dilute-dense semi-analytic results facilitate inclusion of small x evolution, running coupling corrections and, finally, they are superior in terms of simulation time and allow for easier access to the continuum limit.

Returning back to expansion (2), the next contribution, the function f_2, is also termed as the *first saturation correction* in the projectile, since it comes in with two powers of Q_{sp}^2/k^2, corresponding to interactions with two valence sources in the projectile. The efforts to calculate f_2 analytically was started in Ref. [58] and more recently revisited in Ref. [59]. Despite this effort, f_2 is known only partially and its complete analytic calculation is one of the goals of this proposal. Phenomenologically f_2 is of paramount importance because it defines the first non-trivial correction to the strict dilute-dense approximation and thus provides a systematic check on the applicability/convergence of this approximation. f_2 also bridges the gap between dilute-dense and dense-dense approaches.

The same discussion applies to the two-gluon production. For the classical two-gluon production cross section one can write

$$\frac{dN}{d^2k_1\,d^2b_1\,d^2k_2\,d^2b_2\,d^2B} = \frac{1}{\alpha_s^2}\,h\left(\frac{Q_{sp}^2}{k^2},\frac{Q_{sA}^2}{k^2}\right) \tag{4}$$

with the new unknown function h. Here k_1 and k_2 are the gluons' transverse momenta (here to simplify notation we assumed that $|k_1| = |k_2| = k$), while b_i are their transverse positions. Again, assuming a dilute projectile we expand in $\frac{Q_{sp}^2}{k^2}$ getting

$$\frac{dN}{d^2k_1\,d^2b_1\,d^2k_2\,d^2b_2\,d^2B} = \frac{1}{\alpha_s^2}\left[\left(\frac{Q_{sp}^2}{k^2}\right)^2 h_1\left(\frac{Q_{sA}^2}{k^2}\right) + \left(\frac{Q_{sp}^2}{k^2}\right)^3 h_2\left(\frac{Q_{sA}^2}{k^2}\right) + \ldots\right]. \tag{5}$$

The function h_1 can be found from the results of Refs. [60–62], explicitly it is also written in Refs. [63]. Compared to f_1 in Eq. (3), which has two target Wilson lines (dipole), the function h_1 involves four Wilson lines (quadrupole). This part of the two-gluon production cross section is invariant under the reflection of either momenta k_1 or k_2 and thus generates only even harmonics of azimuthal anisotropy. This is why finding the function h_2 was one of the highest priorities for saturation/CGC community. Recently, in Refs. [49, 64], it was shown that the accidental symmetry with respect to the reflection of one of the momenta is lifted by the first saturation contribution, h_2. The complete part of h_2 responsible for the odd harmonics was derived analytically [49, 64]. This progress allowed us to find the leading order contribution to odd harmonics and lead to a successful application of the framework to phenomenology of two particle correlations in p-A collisions [65, 66]. Nevertheless, the complete result for h_2 is currently unknown; deriving and numerically simulating it is one of the goals of this project. The complete results for the first saturation correction h_2 will enable us to quantify the reliability of the expansion (5) for extraction of even harmonics $v_{2n}\{2\}$.

We finally want to comment on the range of applicability of the dilute-dense approximation in terms of hadrons participating in collisions. Besides the obvious application to p-A collisions, dilute-dense expansion can also be applied to A-A and high-multiplicity p-p collisions. The latter, as also supported by experimental data on the event-by-event dependence of the number of particles on rapidity, is dominated by collisions in which one of the proton wave functions experienced a fluctuation with higher than average gluon density, or saturation momentum Q_s. The former, if considered locally, can often be described by the dilute-dense approach at least for some range of transverse momenta. In A-A collisions, the required hierarchy of saturation momenta originates from the fact that in a given event, for a given impact parameter in the transverse plane, it is quite unlikely to have the same number of participants on the target and projectile

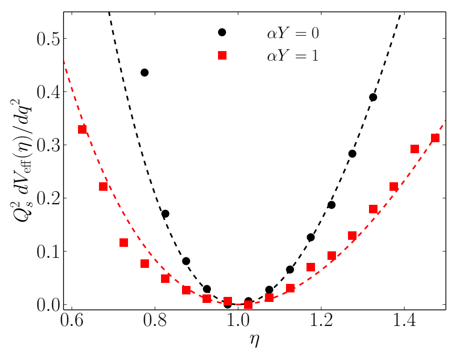

Figure 1: The effective potential describing fluctuations of the covariant gauge gluon field distribution (above the saturation scale) in a transverse area patch of order $2\pi R^2 = 8\pi/Q_s^2(Y)$. Symbols show the results obtained from the Monte-Carlo simulation, lines correspond to the potential derived analytically, see Eq. (6). Here $Y = \log x_0/x$.

side simultaneously. Since the target (projectile) saturation momentum squared is proportional to the number of participants in the target (projectile), the desired hierarchy can be achieved.

High multiplicity events and reweighting

In recent years, the study of multiparticle correlations in p-A and p-p collisions have been a very active area of both experimental and theoretical research due to the observation of the long-range in rapidity azimuthal correlations (the so-called ridge) at the LHC and RHIC. Since the observed ridge correlation is much more pronounced in high multiplicity events, the understanding of the origin of high multiplicity fluctuations and especially of the high multiplicity tail of the distribution describing particle production receives a lot of attention.

Recently, at small x, this problem has been attacked from different angles, but lead to the universal result on the approximate negative binomial distribution for the high multiplicity tail, see e.g. Ref. [30, 67]. In particular, PI with collaborators, derived an effective action describing the covariant gauge gluon field (A^+) distribution in a hadron both in the McLerran-Venugopalan model [68, 69] and in a (non-local) Gaussian approximation [70] for the small-x density matrix of the valence charge distribution. It was shown that the corresponding effective action is a Liouville action (without kinetic term and with negative Ricci scalar):

$$V_{\rm eff}[\eta(\vec{q}_\perp)] = \frac{1}{2}(N_c^2-1)S_\perp \int \frac{d^2q}{(2\pi)^2}\left\{\eta(\vec{q}_\perp) - 1 - \ln\eta(\vec{q}_\perp)\right\}, \quad \eta(\vec{q}_\perp) = \frac{{\rm tr}|A^+(\vec{q}_\perp)|^2}{\langle {\rm tr}|A^+(\vec{q}_\perp)|^2\rangle}. \tag{6}$$

PI also demonstrated that small x evolution preserves the shape of the effective potential and affects only its widths [71], see Fig. 1.

Later, this effective theory was directly connected to the distribution of produced gluons in Ref. [30]. It turned out that the leading effect driving the multiplicity fluctuations at small x is the quantum Bose enhancement of gluons in the proton wave function. Strikingly, from completely different presumptions, the Liouville action was derived for the fluctuations of the effective saturation momentum [25, 72, 73]. In Refs. [71, 74, 75] it was also realized that high multiplicity events at small x cannot be parametrized by just a single quantity Q_s, but rather by a nontrivial function which depends on the transverse momentum and x.

The systematic treatment of high multiplicity color charge configurations has only just begun and although this progress lead to a better understanding of the high multiplicity fluctuations, the state of the art numerical simulations in the saturation/CGC formalism ([12, 65, 66] to name a few) still rely on a brute force numerical approach to access the high multiplicity tail. In this approach, configurations of target and projectile are generated without any bias, the particle production and correlations are computed and a posteriori multiplicity selection is applied. Given the numerical complexity of sampling these configurations on a 2+1 dimensional lattice (two transverse directions and rapidity), this approach is very inefficient in probing the high multiplicity tail, as most of the generated configurations are close to the most probable one.

One of the goals of this proposal is to develop a theoretical high multiplicity "trigger", i.e. the reweighting technique providing efficient access to the high multiplicity tail.

Small-x evolution

Apart from the general advantage of having a semi-analytic solution, the dilute-dense expansion or knowing the function f_i and h_i (see Eqs. (2) and (5)) can facilitate the inclusion of small-x evolution corrections [14–17, 19–21, 76–78]. Presently, in this framework the small-x evolution has not been accounted for with a rare exception of single inclusive gluon production, see e.g. in Ref. [75]. Usually, the dependence on x is approximated by the IP-SAT model [13, 79], which solves the leading order DGLAP (Dokshitzer–Gribov–Lipatov–Altarelli–Parisi) gluon evolution (neglecting its coupling to quarks) with analytically parametrized x dependence at an initial transverse scale μ_0. This approach provides a flexible and numerically simple method to the phenomenology. Nonetheless, incorporating actual non-linear small x evolution is essential to study physics of high partonic densities and to extract phenomenological results from first principles. Doing so in the framework of JIMWLK (Jalilian-Marian–Iancu–McLerran–Weigert–Leonidov–Kovner) equation [14–17] is one of the goals of this project. The JIMWLK equation is a functional integro-differential equation describing evolution of the distribution of Wilson lines (or, alternatively, color sources) in a hadron. At the leading order, JIWMLK equations can be rewritten in the Fokker-Planck form [80] and thus it can be also reformulated as a Langevin equation describing a generalized Brownian motion of the Wilson line. Owing to its complexity, no analytic solution of the JIMWLK equation exists. Its solution has been obtained only numerically, using lattice gauge theory methods for the Langevin form of JIMWLK equation.

At next-to-leading order (NLO), the JIMWLK equation does not allow for a straightforward reformulation in the Langevin form [81, 82]. This is why the NLO JIMWLK equation has not been solved numerically yet.

Physically small x evolution accounts for soft gluon emission and thus also contributes to multiplicity fluctuations. It is an open question how to incorporate high multiplicity "trigger" in small x evolution (that is how to perform reweighting at each step of small x evolution).

Gluon saturation at an Electron-Ion Collider

Because the final state effects are minimal in e-A collisions, the small x saturation/CGC framework can with greater effect be applied to quantifying particle scattering and production at an Electron-Ion Collider. At small x, Deep Inelastic Scattering (DIS) can be described in the so-called color dipole approach [83–86]: the virtual photon emitted by the incoming electron splits into quark and anti-quark. This pair scatters off the target. The scattering is treated in the eikonal approximation. These approach can be used for a wide variety of inclusive and semi-inclusive processes along with smoking gun signatures of gluon saturation: suppression of dihadron correlations and diffraction, in particular diffractive meson production (see most recent study in Ref. [87] and Ref. [88] for a comprehensive review).

One of the processes which received our attention is dijet (a jet pair) production in DIS. And although in the saturation/CGC formalism the color dipole approach is the most natural, it is important to mention, that in the correlations limit [1] it was shown that the saturation/CGC frame-

[1] The correlation limit is the limit of almost back-to-back jets [89, 90].

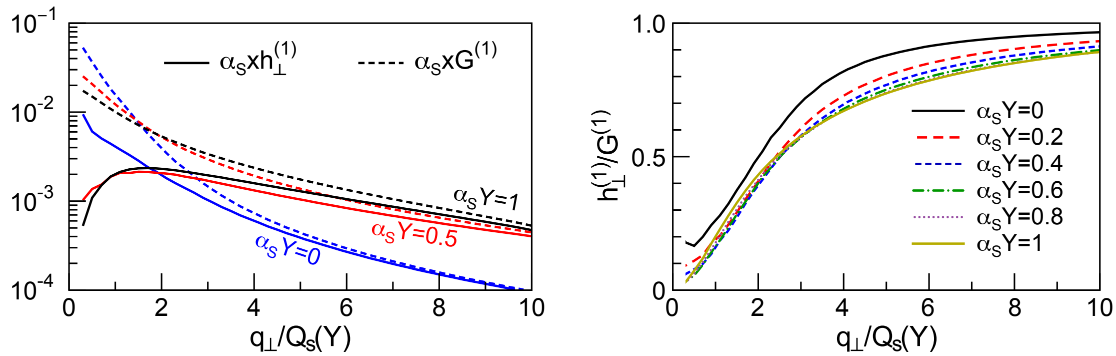

Figure 2: $xG^{(1)}(x,q_\perp^2)$ and $xh^{(1)}(x,q_\perp^2)$ WW gluon distributions versus transverse momentum $q_\perp$ at different rapidities $Y = \log x_0/x$. $Q_s(Y)$ is the saturation momentum. The computations are performed at fixed α_s [95]. The degree of gluon linear polarization is limited by the saturation of positivity bound and is maximal at high transverse momentum (dijet momentum imbalance).

work yields the same result for the dijet production cross section as the one obtained within the Transverse Momentum Dependent (TMD) factorization framework [91–93] at small x [89, 94].

Both approaches universally demonstrated that dijet production depends on the Weizsäcker-Williams (WW) transverse-momentum-dependent gluon distribution. The TMD parton distributions signify the recent progress achieved in developing frameworks to extend our understanding of hadron structure beyond the one-dimensional parton distribution function (PDF), as the TMDs depend not only on the longitudinal momentum fraction x, but also on the transverse momentum and therefore contain more detailed information on the internal structure of hadrons relative to PDFs. Quark TMDs are the most studied, while the available studies of gluon TMDs are rather sparse. In particular, the WW gluon distribution still awaits its experimental determination; also theoretically little had been known about the evolution of the distribution at small x before Ref. [95] where PI and coauthors conducted the first small x computation of both components for the WW gluon distribution: unpolarized and polarized one, see Fig 2. Both components can be accessed through measuring azimuthal anisotropies in processes such as dijet production in e+p and e+A scattering. The linearly polarized gluon distribution causes a nontrivial azimuthal angular $\cos 2\phi$ dependence of the dijet cross section, as we illustrate by the leading order in α_s cross-section for inclusive production of a $q+\bar{q}$ dijet in high energy deep inelastic scattering of a longitudinally [2] polarized virtual photon γ^* off a proton or nucleus is given by [89, 94]

$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A\to q\bar{q}X}}{d^3k_1 d^3k_2 d^2b} = \alpha_{em} e_q^2 \alpha_s \delta(1-z-\bar{z})\, z^2 \bar{z}^2 \frac{8\epsilon_f^2 P_\perp^2}{(P_\perp^2+\epsilon_f^2)^4} \left[xG^{(1)}(x,q_\perp) + \cos(2\phi)\, xh_\perp^{(1)}(x,q_\perp) \right]. \quad (7)$$

Here ϕ is the angle between the total momentum ($P_\perp$) of dijet and the momentum imbalance ($q_\perp$). The feasibility of extracting the azimuthal anisotropy was consider in the proof of principle analysis of Ref. [96], where by doing Monte-Carlo simulations we showed that with some experimental effort the WW gluon distributions can be successfully extracted, see Fig. 3.

The small x saturation/CGC formalism provides access to dijet production beyond the cor-

[2]The cross section for the transversely polarized virtual photon can be found in Refs. [89, 94].

relation limit [89]; we illustrate this for the longitudinally polarized virtual photon (c.f. Eq. (7)):

$$\frac{d\sigma^{\gamma_L^* A\to q\bar{q}X}}{d^2k_1 dz_1 d^2k_2 dz_2} = 8N_c\alpha_{em}e_q^2(2\pi)^2\delta(1-z-\bar{z})z\bar{z}\epsilon_f^2\int\frac{d^2u}{(2\pi)^2}\frac{d^2u'}{(2\pi)^2}e^{-i\vec{P}_\perp\cdot(\vec{u}_\perp-\vec{u}'_\perp)}K_0(\epsilon_f u)K_0(\epsilon_f u') \tag{8}$$

$$\times\frac{1}{N_c}\left[N_c+\underbrace{\langle\mathrm{Tr}\,U^\dagger(\vec{x}_{2\perp})U(\vec{x}_{1\perp})U^\dagger(\vec{x}_1{}'_\perp)U(\vec{x}_2{}'_\perp)\rangle_x}_{\text{quadrupole}}-\underbrace{\langle\mathrm{Tr}\,U^\dagger(\vec{x}_{2\perp})U(\vec{x}_{1\perp})\rangle_x}_{\text{dipole}}-\underbrace{\langle\mathrm{Tr}\,U^\dagger(\vec{x}_1{}'_\perp)U(\vec{x}_2{}'_\perp)\rangle_x}_{\text{dipole}}\right].$$

Here $\vec{u}_\perp=\vec{x}_{1\perp}-\vec{x}_{2\perp}$ and $\vec{u}'_\perp=\vec{x}_1{}'_\perp-\vec{x}_2{}'_\perp$ and the angular brackets represent averages over the target configurations. As we can see in Eq. (9), the production cross section cannot be expressed in terms of gluon TMDs but rather involve two- and four-point fundamental Wilson line (U) correlators in coordinate space. Using the general saturation/CGC framework results, we estimated the amplitude of the azimuthal $\langle\cos 4\phi\rangle$ dependence in Ref. [97]; it involved a new gluon TMD, i.e. it was not reducible to known gluon distribution. Besides higher order harmonics, corrections to the correlation limit also modify the angular independent amplitude and the amplitude of $\langle\cos 2\phi\rangle$ anisotropy. This means that the corrections may also propagate to the observable azimuthal anisotropy. They are controlled by the ratio $q_\perp^2/P_\perp^2$ [97]. At an EIC, given statistical and collision energy limitations, the kinematic range for the momentum imbalance and the total dijet momentum is rather narrow; at best we could hope to get the ratio of $1/4$. This means that higher order corrections at an EIC can be phenomenologically important. This necessitates numerical estimates of these corrections and implementation of the full saturation/CGC formalism result, i.e. including the full quadrupole contribution. This is one of the aims of this proposal.

We note that similar structures involving dipole and quadrupole terms appear in single and double inclusive production in the leading order of dilute-dense expansion in p-A and high multiplicity p-p collisions, see Eq. (3) and the discussion on h_1 after Eq. (5). This illustrates an importance of a common framework to particle production and scattering in p-p/A and e-A.

Besides extending and improving the dijet analysis, the application of the developed framework to the smoking gun signatures of saturation in e-A collisions such as diffractive scattering/production and dihadron correlations [88] is also one of the goals of this project.

3.2 Detailed goals and methods

Our main goal is to provide a unified systematic first-principle based description of initial-state effects and particle production/scattering in p-A, high-multiplicity p-p, e-A and ultra pe-

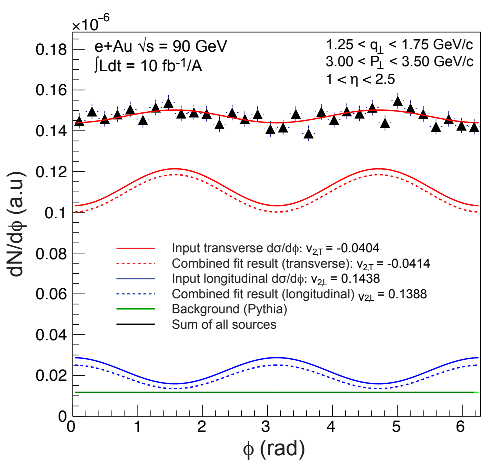

Figure 3: Result of a fit of combined signal and background to a data sample obtained in $\sqrt{s}=90$ GeV e+A collisions with an integrated luminosity of 10 fb^{-1}/A. The results indicate that a proper measurement of the linearly polarized gluon distribution will require integrated luminosities of at least 20 fb^{-1}/A or more. Hence, this measurement would be a multi-year program assuming that an EIC initially starts off with luminosities around 10^{33} cm^{-2} s^{-1}. See details in Ref. [96]

ripheral p/A-A collisions. The ultimate goal is to write and publish an open source simulation code based on the same saturation/CGC framework and the same set of parameters across different colliding systems.

The main milestones to be reached are listed below:

- Derivation of the first saturation correction to the leading order dilute-dense approximation for single and double inclusive gluon production, i.e. f_2 of Eq. (2) and h_2 of Eq. (5) correspondingly. Previously, the PI with collaborators derived the momentum odd contribution to the double inclusive production, h_2, see Eq. (5), in two different gauges: first in the Fock-Schwinger gauge (this gauge is formulated in the coordinate space), see Ref. [64] and then in the global light-cone gauge, see Ref. [49].

  It may be straightforward, although technically difficult to derive complete results for f_2 and h_2 in the light-cone gauge. Thus, instead, our approach will be based on the Fock-Schwinger gauge, where higher order corrections can be obtained by iteratively solving classical Yang-Mills equation [57, 64] with appropriate boundary conditions [98]. The form of the result in the Fock-Schwinger gauge is usually the most convenient for further numerical analysis on the lattice [49]. If we confront with unforeseen difficulties in the Fock-Schwinger gauge, we will be able to perform analytics in the light-cone gauge.

  As was repeatedly pointed out in Refs. [65, 66], the knowledge of the first saturation corrections, f_2 and h_2, is required to estimate systematic uncertainties of the dilute-dense approximation and, potentially, extend the range of applicability of the dilute-dense expansion to higher gluon densities in the projectile. Also, higher order corrections may potentially reveal new non-trivial multi-gluon effects in two particle correlation patterns.

  We will also explore if higher order corrections, f_2 and h_2 can be written in approximately $k_\perp$-factorized form as was previously done for the leading order dilute-dense expansion of the double inclusive production [99].

- Developing reweighting for high multiplicity. A posteriori multiplicity selection is not well suited to probe extremely high multiplicity events. This necessitates establishing an appropriate a priori reweighting techniques. Based on the insights we gained by computing gluon multiplicity distribution in a dilute projectile [71, 74, 75], our goal is to develop a reweighting which would allow us to access the high-multiplicity tail; we will use this technique to compute multiparticle correlations and nuclear modification factor.

- Accounting for small x evolution for particle production and correlations. Application of the framework in the wide range of energies from RHIC and an EIC to the LHC requires inclusion of small x evolution. The dilute-dense approximation allows straightforward numerical implementation of the evolution, which we will account for using the leading order JIMWLK equation.

  Along with this we will consider two high risk problems detailed below. We want to stress that success of this project does not rely on solving them.

  - We plan to explore the possibility of reformulating the NLO JIMWLK in the Langevin form and solving it numerically. It is possible that the reweighting method developed in the course of this project will facilitate projection of each evolution step of the leading order JIMWLK to NLO. These ideas are only in its inception and will be considered in details during the implementation of this stage of the project.

  - From the result of Refs. [49, 64], it appears that the presence of transverse momentum odd correlations in double inclusive production cross section requires some degree of final state interactions (although this statement may be gauge-dependent). It is thus important to understand if there are transverse momentum odd correlations in the *incoming* hadron wave function at small x before scattering and particle production. PI and collaborators explored this in an adhoc JIMWLK-motivated wave function in Ref. [100]; to improve these calculations we will consider the hadron wave function derived from JIMWLK under controlled approximations.

- Implementing the following key improvements to the Monte-Carlo dijet event generator (MCDijet) for an EIC [96]:

  - incorporating event-by-event nucleon position fluctuations in nuclear target;
  - studying correlations between dijet production and gluon multiplicity fluctuations in the nuclear target; this might provide a realistic experimental probe of WW gluon distribution in rare configurations of the nucleus/proton;
  - incorporating corrections to the correlation limit and simulations with complete quadrupole contribution to dijet production;
  - taking into account Sudakov corrections (similar to analysis of Ref. [101]);
  - probing model dependence with different color sources distributions besides commonly used McLerran-Venugopalan (MV) model [68]. Usually the initial conditions for JIMWLK evolution are taken following the MV model which is rigorously formulated only for large nuclei at small x. For a proton at moderate and large x, the color charge distribution can be quite different from the MV model. As was shown in a recent paper [102], a standard light front Hamiltonian framework [103] can be used to compute color charge distribution in nucleons and nuclei [3] ; we want to implement this color distribution to test model dependence of the results and provide better estimates on dijet production at an EIC in a wide range of the targets' atomic number.

  These improvements are required in order to provide a realistic description of DIS dijet production at an EIC.

  Additionally, we plan to extend MCDijet to ultra peripheral collision (UPC) at hadron colliders, such as RHIC and, especially, the LHC. At very large impact-parameters between colliding hadrons the long range electromagnetic force becomes dominant over short-range QCD allowing for the dipole approach to dijet production in UPC. One significant difference compared to DIS is that, for the UPC kinematics, the photon virtuality is negligible; this leads to a vanishing amplitude in front of the linearly polarized gluon distribution $xh_{\perp}^{(1)}$ (see e.g. [90]), but the unpolarized gluon distribution, $xG^{(1)}$, can be extracted. We plan to conduct the realistic feasibility study of extracting $xG^{(1)}$ in UPC by a) replacing the electron's

[3] On the subject of light front quark model, we will tap into the expertise of a local nuclear theorist: Chueng-Ryong Ji.

photon fluxes with that from a proton or nucleus, as detailed in Ref. [104] and b) extending the range of accessible x towards smaller values probed by the LHC.

We also plan to modify MCDijet event generator to simulate the suppression of dihadron correlations and diffractive meson production (beyond IP-SAT-based approach of Ref. [105]).

- Application to phenomenology of p-p, p-A and e-A collisions. In particular, we are interested in extracting the following observables
  - Three-gluon correlations to explore if the framework's systematics is similar to the STAR measurements in peripheral A-A collisions [106, 107];
  - Four particle correlations and integrated and differential $v_n\{4\}$ as a function of multiplicity and collision energy;
  - Nuclear modification factor with multiplicity bias, so-called Q_{pA} [108];
  - Systematics of Dijet Production at an EIC and UPC: dependence on the atomic number, energy dependence, prediction for high order harmonics of azimuthal anisotropy, feasibility check of extracting correlation between dijet production and forward nucleus going multiplicity, as a probe of biased WW gluon distribution, crystallizing the role of gluon saturation in dijet observables.

3.3 Timeline

The targeted due dates for the deliverables are indicated in quarter year increments: e.g., Q4 refers to delivery one year after the project funding begins, and Q12 refers to the end of the three-year project.

1. Tasks oriented towards e-p/A and ultra-peripheral p-A and A-A collisions
   - Extension of MCDijet, Monte-Carlo generator for dijet production, to UPC (Q6)
     - Extending small x evolution to cover LHC energy range, incorporating running coupling corrections (Q2)
     - Incorporating nucleon position fluctuations in nuclear wave function (Q4)
     - Publishing the event generator MCDijet for UPC (Q6)
   - Rare nuclear wave function configurations and dijet production (Q8)
     - Light front quark model for nucleon wave function in e-p collisions (Q2)
     - Incorporating nucleon position fluctuations in nuclear wave function (Q3)
     - Inclusion of Sudakov corrections and estimating their importance (Q6)
     - Complete quadrupole contribution to dijet production (Q8)

1. Tasks oriented towards p-p and p-A collisions
   - Theoretical development for p-A collisions (Q10)
     - Complete result for single and double gluon production with first saturation correction (Q4)
     - High-multiplicity reweighting (Q10)

- Numerical simulations and publishing final version of the code (Q12)
  - Role of complete first saturation correction on event-by-event number of gluon distribution and on even harmonics, v_{2n} (Q5)
  - Inclusion of small-x evolution (Q7)
  - Numerical simulations with high multiplicity trigger (Q11)
  - Application to phenomenology (Q1-Q12)

4 Proposed Research: Entanglement and full density matrix

4.1 Background

A key property distinguishing quantum systems from classical ones is the entanglement of otherwise distinct degrees of freedom. Due to entanglement of certain degrees of freedom (e.g. soft/semi-hard gluons) with the rest of a quantum system (e.g. valence color charges), their description is not possible by a pure state. Rather, the most complete description of a subsystem is via the reduced density matrix obtained by tracing over the degrees of freedom in the complement. Recently, these ideas were considered in the context of small x physics both in momentum [32] (see Ref. [109] for an approach using the AdS/CFT correspondence) and coordinate spaces [33, 35]. It was suggested that, in hadronic collisions, the apparent thermal nature of the produced soft particle spectra might originate from entanglement between the different degrees of freedom in the hadronic wave function; that is the complement hadronic degrees of freedom are entangled by those measured in experiments and thus serve as an effective thermal bath.

The calculations of the momentum entanglement between the valence color charges and soft gluons field of Ref. [32] were performed only in the framework of the MV model and require an extension to account for small x evolution.

All calculations in high-energy hadronic collisions were performed assuming that the density matrix in the basis of valence charge density is diagonal. This assumption is manifest in the MV model. Computing off diagonal components might be a missing link to understanding hadronic wave function.

4.2 Detailed goals and methods

The main idea in computing the off-diagonal component of the density matrix in the basis of valence charge density is that there should be a nontrivial correlation between the profile of the charge density and the current density in the hadronic wave function at high energy. By repeating the JIMWLK derivation, we plan to extract evolution for the full density matrix including the off-diagonal components. We plan to investigate the evolution numerically and to analytically study high-energy fixed point in the non-local Gaussian approximation.

The full density matrix can be generalized by considering the valence charge densities at different rapidities, thus giving access to the evolution of the entanglement entropy.

4.3 Timeline

Momentum entanglement in hadronic wave function

1. Full density matrix in the basis of valence charge density

   - Small-x evolution of full density matrix (Q6)
     - Deriving evolution equation (Q2)

    - Gaussian approximation and application to small-x phenomenology (Q4)
    - Relation to high-multiplicity events and correlation between large and small x components of the hadronic wave function (Q6)
- Small-x evolution of entanglement entropy (Q10)
    - Deriving small-x evolution; establishing connection to Liouville effective action (Q7)
    - Solving small-x evolution on lattice (Q8)
    - Phenomenological applications (Q10)

5 Proposed Research: Quantum statistics at small x

5.1 Background and motivation

Although the quantum statistic effects are exuberant at small x, only recently their significance was recognized in observables. In particular, for gluons, three sources of multiparticle correlations were rigorously established at small x: – Bose enhancement, – Hanbury Brown-Twiss (HBT), and classical effects due to scattering off a domain with spontaneous rotational symmetry breaking of the direction of color field [110–112]. It was shown that two genuinely quantum effects dominate over the classical one almost in the entire phenomenologically relevant kinematic range [30]. Specifically, it was demonstrated that the ridge correlations at small x are due mostly to gluon Bose enhancement and HBT [49, 61–63, 99, 113]; also it was recently identified that gluon Bose enhancement is responsible for the high multiplicity tail in p-A collisions [30]. Finally, it was shown that Fermi statistics may lead to non-trivial effects at small x [114–116] and potentially be responsible for a significant background contribution to the Chiral Magnetic Effect [117]. The latter was established only on the level of particle correlations in the incoming projectile wave function; quite recently the saturation/CGC framework was applied to derive semi-analytic equations describing three particle correlations, including the CME observable [118]. Numerical calculations of these correlations have not yet been performed and currently we can only speculate how large this contribution is in p-A and A-A collisions. One of the goals of this project is to numerically extract CME correlator in dilute-dense saturation/CGC framework and to asses its phenomenological importance for CME studies.

Quantum statistics might be responsible not only for the intriguing observation of three particle CME-like correlations in p-A collisions, but also for an observed near-side baryon–baryon anti-correlation structure in p-p collisions [45] at the LHC. Currently, the description of this effect presents a challenge to all Monte-Carlo models, and its origin is an open question. Exploratory studies to test if these anti-correlations are related to parton statistics at small x will be conducted in the project.

5.2 Detailed goals and methods

Here, the main goal is to elucidate the role of quantum statistics effects at small x by conducting analytical and numerical analysis of quark and gluon production and correlations. The main milestones are

- By conducting numerical simulation of deuteron-A collision on the lattice, test the hypothesis that high multiplicity tail is dominated by configurations of the deuteron with the overlapping nucleons in the transverse direction [30, 65]. The foundation of this hypothesis is based on gluon Bose enhancement in the projectile [65].

- To implement a realistic wave function for the *polarized* deuteron. Due to an admixture of the D-wave state in the deuteron wave function (see e.g. Ref. [119]), the direction of deuteron polarization defines the spatial anisotropy of deuteron. Thus polarized deutron-nucleus collisions at high energy provide unique testing ground for measuring effects of quantum statistics that are sensitive to the deuteron wave function – including Bose enhancement and HBT. Additionally the polarized deuteron collisions provide the knowledge of the initial eccentricity and a good handle on the reaction plane orientation; this may facilitate disentangling and testing the role of initial and final state effects in driving azimuthal anisotropy in d-A collisions.

- To test numerically the saturation/CGC predictions in polarized d-A collisions, in particular: – that the longitudinal deuteron polarization leads to greater multiplicity fluctuations than the transverse deuteron polarization, – that two gluon correlations are stronger along the axis polarization due to gluon HBT. Assessing if this effect can be experimentally measured.

- To implement quark production in the framework. Applying the framework to extract numerically: – the background contribution to the Chiral Magnetic Effect, i.e. the three particle charge-dependent correlator, – the quark–quark and quark–anti-quark correlation function and explore if it may be responsible for the observed baryon-baryon rapidity anti-correlation.

- To provide a realistic initial baryon number distribution in the coordinate space for further hydrodynamic evolution in A-A collisions.

Utilizing the results of the above research, complemented by that conducted previously, we plan to write a comprehensive review on the quantum statistics effects at small x.

5.3 Timeline

1. Exploring role of quantum statistics at small x

    - Investigating the role of gluon quantum statistics (Q8)
        - Numerical simulations of d-A collisions: role of Bose enhancement (Q2)
        - Polarized d wave function and two gluon correlations as a test of quantum statistics effects and collectivity (Q8)
    - Investigating the role of quark statistics (Q10)
        - Implementing quark degrees of freedom in numerical simulations (Q5)
        - Computing 2- and 3-particle correlations involving quark degrees of freedom (Q8)
        - Computing tables of the initial baryon number distribution for further hydrodynamical evolution in A-A collisions (Q10)

End of proposal narrative; supplemental materials to follow.

6 Data Management Plan

We will follow the below protocol:

- The published data will be distributed as supplementary material for each published manuscript in a widely used format, e. g. ASCII or tab-delimited format. Instructional material will be provided in the manuscripts and in text form along with the data. The data will be strictly in standard, non-proprietary file formats to facilitate data sharing.
- For each published manuscript, in case of large data files, the PI will make copies of data available to co-investigators, students, and others by request within 30 days of receipt of the request.
- The simulation code will be developed in C++, Python and Julia, the data processing scripts will be written using sed and awk. Every piece of written software or script will be provided to the public in source code format for non-commercial use under GNU General Public License (GPL). For each code made available, a user's manual will be provided with instructions for compiling the source codes, installing and running the codes, formulating input data streams, and visualizing the output. Documentation will be in PDF format. Source codes will be published on the North Carolina State University GitHub web page `https://github.ncsu.edu`.
- For all of the numerical simulations, representative input files will be kept along with the sources codes. Sample output files will also be provided when possible.

7 Student Tracking Information

Student	Date Entered Grad. School	Date Joined Group	Degree Program	Date Degree Expected	Advisor
Gregory Johnson	August 2017	July 2018	Ph.D.	May 2022	Skokov
Haowu Duan	August 2017	August 2018	Ph.D.	May 2022	Skokov

8 Literature Cited

[1] E. Shuryak, *Heavy ion reaction from nuclear to quark matter. Proceedings, International School of Nuclear Physics, 25th Course, Erice, Italy, September 16-24, 2003*, Prog. Part. Nucl. Phys. **53**, 273 (2004), arXiv:hep-ph/0312227 [hep-ph].

[2] E. V. Shuryak, *Quark gluon plasma. New discoveries at RHIC: A case of strongly interacting quark gluon plasma. Proceedings, RBRC Workshop, Brookhaven, Upton, USA, May 14-15, 2004*, Nucl. Phys. **A750**, 64 (2005), arXiv:hep-ph/0405066 [hep-ph].

[3] J. Adams *et al.* (STAR), Nucl. Phys. **A757**, 102 (2005), arXiv:nucl-ex/0501009 [nucl-ex].

[4] H. Song, S. A. Bass, U. Heinz, T. Hirano, and C. Shen, Phys. Rev. Lett. **106**, 192301 (2011), [Erratum: Phys. Rev. Lett.109,139904(2012)], arXiv:1011.2783 [nucl-th].

[5] T. Schäfer and D. Teaney, Rept. Prog. Phys. **72**, 126001 (2009), arXiv:0904.3107 [hep-ph].

[6] P. Romatschke and U. Romatschke, (2017), arXiv:1712.05815 [nucl-th].

[7] E. Iancu, A. Leonidov, and L. McLerran, in *QCD perspectives on hot and dense matter. Proceedings, NATO Advanced Study Institute, Summer School, Cargese, France, August 6-18, 2001* (2002) pp. 73–145, arXiv:hep-ph/0202270 [hep-ph].

[8] J. L. Albacete and C. Marquet, Prog. Part. Nucl. Phys. **76**, 1 (2014), arXiv:1401.4866 [hep-ph].

[9] Y. V. Kovchegov and E. Levin, *Quantum Chromodynamics at High Energy* (Cambridge University Press, 2012).

[10] H. Mantysaari and B. Schenke, Phys. Rev. Lett. **117**, 052301 (2016), arXiv:1603.04349 [hep-ph].

[11] H. Mantysaari and B. Schenke, Phys. Rev. **D94**, 034042 (2016), arXiv:1607.01711 [hep-ph].

[12] H. Mantysaari, B. Schenke, C. Shen, and P. Tribedy, Phys. Lett. **B772**, 681 (2017), arXiv:1705.03177 [nucl-th].

[13] H. Kowalski and D. Teaney, Phys. Rev. **D68**, 114005 (2003), arXiv:hep-ph/0304189 [hep-ph].

[14] J. Jalilian-Marian, A. Kovner, and H. Weigert, Phys. Rev. **D59**, 014015 (1998), arXiv:hep-ph/9709432 [hep-ph].

[15] J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, Phys. Rev. **D59**, 014014 (1998), arXiv:hep-ph/9706377 [hep-ph].

[16] E. Iancu, A. Leonidov, and L. D. McLerran, Phys. Lett. **B510**, 133 (2001).

[17] E. Iancu, A. Leonidov, and L. D. McLerran, Nucl. Phys. **A692**, 583 (2001), hep-ph/0011241.

[18] I. Balitsky, Nucl. Phys. **B463**, 99 (1996), arXiv:hep-ph/9509348 [hep-ph].

[19] I. Balitsky, Phys. Rev. **D60**, 014020 (1999), hep-ph/9812311.

[20] Y. V. Kovchegov, Phys. Rev. **D60**, 034008 (1999), hep-ph/9901281.

[21] Y. V. Kovchegov, Phys. Rev. **D61**, 074018 (2000), hep-ph/9905214.

[22] D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nucl. Phys. **A803**, 227 (2008), arXiv:0711.0950 [hep-ph].

[23] M. A. Stephanov, Phys. Rev. Lett. **102**, 032301 (2009), arXiv:0809.3450 [hep-ph].

[24] S. Munier and R. B. Peschanski, Phys. Rev. Lett. **91**, 232001 (2003), arXiv:hep-ph/0309177 [hep-ph].

[25] E. Iancu, A. H. Mueller, and S. Munier, Phys. Lett. **B606**, 342 (2005), arXiv:hep-ph/0410018 [hep-ph].

[26] K. Kutak, Phys. Lett. **B705**, 217 (2011), arXiv:1103.3654 [hep-ph].

[27] E. Mac and E. Ugaz, Z. Phys. **C43**, 655 (1989).

[28] R. S. Bhalerao, Phys. Lett. **B380**, 1 (1996), [Erratum: Phys. Lett.B387,no.4,881(1996)], arXiv:hep-ph/9607315 [hep-ph].

[29] C. Bourrely, J. Soffer, and F. Buccella, Eur. Phys. J. **C23**, 487 (2002), arXiv:hep-ph/0109160 [hep-ph].

[30] A. Kovner and V. V. Skokov, Phys. Rev. **D98**, 014004 (2018), arXiv:1805.09296 [hep-ph].

[31] R. Peschanski, Phys. Rev. **D87**, 034042 (2013), arXiv:1211.6911 [hep-ph].

[32] A. Kovner and M. Lublinsky, Phys. Rev. **D92**, 034016 (2015), arXiv:1506.05394 [hep-ph].

[33] D. E. Kharzeev and E. M. Levin, Phys. Rev. **D95**, 114008 (2017), arXiv:1702.03489 [hep-ph].

[34] E. Shuryak and I. Zahed, Annals Phys. **396**, 1 (2018), arXiv:1707.01885 [hep-ph].

[35] Y. Hagiwara, Y. Hatta, B.-W. Xiao, and F. Yuan, Phys. Rev. **D97**, 094029 (2018), arXiv:1801.00087 [hep-ph].

[36] C. Holzhey, F. Larsen, and F. Wilczek, Nucl. Phys. **B424**, 443 (1994), arXiv:hep-th/9403108 [hep-th].

[37] P. Calabrese and J. L. Cardy, *Workshop on Quantum Entanglement in Physical and Information Sciences Pisa, Italy, December 14-18, 2004*, Int. J. Quant. Inf. **4**, 429 (2006), arXiv:quant-ph/0505193 [quant-ph].

[38] A. Strominger, (2017), arXiv:1703.05448 [hep-th].

[39] M. Pate, A.-M. Raclariu, and A. Strominger, Phys. Rev. Lett. **119**, 261602 (2017), arXiv:1707.08016 [hep-th].

[40] A. Ball, M. Pate, A.-M. Raclariu, A. Strominger, and R. Venugopalan, (2018), arXiv:1805.12224 [hep-ph].

[41] V. Khachatryan *et al.* (CMS), JHEP **01**, 079 (2011), arXiv:1011.5531 [hep-ex].

[42] G. Aad *et al.* (ATLAS), New J. Phys. **13**, 053033 (2011), arXiv:1012.5104 [hep-ex].

[43] R. Aaij *et al.* (LHCb), Eur. Phys. J. **C74**, 2888 (2014), arXiv:1402.4430 [hep-ex].

[44] S. Acharya *et al.* (ALICE), Eur. Phys. J. **C77**, 852 (2017), arXiv:1708.01435 [hep-ex].

[45] J. Adam *et al.* (ALICE), Eur. Phys. J. **C77**, 569 (2017), arXiv:1612.08975 [nucl-ex].

[46] B. Abelev *et al.* (ALICE), Phys. Rev. Lett. **110**, 082302 (2013), arXiv:1210.4520 [nucl-ex].

[47] G. Aad *et al.* (ATLAS), Phys. Lett. **B748**, 392 (2015), arXiv:1412.4092 [hep-ex].

[48] G. Aad *et al.* (ATLAS), Phys. Lett. **B756**, 10 (2016), arXiv:1512.00197 [hep-ex].

[49] Y. V. Kovchegov and V. V. Skokov, Phys. Rev. **D97**, 094021 (2018), arXiv:1802.08166 [hep-ph].

[50] Y. V. Kovchegov, Phys. Rev. **D54**, 5463 (1996), hep-ph/9605446.

[51] Y. V. Kovchegov, Phys. Rev. **D55**, 5445 (1997), hep-ph/9701229.

[52] A. Krasnitz and R. Venugopalan, Phys. Rev. Lett. **84**, 4309 (2000), hep-ph/9909203.

[53] A. Krasnitz, Y. Nara, and R. Venugopalan, Nucl. Phys. **A727**, 427 (2003), hep-ph/0305112.

[54] T. Lappi, Phys. Rev. **C67**, 054903 (2003), hep-ph/0303076.

[55] J. P. Blaizot, T. Lappi, and Y. Mehtar-Tani, Nucl. Phys. **A846**, 63 (2010), arXiv:1005.0955 [hep-ph].

[56] Y. V. Kovchegov and A. H. Mueller, Nucl. Phys. **B529**, 451 (1998), arXiv:hep-ph/9802440 [hep-ph].

[57] A. Dumitru and L. D. McLerran, Nucl. Phys. **A700**, 492 (2002), arXiv:hep-ph/0105268 [hep-ph].

[58] I. Balitsky, Phys. Rev. **D70**, 114030 (2004), arXiv:hep-ph/0409314.

[59] G. A. Chirilli, Y. V. Kovchegov, and D. E. Wertepny, JHEP **03**, 015 (2015), arXiv:1501.03106 [hep-ph].

[60] A. Kovner and M. Lublinsky, Int. J. Mod. Phys. **E22**, 1330001 (2013), arXiv:1211.1928 [hep-ph].

[61] Y. V. Kovchegov and D. E. Wertepny, Nucl. Phys. **A906**, 50 (2013), arXiv:1212.1195 [hep-ph].

[62] T. Altinoluk, N. Armesto, A. Kovner, and M. Lublinsky, (2018), arXiv:1805.07739 [hep-ph].

[63] A. Kovner and V. V. Skokov, (2018), arXiv:1805.09297 [hep-ph].

[64] L. McLerran and V. Skokov, Nucl. Phys. **A959**, 83 (2017), arXiv:1611.09870 [hep-ph].

[65] M. Mace, V. V. Skokov, P. Tribedy, and R. Venugopalan, (2018), arXiv:1805.09342 [hep-ph].

[66] M. Mace, V. V. Skokov, P. Tribedy, and R. Venugopalan, (2018), arXiv:1807.00825 [hep-ph].

[67] T. Liou, A. H. Mueller, and S. Munier, Phys. Rev. **D95**, 014001 (2017), arXiv:1608.00852 [hep-ph].

[68] L. D. McLerran and R. Venugopalan, Phys. Rev. **D49**, 2233 (1994), arXiv:hep-ph/9309289 [hep-ph].

[69] L. D. McLerran and R. Venugopalan, Phys. Rev. **D49**, 3352 (1994), arXiv:hep-ph/9311205 [hep-ph].

[70] E. Iancu, K. Itakura, and L. McLerran, Nucl. Phys. **A708**, 327 (2002), hep-ph/0203137.

[71] A. Dumitru and V. Skokov, Phys. Rev. **D96**, 056029 (2017), arXiv:1704.05917 [hep-ph].

[72] C. Marquet, G. Soyez, and B.-W. Xiao, Phys. Lett. **B639**, 635 (2006), arXiv:hep-ph/0606233 [hep-ph].

[73] E. Iancu and L. McLerran, Nucl. Phys. **A793**, 96 (2007), arXiv:hep-ph/0701276 [HEP-PH].

[74] A. Dumitru and V. Skokov, *Proceedings, 47th International Symposium on Multiparticle Dynamics (ISMD2017): Tlaxcala, Mexico, September 11-15, 2017*, EPJ Web Conf. **172**, 03009 (2018), arXiv:1710.05041 [hep-ph].

[75] A. Dumitru, G. Kapilevich, and V. Skokov, Nucl. Phys. **A974**, 106 (2018), arXiv:1802.06111 [hep-ph].

[76] E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, Sov. Phys. JETP **45**, 199 (1977).

[77] I. Balitsky and L. Lipatov, Sov.J.Nucl.Phys. **28**, 822 (1978).

[78] I. Balitsky, *Proceedings, 5th International Workshop on Deep Inelastic Scattering and QCD (DIS 97): Chicago, Illinois, April 14-18, 1997*, AIP Conf. Proc. **407**, 953 (1997), arXiv:hep-ph/9706411 [hep-ph].

[79] A. H. Rezaeian, M. Siddikov, M. Van de Klundert, and R. Venugopalan, Phys. Rev. **D87**, 034002 (2013), arXiv:1212.2974 [hep-ph].

[80] H. Weigert, Nucl. Phys. **A703**, 823 (2002), hep-ph/0004044.

[81] A. Kovner, M. Lublinsky, and Y. Mulian, JHEP **08**, 114 (2014), arXiv:1405.0418 [hep-ph].

[82] I. Balitsky and G. A. Chirilli, Phys.Rev. **D88**, 111501 (2013), arXiv:1309.7644 [hep-ph].

[83] J. F. Gunion and D. E. Soper, Phys. Rev. **D15**, 2617 (1977).

[84] S. Nussinov, Phys. Rev. Lett. **34**, 1286 (1975).

[85] S. Nussinov, Phys. Rev. **D14**, 246 (1976).

[86] C. Marquet, B.-W. Xiao, and F. Yuan, Phys. Lett. **B682**, 207 (2009), arXiv:0906.1454 [hep-ph].

[87] H. Mäntysaari and R. Venugopalan, Phys. Lett. **B781**, 664 (2018), arXiv:1712.02508 [nucl-th].

[88] E. C. Aschenauer, S. Fazio, J. H. Lee, H. Mantysaari, B. S. Page, B. Schenke, T. Ullrich, R. Venugopalan, and P. Zurita, (2017), arXiv:1708.01527 [nucl-ex].

[89] F. Dominguez, C. Marquet, B.-W. Xiao, and F. Yuan, Phys.Rev. **D83**, 105005 (2011), arXiv:1101.0715 [hep-ph].

[90] F. Dominguez, J.-W. Qiu, B.-W. Xiao, and F. Yuan, Phys.Rev. **D85**, 045003 (2012), arXiv:1109.6293 [hep-ph].

[91] P. J. Mulders and J. Rodrigues, Phys. Rev. **D63**, 094021 (2001), arXiv:hep-ph/0009343 [hep-ph].

[92] C. J. Bomhof, P. J. Mulders, and F. Pijlman, Eur. Phys. J. **C47**, 147 (2006), arXiv:hep-ph/0601171 [hep-ph].

[93] S. Meissner, A. Metz, and K. Goeke, Phys. Rev. **D76**, 034002 (2007), arXiv:hep-ph/0703176 [HEP-PH].

[94] A. Metz and J. Zhou, Phys.Rev. **D84**, 051503 (2011), arXiv:1105.1991 [hep-ph].

[95] A. Dumitru, T. Lappi, and V. Skokov, Phys. Rev. Lett. **115**, 252301 (2015), arXiv:1508.04438 [hep-ph].

[96] A. Dumitru, V. Skokov, and T. Ullrich, (2018), arXiv:1809.02615 [hep-ph].

[97] A. Dumitru and V. Skokov, Phys. Rev. **D94**, 014030 (2016), arXiv:1605.02739 [hep-ph].

[98] A. Kovner, L. D. McLerran, and H. Weigert, Phys. Rev. **D52**, 3809 (1995), hep-ph/9505320.

[99] Y. V. Kovchegov and D. E. Wertepny, Nucl.Phys. **A925**, 254 (2014), arXiv:1310.6701 [hep-ph].

[100] A. Kovner, M. Lublinsky, and V. Skokov, Phys. Rev. **D96**, 016010 (2017), arXiv:1612.07790 [hep-ph].

[101] L. Zheng, E. C. Aschenauer, J. H. Lee, and B.-W. Xiao, Phys. Rev. **D89**, 074037 (2014), arXiv:1403.2413 [hep-ph].

[102] A. Dumitru, G. A. Miller, and R. Venugopalan, (2018), arXiv:1808.02501 [hep-ph].

[103] S. J. Brodsky, H.-C. Pauli, and S. S. Pinsky, Phys.Rept. **301**, 299 (1998), arXiv:hep-ph/9705477 [hep-ph].

[104] S. R. Klein and J. Nystrand, Phys. Rev. Lett. **84**, 2330 (2000), arXiv:hep-ph/9909237 [hep-ph].

[105] T. Toll and T. Ullrich, Phys. Rev. **C87**, 024913 (2013), arXiv:1211.3048 [hep-ph].

[106] L. Adamczyk *et al.* (STAR), (2017), arXiv:1701.06496 [nucl-ex].

[107] L. Adamczyk *et al.* (STAR), (2017), arXiv:1701.06497 [nucl-ex].

[108] J. Adam *et al.* (ALICE), Phys. Rev. **C91**, 064905 (2015), arXiv:1412.6828 [nucl-ex].

[109] Y. Liu and I. Zahed, (2018), arXiv:1803.09157 [hep-ph].

[110] A. Dumitru, L. McLerran, and V. Skokov, Phys. Lett. **B743**, 134 (2015), arXiv:1410.4844 [hep-ph].

[111] A. Dumitru and V. Skokov, Phys. Rev. **D91**, 074006 (2015), arXiv:1411.6630 [hep-ph].

[112] A. Dumitru, A. V. Giannini, and V. Skokov, (2015), arXiv:1503.03897 [hep-ph].

[113] T. Altinoluk, N. Armesto, G. Beuf, A. Kovner, and M. Lublinsky, Phys. Lett. **B751**, 448 (2015), arXiv:1503.07126 [hep-ph].

[114] T. Altinoluk, N. Armesto, G. Beuf, A. Kovner, and M. Lublinsky, Phys. Rev. **D95**, 034025 (2017), arXiv:1610.03020 [hep-ph].

[115] A. Kovner and A. H. Rezaeian, Phys. Rev. **D96**, 074018 (2017), arXiv:1707.06985 [hep-ph].

[116] A. Kovner and A. H. Rezaeian, Phys. Rev. **D97**, 074008 (2018), arXiv:1801.04875 [hep-ph].

[117] A. Kovner, M. Lublinsky, and V. Skokov, Phys. Rev. **D96**, 096003 (2017), arXiv:1706.02330 [hep-ph].

[118] M. Martinez, M. D. Sievert, and D. E. Wertepny, (2018), arXiv:1808.04896 [hep-ph].

[119] R. Machleidt, Phys. Rev. **C63**, 024001 (2001), arXiv:nucl-th/0006014 [nucl-th].

9 List of Principle Collaborators

Vladimir Skokov:
Bzdak, Adam (AGH-UST),
Dumitru, Adrian (Baruch College),
Friman, Bengt (GSI),
Fukushima, Kenji (Tokyo Uni),
Kharzeev, Dmitri (SBU),
Koch, Volker (LBNL),
Kovchegov, Yuri (OSU),
Kovner, Alex (UConn),
Lappi, Tuomas (Jyvaskyla Uni),
Levai, Peter (Wigner Institute),
Lublinsky, Michael (Ben Gurion U. of Negev),
Mace, Mark (BNL),
McLerran, Larry (INT),
Nakano, Eiji (Kochi Uni),
Nishimura, Hiromichi (RBRC),
Pisarski, Robert (BNL),
Redlich, Krzysztof (Wroclaw),
Tribedy, Prithwish (BNL),
Ullrich, Thomas (Yale),
Venugopalan, Raju (BNL)

10 Biographical Sketches

Vladimir Skokov

Physics Department, College of Sciences
North Carolina State University, Raleigh, NC 27695
Email: vskokov@ncsu.edu

Education and Training

2006 Ph.D., Physics, Joint Institute for Nuclear Researchers, Dubna, Russian Federation

2002 M. Sc., Physics, Saratov State University & Joint Institute for Nuclear Researchers, Russian Federation

Research and Professional Experience

2018–present Assistant Professor, North Carolina State University, Raleigh, NC.

2018–present Fellow, Riken-BNL Research Center, Brookhaven National Laboratory, Upton, NY.

2015–2018 Research Associate, Riken-BNL Research Center, Brookhaven National Laboratory, Upton, NY.

2013–2015 Visiting Assistant Professor (non-tenure), Western Michigan University, Kalamazoo, MI.

2011–2013 Research Associate, Physics Department, Brookhaven National Laboratory, Upton, NY.

2009–2011 Research Associate, GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt, Germany.

Awards

Fellowship
2012, 2017, 2018 EMMI Research Visiting Professor GSI, Darmstadt, Germany

Fellowship
2003, 2005 Bogoliubov-Infeld Fellowship, JINR, Dubna, Russia

Fellowship
2001 Leonard Euler Fellowship, Justus-Liebig-Universitaet, Giessen, Germany

Fellowship
2000 CRDF Grant for Undergraduate Scientific Research, Saratov State University, Russia

Selected Publications

Most pertinent publications for the past three years

M. Mace, V. Skokov, P. Tribedy and R. Venugopalan,
"Hierarchy of azimuthal anisotropy harmonics in collisions of small systems from the Color Glass Condensate,"
Phys. Rev. Lett. **121**, no. 5, 052301 (2018)

A. Kovner and V. Skokov,
"Does shape matter? v_2 vs eccentricity in small x gluon production",
Phys. Lett. B **785**, 372 (2018)

A. Kovner and V. Skokov,
"Bose enhancement, the Liouville effective action and the high multiplicity tail in p-A collisions,"
Phys. Rev. D **98**, no. 1, 014004 (2018)

Y. V. Kovchegov and V. Skokov,
"How classical gluon fields generate odd azimuthal harmonics for the two-gluon correlation function in high-energy collisions,"
Phys. Rev. D **97**, no. 9, 094021 (2018)

A. Dumitru, G. Kapilevich and V. Skokov,
"The small-x gluon distribution in centrality biased pA and pp collisions,"
Nucl. Phys. A **974**, 106 (2018)

A. Kovner, M. Lublinsky and V. Skokov,
"Initial state qqg correlations as a background for the Chiral Magnetic Effect in collision of small systems,"
Phys. Rev. D **96**, no. 9, 096003 (2017)

A. Dumitru and V. Skokov,
"Fluctuations of the gluon distribution from the small-x effective action,"
Phys. Rev. D **96**, no. 5, 056029 (2017)

A. Kovner, M. Lublinsky and V. Skokov,
"Exploring correlations in the CGC wave function: odd azimuthal anisotropy,"
Phys. Rev. D **96**, no. 1, 016010 (2017)

L. McLerran and V. Skokov,
"Odd Azimuthal Anisotropy of the Glasma for pA Scattering,"
Nucl. Phys. A **959**, 83 (2017)

A. Dumitru and V. Skokov,
"$cos(4\phi)$ azimuthal anisotropy in small-x DIS dijet production beyond the leading power TMD limit,"
Phys. Rev. D **94**, no. 1, 014030 (2016)

A. Dumitru, T. Lappi and V. Skokov,
"Distribution of Linearly Polarized Gluons and Elliptic Azimuthal Anisotropy in Deep Inelastic Scattering Dijet Production at High Energy,"
Phys. Rev. Lett. **115**, no. 25, 252301 (2015)

A. Dumitru, L. McLerran and V. Skokov,
"Azimuthal asymmetries and the emergence of "collectivity" from multi-particle correlations in high-energy pA collisions,"
Phys. Lett. B **743**, 134 (2015)

11 Current and Pending Support

Current Support

Title: BEST
Principal Investigator: ???

12 Facilities and Resources

The work will be mainly conducted at North Carolina State University.

The PI joined the nuclear theory group at North Carolina State University, which consists of Chueng-Ryong Ji, Thomas Schäfer, and Mithat Ünsal. North Carolina State also has a strong representation in nuclear astrophysics, led by Carla Fröhlich, Gail McLaughlin, and Jim Kneller. The groups collaborate with the Nuclear Theory Groups at Duke and the University of North Carolina at Chapel Hill. The nuclear theory faculty at Duke includes Steffen Bass, Shailesh Chandrasekharan, Tom Mehen, and Roxanne Springer. The theory group at UNC Chapel Hill consists of Jon Engel, Joaquin Drut and Amy Nicholson.

The NCSU Nuclear Theory group has access to the computing capabilities of North Carolina State University, which maintains High Performance Computing cluster. The cluster has 1344 computes nodes (mostly dual Xeon), over 11000 cores, 2-4GB per core distributed memory, and 10Gb Ethernet interconnects. GPU (NVIDIA) nodes are available. The cluster provides 1TB mass storage space per project. The PI applied and got access to the cluster under the project titled "Gluon saturation". Currently the PI has common access to the cluster; however, a dedicated high-priority computing queue can be set up if required.

For faculties, North Carolina State University provides free access to many commercial software products including Wolfram Mathematica, Matlab, and Waterloo Maple. The PI will also utilize GitHub, a web-based hosting service for software development projects that use the Git revision control system, provided by North Carolina State University.

The PI is a Riken-BNL fellow and will in-part work at the Riken-BNL research center (RBRC) at Brookhaven National Laboratory (BNL). **During the initial five-year appointment with RBRC (2018-2023), the PIs teaching load is reduced to one course per year.** The nuclear theory group at BNL consists of Yoshitaka Hatta, Frithjof Karsch, Dmitri Kharzeev, Yacine Mehtar-Tani, Swagato Mukherjee, Peter Petreczky, Rob Pisarski, Björn Schenke, and Raju Venugopalan. The nuclear theory group has strong ties with the nuclear theory group at Stony Brook University and specifically to Edward Shuryak, Jacobus Verbaarschot, Ismail Zahed, Derek Teaney, Dmitri Kharzeev, and Sergey Syritsyn. BNL is also home to Relativistic Heavy Ion Collider, the world renowned accelerator facility.

The Computational Science Initiative (CSI) group at BNL provides support in optimizing and writing high performance simulation software. The PI has successfully collaborated with CSI in the past and is going to continue in the future. In particular, the CSI offered support to the PI in rewriting time critical parts of simulations on GPU; the PI exploratory work has demonstrated that for the JIMWLK evolution this leads to a 300 fold decrease in computational time.

Additionally, nuclear physics groups at BNL and SBU launched the Center for Frontiers in Nuclear Science (CFNS), whose mission is to promote and facilitate the realization of the U.S. based EIC by enhancing the science case and collaborations among the scientists around the world interested in the EIC. The PI is in contact with several CFNS working groups.

13 Budget Justification

Personnel

Two months of **summer salary** is requested for the Principal Investigator during each year of the project and is calculated on the current rate with an anticipated (1-3)% annual increase throughout the project. The salary for the PI is based on the current 9-month salary. The PI will be responsible for the overall coordination of the project and the supervision of the graduate students and other project personnel.

Graduate student support is based on the current University rate for graduate students with an anticipated annual increase of 1-3% throughout the project.

Support for a **postdoctoral research associate** is $47,500 and is based on the current common University rate.

Fringe benefits

Fringe benefits are charged at the currently approved and anticipated rates of 33% for PI, 19% for a postdoc, 16% for a graduate student.

Travel

Year	Traveler	Meeting	Cost
1	Skokov	INT Program INT-19-1b “Origins of Correlations in High Energy Collisions”	1000
1	Skokov	International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS19)	2000
2	Skokov	International Conference Hard Probes 2020	2000
2	Postdoc	International Conference Hard Probes 2020	2000
3	Skokov	International Meeting (TBD)	2000
3	Postdoc	International Meeting (TBD)	2000
3	Postdoc	International Meeting (TBD)	2000