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Nuclear Physics at High Energy Density

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1 Introduction

This proposal describes several research projects relevant to the physics of nuclear matter at extreme energy density as it is created in relativistic heavy ion collisions. Our research group has a strong record of combining state-of-the-art transport models with advanced descriptions of important phenomenological observables. During the next funding period, we intend to focus on the physics of the early phase of relativistic heavy ion collisions, i.e., the transition from the color glass condensate to thermal QCD matter, and on final-state observables that are sensitive to fluctuations and dynamics of the initial state. Specifically, the research plan of our group has three main thrusts:

1. Further develop the theoretical foundations of the description of initial-state fluctuations with the goal of utilizing these fluctuations as probes of the initial state as well as the transport properties of the hot QCD matter during the hydrodynamical expansion phase;

2. Develop the computational framework for the turbulent dynamics of the glasma and the pre-equilibrium quark-gluon plasma;

3. Systematically develop and then exploit our capability of making quantitative predictions for a wide variety of hot and dense QCD matter probes in conjunction with realistic, state-of-the-art reaction models.

The last thrust will be supported in significant parts by other grants from the Department of Energy (Topical Collaboration on Jet and Electromagnetic Tomography of Hot QCD Matter) and the National Science Foundation (CDI: Modeling and Data Analysis Initiative). Each of these grants provide support for one graduate student. The research we did in the past with the help of the present grant (DE-FG02-05ER41367) positioned our group to participate successfully in the competitions that resulted in the award of the two more narrowly focused grants mentioned above. We anticipate that the research we propose here will benefit to no small extent from the work supported by these additional grants.

Recent Research Highlights

Some of the highlights of our research accomplishments during the reporting period are:

- **Realistic, comparative jet quenching simulations:** We contributed to the further development of the Higher-Twist formalism of jet quenching, which is unique among jet quenching formalisms in directly connecting medium properties with observables. We collaborated with several other theorists to lead the first systematic comparison of different jet quenching schemes in the same description of the bulk medium. We also played a leading role in the TEC-HQM Collaboration that conducted a comprehensive comparison of the different jet quenching schemes for an idealized medium (“QCD Brick”).

- **Jet induced Mach cone:** We calculated from first principles the sound generated by a fast parton that is perturbatively coupled to a quark-gluon plasma. We explored the sound propagation in the plasma and showed that the intensity of the sound increases with path length due to gluon emission (“crescendo”).

- **Ab-initio calculation of shear viscosity for a hadronic medium:** We developed the framework for microscopic simulations of the shear viscosity over entropy density ratio for a thermal hadron gas, by applying the Kubo formalism to a microscopic hadronic gas model. Using
this tool, we calculated for the first time the shear viscosity for a hadron gas that is not in chemical equilibrium. We also applied the same formalism to a partonic plasma.

- **Chiral magnetic effect:** We showed that hadronic background effects exist which contribute to the same observables as the chiral magnetic effect. We developed a framework for calculating final-state observables resulting from the early phase current fluctuations. We also studied various fluctuations that contribute to the experimental observables studied by the STAR experiment.

- **Thermalization:** We developed a novel framework for the calculation of the growth of the coarse grained entropy in a quantum field theory. We applied the new formalism to the dynamics of non-Abelian gauge fields and showed that it leads to thermalization times of the order of 2 fm/c.

- **Triangular flow:** We performed the first realistic calculation of triangular flow in a complete dynamical collision model, from initial state fluctuations to particle freeze-out.

- **Strangeness production in the PNJL model:** We calculated the effect of the Polyakov loop on strangeness production in the quark gluon plasma. To do so, we extended the PNJL model to include dynamical gluons and showed how the effective Polyakov loop potential can be generated dynamically.

- **Critical point signatures:** We proposed a novel signature for the QCD critical point that is based on the “focusing” of hydrodynamic trajectories in its vicinity.

- **Hadron mass spectrum:** We showed that the most recent, high precision lattice simulations of thermal QCD are sensitive to the hadron mass spectrum up to 3 GeV and provide evidence for an exponential mass spectrum of the Hagedorn type.

**Group Members**

Our research group presently consists of two tenured faculty members (Steffen A. Bass and Berndt Mueller), two postdoctoral researchers (Hannah Petersen, and Guang-you Qin), five graduate students (Shanshan Cao, Chris Coleman-Smith, Fritz Kretzschmar, Hung-Ming Tsai, and Di-Lun Yang), and one undergraduate student (Vivek Bhattacharya) who is in the process of finishing an honors thesis. Another undergraduate student has expressed interest in joining our group.

We wish to point out that due to reduced funding levels in the current grant reporting period our group only had a postdoctoral research associate for two out of the three reporting years: Abhijit Majumder left our group at the end of August 2008 and Guanyou Qin joined our group in September 2009. Hannah Petersen, who is the recipient of a Feodor Lynen Fellowship from the Alexander von Humboldt Foundation, joined our group in January 2010. Graduate students Richard (Bryon) Neufeld and Nasser Demir successfully defended their Ph. D. theses in July 2009 and August 2010, respectively. Neufeld is now a postdoctoral research associate at Los Alamos National Laboratory, where he was recently awarded a Director’s Fellowship. Demir will remain at the Duke Physics Department this fall in a teaching position. Our funding success with the NSF CDI award and the DOE Topical Collaboration grant have enabled us to temporarily expand the number of supported graduate students in our group from two to four.

Over the course of the reporting period we also had several long-term visitors in our group. Two Korean faculty, Kang-Seog Lee and Ghi-Ryong Shin spent their sabbatical leaves with us, and one research associate, Young-Ho Song, was funded by a Korean fellowship and only received support from the grant for the last few months of his stay in our group.
2 Progress Report

2.1 Jet-medium interaction

RHIC has generated a wealth of experimental data on high momentum hadron emission, including, but not limited to, the nuclear modification factor $R_{AA}$, its modification as a function of the reaction plane (a measure of the azimuthal anisotropy of the cross section) and a whole array of high-$p_T$ hadron-hadron correlations. In these observables, one compares the ratio of certain yields in a heavy-ion collision to those in a $p-p$ collision, either scaled up by the number of expected binary collisions, e.g., for the single hadron suppression factor $R_{AA}$, or directly, as in the case of triggered distributions of associated hadrons, e.g., the $I_{AA}$. Experimental data for most of these observables exist as functions of rapidity and centrality, for a wide range of $p_T$ of the produced particle or particles.

The emission of hadrons with large transverse momentum is observed to be strongly suppressed in central collisions of heavy nuclei. The origin of this phenomenon, commonly referred to as jet-quenching, can be understood in the following way: during the early pre-equilibrium stage of the relativistic heavy-ion collision, scattering of partons which leads to the formation of deconfined quark-gluon matter often engenders large momentum transfers which leads to the formation of two back-to-back hard partons. These traverse the dense medium, losing energy and finally fragment into hadrons which are observed by the experiments. Within the framework of perturbative QCD, the process with largest energy loss of a fast parton is gluon radiation induced by collisions with the quasi-thermal medium [1, 2, 3, 4, 5, 6].

2.1.1 Systematic Comparison of Jet Energy-Loss Schemes in a realistic hydrodynamic medium

Computations of jet modification have acquired a certain sophistication as regards the incorporation of the partonic processes involved. However, the role of the medium has often been relegated to the furnishing of an overall density and its variation with time.

The availability of a three-dimensional hydrodynamic evolution code allows for a much more detailed study of jet interactions in a longitudinally and transversely expanding medium. The variation of the gluon density in such a medium is quite different from that in a simple Bjorken expansion. This allows for a step-by-step approach to the study of jet-medium interactions.

We recently made use of our 3-D hydrodynamics results to perform fully dynamical calculations of jet quenching using three different theories of radiative parton energy loss. In [7] we used the quenching weights of Armesto et al. obtained in the BDMPS/ASW approach; in [8] we used the higher-twist formalism of Guo-Majumder-Wang, and in [9] we used the Arnold-Moore-Yaffe approach. One of the significant results of [7] was an estimate of the theoretical error-bar of jet energy-loss calculations induced by the choice of the medium parametrization, which was found to be as large as 50%.

Over the current reporting period we have conducted a detailed comparison of the three approaches [P8,P13], which were constrained to use the same initial structure functions, the same final vacuum fragmentation functions, the same nuclear geometry and identical three dimensional evolution of the produce dense matter. In this first, unified, attempt to understand jet modification in dense matter, the focus was restricted to single inclusive observables. The nuclear modification factor was computed as a function of the transverse momentum, centrality of collision, as well as, the angle with respect to the reaction plane. This was followed by a more detailed, though purely theoretical, analysis of jet origin distribution for the $R_{AA}$ as a function of the reaction plane, as well
as, the $R_{AA}$ for jet origins restricted to lie on a narrow belt on the reaction plane.

Our comparison [P13], has shown that under identical conditions (i.e. same medium evolution, same choice of parton distribution functions, scale etc.) all three jet energy-loss schemes yield very similar results. This finding is very encouraging since it indicates that the technical aspects of the formalisms are well under control. However, we need to point out that there still exists a puzzle regarding the extracted value for the transport coefficient $\hat{q}_0$, which spans a factor of four from a value of 2.3 GeV$^2$/fm for the HT approach on the lower end, to 4.1 GeV$^2$/fm for AMY and 10 GeV$^2$/fm for ASW on the high end, when using the same temperature scaling law for all three approaches. While the discrepancy among these approaches is not new, our work has been able to decisively rule out differences in the medium evolution or initial setup as a cause for the differing values of $\hat{q}$. We are led to conclude that these remaining differences are due, to the different approximations applied, to the different energy scales involved, to the different assumptions on the structure of the QCD matter, inherent in these different approaches. [S.A. Bass and A. Majumder]

2.1.2 Higher Twist Formalism of Jet–Medium Interactions

We made substantial progress in our program to develop a comprehensive description of jet–medium interactions in the framework of the higher twist formalism. The preprint, in which we lay the groundwork for our treatment was published [W1]. We then derived, in collaboration with R. J. Fries (Texas A&M) and along the same lines, the medium induced photon radiation from a jet [P2]. Our result is obtained as a modification of the photon fragmentation function of the original hard parton and thus includes interference with the vacuum bremsstrahlung associated with the jet. A. Majumder, who led this research project, extended the higher-twist approach to include elastic interactions with the medium [P19]. The elastic energy loss is characterized by a new transport coefficient of the medium, which has been precisely defined. This development makes it possible to treat elastic and radiative energy loss on an equal footing without making simplifying assumptions of the structure of the medium. We also applied the higher-twist formalism of jet modification in matter to jet quenching data from HERMES and CLAS [P3]. [A. Majumder]

2.1.3 Jet–Medium Interactions in SCET

Majumder, together with A. Idilbi (a postdoc in the Duke EFT/Lattice group), developed an entirely new conceptual framework for jet interactions in a dense QCD medium as an extension of Soft-Collinear Effective Theory (SCET) [P15]. This required the extension of SCET to include so-called “Glauber” gluons. The hope is that the new formalism will facilitate factorization proofs and the application to more exclusive processes, especially for hard processes initiated by $b$-quarks. [A. Majumder]

2.1.4 Medium–Response to a Fast Parton

We extended our research on the energy and momentum deposition in the quark-gluon plasma due to a fast parton. We derived an analytic expression for the source distribution when color screening is neglected, and completed a numerical calculation, in which color screening is dynamically included in the hard-thermal loop approximation. These results have been published in [P6]. In collaboration with our former postdoc, J. Ruppert, we calculated the hydrodynamic response of a stationary quark-gluon plasma to this energy-momentum source in the linear approximation and found that it generates a clearly discernible sonic Mach cone, as long as the shear viscosity of the medium does not exceed about five times the minimal quantum bound. Our article [P4]
reporting these results was highlighted in *Physical Review Viewpoint* article. A detailed account of the hydrodynamic calculations was published in *Physical Review C* [P12]. We also studied how the Mach cone shows up in the final distribution of hadrons in different freeze-out scenarios [P18].

Subsequently we computed the total energy deposited into the medium per unit length by fast partons traversing a quark-gluon plasma, including both collisional and radiative energy deposition. The main results have been published in *The Physical Review Letters* [P24] as well as in [P28]. In the calculation, the medium excitation due to elastic collisions was taken to be given by the well known expression for the collisional drag force. The radiative energy loss of the parton contributes to the energy deposition because each radiated gluon acts as an additional source of collisional energy loss in the medium. We derived a differential equation which governs how the spectrum of radiated gluons is modified when this energy loss is taken into account. This modified spectrum was then used to calculate the additional energy deposition due to the interactions of radiated gluons with the medium. Numerical results were presented for the medium response for the case of two energetic back-to-back partons created in a hard interaction. The calculation has shown that the contribution of gluon radiation to the medium excitation grows with path length. [R.B. Neufeld and B. Mueller; this work is part of B. Neufeld's Ph.D. thesis]

### 2.1.5 Heavy Quark Energy Loss in the Higher Twist Formalism

The energy loss of heavy quarks stands out as one of the interesting puzzles as they are suppressed almost as much as light flavors, in contrast to the expectation from their large masses [10, 11, 12, 13, 14, 15].

While there exist sophisticated and successful calculations of single inclusive suppression and many-body observables for the light flavors, the heavy flavor sector is less than satisfactory. In [P32], our postdoctoral fellow Guangyou Qin, in collaboration with A. Majumder (Ohio State), presented a successful description of the medium modification of both light and heavy flavor partonic jets within a perturbative QCD based approach. The calculation was performed in the context of higher twist formalism which treats both radiative and elastic energy loss on the equal footing without making simplified assumption for the structure of the medium. The effect of the medium on a hard parton is encoded in terms of three non-perturbative transport coefficients. The results support the assertion that hard partonic jets might be weakly coupled to the quark-gluon plasma, even if the dynamics of the plasma itself is governed by strong coupling.

We have improved our previous treatment in [P32] and allow heavy quarks to radiate gluons down to physical transverse momenta. With a single parameter, i.e., the transport coefficient $\hat{q}$, we can obtain a satisfactory description of both heavy and light flavor quenching data when we use energy-independent transport coefficients [16] compatible with higher-order hard-thermal loop calculations [17]. Our calculation suggests that even if the dynamics of the quark gluon plasma itself is governed by strong coupling, a highly virtual parton may be still weakly coupled to the medium. [G.Y. Qin]

### 2.1.6 Infinite matter calculations of jet evolution and energy-loss in a microscopic transport model

One of the topics of broad current interest is the evolution of parton showers within a hot and dense deconfined medium of quarks and gluons. However, before addressing the full shower evolution, it is necessary to demonstrate that the calculational framework is capable of properly describing elastic energy loss: in [P36] we have studied elastic energy loss of high energy partons in an infinite, homogeneous, thermal medium within the PCM approach and have compared our
results to analytic calculations of the same quantity. In addition, we have calculated the rate of momentum broadening of a hard parton propagating through the medium and have compared the results of our analysis to an analytic expression for the transport coefficient $\hat{q}$. We have found good agreement between the PCM calculations and the analytic expressions (within the approximations used in both cases), giving us significant confidence that our transport approach provides a reliable description of a gas of quarks and gluons at temperatures above $\approx 2T_C$ in the weak coupling limit. We expect that the results of our work can be used as a benchmark by other parton-based microscopic transport calculations. The validation of the PCM against the analytic test cases presented in our work now allows us to advance the application of the PCM to the description of medium modified jets in relativistic heavy-ion collisions and the response of the medium to a hard parton propagating through it. [S.A. Bass, G. Shin and B. Mueller]

2.1.7 Heavy Quarkonium

The production of heavy quarkonia like the $J/\Psi$ in heavy ion collision is an important probe of the formation of quark gluon plasma. However, cold nuclear matter effects on the $J/\Psi$ production are not yet fully understood. Possible sources of nuclear matter dependence are nuclear shadowing of the gluon distribution, initial parton energy loss, nuclear absorption of $c\bar{c}$ pairs. Our analysis indicates that the nuclear shadowing and nuclear absorption cannot explain the $x_F$ distribution of $\alpha$ parameter, defined as $\sigma_{pA} = A^\alpha \sigma_{pp}$. Though the initial parton energy loss can be important to explain the $\alpha$ behavior, the theoretical approaches have remained at the level of simple model calculations. Our postdoctoral fellow Young-Ho Song from South Korean has finished developing a more sophisticated model to study the effects of elastic energy loss of initial partons in p-A collisions. The model has taken into account the elastic energy loss effects due to the scattering between a soft gluon from nuclei and a hard gluon from a proton before the creation of charm quark antiquark pair. The work was done in the framework of the higher twist formalism, and the perturbative hard part of the gluon fusion subprocess was performed by making use of the color singlet s-channel cut theory, which agrees with CDF and PHENIX pp collision data. Numerical programs are currently being developed for further application. [Y. Song]

2.2 Transport Properties of QCD Matter

One of the most important current challenges in QGP research is to quantify the transport coefficients of this novel state of matter. Recently, attention in the field has been primarily focused on the shear viscosity to entropy density ratio $\eta/s$. Calculations utilizing certain strongly coupled supersymmetric gauge theories with gravity duals postulate a lower bound of $\eta_{\text{min}} = s/4\pi$ for this quantity, often referred to as the KSS bound [18]. Relativistic viscous hydrodynamic calculations require very low values of $\eta/s$ in order to reproduce the RHIC elliptic flow ($v_2$) data. However, current calculations assume a fixed value of $\eta/s$ throughout the entire evolution of the system and neglect its temperature dependence. The exact value of $\eta/s$ in these calculations is only known within a factor of two, due to systematic uncertainties related to the choice of equation of state and initial conditions used: the most prevalent Glauber initial condition assumes that the initial energy density in a heavy ion collision scales with the number density of binary collisions, whereas the Color-Glass-Condensate (CGC) initial conditions incorporate a scenario which relates the initial energy density to a gluon density predicted by the CGC model. A viscous hydrodynamical analysis finds that $\eta/s \approx (0.08 - 0.16)$ is permissible with the PHOBOS $v_2$ data if one uses the Glauber initialization, whereas $\eta/s \approx (0.16 - 0.24)$ is compatible if one uses the more realistic CGC initialization [19].
Several analytic calculations of $\eta$ and $\eta/s$ for simple hadronic systems have previously been performed (for a brief compilation, please see [20]). These analytic calculations solved the linearized Boltzmann equation, in which the cross sections in the collision integral were treated using different techniques, such as chiral perturbation theory, effective NN theory, phenomenological amplitudes, and the relaxation time approximation. However, even the most sophisticated analytic calculations model the hadron gas as a binary mixture at best, which is a very crude description of the hadronic matter present at RHIC. Sophisticated Monte Carlo microscopic transport models provide a far more realistic description of the hadronic matter created in relativistic heavy ion collisions. Several studies within those models have focused on equilibration and thermodynamic properties of infinite hadronic matter [21], and have extracted transport coefficients of hadronic gases [22, 23], albeit none have performed a systematic study of $\eta/s$.

It should be noted though that all calculations of $\eta/s$ performed thusfar have assumed zero pion chemical potential, equivalent to unity light quark fugacities. Such an assumption may be reasonable for the formation of a QGP in a relativistic heavy ion collision at RHIC; yet the differing timescales of chemical and kinetic freeze-out in the hadronic phase of the reaction imply an acquiring of non-zero particle species dependent chemical potentials as the system hadronizes.

In our work [P22,P23], which is part of the ongoing Ph.D. thesis of Nasser Demir, we use a microscopic transport model known as the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) model, described in [24, 25], to simulate infinite equilibrated hadronic matter. We confine the particles comprising the system to a box with periodic boundary conditions [21], which forces the system into equilibrium. We verify that the system has achieved chemical equilibrium by checking whether the particle multiplicities in our system saturate as a function of time, and comparing such yields to an independent statistical model of a hadron resonance gas (SHARE). We verify kinetic equilibrium by checking the momentum distributions of the hadrons in our system for isotropy, and fitting particle spectra to Boltzmann distributions. In order to extract the shear viscosity of our system, we employ the Kubo formalism. In addition, we compute the entropy of the system and evaluate $\eta/s$ as a function of temperature, pion- and baryo- chemical potential. We find values for $\eta/s$ near $T_C$ for the zero chemical potential case to be $\approx 1.0$, significantly higher than the KSS bound of $\eta/s \approx 0.08$. If the minimum value of $\eta/s$ for hot dense hadronic matter in the range of hadronic chemical freezeout indeed occurs at zero chemical potential, our results of $\eta/s$ would pose a serious problem to viscous hydrodynamics calculations, since a value of $\eta/s$ of at most 0.24 is needed to reproduce RHIC elliptic flow data. The inclusion of a finite pion chemical potential in the range of hadronic chemical freezeout reduces $\eta/s$ to values as low $\eta/s \approx 0.4$, still significantly above the suggested values $\eta/s \approx 0.16 - 0.24$ from viscous hydrodynamics calculations.

Our work demonstrates that the inclusion of chemical potentials, which is bound to arise due to the separation of chemical and kinetic freeze-out during the heavy ion collision evolution, will significantly reduce the value of $\eta/s$, but not to the value necessary to ensure the successful application of (viscous) hydrodynamics to collisions at RHIC. Our calculation of $\eta/s$ in a hadron gas from a microscopic transport model therefore constrains the origin of the low viscosity matter produced in a relativistic heavy ion collision, which must occur in the deconfined phase, possibly in the range $1 < T/T_c < 2$.

Currently we are in the process of expanding our work on the transport coefficients of a hadron gas to its bulk viscosity and baryon diffusion coefficients. Regarding the bulk viscosity, we are exploring methods which avoid the Kubo Correlator, due to the large amount of fluctuations present in the Kubo Correlator needed for the bulk viscosity calculation. [N.S. Demir and S.A. Bass; this work is part of N.S. Demir’s Ph.D. thesis]
2.2.2 Shear-viscosity over entropy-density of a weakly coupled QGP

In [P37] we have utilized the parton cascade model to simulate a perturbative quark-gluon-plasma in full thermal equilibrium and have extracted its shear-viscosity as well as the shear-viscosity over entropy-density ratio as a function of temperature. This is a continuation of our work on the hadronic $\eta/s$, for which all the relevant techniques employed here have been developed. We find that our results depend significantly on the details of the calculation, i.e. choice of coupling constant and parametrization of the Debye screening mass as well as the degrees of freedom (gluon vs. quark-gluon plasma). One of our key results is that the shear viscosity over entropy-density ratio $\eta/s$ becomes invariant to the chemical composition of the system when plotted as a function of energy-density instead of temperature. This finding is significant, since the chemical composition of the QGP may vary over its lifetime – from a gluon-dominated plasma in the early phase to a QGP in full chemical equilibrium in the later stages of the evolution. The values we obtain for $\eta/s$ are higher than those expected for the near ideal fluid observed at RHIC; in particular they are not compatible with $\eta/s$ values extracted from viscous fluid dynamics analysis [19] of elliptic flow data. By increasing the coupling constant we find values of $\eta/s$ that are compatible with the RHIC data, but only for values of the coupling at which the perturbative assumptions of the PCM may not anymore be valid. Inclusion of quantum-coherence effects, such as the LPM effect, multi-particle scattering processes or turbulent color fields leading to an anomalous viscosity [26, 27] may explain the origin of the observed small $\eta/s$ values, but the final determination of this question remains to be settled in future work. [N.S. Demir and S.A. Bass; this work is part of N.S. Demir's Ph.D. thesis]

2.3 Chiral Magnetic Effect

2.3.1 Electric charge separation in strong transient magnetic fields

The induction of an electric current by a topological (Chern-Simons) number transition in the SU(3) gauge field in the presence of an external magnetic field is called the chiral magnetic effect [28, 29]. Because parity and CP invariance are not broken in QCD, as far as we know, the SU(3) Chern-Simons number only fluctuates, and thus only fluctuations of the electric current are observable in nature. It was originally thought that this effect occurs only in the presence of QCD matter with deconfined quarks and thus would be an unambiguous signature of the quark-gluon plasma (see e.g. D. Kharzeev’s Round Table presentation at QM2008).

In collaboration with M. Asakawa (Osaka U.) and A. Majumder (Ohio State U.), we have investigated hadronic background processes, which can also lead to electric current fluctuations in the strong magnetic field present in noncentral heavy ion collisions [P40]. Such effects are generated by the coupling of the electromagnetic pseudoscalar invariant $(E \cdot B)$ to the hadronic pseudoscalar sector, i.e. the $\pi^0$, $\eta$, $\eta'\) mesons. We identified the effective interactions describing these couplings, which are known experimentally. We also developed a general formalism describing how the electric current fluctuations translate into charge asymmetry fluctuations with respect to the reaction plane in the final state.

We further identified five different mechanisms that contribute to these charge asymmetry fluctuations, including topological fluctuations created during the collision of the two nuclear color glass condensates and thermal fluctuations of the Chern-Simons number in a thermal quark-gluon plasma or hadron gas. We estimated several of these contributions, which had not been studied before. Generally, our results for the observable charge asymmetry fluctuations are several orders smaller than the effects seen in heavy ion collisions at RHIC [30, 31] and suggest that
the observed effect is mainly due to some other mechanism. We also pointed out that the quantitative predictions for final-state charge fluctuations are very sensitive to details of the transport processes from the location where they are created to the freeze-out surface. [B. Mueller]

2.3.2 Charged particle correlations from jet energy-loss and initial state fluctuations

Recently, several charged particle correlation measurements have been claimed to be an observable for \( \text{C}_p \) violating processes in the strong interaction [32, 28, 33, 34]. These local QCD vacuum fluctuations lead to a separation of charges in a small region of the fireball which will be enhanced to a measurable signal by the strong magnetic field that is generated by the two heavy ions that pass through each other [31]. The correlations that are observed can also be understood as a result of the sum of various traditional effects, like e.g. momentum and charge conservation, elliptic flow and resonance decays [35, 36, 37], that provide a large background for a possibly very small signal attributed to the chiral magnetic effect as has been estimated by our group [P40].

We have investigated the contribution of medium-modified jets and initial state fluctuations to the asymmetry in charged particle production with respect to the reaction plane. The different pathlength combinations of jets through the medium in non-central heavy ion collisions result in finite correlations of like and different charged particles emitted in the different hemispheres. Our calculation is based on combining jet events from YaJEM (Yet another Jet Energy Loss Model) and a bulk medium evolution. It is found that the jet production probabilities are too small to observe this effect. The influence of initial state fluctuations on this observable is explored using an event-by-event (3+1)D hybrid approach that is based on UrQMD (Ultra-relativistic Quantum Molecular Dynamics) with an ideal hydrodynamic evolution. In this calculation momentum conservation and elliptic flow are explicitly taken into account. The asymmetries in the initial state are translated to a final state momentum asymmetry by the hydrodynamic flow profile. Dependent on the size of the initial state fluctuations the resulting charged particle asymmetries are in qualitative agreement with the preliminary STAR results. The multi-particle correlation as proposed by the PHENIX collaboration can in principle be used to disentangle the different contributions, however is in practice substantially affected by the procedure to subtract trivial resonance decay contributions. This work has been submitted for publication and can be found in preprint [P44]. [H. Petersen and S.A. Bass]

2.4 Equilibration and Entropy Creation

One important problem in the description of relativistic heavy ion reactions is to understand when and how the produced matter equilibrates. From a thermodynamic standpoint, this question can be answered by studying when and how entropy is created in the reaction. One can distinguish five different stages of entropy production:

1. Decoherence of the initial nuclear wave functions;
2. Thermalization of the partonic plasma (sometimes called the \textit{glasma} because of the presence of strong gluon fields);
3. Dissipation due to shear viscosity in the hydrodynamic expansion;
4. Hadronization accompanied by large bulk viscosity;
5. Viscous hadronic freeze-out.
During the project period, we have made significant progress on our understanding of stages (1), (2), (3), and (4). We have also developed a novel, comprehensive framework for the calculation of entropy production in quantum field theory.

### 2.4.1 Decoherence of the initial nuclear wave functions

In [P11] we were able to improve our calculation of the decoherence time for the initial gluon wave functions of the colliding nuclei. This work, done in collaboration with R. J. Fries (Texas A&M) and A. Schäfer (Regensburg), was made possible by recent advances in the treatment of the scale dependence of the QCD coupling in gluon saturation models. The explicit scale dependence of the coupling allowed us to avoid an infrared singularity, which had required the introduction of heuristic cut-off in our original derivation [38]. Our new, improved result confirms the conclusion reached in our earlier work, that the decoherence time is of the order of the inverse saturation scale, \( \tau_{\text{dec}} \sim Q_s^{-1} \), or about 0.2 fm/c in physical units. Also in [P11], we estimated the entropy created due to decoherence. Our estimate yielded an entropy per unit of rapidity \( dS/dy \approx 1,500 \), which is roughly one-third of the entropy observed in the final state. Since the expansion of the quark-gluon plasma is thought to be that of an almost ideal fluid, and the total entropy immediately after hadronization has been determined to be \( dS/dy \approx 5,000 \) [39], our estimate implies that a very substantial amount of entropy must be produced during the “glasma” phase.

### 2.4.2 Entropy growth in the glasma

One important unsolved problem in the description of relativistic heavy ion collisions is the thermalization of the energy density deposited by the colliding color glass condensates (CGC’s). Numerical simulations of the nonlinear dynamics of the strong color fields suggest that the equilibration occurs very rapidly [40, 41, 42], however the precise mechanism by which equilibrium is achieved remains unclear. In collaboration with A. Schäfer (Regensburg U.) and R. J. Fries (Texas A&M U.) we had shown that about one third of the final observed entropy (\( dS/dy \approx 5,500 \) in central Au+Au collisions at top RHIC energy) is produced by decoherence of the CGC fields [38, 43]. Most of the remaining entropy must be formed in the \( 1 - 2 \) fm/c before the onset of the nearly inviscid hydrodynamic expansion of the quark-gluon plasma. This work was published in [P27].

In collaboration with the QCD theory group at the Yukawa Institute in Kyoto, we applied our new formalism for the growth of the coarse grained entropy in quantum field theory to this problem [P41]. In our 2008 work [P16] we had shown that the entropy defined by the Husimi transform of the Wigner function, the Wehrl entropy, exhibits linear growth in time for quantum fields that contain dynamically unstable modes. For long times, the growth rate of the entropy can be related to the sum of the positive Lyapunov exponents of the classical field theory. We had previously applied this formalism to study entropy growth in scalar field theories, such as models of cosmic inflation. In our most recent work, we studied the dynamics of Yang-mills fields [P41]. Classical Yang-Mills fields have been known to exhibit chaos for a long time [44], but the chaotic properties had only been studied in the ergodic limit. However, for the problem of equilibration of the glasma produced in heavy ion collisions, what matters is the entropy growth rate at early times.

In order to study this question, we developed a novel approach for the calculation of “intermediate” Lyapunov exponents (ILE's), which is based on the Trotter formula for the time evolution operator of the lattice regularized Yang-Mills field. We used our new approach to show that randomly generated initial gauge field configurations simulating a decohered CGC exhibit linear growth of their coarse grained entropy, and we determined the dependence of the entropy growth rate on the energy density. After relating the results of our classical field calculations to physical quantities...
in the continuum limit, we found a characteristic equilibration time of the order of 2 fm/c for the conditions prevalent at RHIC. [B. Mueller]

2.4.3 Dissipation due to shear viscosity in the hydrodynamic expansion

In [P13] we studied entropy production during the hydrodynamic expansion of the quark-gluon plasma due to the effects of shear and bulk viscosity. This work, done in collaboration with R. J. Fries (Texas A&M) and A. Schäfer (Regensburg), is the first systematic exploration of the possible contribution of bulk viscosity to the produced entropy. Our conclusion is that the bulk viscosity can contribute at most 10% to the final entropy, before it becomes so large that the hydrodynamic description breaks down in the vicinity of the hadronization transition. Present lattice results do not support such a scenario, but also do not rule it out. [B. Mueller]

2.4.4 Entropy growth in the Husimi formalism

In [P16] we developed a general framework for the calculation of entropy growth in quantum field theories. This work was done in collaboration with T. Kunihiro and A. Ohnishi (YITP Kyoto) and A. Schäfer (Regensburg). Our approach is based on the Husimi distribution, which is derived from the Wigner functional [45] by Gaussian smearing. We showed that the entropy calculated from the Husimi distribution exhibits linear growth when the quantum field contains unstable modes, and we proved that the long-time limit of the growth rate is equal to the (classical) Kolmogorov-Sinaï (KS) entropy of the field. Our new approach has applications in relativistic heavy-ion physics as well as in cosmology. Since Yang-Mills fields are known to have a finite KS entropy, our method is directly applicable to the problem of entropy production in the glasma phase of the heavy-ion reaction.

Following up on our initial work, we solved the time evolution of the Husimi representation of the density operator, which is then applied to evaluate the time evolution of the coarse-grained entropy. During the past year, we thoroughly investigated various properties of the Husimi distribution and derived the coarse-grained Hamiltonian that serves as a constant of motion for the time evolution of the Husimi distribution. He also analyzed in detail the constraints on the initial conditions imposed by the uncertainty relation. We then solved the equation of motion for the Husimi distribution by means of the Gaussian test function method. We showed that the Husimi distribution of the Yang-Mills quantum system evolves towards a microcanonical equilibrium distribution, and the coarse-grained entropy saturates to the microcanonical entropy. Our results have been published as a preprint [P]. [H. M. Tsai and B. Mueller; this work is part of H.M. Tsai’s Ph.D. thesis]

2.4.5 Quasi-linear transport theory of the quark-gluon plasma

In collaboration with S. Mrówczyński (Kielce/Warsaw), we derived a general set of transport equations of quark-gluon plasma in the quasi-linear approximation [P38]. The equations can be cast either in the Balescu-Lenard or Fokker-Planck form. The novel aspect of these transport equations is that they dynamically take into account the evolution of the soft plasma modes, which describe the dynamical color screening properties of the plasma that regulate the interactions of hard quanta at large distances. As an example of the power of our new formalism we showed how the momentum diffusion coefficient grows exponentially with time in the presence of plasma instabilities, which are thought to be present in the longitudinally expanding quark-gluon plasma during the early phase of a relativistic heavy ion collision. [B Mueller]
2.5 Initial State Fluctuations

2.5.1 Effects of Initial State Fluctuations on Elliptic Flow at SPS

We have conducted a detailed analysis of eccentricity fluctuations and elliptic flow results at SPS energies, which has shown that excitation function and transverse momentum dependence of elliptic flow is rather insensitive to the initial state fluctuations and the equation of state. This statement is especially important for the extraction of transport properties like the shear viscosity from the measured elliptic flow signal. This work was published in [P34]. [H. Petersen]

2.5.2 Triangular Flow

The third coefficient of the Fourier expansion of the azimuthal particle distribution in momentum space is a new observable that indicates collective behavior of the particles and can only arise when event-by-event fluctuations are taken into account. Therefore, in [P35] we have presented the first calculation of triangular flow in a realistic dynamic model in Au+Au collisions at $\sqrt{s_{NN}} = 200$ A GeV. The long-range correlations in the longitudinal direction that arise from a flux tube picture of the initial binary collisions together with the fluctuations in the transverse plane are translated by ideal hydrodynamic to a triangular flow signal with all the features that are expected from experimental data. [H. Petersen, G.Y. Qin, S.A. Bass and B. Mueller]

2.5.3 Mixing of Momentum Anisotropy Moments

Fluctuations of the initial collision geometry have attracted much attention recently owing to their large influence on the extraction of shear viscosity-to-entropy ratio $\eta/s$ of the hot and dense quark gluon plasma created in relativistic heavy ion collisions [46, 47, 48, 49, 50, 51, 52]. We are developing a systematic framework for studying the initial collision geometry fluctuations and investigating how they evolve through different stages of the fireball history and translate into final particle momentum anisotropies. From our event-by-event analysis, we find that only a few lowest momentum anisotropy parameters survive after hydrodynamical evolution. The final momentum anisotropies are found to be influenced by whether one includes early time evolution and how one smooths the discretized initial conditions, both of which tend to smear out the spatial anisotropies. This effect is stronger for higher moments than for lower moments. The correlations between odd and even spatial anisotropy parameters during the early time expansion is also quantitatively investigated and found to be small. Our study provides a theoretical foundation for understanding initial state fluctuations and the collective expansion dynamics in relativistic heavy ion collisions. This work was just submitted as for publication and can be found in [P]. [G.Y. Qin, H. Petersen, S.A. Bass and B. Mueller]

2.6 Reaction Dynamics and Particle Production

2.6.1 Strangeness Production in the PNJL Model

We have studied the effects of chiral and deconfinement phase transitions on the thermal strange quark pair-production in the framework of the Nambu-Jona-Lasinio model with the Polyakov loop (PNJL model). The main results were published this year in [P20] as well as in [P29]. While the dynamics in the quark sector of the PNJL model had been well understood, little was known for the gluon sector. We first developed a self-consistent method to evaluate the thermal average of the adjoint Polyakov loop and the gluon momentum spectrum in the mean-field approximation. By
taking into account the Polyakov-loop suppressed momentum spectrum of incoming partons and the constituent quark masses, we calculated the thermal strange quark pair-production rates. This novel result was also compared with those obtained in free perturbative QCD theory and is helpful to identify the temperature where the gluonic contribution dominates the production rates. The same technique can also be applied to study other signatures of the quark-gluon plasma. [H.M. Tsai and B. Mueller; this work is part of H.M. Tsai's Ph.D. thesis]

2.6.2 Equation of State Dependence of Hadronic Observables

Among the shortcomings of most current RFD and hybrid RFD+Micro models is the use of an equation of state incorporating a sharp first order phase-transition. Such a transition has been ruled out by lQCD calculations for values of the baryon-chemical potential relevant for RHIC energies. Therefore we are currently in the process of implementing a realistic equation of state containing a tri-critical point into our 3D-RFD. This new equation of state will be tested on the regular canon of observables (single particle spectra, elliptic and radial flow observables etc.). first comparison of transverse momentum spectra has been published in [P31] and further detailed studies are in progress. [S.A. Bass in collaboration with C. Nonaka at Nagoya University]

2.6.3 Freeze-out properties of multi-strange baryons

In [P33] we have investigated the excitation function of the freeze-out time, average freeze-out temperature and freeze-out energy density of (multi-) strange baryons created in relativistic heavy-ion collisions. For our study we utilized the UrQMD model and focused onto an energy range from AGS to upper SPS energies, in which UrQMD has proven to reliably describe experimental measurements. We find that the $\Omega$ on average freezes out earlier than the nucleon, $\Xi$ and $\Lambda$. The average freeze-out temperature and energy density as well as the spread between the different baryonic states increase monotonously with increasing beam energy and should approach a universal value in the case of a hadronizing Quark-Gluon-Plasma. Our study provides an important motivation for future experiments to focus on (multi-)strange baryons as sensitive probes to the early hot and dense reaction phase. [S.A. Bass]

2.7 Phenomenology of the Tricritical Point

Lattice-QCD simulations have shown that the transition between the hadronic and quark-gluon plasma phases of quantum chromodynamics (QCD) at vanishing baryon chemical potential $\mu_B$ is a crossover transition. This raises the question whether the crossover transition becomes a first-order phase transition for larger values of $\mu_B$. Several attempts have been made to locate the critical point, i.e. the endpoint of the first-order transition line, in lattice simulations, but its existence is still in doubt. The inconclusive theoretical results have motivated plans for a systematic exploration of the properties of hot QCD matter as a function of the net baryon density by means of a collision energy scan at the Relativistic Heavy Ion Collider (RHIC). The search for the QCD critical point also forms part of the motivation for the NA61 experiment at the CERN-SPS and for a new facility dedicated to the study of compressed baryonic matter at the Facility for Antiproton and Ion Research (FAIR) in Germany.

Ideas for experimental signatures for the presence of the critical point have mostly focused on fluctuations in certain observables related to the order parameter of the chiral transition. General arguments lead one to believe that such fluctuations are enhanced in the vicinity of the critical point. Unfortunately, several reasons throw doubt on the usefulness of fluctuation observables as
practical signatures of the QCD critical point. First, fluctuations are suppressed, compared to the static case, when the matter passes rapidly through the critical region during the expansion due to critical slowing down. Secondly, the hot matter does not freeze out at the critical point, but at a much lower temperature, when the critical fluctuations may well have been washed out. Finally, it is unclear in which observable fluctuations are most promising experimentally. In exploratory experiments at the CERN-SPS, only fluctuations in the $K/\pi$ ratio at beam energies below 40 GeV/A have shown signs of an unusual behavior.

In [P5] we have proposed a possible signature of the presence of a critical point in the QCD phase diagram, which may be more robust than fluctuations associated with the order parameter of the chiral phase transition. Our idea is based on the observation that the critical point serves as an attractor of the hydrodynamical trajectories in the $\mu_B - T$ plane describing the expansion of the hot matter [53]. We show that the evolution of the $\bar{p}/p$ ratio along isentropic curves between the phase boundary in the QCD phase diagram and the chemical freeze-out point is strongly dependent on the presence or absence of a critical point. When a critical point exists, the isentropic trajectory approximately corresponding to hydrodynamical expansion is deformed, and the $\bar{p}/p$ ratio grows during the approach to chemical freeze-out. If nucleons of high transverse momentum are chemically frozen out earlier than the slow nucleons, as it is suggested by microscopic simulations of hadronic dynamics, this result will translate into a $\bar{p}/p$ ratio that falls with increasing transverse momentum instead of a rise or flat behavior in scenarios without critical point. This behavior would only occur at those beam energies, for which the fireball reaches the critical point. Depending on the actual size of the attractive region around the critical point, the search for an anomaly in the $y_T$ dependence of the $\bar{p}/p$ ratio may require small beam energy steps. Note that the location of the critical point in our model study was chosen such that it is encountered by the hydrodynamical trajectory for conditions reached for a beam energy of 40 GeV/A and a fixed-target. For a different location of the critical point, similar behavior would occur at other beam energies. [S.A. Bass and B. Mueller]

2.8 Hadron Mass Spectrum

Lattice simulations of the thermodynamics of baryon symmetric QCD matter with dynamical quarks have finally reached a stage where precision results with physical quark masses are becoming available. [54, 55]. Lattice QCD simulations with stout or other highly improved fermion actions indicate that the quasicritical temperature for zero baryon chemical potential lies in the range $T_c = 160 \pm 5$ MeV [56]. It is generally thought that a hadron resonance gas (HRG) provides a good description of the equation of state and quark flavor susceptibilities in the temperature range below $T_c$ (see e. g. [57, 58]).

In our preprint [P42] we point out that the new lattice results are sufficiently precise even at $T < T_c$ to test this hypothesis. In particular, the QCD trace anomaly $\frac{T}{4} = \varepsilon - 3p$ is sensitive to the hadron mass spectrum, because it vanishes in the limit of free massless particles. Borsanyi et. al. [56] found that the trace anomaly predicted on the basis of the mass spectrum of known hadronic states lies significantly below the results obtained in their lattice simulation in the temperature range $140$ MeV $< T < T_c$. We confirmed this observation and showed that it is a consequence of our incomplete knowledge of the spectrum of hadrons with masses above $\sim 1.7$ GeV. When the artificial cut-off is removed and a full exponential Hagedorn spectrum of hadron states is included, the HRG model agrees with the latest lattice QCD results up to $T \approx 155$ MeV. Our analysis shows that lattice simulation can in this way probe the hadron mass spectrum up to masses around 3 GeV. We also propose ways in which lattice-QCD simulations can be used to provide additional details of the hadron mass spectrum, such as the relative contribution from mesons and baryons.
or the flavor composition. [B. Mueller]

2.9 Physics with Two Time-like Dimensions

Together with former Duke undergraduate student Jacob Foster (who just completed his Ph. D. degree in complex systems science at U. of Calgary and is now a postdoc at U. Chicago), we completed a manuscript on the physics in space-times with two time-like dimensions [P39]. Such theories were widely regarded as pathological, due to violations of causality and unitarity. In our manuscript, we argue that these objections may be evaded under certain circumstances. One possibility is that the dynamics in one of the two time-like dimensions is highly excited and chaotic. We present arguments how unitarity on large scales can be recovered and how a-causal effects may be avoided over macroscopic time scales. If the microscopic time scale is of the order of the Planck time, this would not have adverse observable effects. We also construct a specific model based on AdS/CFT duality which encodes these properties. [B. Mueller]
3 Proposed Research

3.1 Overview

The overarching goal of the investigation of relativistic heavy ion collisions is to explore the properties of hot and dense QCD matter, i.e., matter composed of quarks and gluons. This field of research has now reached the stage where promising strategies for the extraction of important matter properties, including the equation of state $p(\varepsilon)$, the specific shear viscosity $\eta/s$, and the jet transport parameter $\hat{q}$, by comparison of theoretical models with experimental data exist and are ready for implementation. Our research group is centrally involved in a comprehensive effort of this type, which is currently underway with funding by the National Science Foundation (MADAI project). Several members of our group are also contributing to an effort aimed at improving our theoretical control over the connection between matter properties, such as $\hat{q}$, and jet quenching observables (the JET Topical Collaboration). One of us (B. Mueller) serves as co-spokesperson of this collaboration. The support of the activities of our research group through this grant in the past has positioned us to play a leading role in these activities.

A second important direction of research has arisen in recent years, which is aimed at understanding how the gluon structure of the colliding nuclei influences the collision dynamics. On the one hand, one wants to know whether the conjectured universal, saturated state of the color glass condensate is reflected in the final-state observables of a relativistic heavy ion collision and what one can learn from this; on the other hand, one wants to understand how, and how quickly, the highly coherent initial state thermalizes. Related to this problem is the question how event-by-event fluctuations of the energy density in the initial state propagate into various final-state observables, and what we can learn from this connection by comparing data with model simulations. The core of our research projects described in this proposal is focused on these two questions: exploring the connections between initial state fluctuations and final observables, and understanding how the color glass condensate thermalizes. We now present a slightly more detailed outline of these two focus areas:

- The energy density and flavor quantum number distribution fluctuates in the initial state in a relativistic heavy ion collision. Better theoretical control and an improved understanding of these fluctuations is important for two reasons. First, initial state fluctuations have the ability to “pollute” dynamically generated observables of interest, such as elliptic flow, possible Mach cones accompanying quenched jets, and critical fluctuations signaling the proximity of a critical point in the QCD phase diagram. Second, and possibly more importantly, the dynamical evolution of initial state fluctuations during the hydrodynamical expansion may lead to new powerful probes of the hydrodynamic properties of the medium. This is similar to the fluctuations of the cosmic microwave background, which informs us of both, the dynamical history of the hot Big Bang and the nature of the inflationary expansion that precedes it. Our group has made various contributions to this area in the past, including the past year, and we believe that we have the right expertise to be among the leaders in this area. The work dedicated to these phenomena so far only scratches the surface, and there is the potential for extracting much more interesting physics from the RHIC and future LHC data than has been possible so far.

- We want to develop and implement a complete ab initio description of the transport processes in the glasma phase that separates the color glass condensate from the thermal quark-gluon plasma. This includes detailed simulations of transport phenomena in the presence of strong color fields, either remnants of the colliding color glass condensates or fields
that are dynamically generated by plasma instabilities. The basic methods that will be used to perform these studies (parton cascade model and particle-in-cell techniques for simulations of the parton-field interaction) were both pioneered by our group in the 1990's, but have only now become accessible to realistic simulations due to the advance in computing power. The challenge of a quantitative and realistic simulation of the transition from the color glass condensate to thermal equilibrium is one of the grand challenges for the next decade described in the recent DOE Extreme Scale Computing Whitepaper.

We also plan to work on several other problems relevant to the RHIC and LHC data. One project concerns realistic calculations of anomaly driven charge asymmetry fluctuations, also known as the chiral magnetic effect or “local parity violation”. Another project involves improved calculations of identical particle (HBT) correlations including pre-equilibrium flow and initial-state fluctuations. We also plan to implement the exact solution of the Zakharov path integral for radiative energy loss by a fast parton on an event-by-event basis in a realistic bulk evolution model. Finally, as in the past, we intend to address important unanticipated physics questions that arise from the experimental data, including those from the LHC, as they become available.

3.2 Investigating the Initial State of Relativistic Heavy-Ion Collision

Effective approaches based on transport theory or hydrodynamics have been successfully applied for the description of the evolution of the system. These dynamical simulations need to incorporate the different sources of event-by-event fluctuations consistently. During the last few years different hybrid models that combine a transport prescription with a hydrodynamic evolution for the hot and dense stage of the reaction have been developed [59, 60, 61, 62, 63]. Either the initial conditions are generated by a transport approach to take into account event-by-event fluctuations as e.g. realized in the NExspheRIO approach [61] and a new approach by Werner et al. [64]. The other possibility is to use parameterized initial conditions for the hydrodynamical evolution and use a hadronic transport approach to describe the rescatterings in the late stage where the matter is too dilute to employ hydrodynamics [65, 59, 60, 66, 62, 63, 67].

The initial conditions and the freeze-out hypersurface serve as the boundary conditions for hydrodynamic calculations that are used to extract properties of hot and dense strongly interacting matter like the equation of state or the viscosity. Furthermore, the thermodynamic properties of the expanding system are used as an input for jet energy loss calculations. Therefore, it is very important to constrain the initial conditions of the hydrodynamic calculations as much as possible by systematic studies. The longitudinal dynamics can be used to resolve key features, e.g. interesting findings in particle correlation measurements have shown structures in the longitudinal direction known as the ‘ridge’ phenomenon. If one assumes causal evolution of the system longitudinal long-range correlations have to be created in the very early stages of the heavy ion reaction and provide useful insights to investigate the initial conditions. It is therefore necessary to take into account all three spatial dimensions for the further evolution to be able to access this information in the calculations. Since there is no 3-d viscous hydrodynamics code yet and all quantitative studies with lower dimensional codes so far point to the fact that the viscosity is very low, we will initially use established, well-tested 3-d ideal hydrodynamics calculations for the exploration of the initial conditions until 3-d viscous codes become available.

So far, most of the hydrodynamic calculations use smooth parametrized initial profiles fitted to describe final state observables such as multiplicities and transverse momentum spectra. The advantage of using dynamical approaches instead is obvious: Event-by-event fluctuations are taken into account, and there is some description of the pre-equilibrium phase that can be tested. Fur-
thermore, the normalization of the energy density profile is provided by physics assumptions and is no longer a free fit parameter. Therefore, improving the dynamical description, e.g. transport approaches, of the initial state and systematically studying different procedures is a promising approach to constraining the initial state for a heavy ion collision. By employing a dynamical transport approach to initialize macroscopic quantities like energy densities it is possible to learn something about the initial starting time of hydrodynamics and the size of the initial state fluctuations. The group will develop an improved prescription of fluctuations in various early collision phase models, including the Glauber model, the Color Glass Condensate model, and the Parton Cascade model, and develop parametrizations for the early time non-equilibrium evolution. This idea complements the studies employing transport approaches and might lead to a clearer identification of the crucial inputs. The different approaches are outlined in more detail below.

3.2.1 Improved Glauber and CGC Initial Conditions with Pre-Equilibrium Evolution

Relativistic hydrodynamics has been very successful in understanding the collective behavior exhibited by the bulk matter created in relativistic heavy-ion collisions [68, 69]. It has been used to quantitatively extract the shear viscosity-to-entropy ratio $\eta/s$ via comparison with precise flow measurements [70, 71, 72, 73, 74, 75]. The initial conditions play an important role in these efforts due to the strong sensitivity of the final flow to the initial collision geometry as inferred from different initial condition models [62, 19].

Currently, the two widely used initial conditions models, namely, the Glauber [76, 77] and color glass condensate (CGC) [78, 79, 80, 81] models, have neglected the influence of the early time evolution of the colliding matter on the hydrodynamical simulation. Unlike hydrodynamical evolution which directly translates the initial geometric anisotropies into observed momentum anisotropies, early time evolution will not only smear out the spatial fluctuations and change the local momentum distribution, but also build the correlations between odd and even moments.

We plan to incorporate the pre-equilibrium evolution and develop a comprehensive model of the initial conditions prior to hydrodynamical evolution. The full phase space distribution at initial production time will be obtained for the above two models with various fluctuations built in, such as individual nucleon-nucleon fluctuations in the Glauber model, color charge fluctuations in the CGC model. The evolution of the system at early times will be simulated by solving Boltzmann equations for the phase space distribution using Monte-Carlo method. From the success of hydrodynamics in heavy-ion collisions, the system must have achieved local thermal equilibrium before entering into hydrodynamical evolution.

With little knowledge of thermalization mechanisms up to now, we will approximate the equilibration process by the interaction of the system with the thermal distribution that the system will gradually approach. Combining such calculations with hydro+micro simulations, we will be able quantify the influence of various fluctuations on the initial collision geometry and the role of the pre-equilibrium stage on the flow built up during the system evolution. These will improve our knowledge of the collective dynamics of the expanding fireball and put tighter constraint on the extraction of its various transport properties.

[G.Y. Qin, H. Petersen, B. Mueller, S.A. Bass]

3.2.2 Fluctuating Initial Conditions from a Hadron-String Approach

The microscopic Ultra-relativistic Quantum Molecular Dynamics transport approach [24, 25, 82] is used to generate the initial conditions for the hydrodynamic evolution in the hot and dense stage of the heavy ion reaction. The nuclei are initialized according to Woods-Saxon profiles and binary
nucleon-nucleon collisions are dynamically evaluated until the energy has been deposited. The hadrons that belong to the core region of the fireball are translated to provide the initial profiles for the ideal hydrodynamic calculation. This approach allows to study the size of initial state fluctuations, the starting time and the degree of equilibration in one framework. Approximate local thermal equilibrium is a necessary assumption for the hydrodynamic evolution. To quantify the deviation from local equilibrium, the energy-momentum tensor in the initial state generated by the hadronic transport approach has to be calculated. The remaining off-diagonal components of this tensor after a transformation to the local rest frame govern the information about the departure from equilibrium.

The freeze-out prescription will be investigated further and different freeze-out hyper-surfaces will be implemented to test the sensitivity of the results on the transition criteria. By taking into account the final hadronic rescatterings in a hadron cascade approach, it is possible to create a model for the full dynamics of the heavy ion reaction from initial to final state with state-of-the-art ingredients. The hybrid model allows to explore the differences between transport and hydrodynamics - viscosity effects - and changes of the equation of state using the same initial conditions and freeze-out. The sensitivity on different initial conditions and freeze-out prescriptions can be tested separately. This offers the possibility to disentangle the influence on the results of the different uncertainties within a single framework.

[H. Petersen, S.A. Bass]

3.2.3 Fluctuating Initial Conditions from a Parton Cascade

The Parton Cascade Model (PCM) [83, 84] is a microscopic transport model which is used to simulate the time evolution of a system of quarks and gluons utilizing the Boltzmann equation. Here, we plan to use the BMS implementation, which has been applied successfully to the calculation of direct photon production [85, 86] and baryon stopping [87] at RHIC. PCM implementations by other groups have been used to address collective flow, parton energy-loss as well as multi-particle effects on transport coefficients [88, 89, 90, 91, 92, 93, 94]. The PCM initial configuration for the two colliding nuclei is generated by sampling known parton distribution functions (e.g. GRV or CTEQ) at an initialization scale $Q_0^2$ to create a discrete set of partons for each proton or neutron. The nuclei then are initialized according to Woods-Saxon profiles for the respective nucleons which in turn are expressed by the aforementioned partons.

After generating the initial parton configuration for the two colliding nuclei, partons generally propagate on-shell and along straight-line trajectories between interactions. Before their first collision, partons may have a space-like four-momentum, especially if they are assigned an “intrinsic” transverse momentum. We then let the PCM evolve to a pre-determined hydrodynamic initial time, at which the partons that belong to the core region of the fireball are used to calculate the initial components of the energy-momentum tensor for the further hydrodynamic evolution of the system. The final step of the evolution of the system will be the same as in the previous project, i.e. using UrQMD as hadronic afterburner after hadronization and conversion of the fluid cells into an ensemble of discrete hadrons. As in the previous section, we plan to study the sensitivity the size of initial state fluctuations and the varying the starting time have on the resulting degree of equilibration of the system and its hadronic final state.

[Vivek Bhattacharya, H. Petersen and S.A. Bass]
3.2.4 Chiral Magnetic Effect

We plan to extend our investigations of the chiral magnetic effect by calculating the response of the hot QCD medium to the electromagnetic current created by topological gauge field fluctuations in the strong magnetic field. We have derived a nonlocal effective QED–QCD action, which encodes the chiral magnetic effect as well as nonlinear QED effects in the superstrong magnetic field generated by the colliding nuclei. Using our previously derived formulation of the transport of the charge density fluctuations from their origin to the freeze-out hypersurface, we will calculate the predicted fluctuation of the charge asymmetry among emitted hadrons with respect to the collision plane. This will allow us to make (the first) quantitative predictions of the chiral magnetic effect for the observables studied by the RHIC experiments.

[B. Mueller in collaboration with A. Majumder (OSU) and A. Schäfer (Regensburg)].

3.2.5 HBT in (3+1)-dimensional Hydro+Micro

We intend to revisit the topic of HBT interferometry utilizing our improved 3+1D Hydro+UrQMD model: all current hydrodynamic calculations have failed to reasonably describe the measured RHIC HBT data, giving rise to the so-called HBT puzzle at RHIC. Recently there has been a lot of progress in identifying the physics driving the discrepancy between RFD and data [95]. Key among the effects are the equation of state and the initial condition for the hydrodynamic calculation. With our novel equation of state implementation as well as the currently being developed CGC initial condition we will be able to verify within a state-of-the-art hydro+micro calculation whether the EoS plus appropriate initial conditions containing a strong longitudinal acceleration [96] provide a solution to the HBT puzzle.

[H. Petersen, S.A. Bass]

3.3 Transport Properties of Hot QCD Matter

3.3.1 Decoherence and Thermalization

Introduction

A quantitative understanding of transport properties of strongly interacting matter that is based on more fundamental QCD calculations is needed to provide input to the phenomenological models. These calculations can then be compared to the experimental measurements to draw conclusions about the newly produced state of matter. This is the most promising way to a further understanding of the properties of hot and dense nuclear matter.

Due to the running of the coupling constant, QCD cannot be treated perturbatively in the regime (a few times $T_c$) that is relevant for heavy ion collisions. One approach to attack the problem is to discretize the QCD action and to solve it on a lattice [97, 98, 99]. Due to the euclidean formulation in imaginary time one can only calculate static and thermodynamic properties in this formalism.

In partonic transport approaches the dynamical scatterings between partons are simulated [83, 89, 90]. These parton cascades are based on non-equilibrium methods and solve the Boltzmann equation as the above described approach for hadrons. The calculation of the cross sections from the QCD matrix elements involves either a low-momentum cut-off or a Debye screening mass to avoid infrared divergences. Therefore, these approaches are not well suited to account for soft interactions with relative momenta below the momentum cut-off or which are screened by $m_D$.

An alternative approach to treat the non-equilibrium processes in the deconfined phase is based on a classical treatment of the soft color fields (Yang-Mills equation) in combination with
hard scatterings of partons similar to a parton cascade [100, 101]. The particle-field interactions are taken into account self-consistently according to the Wong equations. This ansatz has the advantage that the infrared cut-off problem is solved dynamically due to the separation of scales.

Current Status

Since the matter created in heavy ion collisions at RHIC has been found to behave like an almost ideal fluid there is a big interest in quantifying the viscosity of the matter by using, e.g., viscous hydrodynamics simulation [102, 72]. To be able to extract transport properties as the viscosity from a more fundamental approach is necessary to provide an input for the dynamical simulations. More general, also other quantities that are used to characterize the strongly interacting medium like the transport coefficient $\hat{q}$ that is extracted from energy loss measurements are of great interest.

During the last years, a very sophisticated numerical implementation of a QCD transport algorithm has been developed [101]. It is based on the concept originally developed by the Duke group [103], where the soft modes of the gauge field is represented by classical background color fields that are evolved in the presence of colored particles representing the hard thermal modes of the gauge field. The evolution of the fields is described by the Yang-Mills equations, and the interactions between particles and particles and fields are governed by the Wong equations. The scale separation happens naturally because the modes with a wavelength that is too short to be resolved by the structure of the lattice are treated as hard particles. Therefore, by varying the lattice and cell sizes it is possible to demonstrate the independence of the results on this cut-off.

This implementation has the great advantage that non-equilibrium dynamical calculations in real time are possible. Compared to parton cascades the field degrees of freedom are consistently taken into account [100, 101]. This formalism has been used to explain early thermalization due to instabilities in anisotropic plasmas [104], to calculate the influence on jet quenching and the ridge [105, 106] and in medium photons. More recently, our group has worked on the calculation of transport properties like the anomalous viscosity [26], the ridge phenomenon [107] and the transport coefficient $\hat{q}$ [108] analytically based on qualitative approximations.

Proposed Project

The main idea is to calculate the field correlator in the above described framework of a numerical implementation of QCD parton transport including field degrees of freedom. The field correlator can be related to transport properties of deconfined matter, such as the energy loss parameter $\hat{q}$ that quantifies the density of scattering centers, and the anomalous viscosity that is generated due the field degrees of freedom. Also the shear viscosity can be calculated via the Kubo formalism. The Duke group has just developed a similar calculation for a hadron cascade case [109]. The experience from this study will be helpful to apply the technique to the more involved case with non-abelian color fields coupled to particle degrees of freedom.

The aim of the project is to justify input of phenomenological models within a more fundamental calculation and to calculate the temperature dependence of the transport coefficients instead of only using averaged values. At high energies or temperatures the calculation should match the analytical results that have been obtained using perturbative methods. With this approach one might be able to extrapolate the results down towards the hadronic regime where quantitative predictions already exist. The expected results are highly relevant for a better understanding of non-equilibrium QCD matter in the deconfined phase and therefore especially at high RHIC and future LHC energies.
Computational Challenges

The next generation of codes for simulating the time evolution of the chromo-Weibel instability will extend the work of Ref. [110] to simulate fully three-dimensional dynamics of the collective modes in an expanding background. Additionally, the class of codes which include particle back reaction [101] dubbed Colored-Particle-in-Cell (CPIC) codes will also have to be enhanced. The CPIC codes currently include both soft-soft interactions to all orders by solve the Yang-Mills in realtime, include soft-hard interactions via particle bending and color rotation, and also hard-hard interactions through the inclusion of binary particle collisions. The current version of the CPIC code is fully parallelized using MPI and the computation time scales inversely with the number of cores used; however, for this scaling to hold the machines should be connected via an ultrafast network and housed in the same facility in order to reduce communications overhead. There is currently effort underway to include hard-particle brehmmstrahlung (high-momentum radiative processes) in a way consistent with LPM suppression at forward angles.

What is needed is a code which can self-consistently describe both the earliest-times when the physics of saturation is important and also the intermediate times which the physics of the chromo-Weibel instability becomes important. In order to do this requires the real-time solution of Yang-Mills on three-dimensional lattices coupled self-consistently to the Wong equations. Such codes already exist [101, 106]; however, in order to make it possible to describe the full early-time dynamics of the quark-gluon plasma they will have to be refined and scaled-up to the petaflop (and later exaflop) regime. In addition, it will be necessary to implement strategies for measuring a host of observables which can then be compared with real-world data.

In order to have a description of the first 0.1-0.2 fm/c of the plasma lifetime at phenomenologically relevant collision energies it is necessary to (a) relax the assumption of longitudinal boost invariance inherent in traditional CGC treatments and (b) include large-\(x\) effects necessary to guarantee energy conservation and properly take into account recoil effects. This will require going to three-dimensional lattices with a fine lattice spacing in the longitudinal direction. To determine the three-dimensional structure of the gluon field produced in a relativistic heavy-ion collision requires solving the classical Yang-Mills equations in real time on a three-dimensional lattice with about \(512^3\) sites. The field equations describing the small-\(x\) gluons need to be coupled self-consistently to the Wong equations which describe the propagation of the hard valence sources in the soft background, including energy-momentum conservation [101]. Beyond the classical limit, a simultaneous solution of the rapidity dependence of the JIMWLK measure together with the real-time evolution of the initial fields is required.

Beyond that it is necessary to have a lattice which is capable to describe the dynamics of the chromo-Weibel instability and the subsequent non-abelian cascade to high-momentum modes. The brute force way to ensure this is to make sure that the lattice spacing is incredibly fine. This means that one might need lattices even larger than \(512^3\). Since some of the processes, e.g. initial conditions, binary particle collisions, and hard radiation, are stochastic it will be necessary to average observables over multiple runs. We will also have to generate runs for each different nucleus and impact parameter.
Outcomes and Impacts

The project will deliver the first calculation in real time of the collision of two heavy ions at high energy, retaining the complete three-dimensional structure of the field of produced gluons (in impact parameter and rapidity space), energy-momentum conservation, and quantum evolution of the measure. The subsequent real-time evolution of the color fields following the initial impact will clarify the time scales and processes that lead to thermalization and formation of a QGP and the possible role played by non-Abelian gauge-field instabilities. The distribution of the thermalized gluons in impact parameter and rapidity will provide much needed initial conditions for hydrodynamic modeling of the late stages of the collision and enable quantitative extraction of the equation of state and of the viscosity of hot QCD matter. The project would also provide predictions for the effect of early-time non-equilibrium dynamics on important QGP observables such as jet quenching, anomalous transport, and fluctuations.

3.3.2 Path-Integral based simulation of radiative partonic energy loss in a realistic evolving medium

The energy loss of hard partons emerging from central rapidity region in heavy ion collisions has been extensively investigated [4, 5, 6]. The main goal is to obtain a quantitative understanding of the transport properties of the hot, dense matter created in these collisions [111]. Of great current interest is simulating the parton energy loss and the resulting parton shower evolution within a hot, dense deconfined medium of quarks and gluons [112, 113, 114, 115, 116, 90].

We plan to develop an event generator for modeling the interaction between the hard parton and the hydrodynamical medium. We intend to implement the Z-BDMPS [117, 118, 119, 120] path integral approach to radiative energy loss using Monte-Carlo methods. The advantage of such an approach is that it allows for the flexible incorporation of the bulk matter with density varying arbitrarily in both space and time [121]. We intend to be extend this approach to study heavy quark energy loss. This method also has the potential to permit an investigation of the energy loss in the pre-equilibrium stage, which has not been properly taken into account in current calculations. Combining this with fluctuating initial conditions and embedding the resulting model in hydro+micro codes, we will be able to improve the accuracy of radiative energy loss calculations and provide better quantification of the interactions between jets and strong interacting medium on an event-by-event basis.

[C. Coleman-Smith]

Note for clarification: This project is not part of the research plan of the Topical Collaboration on Jet and Electromagnetic Tomography of Extreme Phases of Matter in Relativistic Heavy Ion Collisions (JET Collaboration).

3.4 Heavy Quark Production and Medium Interactions

The production and transport of heavy quark flavors, i.e. charm or bottom quarks, create important probes of the properties of the hot, dense medium created in relativistic nuclear collisions. Measurements of hadrons containing heavy quarks are be among the most exciting results of RHIC Run-4 and later and have revealed a surprising picture, namely that the heavy quarks seem to be strongly affected by their surrounding medium.

Over the past year, and in collaboration with D.K. Srivastava (VECC Kolkata), we have implemented heavy-quark matrix elements for the production and scattering of heavy quarks into our version of the Parton Cascade Model. This puts us in a position to study the dynamics of heavy
quark production and possible thermalization in a weakly coupled pQCD medium as well as allows us to utilize the distribution of initially produced heavy quarks in the PCM for studies in transport approaches for a strongly coupled QGP, such relativistic fluid dynamics.

In the context of Parton Cascade Model calculations, we plan to address the following questions:

- Dynamics of heavy quark production: what are the dominant processes for the production of heavy quarks in a relativistic heavy-ion collision? What is the role of early parton rescattering? What are the timescales of heavy quark production? How does the production and rescattering of heavy quarks depend on the formation time in light parton interactions (i.e. the implementation of the LPM effect)?

- Heavy quark energy loss: how does the heavy quark lose energy and what fraction of heavy quark energy-loss is due to elastic scattering and what role do radiative processes play? We intend to address this question first for infinite QGP matter at fixed temperature before comparing our results to same analysis performed for the initial stage of a heavy-ion collision, modeled in the PCM approach.

- Heavy quark thermalization: how do heavy quarks thermalize and on what time-scales? This question will be addressed in the same fashion as the previous one: first in infinite matter at fixed temperature at which thermalization is assured and then subsequently for the initial stage of a heavy-ion collision. Particular emphasis in the latter case will be placed on determining whether the heavy quark actually thermalizes in the dynamic medium or remains off-equilibrium over the course of its evolution.

A new graduate student, Shanshan Cao, has joined our research group in order to conduct research on heavy quark dynamics in a fully thermalized medium, e.g. a strongly interacting QGP. This research centers on the utilization of a Langevin Equation for describing the heavy quark dynamics in terms of a diffusion process. Within this approach, we intend to conduct the following research:

- Heavy quark thermalization: what are the time-scales for a heavy quark to thermalize in an infinite medium at fixed temperature? How does the heavy quark thermalize in such a medium (longitudinal vs. transverse degrees of freedom)? Does thermalization actually occur in an expanding and cooling finite system (i.e. a sQGP), or do the heavy quarks never acquire the properties of their surrounding medium?

- Langevin equation with memory kernel: current heavy quark diffusion calculations do not account for QCD-specific characteristics of the medium, such as the dynamics of turbulent color fields

[S.S. Cao, S.A. Bass]

3.5 AdS/CFT Approach to Thermalization

Thermalization in strongly coupled field theories with a gravity dual is generally described as the formation of a black hole (more precisely, a black brane) in the five-dimensional bulk space-time. The thermal state of the field theory on the Minkowski space boundary is encoded in the classical physics of the event horizon. This picture gives rise, e.g., to the celebrated quantum lower limit of the shear viscosity-to-entropy density ratio $\eta/s \geq 1/4\pi$ [18]. While the physics in thermal equilibrium has been extensively studied, the equilibration process itself remain largely unexplored. One
conjecture is that the growth of entropy is reflected in the growing area of the apparent horizon of the bulk black hole. Specific models in which the approach to the thermal state have been studied are a mass shell descending into the bulk [122, 123, 124] and infalling energy density generated by metric deformations at the boundary [125].

We have begun to study the time evolution of Minkowski space (boundary) correlation functions in the semi-classical approximation when a thin mass shell is either freely infalling or being adiabatically lowered toward the future event horizon. In the near future, we plan to analyze these correlation functions to understand the thermalization process in detail. We also plan to investigate the growth of the entropy of the field theory by calculating the entanglement entropy for a region in the boundary space-time [126, 127]. We hope that these studies will yield a detailed picture of the thermalization process of the field theory in the strong coupling limit.

[B. Mueller in collaboration with V. Balasubramanian (U. Pennsylvania), A. Bernamonti, C. Craps, and W. Staessens (Brussels), J. de Boer and M. Shigemori (Amsterdam), E. Keski-Vakkuri (Helsinki), A. Schäfer (Regensburg)]

3.6 Triangle Nuclear Theory Colloquium

The biweekly Triangle Nuclear Theory (TNT) Colloquium, which has been funded as a part of this grant, is jointly organized by the nuclear theory community in the NC Triangle. Its location rotates among Duke University, the North Carolina State University (NCSU), and the University of North Carolina at Chapel Hill (UNC).

The Colloquium is regularly attended by the members of the nuclear and particle theory groups of the three institutions and at times by local experimentalists from the Triangle Universities Nuclear Laboratory (TUNL) and faculty from North Carolina Central University (NCCU) in Durham. Invited speakers are always asked to start with a fairly general introduction into the topic appropriate for the non-experts in the audience but then may go into as much detail concerning their current research as is suitable for a nuclear theory seminar. Attendance varies between 15 and 25 or more depending on the subject matter and speaker. A list of speakers and titles for the past three years is given in the Appendix. The seminar series has been a tremendous benefit to our community of scientists, including 11 nuclear theory faculty, especially to our postdoctoral fellows and our graduate students, for whom the series has provided opportunities to become acquainted with a wide range of topics and to meet many of the leading members of the nuclear theory community in the United States and abroad.

As has been customary, different members of the three groups [most recently T. Schäfer (NCSU) and T. Mehen (Duke)] will be asked to take responsibility for the organization of the TNT colloquium series in rotation, so that all members of the local theory community retain “ownership” of the series, while ensuring a broad scope and attractiveness of the speakers program.
4 Documentation

Published works from previous reporting periods

[W1] A. Majumder and B. Müller,
"Higher twist jet broadening and classical propagation,"

"Radiative jet energy loss in a three-dimensional hydrodynamical medium and high $p_T$ azimuthal asymmetry of $\pi^0$ suppression at mid and forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV,"

[W3] C. Nonaka and S. A. Bass,
"Space-time evolution of bulk QCD matter at RHIC,"

[W4] S. A. Bass and C. Nonaka,
"Modeling of heavy-ion collisions at the Relativistic Heavy-Ion Collider,"

Works completed in current reporting period

[P1] B. Müller,
"From Quark-Gluon Plasma to the Perfect Liquid,"

[P2] A. Majumder, R. J. Fries and B. Müller,
"Photon bremsstrahlung and diffusive broadening of a hard jet,"

[P3] A. Majumder,
"The study of dense matter through jet modification,"

[P4] R. B. Neufeld, B. Müller and J. Ruppert,
"Sonic Mach Cones Induced by Fast Partons in a Perturbative Quark-Gluon Plasma,"

"Transverse Velocity Dependence of the Proton-Antiproton Ratio as a Signature of the QCD Critical Point,"

[P6] R. B. Neufeld,
"Fast Partons as a Source of Energy and Momentum in a Perturbative Quark-Gluon Plasma"
[P7] B. Müller,  
“Theoretical Challenges Posed by the Data from RHIC,”  

[P8] H. Petersen, M. Bleicher, S. A. Bass and H. Stöcker,  
“UrQMD-2.3: Changes and Comparisons”  

“Systematic Comparison of Jet Energy-Loss Schemes in a 3D hydrodynamic medium,”  

[P10] A. Majumder and X. N. Wang,  
“Modification of the dihadron fragmentation function in nuclear matter,”  
preprint [arXiv:0806.2653 [nucl-th]].

[P11] R. J. Fries, B. Müller and A. Schäfer,  
“Decoherence and Entropy Production in Relativistic Nuclear Collisions,”  

[P12] R. B. Neufeld,  
“Mach Cones In The Quark-Gluon Plasma: Viscosity, Speed Of Sound, And Effects Of Finite Source Structure”  

[P13] R. J. Fries, B. Müller and A. Schäfer,  
“Stress Tensor and Bulk Viscosity in Relativistic Nuclear Collisions,”  

“Systematic Comparison of Jet Energy-Loss Schemes in a realistic hydrodynamic medium,”  

[P15] A. Idilbi and A. Majumder,  
“Extending Soft-Collinear Effective Theory to describe hard jets in dense QCD media,”  

[P16] T. Kunihiro, B. Müller, A. Ohnishi and A. Schäfer,  
“Towards a Theory of Entropy Production in the Little and Big Bang,”  

[P17] A. Majumder,  
“Characterizations of the medium in jet quenching calculations,”  
preprint [arXiv:0810.1367 [nucl-th]].

[P18] R. B. Neufeld,  
“Comparing different freeze-out scenarios in azimuthal hadron correlations induced by fast partons,”  

[P19] A. Majumder,  
“Elastic energy loss and longitudinal straggling of a hard jet,”  
[P20] H. M. Tsai and B. Müller,
"Phenomenology of the three-flavour PNJL model and thermal strange quark production,"

[P21] B. Müller,
"The 'Perfect' Fluid Quenches Jets Almost Perfectly,"
preprint [arXiv:0811.2979 [nucl-th]].

[P22] N. Demir and S. A. Bass,
"Extracting Hadronic Viscosity From Microscopic Transport Models"

[P23] N. Demir and S. A. Bass,
"Shear-Viscosity to Entropy-Density Ratio of a Relativistic Hadron Gas"

[P24] R. B. Neufeld and B. Müller,
"The sound produced by a fast parton in the quark-gluon plasma is a 'crescendo'"

[P25] A. Majumder, B. Müller and St. Mrówczyński,
"Momentum Broadening of a Fast Parton in a Perturbative Quark-Gluon Plasma"

[P26] S. A. Bass,
"Modeling Of Relativistic Heavy-Ion Collisions With 3+1d Hydrodynamic And Hybrid Models"

[P27] R. J. Fries, T. Kunihiro, B. Müller, A. Ohnishi and A. Schäfer,
"From 0 to 5000 in $2 \times 10^{-24}$ seconds: Entropy production in relativistic heavy-ion collisions"

[P28] R. B. Neufeld and B. Müller,
"The sound generated by a fast parton in the quark-gluon plasma is a crescendo"

[P29] H. M. Tsai and B. Müller,
"Aspects of thermal strange quark production: the deconfinement and chiral phase transitions"

[P30] N. Demir and S. A. Bass,
"$\eta/s$ of a Relativistic Hadron Gas at RHIC: Approaching the AdS/CFT bound?"

[P31] C. Nonaka, M. Asakawa, S. A. Bass and B. Müller,
"Signals of the QCD Critical Point in Hydrodynamic Evolutions"

[P32] G. Y. Qin and A. Majumder,
"A pQCD-based description of heavy and light flavor jet quenching"
[P33] Z. Xie, P. Ning and S. A. Bass,
“The freeze-out properties of hyperons in a microscopic transport model”
[arXiv:0911.4410 [nucl-th]]

[P34] H. Petersen and M. Bleicher,
“Eccentricity fluctuations in an integrated hybrid approach: Influence on elliptic flow”

[P35] H. Petersen, G.Y. Qin, S.A. Bass and B. Müller,
“Triangular flow in event-by-event ideal hydrodynamics in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) A GeV”
[arXiv:1008.0625 [nucl-th]]

[P36] G. Shin, S.A. Bass and B. Müller,
“Transport Theoretical Description of Collisional Energy Loss in Infinite Quark-Gluon Matter”

“Shear Viscosity in a Perturbative Quark-Gluon-Plasma,”
arXiv:1008.2306 [nucl-th].

[P38] S. Mrówczyński and B. Müller,
“Quasi-linear transport approach to equilibration of quark-gluon plasmas”

[P39] J. G. Foster and B. Müller,
“Physics With Two Time Dimensions”
[arXiv:1001.2485 [hep-th]].

[P40] M. Asakawa, A. Majumder and B. Müller,
“Electric Charge Separation in Strong Transient Magnetic Fields”

[P41] T. Kunihiro, B. Müller, A. Ohnishi, A. Schäfer, T. T. Takahashi and A. Yamamoto,
“Chaotic behavior in classical Yang-Mills dynamics”
[arXiv:1008.1156 [hep-ph]].

[P42] A. Majumder and B. Müller,
“Hadron Mass Spectrum from Lattice QCD”
[arXiv:1008.1747 [hep-ph]].

[P43] M. Asakawa, S. A. Bass, and B. Müller,
“Anomalous Transport Processes in Turbulent non-Abelian Plasmas”

[P44] H. Petersen, T. Renk and S. A. Bass,
“Medium-modified Jets and Initial State Fluctuations as Sources of Charge Correlations Measured at RHIC,”
arXiv:1008.3846 [nucl-th].
List of Principal Collaborators

List of Collaborators of Berndt Mueller:
M. Asakawa (Osaka), S.A. Bass (Duke), T.S. Biró (Budapest, Hungary), R.J. Fries (Texas A&M), Y. Kanada-En'yo (Kyoto, Japan) J.I. Kapusta (Minnesota), T. Kunihiro (Kyoto, Japan) A. Majumder (Ohio State), S.G. Matinyan (Yerevan), H. Minakata (Tokyo, Japan), J.L. Nagle (Colorado), C. Nonaka (Nagoya, Japan), A. Ohnishi (Kyoto, Japan), G. Purcsel (Budapest, Hungary), J. Rafelski (Arizona), K. Rajagopal (MIT), T. Renk (Jyväskylä, Finland), J. Ruppert (McGill, Canada), A. Schäfer (Regensburg, Germany), G.R. Shin (Andong, Korea), D.K. Srivastava (VECC Kolkata, India), C.I. Tan (Brown), T. Takahashi (Kyoto, Japan), X.N. Wang (LBNL), A. Yamamoto (Kyoto, Japan).

Names of graduate and postdoctoral advisors of B. Mueller:
Graduate advisor: W. Greiner J.W. Goethe Universität Frankfurt, Germany
Postdoctoral advisor: L. Wilets University of Washington

List of Collaborators of Steffen A. Bass:
F. Antinori (INFN Padova), M. Asakawa (Osaka), R. Bellwied (Wayne State) M. Bleicher (Frankfurt), H. Caines (Yale), M. Calderon de la Barca Sanchez (UC Davis), J. Casalderrey-Solana (CERN) A. de Falco (INFN Cagliari), R.J. Fries (Texas A&M), U. Heinz (Ohio State), J. Kapusta (Minnesota), C. Kuhn (IN2P3, Strassbourg), J. Nagle (U. of Colorado, Boulder), A. Majumder (Ohio State), M. Nardi (INFN Torino), C. Nonaka (Nagoya), G. Y. Qin (Duke), T. Renk (Jyväskyla), J. Ruppert (McGill), C. Salgado (Santiago de Compostela), G.R. Shin (Andong, Korea), H. Song (Ohio State / LBNL) D.K. Srivastava (VECC Kolkata), T. Ullrich (Brookhaven), J. Velkovska (Vanderbilt), U.A. Wiedemann (CERN)

Names of graduate and postdoctoral advisors of S.A. Bass:
W. Greiner J.W. Goethe Universität Frankfurt, Germany graduate advisor
H. Stöcker J.W. Goethe Universität Frankfurt, Germany graduate advisor
B. Müller Duke University postdoctoral advisor
W. Bauer Michigan State University postdoctoral advisor
<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Present position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steffen Bass</td>
<td>2000–01</td>
<td>Assoc. Professor, Duke University</td>
</tr>
<tr>
<td>Rainer Fries</td>
<td>2002–03</td>
<td>Asst. Professor, Texas A&amp;M University</td>
</tr>
<tr>
<td>Carsten Greiner</td>
<td>1993–95</td>
<td>Professor, Universität Frankfurt, Germany</td>
</tr>
<tr>
<td>Klaus Kinder-Geiger</td>
<td>1990–91</td>
<td>Deceased (previously BNL staff member)</td>
</tr>
<tr>
<td>Sen-Ben Liao</td>
<td>1993–96</td>
<td>Staff Scientist, LLNL</td>
</tr>
<tr>
<td>A. Majumder</td>
<td>2005–08</td>
<td>Visiting Assistant Professor, Ohio State University</td>
</tr>
<tr>
<td>Chiho Nonaka</td>
<td>2001–04</td>
<td>Asst. Professor, Nagoya University, Japan</td>
</tr>
<tr>
<td>Thorsten Renk</td>
<td>2003–05</td>
<td>Postdoc, Jyväskylä University, Finland</td>
</tr>
<tr>
<td>Dirk Rischke</td>
<td>1995–96</td>
<td>Professor, Universität Frankfurt, Germany</td>
</tr>
<tr>
<td>Jörg Ruppert</td>
<td>2004–06</td>
<td>Postdoc, McGill University, Canada</td>
</tr>
<tr>
<td>Alec Schramm</td>
<td>1990–91</td>
<td>Professor, Occidental College</td>
</tr>
<tr>
<td>Young-ho Song</td>
<td>2008–10</td>
<td>Postdoc, Univ. South Carolina</td>
</tr>
<tr>
<td>Markus Thoma</td>
<td>1993</td>
<td>MPI f. Extraterr. Physik, München, Germany</td>
</tr>
<tr>
<td>Atanas Trayanov</td>
<td>1991–93</td>
<td>NASA Goddard Space Flight Center, GMAO</td>
</tr>
<tr>
<td>Xin-Nian Wang</td>
<td>1991–92</td>
<td>Senior Staff Member, LBNL</td>
</tr>
</tbody>
</table>

Table 1: Names and current positions of former postdoctoral fellows.

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<thead>
<tr>
<th>Name</th>
<th>Adviser</th>
<th>Date</th>
<th>Current Employment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chris Coleman-Smith</td>
<td>Bass &amp; Mueller</td>
<td>2009–</td>
<td>grad. student (Duke)</td>
</tr>
<tr>
<td>Shanshan Cao</td>
<td>Bass</td>
<td>2010–</td>
<td>grad. student (Duke)</td>
</tr>
<tr>
<td>Nasser Demir</td>
<td>Bass</td>
<td>2006–10</td>
<td>Lecturing Fellow (Duke)</td>
</tr>
<tr>
<td>Glen Doki</td>
<td>Mueller</td>
<td>1997–00</td>
<td>U. S. Navy instructor</td>
</tr>
<tr>
<td>Cheng-Qian Gong</td>
<td>Mueller</td>
<td>1991–95</td>
<td>Chase Manhattan Bank, Hong Kong</td>
</tr>
<tr>
<td>Fritz Kretzschmar</td>
<td>Bass</td>
<td>2010–</td>
<td>grad. student (Duke)</td>
</tr>
<tr>
<td>R. Bryon Neufeld</td>
<td>Mueller</td>
<td>2006–09</td>
<td>Director’s Fellow, LANL</td>
</tr>
<tr>
<td>Andru Prescod</td>
<td>Mueller</td>
<td>1996–97</td>
<td>Corning Corporation</td>
</tr>
<tr>
<td>Jochen Rau</td>
<td>Mueller</td>
<td>1990–94</td>
<td>Goethe Univ., Frankfurt, Germany</td>
</tr>
<tr>
<td>Michael Strickland</td>
<td>Mueller</td>
<td>1993–97</td>
<td>Asst. Professor, Gettysburg College</td>
</tr>
<tr>
<td>Hung-Ming Tsai</td>
<td>Mueller</td>
<td>2007–</td>
<td>grad. student (Duke)</td>
</tr>
<tr>
<td>Di-Lun Yang</td>
<td>Mueller</td>
<td>2010–</td>
<td>grad. student (Duke)</td>
</tr>
</tbody>
</table>

Table 2: Names and careers of current and former graduate students.
Talks and Seminars

Steffen A. Bass

10/13/07 Probing the QGP Structure at RHIC with Jet-Medium Correlations
Invited talk at the APS Division of Nuclear Physics fall meeting, Newport News, VA, USA.

02/05/08 Comparison of Jet Energy-Loss Schemes in a 3D Hydrodynamic Medium
Quark Matter 2008, Jaipur, India.

06/10/08 Comparison of Jet Energy-Loss Schemes in a 3D Hydrodynamic Medium

09/11/08 Modeling of Relativistic Heavy-Ion Collisions with 3+1D Hydrodynamic and Hybrid Models
Invited talk at the IV Workshop on Particle Correlations and Femtoscopy, Krakow, Poland.

10/26/08 Systematic Comparison of Jet Energy-Loss Schemes in a 3D hydrodynamic medium
APS Division of Nuclear Physics fall meeting, Oakland, CA, USA.

10/30/08 The Nature of the Quark-Gluon-Plasma
Invited talk at the 75th Annual Meeting of the Southeastern Section of the American Physical Society, Raleigh, NC, USA.

01/28/09 Hot and Dense QCD
Workshop on Forefront Questions in Nuclear Science and the Role of High Performance Computing, Washington DC, USA.

01/30/09 What do we know about the viscosity of QCD matter?
Nuclear Theory Seminar at Texas A&M University, College Station, TX, USA.

08/16/09 Extracting the Transport Coefficients of QCD Matter with Relativistic Heavy-Ion Collisions
Invited talk at the 10th International Conference on Nucleus-Nucleus Collisions (NN2009), Beijing, China.

10/14/09 Infinite Matter Calculations of Jet Energy-Loss with the Parton Cascade Model
Third Joint Meeting of the Nuclear Physics Divisions of the American Physical Society and The Physical Society of Japan, Kona, HI, USA.

10/23/09 From the Big Bang to Atmospheric Modeling: Developing Advanced Model to Data Analysis Techniques
Annual Center for Theoretical and Mathematical Sciences Retreat, Duke University, NC, USA.

10/29/09 What do we know about the viscosity of QCD matter?
Nuclear Theory Seminar at McGill University, Montreal, QC, Canada.

11/12/09 The Quest for the Quark-Gluon-Plasma
Physics Colloquium at Texas A&M University, Commerce, TX, USA.

12/14/09 Hybrid Hydro+Micro Models: Status and Outlook
Joint CATHIE/TECHQM workshop at Brookhaven National Laboratory, Upton, NY, USA.
Nasser Demir

10/10–13/07 Transport Coefficients of Hadronic Matter
Contributed talk at the 2007 Annual Meeting of the Division of Nuclear Physics of the American Physical Society (DNP 2007), Newport News, VA.

4/21–22/08 Hadronic Transport Coefficients from a Microscopic Transport Model
Workshop on Hydrodynamics in Heavy Ion Collisions and QCD Equation of State at Brookhaven National Laboratory, Upton, NY.

8/18–23/08 Hadronic Shear Viscosity from a Microscopic Transport Model
2008 Hot Quarks Workshop, Estes Park, CO.

10/23–26/08 Influence of Finite Chemical Potential on Hadronic Shear Viscosity
Contributed talk at the 2008 Annual Meeting of the Division of Nuclear Physics of the American Physical Society (DNP 2008), Oakland, CA.

3/19/09 Hadronic Transport Coefficients from a Microscopic Transport Model
Nuclear Theory Seminar at Ohio State University, Columbus, OH, USA.

4/03/09 Shear-Viscosity to Entropy Density Ratio of a Relativistic Hadron Gas at RHIC: Approaching the AdS/CFT bound?
Parallel talk given at Quark Matter 2009: the 21st International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Knoxville, TN, USA.

6/01/09 $\eta/s$ of a Relativistic Hadron Gas at RHIC
RHIC & AGS Annual Users’ Meeting, Brookhaven National Laboratory, Upton, NY, USA.

6/05/09 $\eta/s$ of a Relativistic Hadron Gas from a Hadronic Cascade
Nuclear Theory Seminar at Brookhaven National Laboratory, Upton, NY, USA.

Kang-Seog Lee

10/6–10/08 Hadronization of a quark-gluon plasma via recombination
Invited talk, International Conference on Strangeness in Quark Matter (SQM2008), Beijing (China).

10/13–15/08 Hadronization of a Quark-gluon Plasma via Recombination
Asian Triangle Heavy-Ion Conference (ATHIC 2008), Tsukuba, Japan.
Abhijit Majumder

6/8–14/08 Characterizations of the medium in jet quenching calculations

5/6/08 Jet quenching: status and open questions

4/12–15/08 Hard probes of the quark gluon plasma
Invited talk at the APS April meeting, Mini-symposium on “Hard Probes of the Quark-Gluon Plasma”, St. Louis, MO, April 2008.

3/3/08 Hard probes of strongly coupled QCD matter
Special Nuclear Physics Seminar, The Ohio State University, Columbus, OH, March 2008.

2/14/08 Jet modification: the perturbative probe of non-perturbative QCD matter

2/13/08 Studying QCD matter in the laboratory, from atomic nuclei to quark gluon plasma

12/13–14/08 Jet modification in deconfined media: Beyond $q$ and $R_{AA}$
PHENIX collaboration meeting, Brookhaven National Laboratory, Upton, NY, December 2007.

11/29/08 Probing QCD matter with jets and jet correlations

Berndt Mueller

11/22/08 Summary and Future of Heavy Ion Physics
Tamura Memorial Symposium, University of Texas, Austin, TX.

11/19/08 What Does a Quark-Gluon Plasma Sound Like?
Physics Colloquium, University of Texas, Austin, TX.

10/6/08 The Flavors of the Quark-Gluon Plasma
Opening Lecture, International Conference on Strangeness in Quark Matter (SQM2008), Beijing (China).

9/23/08 The Perfect Liquid Extinguishes Jets (nearly) Perfectly
30th Int. Ettore Majorana School on Nuclear Physics, Erice, Sicily (Italy).

8/28/08 What Does a Quark-Gluon Plasma Sound Like?
Physics Colloquium, Vanderbilt University, Nashville, TN.

8/13/08 The Wigner Functional Method in Quantum Field Theory
Workshop on Entropy Production, Yukawa Institute for Theoretical Physics, Kyoto, Japan.
6/19/08 Life at the Edge of Chaos: Vacuum Instability and Color Turbulence in QCD
Maier-Leibnitz Kolloquium, Ludwig-Maximilian Universität, Munich, Germany.

5/28/08 Quark-Gluon Plasma: From Concepts to "Precision" Science
RHIC Users Meeting, Brookhaven National Laboratory, Upton, NY.

5/5/08 The Future of RHIC
STAR Collaboration Meeting, Brookhaven National Laboratory, Upton, NY.

3/28/08 What Does a Quark-Gluon Plasma Sound Like?
Physics Colloquium, University of Calgary, Alberta, Canada.

3/4/08 Theoretical Challenges posed by the Data from RHIC
Symposium on Fundamental Problems in Hot and/or Dense QCD, Yukawa Institute for Theoretical Physics, Kyoto, Japan.

2/26/08 The Sound of Fast Partons in the Quark-Gluon Plasma
Workshop on New Frontiers in QCD 2008, Yukawa Institute for Theoretical Physics, Kyoto, Japan.

2/9/08 Panel Discussion
Quark Matter 2008, Jaipur, India.

2/8/08 Mach Cones in a Perturbative Quark-Gluon Plasma
Quark Matter 2008, Jaipur, India.

11/25/08 From Quarks and Gluons to the "Perfect Fluid"
Physics Colloquium, Virginia State University, Blacksburg, VA.

04/02/09 From 0 to 5000 in 2 x 10^{-24} s: Entropy Production in Relativistic Heavy Ion Collisions
Quark Matter 2009, Knoxville, TN.

06/12/09 What Does a Quark-Gluon Plasma Sound Like?
Tenth Workshop on Nonperturbative QCD, Paris (France).

08/05/09 Exploring the "Perfect Fluid"
PHENIX Collaboration Meeting, Brookhaven National Laboratory.

09/11/09 Can You Hear and See a Quark-Gluon Plasma?
The John Cramer Symposium, University of Washington, Seattle, WA.

09/23/09 From 0 to 5000 in 2 × 10^{-24} s: Entropy Production in Relativistic Heavy Ion Collisions
Nuclear Physics Seminar, University of Maryland, College Park, MD

10/14/09 Stranger Than Fiction: Adventures in the QCD Wonderland
Joint Meeting of the DNP/JPS, Big Island, Hawai‘i

12/18/09 Status and Prospects of Jet Quenching: Lessons from the QGP Brick Problem
Joint CATHIE-TECHQM Workshop, BNL, Upton, NY

11/11/09 Probing QCD Matter with Relativistic Heavy Ions
KEK Cosmophysics Workshop (KEK-CPWS-HEAP2009), KEK (Japan)
4/12/10  *Physics with Two Time-Like Dimensions*
Physics Colloquium, Columbia University, New York, NY

4/27/10  *Hadronic and Partonic Mechanisms of Charge Asymmetry Fluctuations*
Workshop on P- and CP-odd Effects in Hot and Dense Matter, BNL, Upton, NY

5/10/10  *Anomalous Transport Processes in the Turbulent Non-Abelian Plasmas*
Workshop on Saturation, the Color Glass Condensate and Glasma, BNL, Upton, NY

6/11/10  *Exploring the Wonderland of the QCD Phase Diagram*
School of Collective Dynamics in High Energy Collisions, LBNL Berkeley, CA

9/03/10  *Exploration of Hot QCD Matter: The Next Decade*
CERN Theory Institute: TheFirst Heavy Ion Collisions at the LHC (HIC10), CERN, Geneva (Switzerland)

**R. Bryon Neufeld**

10/10–13/07  *The hydrodynamic response of a QGP to fast partons*
Contributed talk at the Annual Meeting of the Division of Nuclear Physics of the American Physical Society, Newport News, VA.

11/25/07  *Fast partons as a source of energy and momentum in a thermal quark gluon plasma*
Nagoya University Department of Physics, Nagoya, Japan.

3/19/08  *Sonic Mach cones induced by fast partons in a perturbative quark gluon plasma*
Los Alamos National Laboratory (Subatomic Physics Group (P-25)), Los Alamos, NM.

4/21–22/08  *Sounding out the QGP*
Workshop on Hydrodynamics in Heavy Ion Collisions and QCD Equation of State at Brookhaven National Laboratory, Upton, NY.

8/18–23/08  *Fast partons as a source of energy and momentum in a perturbative QGP*
Hot Quarks 2008 Workshop, Estes Park, CO.

10/23–26/08  *Propagating Mach cones in a viscous quark gluon plasma*
Contributed talk at the Annual Meeting of the Division of Nuclear Physics of the American Physical Society, Oakland, CA.

01/21/09  *Fast partons as a source of energy and momentum in a thermal QGP*
Nuclear Theory Seminar at Lawrence Berkeley National Lab, Berkeley, CA, USA.

01/27/09  *Fast partons as a source of energy and momentum in a thermal QGP*
Subatomic Physics Seminar at at Los Alamos National Lab, Los Alamos, NM, USA.

02/12/09  *The Response of a QGP to Radiating Hard Partons*
Nuclear Physics Seminar at Ohio State University, Columbus, Ohio, USA

02/25/09  *Recent Developments in the Theory of Mach Cones in the QGP*
Talk given at workshop on Particle Correlations In Relativistic Heavy Ion Collisions, Brookhaven National Lab.
02/27/09  *The Response of a Thermal QGP to Radiating Hard Partons*
Nuclear Physics & RIKEN Theory Seminar at Brookhaven National Laboratory, Upton, NY, USA.

04/03/09  *The Sound Produced by a Fast Parton in the Quark-Gluon Plasma is a Long*

**Hannah Petersen**

03/22/10  *Eccentricity fluctuations in an integrated hybrid approach: Influence on elliptic flow*
Kernphysikalisches Kolloquium at Goethe University, Frankfurt am Main, Germany.

04/28/10  *Medium-modified jets and initial state fluctuations as sources of charge correlations measured at RHIC*
Workshop on P- and CP-odd effects in hot and dense matter, Brookhaven National Laboratory, Upton, NY, USA.

05/11/10  *Modeling of heavy ion collisions*
MADAI Collaboration Workshop, Sandia National Laboratory, Albuquerque, NM, USA.

06/04/10  *Comparing initial conditions in a (3+1)d Boltzmann+Hydrodynamics transport approach*
Institute for Nuclear Theory, University of Washington, Seattle, WA, USA.

**Guangyou Qin**

06/08/10  *Gamma-jet correlations*
Talk at RHIC/AGS Annual Users’ Meeting, Brookhaven National Laboratory, NY, USA.

06/19/10  *A systematic approach to fluctuating initial conditions from Glauber and CGC*
Talk at 2010 JET collaboration meeting, 2010, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

06/24/10  *Perturbative description of jet-medium interaction*
Talk at 2010 INT workshop on “Quantifying properties of Hot QCD Matter”, University of Washington, Seattle, WA, USA.

07/27/10  *Interactions between jets and the hot, dense medium*
Talk at Seminar in Hadronic Physics at McGill University, Montreal, QC, Canada.

**Hung-Ming Tsai**

03/07/09  *Phenomenology of the three-flavor PNJL model and thermal strange quark production*
Talk given at Duke physics graduate student seminar

04/02/09  *Aspects of thermal strange quark production: the deconfinement and chiral phase transitions*
Parallel talk given at Quark Matter 2009: the 21st International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Knoxville, TN, USA.
**TNT Colloquium Schedule**

The Triangle Nuclear Theory Colloquium, which has been funded by the grant is jointly organized and held at Duke University, the University of North Carolina at Chapel Hill (UNC) and the North Carolina State University (NC-State).

09/18/07 Mark Wise (Caltech) *High Energy Theorists Gone Wild: Speculations on Physics at the Weak Scale*

09/25/07 Joerg Ruppert (McGill) *Low Mass Dimuons Produced in Relativistic Nuclear Collisions*

10/02/07 Jon Engel (UNC) *Nuclear Density-Functional Theory and the UNEDF Collaboration*

10/16/07 Carl Carlson (William and Mary) *Empirical transverse charge densities in the nucleon and in the nucleon-to-Delta transition*

10/23/07 Thomas Cohen (Maryland) *Is there a fundamental bound on the ratio of viscosity to entropy density?*

10/30/07 George Sterman (SUNY Stony-Brook) *Jets, energy flow and the 'real gluon’*

11/06/07 Scott Bogner (Ohio State) *Building a Microscopic Nuclear Energy Density Functional*

11/13/07 Harvey Meyer (MIT) *Heavy ion collisions and the transport coefficients of QCD*

12/04/07 Dam Thanh Son (INT Seattle) *Graphene as a laboratory for quantum field theory methods*

03/18/08 Paul Hohler (Maryland) *Doubly heavy diquark-antiquark symmetry: The little symmetry that might*

04/11/08 Sean Fleming (Arizona) *Top Jets and Precision Measurements of the Top Quark Mass*

04/15/08 Giuseppe Vitiello (Salerno University) *Particle Mixing in QFT and Flavor States*

04/22/08 Charles Gale (McGill) *Relativistic Nuclear Collisions: Towards a Consistent Tomography of Matter Under Extreme Conditions*

04/29/08 Zackaria Chacko (Maryland) *New Ideas in Electroweak Symmetry Breaking*

05/06/08 Ben Bakker (Vrije University Amsterdam) *Deeply-virtual Compton scattering off the pion: Clarifying conceptual issues*

09/02/08 Lukas Platter (Ohio State) *Universal Relations for Strongly-Interacting Fermi Gases from the Operator Product Expansion*

10/14/08 Matthias Burkardt (New Mexico State) *Transverse Structure of Hadrons*

10/28/08 Sanjay Reddy (Los Alamos National Laboratory) *Superfluid Heat Conduction in the Neutron Star Crust*

11/11/08 Bjoern Schenke (McGill) *Jet energy loss in stable and unstable non-Abelian plasmas*

12/02/08 Felix Werner (U. Mass-Amherst) *Cold Atoms near a Feshbach Resonance: Analytical Results*
12/09/08 Matthias Schindler (Ohio University) *Bayesian parameter estimation in effective field theories*

01/13/09 John Ralston (Kansas U.) *Mixing Color and Spin*

02/24/09 Paul Romatschke (U. of Washington) *Fluid Dynamics of Weakly and Strongly Coupled Field Theories*

03/26/09 Michael Ramsey-Musolf (U. of Wisconsin) *Electric Dipole Moments, the LHC, and the Origin of Matter*

04/09/09 Silas Beane (U. of New Hampshire) *Few-nucleon effective field theory with perturbative pions*

04/14/09 Barry Holstein (U. of Mass. Amherst) *Why Didn’t I Think of That?*

04/17/09 Vijay Balasubramanian (U. of Pennsylvania) *Black Hole Microstates, the AdS/CFT correspondence and thermalization of strongly coupled gauge theory*

09/01/09 Huichao Song (The Ohio State University) *Viscous Relativistic Fluid Dynamics*

10/06/09 Joaquin Drut (The Ohio State University) *What can Lattice QCD do for Condensed Matter Physics?*

11/03/09 Michael Buchoff (U. of Maryland) *Search for Chiral Fermion Actions on Non-Orthogonal Lattices*

11/10/09 Marco van Leeuwen (Utrecht University) *What do we know about parton energy loss in a QCD medium?*

11/17/09 Johannes Kirschner (George Washington U.) *Universality in Pion-less EFT with the Resonating Group Model: Three, Four, and Six Nucleons*

11/24/09 Aleksey Cherman (U. of Maryland) *Transport Coefficients and Universality in High T Holography*

12/01/09 Barak Bringoltz (U. of Washington) *Space-Time Reduction of Large N Gauge Theories*

12/08/09 Kevin Dusling (Brookhaven National Lab) *Radiative energy loss and v2 spectra for viscous hydrodynamicse*

12/15/09 Sanjib Kumar Agarwalla (Virgina Tech) *Neutrino Parameters with a Mono-flavor Beta-beam*

01/12/10 Jinfeng Liao (LBNL) *Characterizing the QCD X-Matter from "Little Bang"*

01/15/10 Carla Frohlich (U. of Chicago) *Core Collapse Supernovae as Laboratory for Radioactive Nuclei*

01/26/10 Zainul Abidin (William And Mary) *Gauge/gravity duality: applications to meson’s form factors*

02/16/10 Andrew Steiner (Michigan State U.) *Neutron Star Seismology and the Equation of State of Dense Matter*

03/23/10 Fu-Juin Jiang (MIT) *A Monte Carlo investigation of spatially anisotropic Heisenberg models*

04/20/10 Thorsten Renk (University of Jyvaskyla, Finnland) *Medium Modified Jets*
04/27/10 Petr Navratil (Lawrence Livermore National Laboratory, Livermore, CA) *Structure and reactions of light nuclei from the first principles*

06/29/10 Kuang-Ta Chao (Peking University) *Interpretation of the X(3872): charmonium vs. molecule*

07/27/10 Rupa Chatterjee (VECC Kolkata) *Elliptic flow and electromagnetic radiation in relativistic heavy-ion collisions*
5 Appendices

Biographical Sketch: Steffen A. Bass

Address: Department of Physics
Duke University
Durham, NC 27708-0305, USA
E-mail: bass@phy.duke.edu

Education:

• M.S. (Diplom): Physics, 1993, J.W. Goethe Universität Frankfurt (Germany), “mit Auszeichnung”
• Ph.D. (Dr. phil. nat.): Theoretical Physics, 1997, J.W. Goethe Universität Frankfurt (Germany), “summa cum laude”

Professional Experience:

• 2008 - present Associate Professor (with tenure) Duke University
• 2000 - 2007 Assistant Professor (tenure track) Duke University
• 2000 - 2005 RIKEN BNL Research Center Fellow
• 1999 - 2000, Visiting Assistant Professor, Michigan State University
• 1998 - 99 Feodor Lynen Fellow and Research Associate at Duke University
• 1995 - 97 Research Assistant, J.W. Goethe Universität Frankfurt
• 1993 - 95 Research Assistant, Gesellschaft für Schwerionenforschung (GSI), Darmstadt

Awards:

• 1993: W.E.-Heraeus-Award, W.E.-Heraeus Foundation, Germany
• 1997: Feodor-Lynen Fellow, A.v.Humboldt Foundation, Germany
• 2003: Outstanding Junior Investigator Award, US Department of Energy

Publications:

• 120 published articles with (according to SPIRES) over 4700 citations
  (av. per paper: 39, h-index: 34, TOPCITE250+: 4, TOPCITE100+: 7, TOPCITE50+: 16)

Synergistic activities:

• co-convener (Hot & Dense QCD working group): Workshop on Forefront Questions in Nuclear Science and the Role of High Performance Computing, January 26-28, 2009, Washington DC, USA
• member, local organizing committee: 21st International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2009), March 30 - April 4, 2009, Knoxville, TN, USA
• co-organizer: Workshop on Nearly Perfect Fluids: from the Quark-Gluon Plasma to Ultra-Cold Atoms, April 6 - April 9, 2009, Durham, NC, USA
Publications related to the proposal:

1. S. A. Bass et al.,
   *Microscopic Models for Ultrarelativistic Heavy Ion Collisions*

2. S. A. Bass, B. Müller and W. Pöschl,
   *Lattice Gauge Theory of Colliding Nuclei*,

3. S.A. Bass and A. Dumitru,
   *Dynamics of Hot Bulk QCD Matter: from the Quark-Gluon Plasma to Hadronic Freeze-Out*,

4. S.A. Bass, B. Müller and D.K. Srivastava,
   *Parton rescattering and screening in Au+Au collisions at RHIC*,

5. T. Renk, S. A. Bass and D. K. Srivastava,
   *Dynamics of the Landau-Pomeranchuk-Migdal effect in Au + Au collisions at 200-AGeV*,

6. M. Asakawa, S. A. Bass and B. Müller,
   *Anomalous viscosity of an expanding quark-gluon plasma*,

7. M. Asakawa, S. A. Bass and B. Müller,
   *Anomalous transport processes in anisotropically expanding quark-gluon plasmas*,

8. C. Nonaka and S. A. Bass,
   *Space-time evolution of bulk QCD matter*,

9. A. Majumder, B. Müller and S.A. Bass,
   *Longitudinal Broadening of Quenched Jets in Turbulent Color Fields*,

10. M. Asakawa, S.A. Bass, B. Müller and C. Nonaka,
    *Transverse Rapidity Dependence of the Proton-Antiproton Ratio as a Signature of the QCD Critical Endpoint*

11. S.A. Bass, C. Gale, A. Majumder, C. Nonaka, G.Y. Qin, T. Renk and J. Ruppert,
    *Systematic Comparison of Jet Energy-Loss Schemes in a realistic hydrodynamic medium*,
Biographical Sketch: Berndt Mueller

Address: Department of Physics
Duke University
Durham, NC 27708-0305, USA
Phone: (919) 660-2570
E-mail: mueller@phy.duke.edu

Education:
• M.S. (Diplom): Physics, 1972
  J.W. Goethe Universität Frankfurt (Germany)
• Ph.D. (Dr. phil. nat.): Theoretical Physics, 1973
  J.W. Goethe Universität Frankfurt (Germany), summa cum laude

Professional Experience:
Duke University (Durham, NC):
  1996 – Present: James B. Duke Professor of Physics
  1999 – 2004: Dean of the Natural Sciences
  1997 – 1999: Physics Department Chair
  1990 – 1996: Professor of Physics
J. W. Goethe Universität (Frankfurt, Germany):
  1976 – 1989: Associate Professor (C3)
  1972 – 1974: Research Assistant
University of Washington (Seattle, WA)
  1974 – 1975: Research Associate

Awards and Honors:
1998 Senior U.S. Scientist Award, A. v. Humboldt Foundation
1994 Fellow APS and AAAS
1975 Röntgen Prize, Universität Giessen (Germany) [with P. Mokler and F. Saris]

Publications: More than 300 refereed publications with over 7900 citations (SPIRES-HEP).

Synergistic activities:
2009 Director, Duke Center for Theoretical and Mathematical Science
2005 Member, NSAC Subcommittee on LRP Implementation
2003 Chair, NSAC Subcommittee on Nuclear Theory
2003 Lead Organizer, 7th Int. Conference on Strangeness in Quark Matter (SQM2003)
Selected publications related to the proposal:

Current and Pending Support

- **Nuclear Physics at High Energy Density:**
  US Department of Energy Nuclear Theory Grant, Grant-# DE-FG02-05ER41367-A, B. Müller (PI) and S.A. Bass (Co-PI), March 15, 2008 – March 14, 2011, award amount: $1,045,000.

- **From Models and Data to Knowledge and Understanding:**
  National Science Foundation, Cyber Discovery and Innovation (CDI) Award, Grant-# NSF-PHY-09-41373, Scott E. Pratt (PI), Brian W. O’Shea (Co-PI), Daniel W. Dougherty (Co-PI), Shiyuan Zhong (Co-PI) and Steffen A. Bass (Co-PI), September 1, 2009 – August 31, 2013, award amount: $1,800,000.

- **Topical Collaboration on the Quantitative Study of Properties of the Quark-Gluon-Plasma through Jet-Emission Tomography (JET):**
  US Department of Energy, Grant-# (award pending), X.N. Wang (PI), B. Müller (co-PI), and several other co-PI’s, June 1, 2010 – May 31, 2015, anticipated award amount (Duke Univ. only): $152,000.

- **Nuclear Physics at High Energy Density:**
  US Department of Energy Nuclear Theory Grant, Grant-# DE-FG02-05ER41367-A, B. Müller (PI) and S.A. Bass (Co-PI), March 15, 2011 – March 14, 2014, award amount: $1,198,000 (this proposal).

It is important to note that the R&D in NSF CDI and DOE Topical Collaboration awards are complementary in nature to the research described in this proposal. However, significant synergy effects exist – this proposal will benefit strongly from the simulation framework and analysis tools developed in the context of the NSF CDI grant. Likewise, the JET Topical Collaboration research will benefit directly from the novel jet energy-loss techniques and phenomenological analyses proposed in this research proposal.

**Anticipated Carryover**

At this time, we do not anticipate any unspent funds from grant DE-FG02-05ER41367 at the end of the current grant period (3/14/2011).
References


Resources and Facilities

We are currently operating a 4-node Linux cluster with 32 cores, which was acquired in 2008 with funds from the University. We are also operating a 100 TB storage array, acquired in late 2009, funded by a supplement to our current DOE grant. We have secured university funds allowing us to replace the cluster nodes on a rolling basis.