Research Statement

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The QCD Lagrangian is known and well verified by particle experiments over many orders of magnitude. But just as the collective behavior of electrically charged objects—take for instance the phase diagram of water—is far from obvious given the QED Lagrangian, the **bulk dynamics of QCD** are not well understood [1]. With RHIC and the soon-to-be-running FAIR and LHC the world scientific community has a novel opportunity to experimentally explore the state of the universe a few microseconds after the Big Bang by colliding heavy nuclei, such as gold and lead, at near the speed of light. In particular rare high momentum partons, those that produce jets of particles, provide the most direct probe of the fundamental degrees of freedom in the new phase of QCD matter created at these cutting-edge facilities [2]. My interests lie in theoretically understanding ***analytically*** these **jet phenomena in heavy ion collisions**.

The phenomenological application of the anti-de Sitter/conformal field theory (AdS/CFT) conjecture [3, 4]—which posits an analytic understanding of strongly-coupled systems, for instance the quark-gluon plasma (QGP) at RHIC [5], the unitary Fermi gas [6], superfluidity [7], and superconductivity [8]—is one of the most exciting developments in physics in recent years. Unfortunately the use of AdS/CFT requires a *double* conjecture that (1) the unproven correspondence does exist and (2) the simplified dual field theory captures the physics relevant to the problem at hand. Jet phenomenology in heavy ion collisions (HIC) provides a *sui generis*, controlled laboratory setting for testing these new string theoretic ideas by comparing them to the results of both experiment and traditional perturbative QCD (pQCD) methods. Some of my earliest work [9–11] applied pQCD to partons in HIC with very large momentum transverse to the beam (high-p_T). Recently, in addition to continuing to explore pQCD results [12, 13], I have also used and extended the strong coupling techniques of AdS/CFT [14–16]. In this way I am **unique** in the community in my **expertise in both pQCD *and* AdS/CFT methods** as applied to jets.

The future of heavy ion physics lies in well-controlled theoretical predictions compared to precise experimental data. Only in this way can the phenomenology become science: when theoretical tools and ideas may be **quantitatively falsified**. Both the pQCD and AdS/CFT calculations need extensive work before rigorous falsification is possible. In particular the AdS calculations need to be extended to a greater range of heavy ion observables: are the quantitative differences between pQCD and data also seen when using AdS/CFT? (It's likely.) What is the regime of applicability for AdS/CFT in HIC? This will likely be found by quantifying the importance of higher order effects and establishing a serious estimate of the systematic theoretical uncertainty when using AdS/CFT in HIC. Estimates of the uncertainty inherent in current perturbative calculations are large [13]. In order to falsify pQCD or use it for the meaningful extraction of information on the medium these uncertainties must be reduced. Irreducible systematic uncertainties, for example those induced by the nonperturbative effects when the running coupling is large, must be quantified in order to rigorously establish a regime of applicability for pQCD calculations. These are issues of the utmost importance in heavy ions, with significant implications for the wider physics community, and I am interested in all of them.

The long-term future of high energy QCD research in the United States is in **electron-**

ion collider physics. Currently I am most interested in how measurements from an electron-ion collider can constrain the initial conditions of a heavy ion collision, thus allowing for a more precise determination of the properties of the QGP. However an electron-ion collider also provides a fantastic testbed for the uniquely accessible non-Abelian properties of QCD such as gluon saturation, a field I am rapidly becoming deeply involved in.

Research Background

I was originally trained in the application of pQCD techniques to high-p_T partons in HIC. My first paper [9] reduced the qualitative disagreement between perturbative predictions of the suppression of high-p_T charm and bottom quarks, as measured by their non-photonic single electron decay fragments, to a quantitative one by including (1) a previously neglected energy loss channel and (2) a realistic integration over production points and path lengths for the heavy quarks. In this way Simon Wicks, Magdalena Djordjevic, Miklos Gyulassy, and I found that, although energy loss models based on perturbative calculations of radiative energy loss alone were falsified by data, by including collisional energy loss we were able to keep perturbative methods in high-p_T physics in HIC from falsification *in toto*. A subsequent paper [10] demonstrated that the asymptotic formula for elastic energy loss used in [9] was a good approximation to the full, finite-time result, in contradistinction to the claims of [17]. The ideas of [9] were further explored in proceedings [11, 12].

During my graduate student career I became interested in the application of AdS/CFT techniques to high-p_T partons in HIC [18, 19]. After finding that these strong-coupling methods yielded results in qualitative agreement with the suppression of high-p_T charm and bottom quarks [20], Miklos Gyulassy and I found a novel observable for easily qualitatively distinguishing between the pQCD and AdS/CFT pictures experimentally [14]. One may hope, then, to falsify one or both of these approaches with the first month of dedicated heavy ion collisions at LHC; a prediction for RHIC, with unfortunately a much less clean signal, was presented in [15]. Yuri Kovchegov and I then extended the AdS techniques to a new class of metrics, thus generalizing the heavy quark drag results explicitly to the case of cold nuclear matter [16]. This work simultaneously gave greater confidence to the possible universality of the qualitative differences between the weakly- and strongly-coupled predictions for the ratio of charm to bottom suppression found in [14].

More recently I returned to perturbative calculations. Intriguingly, Brian Cole and I discovered [13] that the GLV formalism [21, 22] has a strong dependence on the exact implementation of the collinear approximation, which is the usual assumption made in bremsstrahlung calculations that radiation is emitted at small angles. In particular a reasonable exploration of parameter space yielded a factor of 3 range in the medium density extracted from comparing theoretical predictions to data. Quantitative falsification with such large uncertainties will be difficult. For some additional context, there has been considerable controversy in the field over the past several years as the various pQCD-based energy loss groups extracted very different (by a factor of $4-5$) values of the transport coefficient $\hat{q}$ that can characterize the medium (this is done, essentially, by varying $\hat{q}$ in calculations and then comparing to data). In fact, this vast disagreement was one of the two main reasons for the creation of the JET collaboration. As all perturbative energy loss calculations currently assume collinearity we think it almost certain that these disparate extracted values are actually consistent within the bounds set by the uncertainty from this approximation.

One might wonder whether next-to-leading order effects are important in pQCD energy loss calculations and at what momentum scales an energy loss calculation breaks down. A related question, important in its own right for quantitative predictions of the initial state dynamics in electron-ion and heavy ion collisions, is: what are the running coupling effects in gluon production? Yuri Kovchegov and I computed these corrections in the dilute limit and conjectured on their implications in nucleus-nucleus collisions in [23]. The next logical step is to apply the tools used in the gluon production derivation to the energy loss problem, a current work in progess.

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