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I. OVERVIEW:

In the course of this project the Ohio State University group led by the PI, Professor Ulrich Heinz, developed a comprehensive theoretical picture of the dynamical evolution of ultra-relativistic heavy-ion collisions and of the numerous experimental observables that can be used to diagnose the evolving and short-lived hot and dense fireball created in such collisions. Starting from a qualitative understanding of the main features based on earlier research during the last decade of the twentieth century on collisions at lower energies, the group exploited newly developed theoretical tools and the stream of new high-quality data from the Relativistic Heavy Ion Collider at Brookhaven National Laboratory (which started operations in the summer of the year 2000) to arrive at an increasingly quantitative description of the experimentally observed phenomena. Work done at Ohio State University (OSU) was instrumental in the discovery during the years 2001-2003 that quark-gluon plasma (QGP) created in nuclear collisions at RHIC behaves like an almost perfect liquid with minimal viscosity. The tool of relativistic fluid dynamics for viscous liquids developed at OSU in the years 2005-2007 opened the possibility to quantitatively determine the value of the QGP viscosity empirically from experimental measurements of the collective flow patterns established in the collisions. A first quantitative extraction of the QGP shear viscosity, with controlled theoretical uncertainty estimates, was achieved during the last year of this project in 2010. OSU has paved the way for a transition of the field of relativistic heavy-ion physics from a qualitative discovery stage to a new stage of quantitative precision in the description of quark-gluon plasma properties.

To gain confidence in the precision of our theoretical understanding of quark-gluon plasma dynamics, one must test it on a large set of experimentally measured observables. The following achievement reports demonstrate that we have, at different times, systematically investigated both so-called "soft" and "hard, penetrating" probes of the fireball medium: hadron yields and momentum spectra and their anisotropies, two-particle momentum correlations, high-energy partons fragmenting into jets, heavy quarks and heavy-flavor mesons, and electromagnetic probes (photons and dileptons). Our strongest emphasis, and our most significant achievements, has, however, always remained on understanding the bulk behavior of the heavy-ion fireball medium, for which soft probes provide the most abundantly available data and thus the most stringent constraints.

II. ACCOMPLISHMENTS:

II.A. 2001-2003

II.A.1. Radial and elliptic flow and evidence for a thermalized quark-gluon plasma

Collective flow is a necessary consequence of thermalization in heavy-ion collisions, and a large degree of thermalization is required for the creation of a quark-gluon plasma in such collisions. Dynamical studies have therefore played a key role in heavy-ion theory from the beginning of heavy-ion physics in the 1970's.

Collective flow is driven by pressure gradients acting against the inertia of the matter resulting from its energy density. In its ideal form, corresponding to a fluid in perfect local thermal equilibrium, it is thus a direct reflection of the equation of state $p(e, n)$ of the matter (where p, e, n are pressure, energy and baryon density, respectively), integrated over the expansion history. The manifestation of this equation of state, in particular its interesting structure related to the quark-hadron color confinement phase transition at a critical energy density of about $1\,\mathrm{GeV/fm^3}$, in the collective flow pattern of a heavy-ion collision fireball can be studied with the tool of relativistic ideal fluid dynamics ("hydrodynamics").

In 1998 we started, as part of Peter Kolb's diploma and PhD theses, a systematic investigation of the predictions of the hydrodynamical model for hadron spectra in Au+Au or Pb+Pb collisions from AGS to LHC energies. We were especially interested in the flow anisotropies generated in non-central collisions as a result of the anisotropic pressure gradients in the spatially deformed overlap region created in such collisions. In 1997-99 Heinz Sorge [PRL **78** (1997) 2309, PRL **82** (1999) 2048] had realized that these spatial anisotropies get quickly washed out by dynamical evolution and thus persist only for a short time period after nuclear impact. This suggested that any flow anisotropies must be created during the very early expansion stage when the spatial deformation of the nuclear reaction zone had not yet been washed out. If true, anisotropic flow would open a unique window on the equation of state during the interesting early hot and dense stages of the expanding fireball.

To this end we generalized an existing 1+1 dimensional hydrodynamic code to 2+1 dimensions. For reasons of simplicity and calculational efficiency, we kept the assumption of longitudinal boost invariance, i.e. that the dynmical evolution along the beam direction follows Bjorken's scaling velocity profile. Our analysis therefore focussed on the midrapidity region where this scaling assumption has the highest probability of being accurate, especially at high collision energies. The hydrodynamic code then solves dynamically for the transverse expansion of a slice of matter created at midrapidity.

The hydrodynamical model needs initial conditions describing the result of the initial pre-equilibrium ("thermalization") stage of the heavy-ion collision and a freeze-out criterium describing the transition from thermalized matter to freely propagating particles at the end of the collision. The initial conditions are an initial transverse profile for the energy density, which is computed geometrically from a Glauber model and requires a single constant (the energy density in the center) for normalization, and the time when the matter is assumed to be thermalized (i.e. when the hydrodynamic evolution begins) [Kolb, Sollfrank, Heinz, PRC **62** (2000) 054909]. Different possibilities for the scaling properties of the initial conditions (participant vs. binary collision scaling) were investiated in [4], and the relative contribution from these two mechanisms was fixed [4] using data on the centrality dependence of particle (entropy) production at midrapidity. For freeze-out we use the Cooper-Frye prescription with a freeze-out surface parametrized by a critical value for the freeze-out energy density resp. temperature. Comparison with calculations by D. Teaney et al., who replaced this simplistic freeze-out by coupling hydrodnamics to a hadronic cascade after hadronization and letting the cascade do the decoupling microscopically [Teaney, Lauret, Shuryak, arXiv:nucl-th/0110037], showed that at RHIC energies and above the simple Cooper-Frye algorithm does a very good job and leads to almost identical conclusions, if the system-size and (in some cases) the particle species dependence of the freeze-out energy density is properly adjusted to the microscopic calculations.

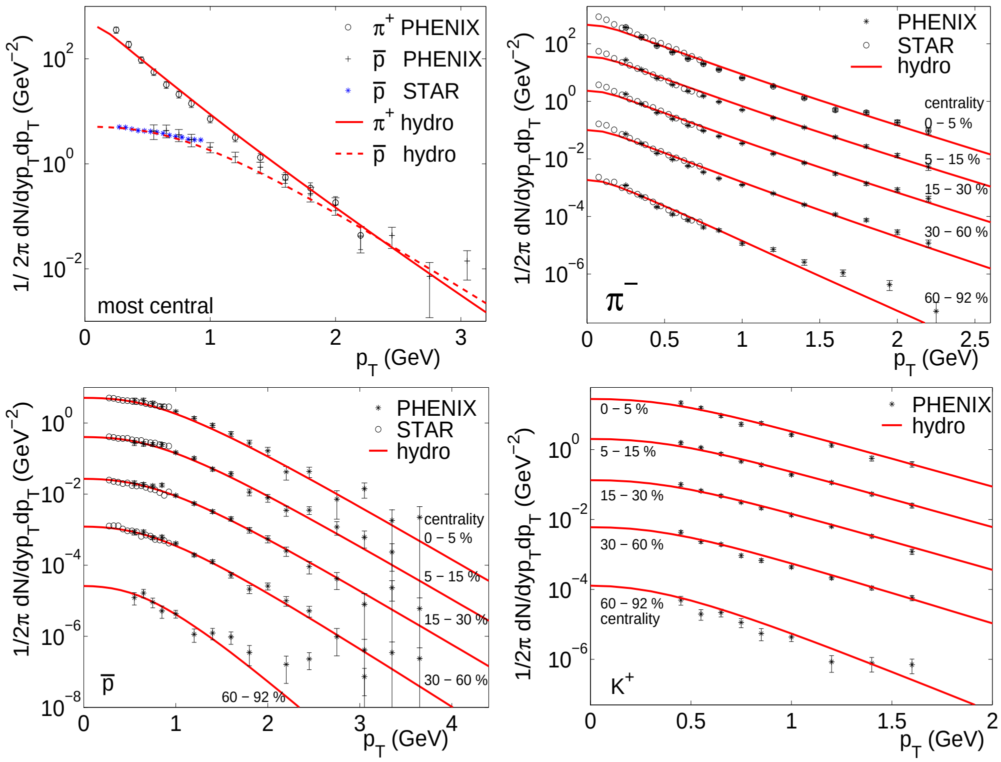

Fig. 1: Identified pion, antiproton and kaon spectra for $\sqrt{s_{\rm NN}} = 130$ GeV from the PHENIX and STAR collaborations in comparison with results from a hydrodynamic calculation [15,20]. The top left panel shows pion and (anti-)proton spectra from central collisions. Shown in the other panels are spectra of five different centralities: from most central (top) to the most peripheral (bottom). The spectra are successively scaled by a factor 0.1 for clarity.

When the hydrodynamic model parameters are adjusted to describe data from central Pb+Pb collisions at the SPS, a simple extrapolation already gives a very good description of the Au+Au collision data at RHIC. After fine-tuning the parameters to pion and proton spectra from central (b=0) Au+Au collisions at RHIC, the description of other hadron spectra from central and non-central collisions (out to impact parameters of about 8-10 fm) for transverse momenta below about 2 GeV/c is almost perfect [15,20] (see Fig.1). In Ref. [2] we made predictions for the shape of the spectra and for the elliptic flow for a variety of different hadron species before they were measured. When they came in, the data confirmed these predictions, even for the Ω baryon (see Fig. 2). In fact, the measured Ω spectra are so flat that that they cannot be described hydrodynamically assuming decoupling directly after hadronization (dotted curve in Fig. 2) – hydrodynamics has not yet developed enough radial flow at this point. It appears that the Ω remains strongly coupled to the expanding hadron fluid until the pions decouple at around $T_f \sim 120 - 130$ MeV [42]. This is not yet fully understood since, based on the constituent quark model, one would expect that the triply-strange Ω couples only weakly to the dominant pions [van Hecke, Sorge, Xu, PRL **81** (1998) 5764]. All other strange hadrons are also correctly described by the hydrodynamic model if one assumes that all hadrons decouple essentially simultaneously with the dominant pions. At that point the average transverse flow velocity ("radial flow") of the fireball is close to 0.6 c.

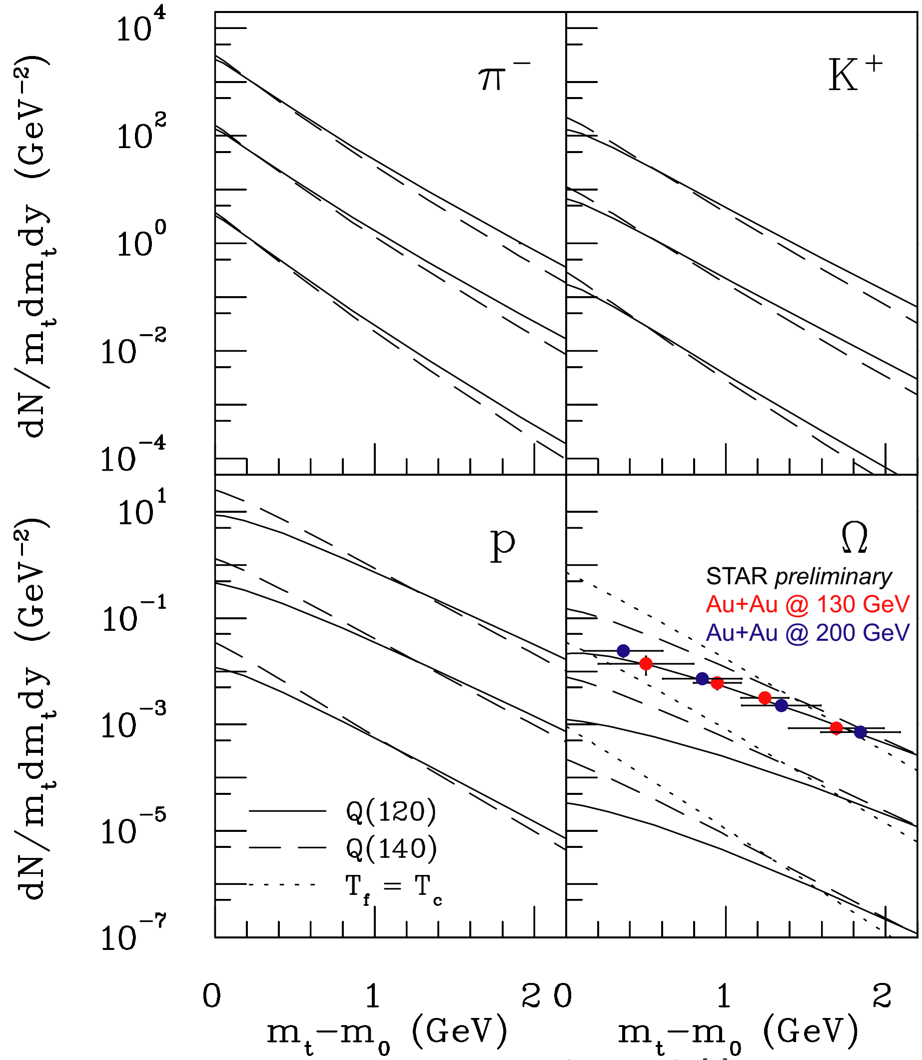

Fig. 2: Hydrodynamically predicted hadron spectra from Ref. [2], together with preliminary $\Omega+\bar{\Omega}$ spectra from the STAR collaboration [42]. The three sets of curves correspond, from top to bottom, to central ($b < 5.4$ fm), semiperipheral ($5.4\,\mathrm{fm} < b < 9.9$ fm) and peripheral ($9.9\,\mathrm{fm} < b < 13.5$ fm) Au+Au collisions at $\sqrt{s} = 130\,A\,\mathrm{GeV}$.

Even more impressive was the discovery that hydrodynamics not only correctly describes the angular-averaged transverse momentum spectra at RHIC and their hadron mass dependence, but also the flow anisotropy in non-central collisions, quantified by the elliptic flow coefficient v_2 [2,4,15,20]. This is a genuine test of the model since, after the thermalization time and freeze-out temperature have been fixed in central collisions, the initial conditions for non-central conditions are simply calculated from geometry and all flow features are predicted without additional free parameters [4]. The model correctly reproduces the measured centrality dependence of the p_T-averaged elliptic flow and its p_T-dependence [STAR Coll., PRL **86** (2001) 402; PHENIX Coll., NPA **698** (2002) 559], including the predicted dependence of v_2 on the hadron mass at low p_T [2,20,25]. Selected examples showing the quality of the agreement between data and model prediction are shown in Fig. 3. It should be noted that the right panel shows that the mass-dependence of v_2 is sensitive to the equation of state, and that the data prefer an equation of state with a deconfining phase-transition over one without it.

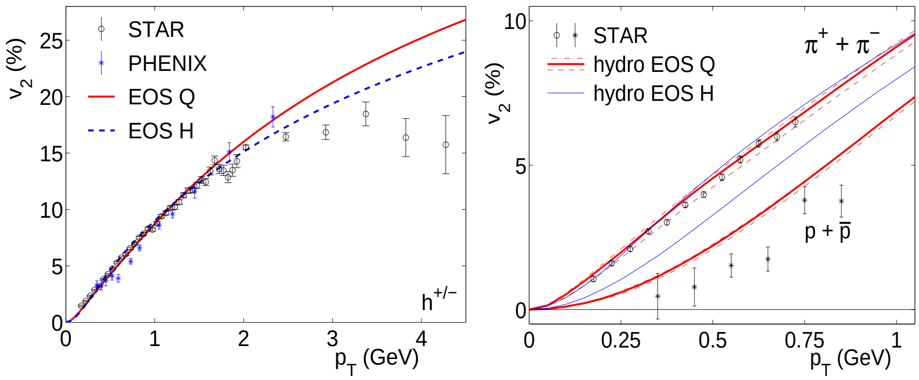

Fig. 3: The elliptic flow coefficient $v_2(p_\perp)$ for all charged particles (left) and for identified pions and protons (right) from 130 A GeV minimum bias Au+Au collisions. The curves are hydrodynamic calculations corresponding to equations of state with (Q) and without (H) a phase transition and (in the right panel) three different freeze-out temperatures ($T_\mathrm{f} = 128$ MeV (dash-dotted), 130 MeV (solid) and 134 MeV (dashed)).

The agreement of the hydrodynamic model with the elliptic flow data is remarkable since the hydrodynamic model is based on the assumption of perfect local thermalization (zero mean free path) and is therefore expected to give an upper limit for the elliptic flow. The fact that the experimental data exhaust this upper limit provides strong evidence for rapid thermalization in Au+Au collisions at RHIC [15,20,25]. The thermalization time scale suggested by the hydrodynamic simulations is of the order of 0.5 fm/c and definitely not larger than 1 fm/c [15,20,46]. Since the elliptic flow is built up early in the fireball expansion and, at RHIC energies, already has almost saturated by the time the initial quark-gluon plasma hadronizes, the thermalization must happen during the quark-gluon plasma stage, at energy densities well above the deconfinement value of about 1 GeV/fm^3. This points to the creation of a well-developed QGP in Au+Au collisions at RHIC [15,20,25]. A comprehensive parameter study [4] showed that these conclusions do not depend on details of the parametrization of the initial transverse density profile.

The hydrodynamic prediction gradually breaks down for larger impact parameters (i.e. smaller initial overlap regions) and for higher p_T (see left panel in Fig. 3). The p_T-dependence of v_2, including its breaking away from the hydrodynamic curve at $p_T > 1.5 - 1.6$ GeV for mesons and $p_T > 2.4 - 2.5$ GeV for baryons [46], can be reproduced in microscopic kinetic theories, such as Molnar's Parton Cascade [Molnar and Gyulassy, NPA **697** (2002) 495], after judiciously adjusting the microscopic scattering cross section among the matter constituents. Non-ideal viscous effects increase with p_T [Teaney, PRC **68** (2003) 034913] and cause the data to lag behind the ideal fluid prediction at high p_T. (Note that more than 99% of the hadrons are emitted at $p_t < 2$ GeV where hydrodynamics works well, so the bulk of the matter produced at RHIC *does* behave hydrodynamically.) Apparently, the elliptic flow is very sensitive to such viscous effects.

In a toy model study [21,28] we explored an extreme case of rather strong viscosity where we postulated perfect thermalization of the transverse momenta but complete absence of thermalization in the longitudinal direction. The result was a reduction of the elliptic flow by more than a factor 2, to values well below the experimental results, if the slope of the angle-averaged spectra was held fixed. (As an aside we mention that this paper [21] also contains a generalization of the Schnedermann-Heinz blast-wave formula. It allows to simultaneously fit the spectra and elliptic flow with a small number of thermal and hydrodynamic parameters and may in the future prove similarly useful as its parent which is broadly used by experimentalists to characterize their spectra.) Our study [21] showed that elliptic flow is very sensitive to viscous effects (see also the recent study by Teaney cited above) and that the RHIC data clearly exclude large viscosities. Low viscosity implies a large degree of thermalization and requires a strongly interacting medium. The quark-gluon plasma created at RHIC is therefore clearly not a weakly interacting gas of quarks and gluons, but must be a rather strongly interacting fluid, presumably requiring a non-perturbative description [15]. This observation leads us to the second theme of our studies:

II.A.2. Transport coefficients for hot plasmas from thermal quantum field theory

Transport coefficients, such as the abovementioned shear viscosity, can be calculated from linear response functions of a thermal medium via the Kubo formulae. Calculating the response functions requires the summation of large classes of diagrams using the formalism of finite temperature quantum field theory. Alternatively, they can be obtained from a linearized Boltzmann equation using a collision kernel calculated from quantum field theory [Arnold, Moore, Yaffe, JHEP **0301** (2003) 030]. The response functions can be related to spectral densities [Wang, Heinz, Zhang, PRD **53** (1996) 5978; Wang and Heinz, PRD **53** (1996) 899 and **67** (2003) 025022] which, in principle, can be calculated numerically on the lattice. In practice, this is made difficult by the need for an analytic continuation of the lattice results from discrete imaginary to continuous real frequencies. This is nowadays done with the help of the "Maximum Entropy Method" [Asakawa et al., Prog. Part. Nucl. Phys. **46** (2001) 459; Karsch et al., PLB **530** (2002) 147]. This method requires a trial ansatz for the functional dependence of the spectral density whose form can be constrained from diagrammatic calculations in thermal quantum field theory.

In Ref. [14] we studied in some detail this connection between transport coefficients, spectral functions and what can be calculated on the lattice, for weakly-coupled scalar and nonabelian gauge theories at high temperature. Transport coefficients are determined by the slope of spectral functions of composite operators at zero frequency. We showed that this slope at zero frequency is very difficult to extract from euclidean lattice simulations. In order to do a good job one should use an optimized trial function as input for the Maximum Entropy Method. Such a function was derived in [14] through an explicit calculation of the spectral density at all frequencies in the weak-coupling limit. It has found widespread acceptance in recent lattice calculations of transport coefficients.

Even at weak coupling, the calculation of the spectral densities for transport coefficients requires the resummation of large classes of diagrams. There are two reasons for this: 1. Even if the medium consists of particles with zero vacuum mass or whose vacuum masses can be neglected on the scale of their thermal energies, the interactions in the medium generate dynamical masses of order coupling constant times temperature which affect the dynamical response of the medium at low frequency and momentum where the transport coefficients are calculated. In standard perturbation theory, which is formulated in terms of particles with vacuum masses, inclusion of the dynamical mass requires resumming infinite sets of "bubble diagrams" in the quasi-particle propagator. 2. Transport effects are associated with scattering in the medium, and for massless bosons with a Bose-Einstein distribution the corresponding scattering rates are infrared divergent, due to the macroscopic occupation of low-frequency modes. This infrared divergence is cut off dynamically by the fact that scattering happens sufficiently frequently that the scattering particles are never completely on-shell, i.e. their own spectral densities have a finite scattering width ("collision broadening"). This thermal scattering width regulates so-called "pinch singularities" in the calculation; however, its consistent consideration in the calculation of the transport coefficient at leading order in the coupling constant requires another resummation of so-called "ladder diagrams". This ladder resummation leads to an integral equation for some scattering vertex which must be solved either analytically or, more likely, numerically.

The identification of the correct sets of diagrams to be resummed at a given order of the coupling constant has been a notorious problem which presents itself in different ways for different types of theories. Gauge theories, such as QED and QCD, pose the additional difficulty that the selected set of resummed diagrams must preserve the Ward identities. With the work of Aarts and Martinez Resco [16,17,40] and some general formal development by Wang and Heinz [22,32] we have made significant progress on this problem. In [16] we studied the Ward identity for the effective photon-electron vertex in hot QED, summing the ladder diagrams contributing to the electrical conductivity at leading logarithmic order. We showed that the Ward identity requires the inclusion of a new diagram in the integral equation for the vertex that had not been considered before. However, the real part of this diagram is subleading and therefore the final expressions for the electrical conductivity at leading logarithmic order are not affected. This clarified why previous calculations which violated the Ward identity had still been able to yield the correct leading logarithmic result for the conductivity.

Our desire to find a systematic organization scheme for selecting, for any theory, the correct set of diagrams for a complete leading order calculation of the transport coefficients culminated in Ref. [40], where we showed for several relativistic field theories that the two-particle irreducible (2PI) effective action, when truncated at the lowest nontrivial order, correctly determines transport coefficients in a weak coupling or $1/N$ expansion at leading (logarithmic) order. This was an important insight since it not only provided a simple organizational framework in which one could understand all existing calculations of transport coefficients, but it also linked these calculations to a formalism which had previously been used to identify the leading entropy-generating processes in a quantum field theoretical approach to thermalization of far-off-equilibrium systems [13]. The 2PI effective action thus appears as the key concept linking equilibration processes in systems very close to and very far away from thermal equilibrium. That the same types of diagrams control entropy generation at early times in out-of-equilibrium systems and the long-time behaviour of their eventual approach towards equilibrium is very reassuring. We believe that this insight will have profound impact on future studies of thermalization in hot field theories.

The general framework developed in [40] suggested a calculation of the shear viscosity in scalar field theories with $O(N)$ symmetry, using the $1/N$ expansion to generalize the previously obtained weak-coupling result for ϕ^4 theory [Jeon, PRD 52 (1995) 3591] (which we reproduced in [32] using a much more efficient method based on new thermal field theory techniques [22]) to the case of strong coupling. This calculation, which had not been done before, has just been completed [Aarts and Martinez Resco, to be published]. We found not only that in the weak coupling limit the integral equation derived by Jeon can be solved analytically to excellent approximation ($\sim 0.3\%$), but also that even at strong coupling the viscosity is still quite accurately described by the leading order result derived from a weak-coupling approximation. The differences between the weak-coupling expression, evaluated for large values of the coupling constant, and the complete result at leading order in $1/N$, evaluated at the same value of the coupling, never exceed 10-15%, at least as long as one stays safely away from the Landau pole in this theory. This is an interesting result whose implications deserve further exploration.

II.A.3. Quark coalescence and the transition from soft to hard physics

At high transverse momenta ($p_T > 3\,\mathrm{GeV}$) the single-particle spectra from Au+Au collisions at RHIC gradually switch over from an exponential hydrodynamic shape to a power law. While the former is indicative of a thermalized system with superimposed collective expansion flow, the latter reflects the perturbative QCD structure of the primary production process for the leading parton whose fragmentation generates the high-p_T hadron. The switchover is not easily visible in the steeply falling angle-averaged p_T-spectra, making it hard to quantify the position of the crossing point and to study its systematics with collision centrality and hadronic species. It exhibits itself much more clearly in the azimuthal anisotropy of the spectra which, for example, can be characterized in terms of the yield ratios at a given p_T parallel and perpendicular to the direction of the impact parameter. At low p_T this ratio rises with p_T, first quadratically, then almost linearly until it appears to saturate at transverse momenta above 2 GeV for mesons and above 3 GeV for baryons. As shown in various talks from the different RHIC Collaborations at a recent workshop on "Collective Flow and QGP Properties" at BNL, in minimum bias Au+Au collisions at RHIC this ratio is found to be almost independent of p_T in the region $2\,\mathrm{GeV} < p_T < 6\,\mathrm{GeV}$ and equal to $\simeq 1.8$ for mesons and $\simeq 2.4$ for baryons. This rather large effect makes a quantitative discussion of exactly where hydrodynamics begins to break down much easier.

In 2002 first experimental indications appeared that the proton and Λ elliptic flow follows the hydrodynamic behaviour out to larger p_T than that of pions and kaons [PHENIX and STAR Collaborations at Quark Matter 2002, see Fig. 4 in Voloshin's summary talk, NPA **715** (2003) 379]. Voloshin suggested that this could be explained by hadron formation through quark coalescence, and that the finally observed hadronic elliptic flow is really a reflection of partonic elliptic flow generated before hadronization. This idea was worked out in Refs. [37,44] and further extended to predict the p_T-dependence of elliptic flow of charmed hadrons in Ref. [38]. The idea relies on the observation, made in hydrodynamic [46] and microscopic kinetic models, that at RHIC energies and above all flow anisotropies essentially saturate before the hadronization process is complete, due to the absence of a significant spatial deformation of the source after hadronization which could further drive the buildup of anisotropic flow by hadronic rescattering.

According to the coalescence model, at least in its presently studied simplified version, quarks with roughly equal momenta combine to make a hadron. In this picture, the momentum of a meson (baryon) is twice (three times) the momentum of its constituent quarks. Anisotropies in the quark momentum distributions thus get enhanced by a factor two (three) in the resulting meson (baryon) momentum distributions, if all constituent quarks feature the similar anisotropies. In the more general case that the hadrons are made up of quarks with different anisotropies, the quark anisotropies simply add to yield the hadron momentum anisotropies. (All these statements are correct up to second order terms in the (small) anisotropy coefficients [37].) The left panel of Fig. 4 illustrates this schematically: an assumed shape for the partonic elliptic flow $v_2(p_T)$ gets stretched in both vertical and horizontal directions by a factor n where $n = 2$ for mesons and $n = 3$ for baryons is the number of constituent quarks.

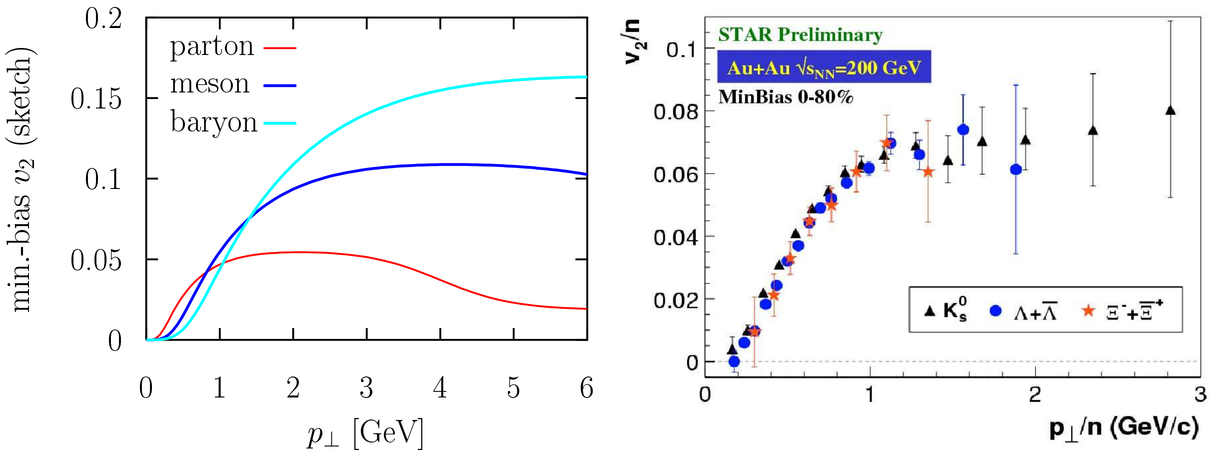

Fig. 4: Left: Schematic model for the partonic elliptic flow coefficient $v_2(p_\perp)$ (bottom curve) together with resulting elliptic flow coefficients for mesons and baryons, respectively [37]. Right: scaled elliptic flow v_2/n for neutral kaons, Λ and Ξ, plotted against scaled transverse momentum p_T/n [J. Castillo (STAR Coll.), presented at HIC03, Montreal, June 2003].

Conversely, if this idea holds, we should be able to collapse the experimental $v_2(p_T)$ curves for different hadrons onto a single partonic $v_2(p_T)$ curve by scaling both the vertical v_2 and horizontal p_T axes by a factor $1/n$. The right panel of Fig. 4 shows that this works surprisingly well. In fact, strange and nonstrange hadrons essentially collapse onto the same curve [S.S. Adler et al. (PHENIX Coll.), PRL **91** (2003) 182301; P. Sorensen (STAR Coll.), JPG **30** (2003) S217], implying that the elliptic flows of light and strange quarks in the partonic phase agree with each other. Fig. 5 shows what should happen if different quark flavors had different elliptic flow [38]: it uses the coalescence model to calculate $v_2(p_T)$ for various hadrons containing zero, one, or two charmed quarks under the assumptions that either (i) charm and light quarks have identical elliptic flow or (ii) charm quarks have no elliptic flow at all. This figure also shows the kinematic effects resulting from the mass difference between the charm and light quarks and from the fact that coalescence happens at small relative momentum in the *hadron rest frame* [38].

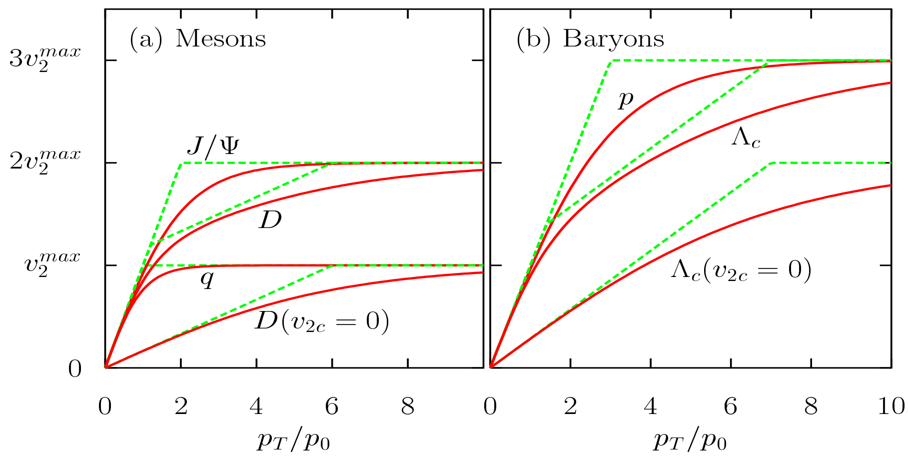

Fig. 5: Elliptic flow of charmed hadrons, calculated from the coalescence model with charm quark elliptic flow that is either zero or equal to the light quark elliptic flow. Dashed curves assume a schematic linear/constant v_2 for quarks while the solid curves are for a smooth quark $v_2(p_T)$ [38].

Coalescence combines several quarks into a single hadron which reduces the entropy. Therefore it cannot be the correct approach at low p_T where the bulk of the hadrons (which carry most of the entropy) are produced. As it is presently formulated, it can only be applied in a p_T region where coalescence is a sufficiently rare process that one need not account for the loss of quarks in the quark reservoir due to hadron formation. At low p_T the hydrodynamic approach works better, and in fact the scaled v_2 for pions, kaons, and protons clearly exhibit the hydrodynamically predicted [2] hadron mass dependence of the elliptic flow [S.S. Adler et al. (PHENIX Coll.), PRL **91** (2003) 182301] which the coalescence model cannot give. At very high p_T, on the other hand, quark coalescence is overwhelmed by string fragmentation of fast partons, as discussed by several groups [Fries et al., PRL **90** (2003) 202303 and nucl-th/0308051; Greco et al., PRC **68** (2003) 034904]. It is a fortunate accident that the coalescence model happens to work well in the transition region between soft hydrodynamics and hard parton production. It even correctly reproduces the systematics of the breakaway from the low-p_T hydrodynamic behaviour as a function of centrality: even though $v_2(p_T)$ changes dramatically between central and peripheral collisions, in each centrality bin the scaled elliptic flows of neutral kaons and Λ's collapse to a single "partonic elliptic flow" curve (which, of course, varies as a function of centrality) [P. Sorensen (STAR Coll.), JPG **30** (2003) S217].

The amplification of partonic elliptic flow by a factor n (where n counts the number of constituent quarks inside the hadrons) has another important consequence, related to the question of the microscopic mechanisms responsible for early thermalization at RHIC [37]. The right panel of Fig. 4 shows that the partonic elliptic flow follows the hydrodynamically predicted, approximately linear rise as a function of p_T only up to transverse momenta of about 750-800 MeV before gradually breaking away. It is therefore not necessary to thermalize partons all the way out to $p_T \sim 2-3$ GeV, where the final hadrons stop following the hydrodynamic curve. As shown by Molnár and

Gyulassy [NPA **697** (2002) 495], to thermalize partons up to $p_T = 750\,\mathrm{MeV}$ requires transport opacities which are about a factor 3 smaller than those needed to thermalize them up to $p_T = 2\,\mathrm{GeV}$. Quark coalescence thus helps to "thermalize" the hadrons out to larger transverse momenta than required for the partons themselves. Although the mechanisms responsible for early parton thermalization still remain somewhat mysterious, this renders the thermalization problem at least less severe than originally thought [37].

II.A.4 The "RHIC HBT Puzzle" and HBT studies for non-central collisions
The same hydrodynamic calculations which yield such an excellent description of the single-particle momentum spectra and their anisotropies [46] fail to decribe the two-particle HBT correlation measurements [15,20]. As shown in Fig. 6, the longitudinal and outward radii come out about 30-50% too large whereas the sideward radius is, at low transverse momenta, about 30-40% too small. Furthermore, both R_{out} and R_{side} depend on transverse momentum much more weakly than the data. These problematic features are shared by most dynamical models, in particular those which use hydrodynamics during the early collision stages (see [47] for a review). This failure has become known as the "RHIC HBT Puzzle".

We have tried, without much success, a number of possibilities to alleviate this problem. For a boost-invariant source, the longitudinal radius is controlled by the interplay between the longitudinal expansion rate and thermal motion. Smaller longitudinal radii require faster longitudinal expansion which implies an earlier decoupling time. We tried to force earlier decoupling by generating radial flow more quickly, initializing the hydrodynamic expansion at $\tau_{\mathrm{therm}} = 0.6\,\mathrm{fm}/c$ already with a nonzero radial flow velocity ("hydro with FS" in Fig. 6) [5]. This reduced the difference between theory and data for R_{long} by about 50% and helped a bit with R_{out}, but not at all with R_{side} and with the missing $K_\perp$-dependence of the transverse radii.

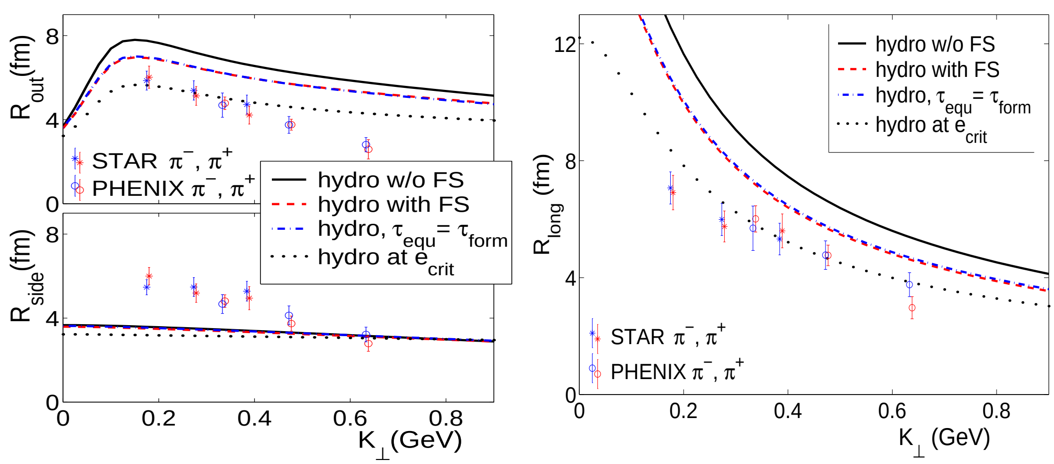

Fig. 6: HBT radii from a hydrodynamic source compared to RHIC data from STAR and PHENIX. The solid lines show hydrodynamic results with standard initialization and freeze-out [20]. The dotted lines assume freeze-out directly after hadronization at $e_{\mathrm{dec}} = e_{\mathrm{crit}}$. The other lines correspond to modified initial conditions as described in [20].

We even tested still earlier freeze-out directly at hadronization (dotted lines in Fig. 6), ignoring likely problems with the single particle spectra which require the extra radial flow generated during the hadronic phase after hadronization; this helped some more with the magnitudes of $R_{\rm long}$ and $R_{\rm out}$, but the other problems remained [20]. We also studied whether non-Gaussian features of the source could spoil the agreement of the source rms width parameters in coordinate space (from which the HBT radii were calculated) with the measured HBT radii which are extracted from Gaussian fits to the correlation function in momentum space. Again the largest effect was found for $R_{\rm long}$, pushing it down by about 1 fm towards the data, but no effect was found for $R_{\rm side}$ and very little for $R_{\rm out}$ [Kolb and Heinz, unpublished notes]. Others [Hirano and Tsuda, PRC **66** (2002) 054905] eliminated the assumption of longitudinal boost-invariance and also realized that chemical freeze-out already at hadronization implies lower temperatures at a given energy density at later times. The resulting lower kinetic freeze-out temperature and the finite longitudinal geometry in their model reduced the longitudinal and outward radii essentially to the dotted curves in Fig. 6, but also agreed with the dotted curve for $R_{\rm side}$; again, the lack of $K_\perp$ dependence in the transverse radii and the incorrect $R_{\rm out}/R_{\rm side}$ ratio remained essentially unaffected even though the lower decoupling temperature increases the correlations between coordinate and momentum space (but apparently not enough).

Although these tests did not much to support the possibility of a shorter expansion time, we decided to further test this hypothesis using an alternate approach, namely by constraining the geometric deformation of the source in non-central collisions at freeze-out with the help of emission-angle dependent HBT measurements. As we will see, these studies show that the hydrodynamic evolution picture indeed gives roughly the correct spatial deformation at freeze-out, indicating that hydrodynamics does not yield dramatically incorrect expansion time scales. (If anything, the measured source is slightly less deformed than the hydrodynamic one [M. Lisa, private communication], indicating a need for *more* rather than less expansion time until freeze-out.) The resolution of the HBT puzzle therefore most likely lies elsewhere. Towards the end of this section we report on some insights from recent studies on x-t correlations which may hold the key to the puzzle's resolution and whose deeper investigation has therefore become a priority for our proposed research in the coming three years.

Let us first discuss, however, the recent progress made in azimuthally sensitive HBT (asHBT) analysis [23,24,42,45]. Azimuthally sensitive HBT measurements of spatially deformed sources complement the momentum space information obtained from the single-particle spectra and their anisotropies with respect to the reaction plane by a corresponding snap-shot in coordinate space. The snap-shot is taken on the last-scattering surface of the particle species used for the measurement; for pions this is the kinetic freeze-out surface, whereas for photons (which do not rescatter) it is the entire space-time volume. Different species therefore "see" the deformation of the source at different stages of its evolution. So far only pion asHBT data are available.

The source information obtained from azimuthally sensitive HBT measurements is ambiguous in the same sense that applies to all HBT measurements: The particles used for the measurement are on mass-shell, and therefore only three of the four momentum components can be separately varied. The on-shell Fourier transformation of the space-time structure of the source, which generates the two-particle correlation function, can therefore not be completely inverted. The first order of the day was therefore a generalization of the usual HBT formalism to deformed sources [Wiedemann, PRC **57** (1998) 266; Lisa, Heinz, Wiedemann, PLB **489** (2000) 287], followed by a theoretical assessment of what kind of angular modulations of the HBT source radii as a function of the azimuthal emission angle should, in the most general case, be expected. In [23] we performed a complete analysis of this question, derived for symmetric collisions the most general azimuthal oscillation patterns for the HBT radii which are consistent with general source symmetries, and gave a simple explicit and model-independent alghorithm to correct the measured oscillations for finite event-plane resolution errors and finite angular bin size effects. The general relationship between higher order harmonic oscillations of the HBT radii and the harmonic coefficients of the "spatial correlation tensor" (which describes the space-time widths of the source) was also derived [23,45], and a variety of approximations which can be employed in order to reduce the degree of amiguity in the interpretation of asHBT data were described and discussed. This work [23] is expected to become the standard reference for all future experimental asHBT analyses and to help significantly in their theoretical interpretation.

In order to have an explicit example for how specific deformed source characteristics manifest themselves through azimuthal HBT oscillations and to test the validity of some of the just mentioned ambiguity-reducing approximations, we performed in [24,29] a hydrodynamic case study. For Au+Au collisions at impact parameter $b = 7\,\mathrm{fm}$, two types of hydrodynamically generated, elliptically deformed pion sources were analyzed with HBT correlations. The first type used the same initial and final conditions which successfully reproduced the measured spectra and anisotropic flow in Au+Au collisions at RHIC. At pion freeze-out this source is still slightly elongated in the direction perpendicular to the reaction plane, although less so than initially. The second type of source was created with much higher initial energy density, corresponding to an initial temperature of 2 TeV. This source takes much longer to dilute down to freeze-out conditions and, due to elliptic flow which makes it expand faster into the reaction plane than perpendicular to it, it decouples in an in-plane-elongated configuration. For both cases the effective emission regions for pions of different transverse momenta were plotted as a function of azimuthal emission angle in order to have a visual impression of their sizes and shapes. These were then compared with the resulting azimuthal oscillations of the HBT radii, shown in Fig. 7.

Geometrically, a given sign and magnitude of the spatial deformation of the source translates into a corresponding sign and magnitude of the azimuthal oscillations of the HBT radii. However, since the effective emission regions for pions of a given momentum cover only parts of the entire source, the observed azimuthal oscillations cannot be immediately interpreted in terms of shape properties of the full source. This becomes particularly clear in the right part of Fig. 7 where some of the oscillations are seen to even change sign as the pion transverse momentum increases.

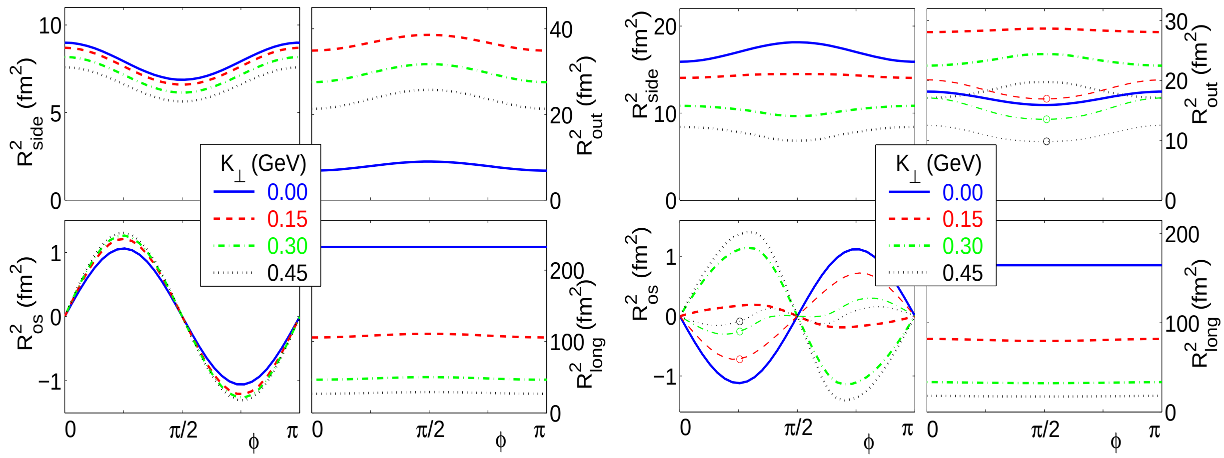

Fig. 7: Azimuthal oscillations of the HBT radii at $Y = 0$ for $b = 7\,\mathrm{fm}$ Au+Au collisions at $\sqrt{s} = 130\,A\,\mathrm{GeV}$ (left) and at LHC energies (right), for four values of the transverse momentum $K_\perp$ as indicated [24].

We could show, however, that the overall shape of the source and the sign of its elliptic deformation can be approximately reconstructed from the sign and amplitude of the oscillations at (approximately) zero transverse momentum [24]. In fact, at RHIC energies the ratio between the oscillation amplitude and the Φ-averaged value of R^2_{side} happens to be almost independent of $K_\perp$, allowing the extraction of the overall deformation of the source from this ratio *at any* $K_\perp$ even though the absolute value of R_{side} is too small and has the wrong $K_\perp$-dependence (as discussed above). This point was confirmed in a recent comprehensive model study within the so-called "blast-wave parametrization" [Retiere and Lisa, nucl-th/0312024], and it has recently been used by the STAR Collaboration [J. Adams et al., nucl-ex/0312009] to extract the freeze-out deformation of the source generated at RHIC. Its sign and magnitude agree with the hydrodynamic simulations in [24; M. Lisa, private communication]. This gives further support to the dynamical consistency of the hydrodynamic model with the data, prompting us to look elsewhere for the resolution of the RHIC HBT puzzle.

The weak $K_\perp$-dependence in particular of R_{side} indicates that the hydrodynamic model features weaker space-momentum correlations than the data. The space-momentum correlations relevant for R_{side} are generated by transverse flow but counteracted by thermal motion in the source. To obtain sufficiently strong space-momentum correlations to fit the data, the freeze-out temperature must be dramatically lowered, to about 33 MeV [B. Tomášik, nucl-th/0304079]. Within a hydrodynamic approach, this does not appear to make much sense. However, the microscopic kinetic code AMPT seems to able to reproduce this feature of the data [Lin, Ko, Pal, PRL **89** (2002) 152301]. The origin of these stronger than hydrodynamic space-momentum correlations is not clear. The authors of this paper also discovered another important effect in their code, namely a *positive* x_{out}–t correlation (see right panel in Fig. 8). This is opposite to the hydrodynamic model where the source decouples from the outside inward, yielding a negative x_{out}–t correlation. This observation is important since the x_{out}–t correlation term contributes with a *negative sign* to the difference between R^2_{out} and R^2_{side}. The hydrodynamic sign for this correlation thus tends to increase R_{out} relative to R_{side}, thereby definitely contributing to the RHIC HBT puzzle (see Fig. 6), whereas the AMPT sign of this correlation reduces the difference $R^2_{\rm out} - R^2_{\rm side}$, bringing it closer to the data. A similar positive $x_{\rm out}{-}t$ correlation was found by Dénes Molnár in his parton cascade [Molnár and Gyulassy, HIP **18** (2003) 69] which does not include hadronization and subsequent hadronic rescattering.

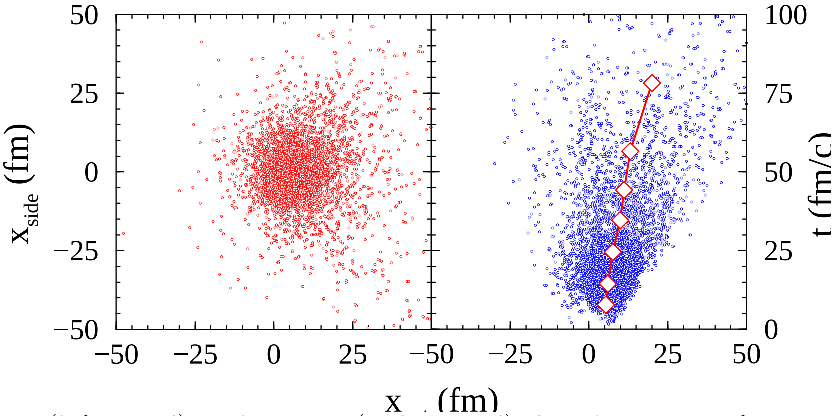

Fig. 8: $x_{\rm out}{-}x_{\rm side}$ (left panel) and $x_{\rm out}{-}t$ (right panel) distributions at freezeout for midrapidity charged pions with $125 < p_{\rm T} < 225$ MeV/c, from he AMPT model [Lin et al., PRL **89** (2002) 152301]. The curve with open diamonds represents $\langle x_{\rm out}\rangle$ as a function of t.

These positive $x_{\rm out}{-}t$ correlations are instrumental for reproducing the RHIC HBT data which give $R_{\rm side} \approx R_{\rm out}$ essentially independent of $K_\perp$. We have tried to elucidate their origin by performing detailed studies under controlled modifications within the AMPT model [Lin and Heinz, to be published]. While this work is still ongoing and the complete picture is not yet entirely clear, we found a surprising and possibly very important result: the positive $x_{\rm out}{-}t$ correlations appeared even when we initialized the hadronic rescattering phase of AMPT with hydrodynamic-like initial conditions featuring *negative* $x_{\rm out}{-}t$ correlations! We checked that it was hadronic rescattering and not the decay of unstable hadronic resonances which changed the sign of the $x_{\rm out}{-}t$ correlations. This strongly suggests a viscous, weak rescattering mechanism underlying the finally observed positive $x_{\rm out}{-}t$ correlations. This is why during the coming three years we want to study the late decoupling stages of the fireball and its influence on the HBT radii in greater detail with the help of a semi-analytic "post-freeze-out single-rescattering" model.

Before closing, let us mention that HBT correlations can also be used to test the hypothesis of different chemical and kinetic freeze-out temperatures. If hadron abundances freeze out early, immediately after hadronization at $T_c \approx 170$ MeV as the data indicate [Braun-Munzinger et al., PLB 518 (2001) 41], pions must subsequently build up a positive chemical potential to avoid annihilation as the system cools down further. For kinetic freeze-out around $T_{\rm dec} \sim 100$ MeV, pion chemical potentials of the order of 80 MeV have been predicted [Rapp, PRC 66 (2002) 017901; Hirano and Tsuda, *ibid.* 054905]. This leads, relative to chemical equilibrium at the kinetic decoupling temperature $T_{\rm dec}$, to an increased pion phase-space density and to a reduced entropy per pion. These latter quantities can be extracted from HBT correlation measurements [Bertsch, PRL 72 (1994) 2349; Ferenc et al., PLB 457 (1999) 347; Brown et al., PRC 62 (2000) 014904]. In [11] we showed that, when doing so, it is important to properly include the collective expansion flow. Collective flow, in particular the strong flow along the beam direction, reduces the apparent spatially averaged phase-space density which, unless corrected for, would lead to a significant under-estimation of the pion chemical potential (and therefore an overestimate of the entropy) at kinetic freeze-out [11]. The STAR Collaboration is presently using this method, together with a correction scheme based on our work [11], to extract the freeze-out entropy per pion at RHIC [see also Pal and Pratt, arXiv:nucl-th/0308077].

II.B. 2004-2006

II.B.1. Relativistic hydrodynamics and collective flow at RHIC

Following up on our success in applying relativistic fluid dynamics to the expansion of the collision fireball created in nuclear collisions at RHIC [46], we continued to exploit this approach to address new physics questions, while at the same time moving forward towards an exploration of non-ideal (viscous) effects during the early and late stages of the evolution on the observed collective flow patterns.

(1) Parton cascade and the ideal fluid limit. Denes Molnar, in collaboration with Pasi Huovinen, revisited the question what it takes to reach the ideal fluid limit in a microscopic kinetic code with 2-to-2 scattering (such as MPC) [51]. Based on a thorough comparison of MPC output with hydrodynamic calculations corresponding to the *same* EOS (previous such comparisons had implicitly used different equations of state), they concluded that it seems very difficult to reach this limit, and that viscous effects remain important even when the transport mean free path reaches its quantum mechanically allowed lower limit. It will be interesting to compare this finding with viscous hydrodynamic results.

(2) Hydrodynamic Mach cones from parton energy loss. With Asis Chaudhuri (VECC Calcutta) we made the first semi-realistic numerical calculation [71] of the angular correlations in hadron emission resulting from the hydrodynamical response to the energy and momentum deposited in the liquid medium by quenching jets. It had been suggested by Shuryak and others that the energy-momentum deposited by a quenching jet moving with supersonic speed through the QGP medium should generate Mach cones, and that these might be responsible for certain structures seen in the angular correlation function of hadrons associated with a fast trigger particle. Assuming that the deposited energy thermalizes and heats the system locally, we found that its subsequent hydrodynamic evolution indeed generates a Mach cone, but no associated peaks at the Mach angle in the angular correlation function [71]. Directed emission perpendicular to the Mach shock front is not the dominant effect controlling the shape of the emitted angular distribution; other effects, in particular the back-splash from the hard particle entering the fluid, wash out the predicted Mach cone peaks. Our work was not completely realistic in that (for compatibility with our boost-invariant hydro code) it used a source current with longitudinal boost-invariance, corresponding to an entire longitudinal line of jets hitting the fire-cylinder simultaneously in proper time. This over-idealization should, however, have only exaggerated any Mach cone peaks. Our paper concludes that the angular structures in the emission pattern relative to the direction of the jet seen by PHENIX cannot be of hydrodynamic nature. These data require either a non-thermal angle-dependent emission mechanism or a more complicated thermalization process which feeds more of the deposited energy directly into the collective Mach shock wave.

(3) RHIC hydrodynamics with an equation of state from Lattice QCD. One unrealistic aspect of our hydrodynamic studies of RHIC dynamics has always been the employed equation of state (EOS) which uses a Maxwell construction to match a realistic hadron resonance gas below T_c to a free quark-gluon gas above T_c, with a free parameter that adjusts T_c to the value measured on the lattice. Although this gives the correct speed of sound c_s^2 above about $2\,T_c$, Lattice QCD (LQCD) data show that below $T \approx 2\,T_c$ the sound speed begins to drop below the ideal gas value $c_s^2 = \frac{1}{3}$, decreasing to almost 1/10 of that value near T_c. Although the rise of c_s^2 with temperature above T_c is rapid, this does render the EOS somewhat softer between T_c and $2\,T_c$ than previously assumed by us.

With the Rossendorf group around Burkhart Kämpfer we therefore performed a study where we used a quasiparticle model to fit the LQCD equation of state and match it to a hadron resonance gas EOS below T_c. With this EOS, we redid the ideal fluid dynamic calculations of elliptic flow at RHIC, exploring different matching procedures. Very little sensitivity to the details of this matching was found [66,89], confirming our earlier contention that the discontinuity present in the previously employed bag model EOS is dynamically irrelevant. What does matter, however, is that the EOS has a speed of sound that rises above T_c quickly towards the ideal gas value, as indicated by lattice QCD. Our study [89] is similar in spirit, but different in detail from the recent work by Huovinen [NPA 761 (2005) 296] who uses a different quasiparticle parametrization to extrapolate the LQCD data to physical quark masses. In that approach the growth of the speed of sound with temperature above T_c is slowed significantly, and he finds that then the discrepancies between ideal fluid dynamics and elliptic flow data become unacceptably large. A simple continuous (tanh) interpolation between hadron resonance and ideal quark-gluon gases gives phenomenologically much better results, of similar quality as our earlier work [46]. It also reproduces the LQCD data on $c_s^2(T)$ much better than the extrapolated quasiparticle model. It seems that the elliptic flow data require a rapid stiffening of the QGP EOS above T_c, very close to what present LQCD data show.

(4) Elliptic flow of thermal photons and dileptons at RHIC. With student Evan Frodermann, we have computed the emission function for thermal photons from ideal hydrodynamic evolution at RHIC energies. From it the photon spectra and two-photon correlation functions can be computed. As a first application we have, in collaboration with the group of Dinesh Srivastava at VECC Calcutta, worked out the elliptic flow of thermal photons [70]. In contrast to hadron elliptic flow, which in the hydrodynamic model keeps rising with increasing p_T and in real life saturates above about 1.5-2 GeV/c, photon elliptic flow from hydrodynamics is found to first rise and then decrease again as p_T increases [70]. This reflects the fact that photons, in contrast to hadrons, are emitted throughout the fireball evolution, and that high-p_T photons in particular are emitted from the hot early stage when collective flow, in particular its elliptic anisotropy, is still very small. This calculation demonstrates again the complementarity of photon and hadron emission for diagnosing the dynamical evolution of the fireballs created in RHIC collisions, in this case the dynamical evolution of flow anisotropies.

This calculation also brought to light an interesting peak-valley structure of photon v_2 at low transverse momenta $\sim 0.4 - 0.5\,\mathrm{GeV}/c$ which is related to the competition between two different kinds of photon production mechanisms in the late hadronic collision stage: photon emission by scattering pions, and collision-induced conversion of vector mesons into photons [70,80,88]. The first (second) of these processes dominates at low (higher) p_T, leading to a relatively sudden decrease of the photon elliptic flow as the heavy vector mesons take over. This is an interesting manifestation of the hydrodynamic rest mass effect (well known from hadron elliptic flow) in the photon emission spectrum. Its experimental verification would validate our understanding of the microscopic photon emission processes during the late hadronic rescattering phase.

The above calculation of thermal photon elliptic flow has recently been complemented by an analogous hydrodynamic computation of the elliptic flow of thermal dileptons [80,88]. In this case the spectrum of observable structures is even richer, due to the varying competition between hadronic and QGP emission processes in different regions of invariant mass of the dileptons. For invariant masses close to the vector meson peaks in the mass spectrum, hadronic emission dominates and the dileptons show large elliptic flow, tracking that of the corresponding vector mesons. Away from these peaks, dilepton elliptic flow is small, reflecting early emission from the QGP phase when collective wasw not yet fully developed. Together with the elliptic flow of thermal photons, measurements of dilepton elliptic flow can thus provide tight constraints on the *dynamical evolution* of collective flow in relativistic heavy ion collisions which cannot be accessed with hadrons [80,88]. These results have been selected for a plenary talk at *Quark Matter 2006* (presented by D. Srivastava).

(5) Elliptic flow at high p_T. One of the still not completely understood phenomena observed at RHIC is the persistence of large elliptic flow even at high $p_T > 4-6\,\mathrm{GeV}/c$ where the hydrodynamic model no longer applies and hadron production begins to be dominated by jet fragmentation. In [61] Denes Molnar used his parton cascade model with large parton-parton cross sections, as required for a successful description of elliptic flow at low p_T, to show that for particle production in the intermediate p_T region ($3 < p_T < 10$ GeV) acceleration of lower-p_T particles by the developing radial flow is a mechanism that can compete with the downward shift of high-p_T particles via (collisional) parton energy loss. This is similar to, but not identical with the idea behind the coalescence model [37,38,44,67] that, due to their higher abundance, coalescence of two low-momentum partons can compete in this region with fragmentation of rare high-momentum partons. The acceleration mechanism was found to be multiple scattering off the abundant bulk matter particles which, as radial flow develops, leads to probabilities for scattering towards higher momentum which increase with time. In non-central collisions, the developing flow is anisotropic, and the scattering off the bulk matter imprints this flow anisotropy on the intermediate-p_T particles. This may help understand the observed large elliptic flow at intermediate and high p_T.

(6) Hadronic dissipation effects on elliptic flow at RHIC. One of the key observations made at RHIC is the apparently extremely low value of the viscosity of the QGP fluid, implied by the excellent quantitative success of *ideal* fluid dynamics in describing the momentum spectra and momentum anisotropies of hadrons emitted near midrapidity and at low $p_T < 2\,\mathrm{GeV}/c$ from not-too-peripheral Au+Au collisions [46]. This prompted the announcement by BNL of the discovery that the QGP created at RHIC behaves like a "perfect fluid" (see the RHIC White Papers [NPA 757 (2005)]). On the other hand ideal fluid dynamics gradually breaks down at higher p_T and away from midrapidity, as well as for larger impact parameters and lower collision energies. In [48] we showed that all of these observations of "imperfect fluidity" seem to have the same origin and scale with the initial entropy density. That analysis left open, however, whether the "imperfect fluidity" effects are due to early viscosity, i.e. to delayed thermalization of the QGP at early times, or to late viscosity during the hadronic rescattering stage at the end of the collision.

With Tetsufumi Hirano at Columbia University we studied the effects of hadronic dissipation on the generation of elliptic flow at RHIC, by coupling an ideal fluid dynamical evolution of the initial QGP phase to a realistic hadron cascade after hadronization [69]. We found that late hadronic dissipation has the correct characteristics to qualitatively reproduce all the observed discrepancies between ideal fluid calculations and experimental data, as well as their systematics. In fact, if the hydrodynamic evolution of the QGP is initialized with Glauber model initial conditions, hadronic dissipative effects are sufficient to *quantitatively* reduce the calculated elliptic flow from its ideal fluid dynamical prediction to the measured value, at all collision centralities and all rapidities. It is quite impressive how well this works also for the p_T distribution of the pion and proton spectra and of their elliptic flow. With these "standard" initial conditions, the RHIC data leave very little room for early QGP viscosity.

A fly in the ointment was, however, our discovery that if one starts with initial conditions based on the Color Glass Condensate (CGC) picture of gluon saturation at RHIC, using the so-called KLN parametrization for initial entropy production, the calculated initial eccentricities are higher, and the resulting larger elliptic flow overpredicts the data, especially at large impact parameters and high rapidity, even when hadronic dissipation is taken into account. With KLN initial conditions the data can only be reproduced if the QGP has significant viscosity (i.e. is not a "perfect fluid") or a much softer equation of state than generally assumed.

(7) Viscous relativistic hydrodynamics. Even if all evidence presently points to a small viscosity for the QGP, theory tells us that it can not be strictly zero, and one would eventually like to measure its value quantitatively. Such a measurement would also provide valuable input to theory since perturbative methods give calculated values for the QGP shear viscosity which seem to be too large to explain the rapid thermalization apparently required by the data, and non-perturbative tools to compute viscosities in a strongly interacting QGP are not yet well-developed.

This obviously requires a generalized hydrodynamic framework for non-ideal fluids in which viscosity appears as a (tunable) parameter which can be adjusted to experimental precision data. Including transport effects into relativistioc hydrodynamics is not completely trivial since the standard Navier-Stokes procedure is known to lead to equations with acausal signal propagation and dynamical instabilities for relativistic fluids. A method that avoids these problems is the causal "second order" approach developed by Israel and Stewart in the 1970's and resurrected by Muronga and Teaney in 2002-2004. Muronga worked out and numerically solved these second-order equations for (0+1)- and azimuthally symmetric (1+1)-dimensional systems with longitudinal boost invariance. We discovered some problems with his work and, with the PI's student Huichao Song, performed an independent analysis of these equations [68], providing a corrected explicit form for the (1+1)-dimensional case and deriving for the first time the equations needed for the (2+1)-dimensional case of non-central collisions with longitudinal boost-invariance.

In collaboration with Asis Chaudhuri from the VECC in Calcutta, we numerically implemented these causal equations for viscous hydrodynamics of (1+1)-dimensional, azimuthally symmetric radial expansion in a longitudinally boost-invariant background. First results [63] extended the work by Muronga by a parameter study where we investigated the sensitivity of the dynamical evolution to initial conditions for the viscous pressure and variations of the shear viscosity coefficient and kinetic equilibration time. Unfortunately, the PI's collaboration with Chaudhuri ended due to differences in taste before stringent tests of the accuracy of the code used in [63] were completed. A numerical code implementing the (2+1)-dimensional equations, which (due to the lack of azimuthal symmetry) have a completely different structure from those governing the (1+1)-dimensional case, was written and tested by graduate student Huichao Song in 2006-2007.

(8) Elliptic flow fluctuations. At *Quark Matter 2005*, the PHOBOS Collaboration showed that to understand the scaling behaviour of the measured hadron elliptic flow with impact parameter and system size, it is important to take into account that the initial eccentricity of the nuclear overlap region, as well as the orientation in the transverse plane of its major axes, fluctuate from event to event. Since hydrodynamic flow is a property of each individual collision event, and not only of the ensemble of collisions, flow anisotropies react to these fluctuations in shape and orientation from one event to the next. Extensive Monte Carlo studies are necessary to clarify how different methods to extract v_2 from the experimental data are affected by these event-by-event fluctuations. With a group of PHENIX Collaboration members, under the leadership of Constantin Loizides, the PI wrote an extensive paper on elliptic flow fluctuations and scaling laws, acting as theoretical advisor for the experimental analysis and Monte Carlo studies [101].

II.B.2. Uranium-uranium collisions at RHIC

About 2 years ago the PI realized that full-overlap uranium-uranium collisions at RHIC provide a powerful tool to test the hydrodynamic behaviour of elliptic flow and the path-length dependence of parton energy loss at RHIC. Due to their deformation, full-overlap U+U collisions in side-on-side geometry provide a large elliptic flow signal even at zero impact parameter, from a much larger fireball than in similarly deformed peripheral Au+Au collisions. In almost head-on-head geometry, the elliptic flow signal is similar to almost central Au+Au collisions (where it has been measured), but driven by a much larger initial energy density which should bring the system closer to the ideal hydrodynamic limit. Due to the much larger size of the fireball and larger path length difference in and out of the reaction plane, collisions in side-on-side geometry also provide much enhanced discriminating power for the path length dependence of parton energy loss. With the PI's student A.J. Kuhlman, we worked these ideas out in quantitative detail and showed how a full-overlap U+U collision program can be realized experimentally, and what can be learned from it [58].

This first paper made the assumption that zero impact parameter, full overlap collisions (with coplanar major axes of the two deformed uranium nuclei) can be experimentally selected with perfect efficiency. In a longer follow-up paper [64,65], Kuhlman used a Monte Carlo simulation for the distribution of hadron multiplicities and spectator nucleons from U+U collisions of all impact parameters and orientations to explore how experimental cuts on the spectator and multiplicity distributions can be realistically used to select event samples with well-defined source deformations, in order to study how much elliptic flow and anisotropic high-p_T suppression they generate. He found that meaningful selections of event classes are possible and practically achievable. By cutting on low spectator numbers and high multiplicities, events with small eccentricity, but energy densities which exceed those of central Au+Au collisions by about 35% can be selected. By cutting on low spectator numbers and (within that class) on low multiplicities, events with almost 20% eccentricity and energy densities equal to those in central Au+Au are singled out. These should produce a strong elliptic flow signal which can be used to test the ideal fluid dynamic behaviour of elliptic flow at RHIC energies.

Our analysis in [58,65] was based on a standard Glauber model calculation of the initial entropy density distribution from which the initial source eccentricity was computed, with parameters fixed to reproduce Au+Au collision data at RHIC. In view of our realization in [69] that CGC initial conditions within the KLN parametrization generate larger eccentricities in peripheral Au+Au collisions than the Glauber model, Kuhlman and co-PIs revisited the U+U case within the CGC/KLN approach [78]. Contrary to the peripheral Au+Au case, in central, full-overlap U+U collisions we found only small quantitative differences between Glauber and CGC/KLN initial conditions [78], thereby further supporting the robustness of the generic idea.

The U+U case study by the OSU group found strong resonance in the RHIC community (a first U+U run at RHIC was finally executed in 2012). This work won A. J. Kuhlman 3rd prize in the Mathematical and Physical Sciences Section of the 2005 Hayes Graduate Research Forum at Ohio State University.

II.B.3. Particle interferometry

(1) Projected three-pion correlation functions. A few years ago the PI pointed out that 3-pion correlations from heavy-ion collisions can be used to determine the degree of chaoticity and certain source asymmetries of the pion emitting source. To fully exploit this tool requires, however, a multidimensional analysis which is beyond present statistical capabilities of the experiments which must project their data onto a single relative momentum variable. The PI realized several years ago that this projection distorts the shape information of the source and also affects the extrapolation to zero relative momentum from which the chaoticity parameter is extracted, but that an alternative projection algorithm exists that is experimentally feasible and should avoid most of the worst projection artifacts. With an REU summer student, Alex Sugarbaker, we published a model study [56] which showed explicitly that this indeed the case. The new projection algorithm facilitates comparison with theory which can easily implement it on the calculated correlation functions. The method can be generalized in a straightforward fashion to less restrictive projections onto more than one relative momentum component. We hope that it will be used in future analyses.

(2) A VEGAS Monte Carlo routine for the calculation of HBT radii. As a warm-up project for his thesis research, graduate student A.J. Kuhlman developed and perfected a VEGAS Monte Carlo integration routine for the computation of HBT radii from the spatial correlation tensor for arbitrary source functions which do not assume longitudinal boost invariance and/or azimuthal symmetry. With this routine, HBT data (including the emission angle dependence of the HBT radii in noncentral collisions [23,24,45]) can be analyzed within given classes of source models by optimizing the model parameters iteratively in an efficient way. This generalizes so-called "blast-wave" model analyses exploited previously by our group as well as various experimental collaborations, by removing systematic biases resulting from intrinsic model symmetries which so far had to be assumed for technical reasons. Kuhlman has now started using this code to perform correspondingly generalized model fits to the STAR azimuthal HBT data, in order to explore more systematically the range of model freedom allowed by the data, and thereby shed more light on possible ways out of the "RHIC HBT puzzle".

(3) Pion HBT correlations from blast wave models and hydrodynamics. Experimentally, HBT radii are extracted from three-dimensional Gaussian fits to the measured Coulomb corrected correlation function (unless the Coulomb effect is included in the fit function), whereas theorists have often exploited a theoretical shortcut which calculates them directly (and with less effort) from the space-time variances of the emission function. The latter can be either modeled (as in the so-called "blast wave model" approach) or computed from a hydrodynamic model [24]. However, the mentioned shortcut yields accurate results only if the emission function is, to good approximation, a Gaussian function of the space-time coordinates, and this assumption has long been known to be problematic in the beam direction, at least for sources with boost-invariant longitudinal expansion.

In view of the "RHIC HBT Puzzle", i.e. the inability in particular of the otherwise successful hydrodynamical model to reproduce the experimentally measured HBT radii [20], it appeared prudent to exclude the possibility that the "puzzle" results from the abovementioned apples-to-oranges comparison. For this our graduate student Evan Frodermann computed the HBT correlation function by numerically Fourier transforming the hydrodynamic emission function, using and upgrading a program previously developed by Peter Kolb, to which then our colleague Mike Lisa performed a three-dimensional Gaussian fit just as if it were a measured correlation function, using a simple analytic fit algorithm that he had developed. The result of this exercise [76,84] was quite interesting: as expected, the corrections relative to the "shortcut method" were largest in the longitudinal direction, where (especially when the hydrodynamic model was run with an equation of state which correctly implemented hadronic chemical freeze-out already at $T_c \simeq 170\,\mathrm{MeV}$) the HBT radii extracted from the Gaussian fit were systematically and significantly smaller than from the space-time variances. As a result, the discrepancy between calculated and measured $R_l(K_T)$ values is almost completely eliminated! Even though the correlation function is pretty Gaussian in the transverse directions, the three-dimensional fit "feels" the non-Gaussian longitudinal structure also in the transverse HBT radii, leading to a systematic reduction of the outward radius, too. Still, R_o is still overpredicted and R_s is still underpredicted by hydrodynamics, and both have much weaker K_T-dependence than the data. The "RHIC HBT Puzzle" thus persists, but it is now focussed on the theoretically too large R_o/R_s ratio and the too weak K_T-dependence of the transverse HBT radii, while the problems with R_l seem to be largely resolved.

II.B.4. Energy loss and elliptic flow of charmed mesons in a dynamically evolving medium

Heavy quark energy loss and collective flow has recently attracted theoretical attention, due to the potential of pQCD calculations being able to make quantitative predictions and of using their heavy mass as an additional control parameter in the evaluation of QGP transport coefficients.

(1) Elliptic flow of charmed particles. With his parton cascade MPC, Denes Molnar studied the question to what extent charmed quarks are expected to participate in the collective transverse dynamics of RHIC collisions and thereby develop an elliptic flow signal [55,57]. Whereas at low p_T, charm elliptic flow is below that of light quarks (consistent with hydrodynamic expectations), at higher p_T, where hydrodynamics begins to break down and light quark elliptic flow is seen to saturate, the elliptic flow of charm quarks was observed to become as large as that of the light quarks. Preliminary STAR and PHENIX data, which track charm meson elliptic flow through their decay electrons, seem to indicate large charm elliptic flow, consistent with Molnar's predictions [57] as well as other models that assume that charm quarks flow with the medium. This large signal was unexpected and needs futher corroboration, but, if confirmed, provides further evidence for the strongly coupled nature of the QGP formed at RHIC.

This work used the quark coalescence model to transfer the charm quark elliptic flow to charmed mesons. The conditions for validity of this model were investigated in some detail by Molnar in [55] where he showed that the observed valence quark number scaling of elliptic flow at intermediate p_T is non-trivial and requires that the elliptic flow is dominated by local momentum-space correlations rather than by an overall geometric deformation of the source.

(2) Charm quark energy loss. Since joining the group in 2005, Magdalena Djordjevic has continued to try to arrive at a theoretical understanding of the unexpectedly large suppression of intermediate-p_T charm and beauty decay electrons observed in Au+Au collisions at RHIC. In work still done partially in collaboration with her thesis advisor [74], in which the gluon radiative energy loss by heavy quarks was solved to all orders in opacity and finite-medium-size effects were also included, she found that radiative QCD energy loss is insufficient to describe the data. She then proceeded, on her own, to do a complete lowest order calculation of collisional energy loss for heavy quarks [77] in a thermalized, finite-size QGP. Her approach, which she defended very convincingly during a panel discussion at the *Hard Probes 2006* conference [81], settled a few controversial theoretical issues, but it also made clear that even the combined effects of leading-order radiative and collisional energy loss are barely able to reproduce the data. All of this supports the picture of a strongly coupled QGP, suggesting very strong coupling even between heavy quarks and the QGP fluid. Together with the PI, she extended this work to dynamically evolving media in 2007 [90,98].

II.C. 2007-2010

II.C.1. Relativistic ideal and viscous fluid dynamics for heavy-ion collisions

(1) Elliptic flow and azimuthal HBT oscillations of thermal photons. Graduate student Evan Frodermann, who completed his PhD thesis in 2008, implemented state-of-the-art emission rates for thermal photons from a quark-gluon plasma and a thermal hadron resonance gas into the (2+1)-dimensional ideal fluid dynamical code `AZHYDRO` developed earlier by my student P. Kolb [46] and used it to compute photon elliptic flow [70,80] and azimuthal oscillations of 2-photon correlations [125] in non-central Au+Au collisions at RHIC. In collaboration with D. K. Srivastava's group in Kolkata and C. Gale's group at McGill University the PI generalized this study to the elliptic flow of dileptons (i.e. massive virtual photons) [88]. These were pioneering calculations that computed for the first time spatial and momentum anisotropies for thermal electromagnatic radiation from a realistic dynamical model for the fireball evolution.

The model parameters in `AZHYDRO` had been tuned to hadron spectra from central Au+Au collisions at RHIC [46], and the model had been surprisingly successful in predicting the charged and identified hadron elliptic flow [2] and azimuthal oscillations of the pion HBT radii [24] measured in non-central Au+Au collisions. Frodermann's work extended the successful strategy of combining the measurements of momentum spectra and two-particle correlations to constrain the particle emitting source both in momentum and coordinate space from hadrons (which are only emitted from a relatively thin freeze-out surface at the very end of the fireball expansion) to electromagnetic signals (which decouple immediately and are thus emitted throughout the evolution of the collision fireball). He showed that by comparing anisotropy measurements of hadrons [91] and electromagnetic signals [125] can help to map out the evolution of the source eccentricity and flow anisotropy during the early expansion stage when the system is still in the QGP phase. This has motivated experimentalists to think about the feasability of such measurements.

Existing direct photon spectra are averaged over the azimuthal emission angle for reasons of statistics. In collaboration with the McGill group we showed that these data can be well described by the hydrodynamic model [102,110] when adding to the thermal radiation also hard photon production mechanisms from the early collision stages and from jet fragmentation, where the fragmenting jets suffer radiative energy loss in *the same hydrodynamically expanding medium* that radiates the thermal photons. The energy loss calculations have since been updated to include elastic collisions by former McGill student and OSU postdoc Guang-You Qin and used to additionally compute photon-hadron correlations [112,118]. This work is an important milestone towards the goal of eventually describing all experimental observables within a single fireball evolution model that includes all dynamical collision stages consistently.

(2) Excitation function of elliptic flow. With undergraduate student Greg Kestin we completed a systematic study of the beam energy dependence of hadron spectra and elliptic flow [96,111,128], complementing similar studies with graduate students E. Frodermann and R. Chatterjee on photon elliptic flow [99] and pion HBT radii [97]. We showed that, while the p_T-integrated elliptic flow is expected to increase monotonically by about 15% from RHIC to LHC energies, the differential elliptic flow $v_2(p_T)$ at fixed p_T-values should first increase, but then reach a maximum and decrease again [111]. This is a consequence of increasing radial flow and independent of whether or not there is a phase transition between hadronic matter and the QGP [128]. These studies were done with ideal fluid dynamics; a similar investigation using viscous fluid dynamics is presently ongoing.

(3) Relativistic viscous fluid dynamics for non-central heavy-ion collisions. A real breakthrough in RHIC theory has been the development over the last 3 years of viscous relativistic fluid dynamical codes that describe the transverse expansion of dissipative quark-gluon matter created in non-central heavy-ion collisions. The problem of relativistic hydrodynamics for dissipative fluid had never before been solved in practice. Although the formalism, due to Müller, Israel and Stewart, is over 30 years old, only now the computational resources have become available to turn this into a practically viable approach.

After exploratory work in 1+1 dimensions [63] assuming longitudinal boost-invariance and azimuthal symmetry (i.e. zero impact parameter) that built upon pioneering studies by Muronga, my student Huichao Song and I started work on a (2+1)-dimensional code (still assuming longitudinal boost-invariance but allowing for non-central collisions) in 2005 [68]. The code `VISH2+1` ("Viscous Israel-Stewart Hydrodynamics in 2+1 dimensions") was finished early in 2007, and I reported first results at two meetings on May 22 and June 5, 2007. A few days after the second talk, a preprint by Romatschke appeared who had independently developed a similar code; he found a weaker viscous suppression of elliptic flow v_2 than we did, so we got worried and delayed publication. Scrupulous tests did not reveal any errors in our code, so we submitted a short letter in early Sep. 2007 [92], followed by a longer account in December 2007 [104] where we elucidated the effects of shear viscosity on the evolution of thermodynamic quantities, flow profiles and momentum anisotropies in great detail. In the meantime, also K. Dusling and D. Teaney from Stony Brook had gotten into the game, again with results that appeared to disagree with both our and Romatschke's results.

The disagreements between the three groups bothered us greatly, so H. Song embarked on a comparison between the three approaches, accounting one-by-one for differences in the initial conditions, equations of state (EOS), detailed form of the Israel-Stewart equations (or rather, in the Stony Brook case, Öttinger-Grmela equations), and freeze-out conditions [106]. The result was eye-opening: When used with identical initial and final conditions and the same EOS, the codes produced (within discretization errors) identical results. The largest difference between Romatschke and us was due to the size of the collision system – Romatschke had studied Au+Au collisions whereas we had, for technical reasons, done our first systematic studies for the much smaller Cu+Cu system. In Cu+Cu the same amount of shear viscosity suppresses the pion elliptic flow almost twice as much as in Au+Au when compared with an ideal fluid [106]. This revealed that there are two roads toward extracting the specific shear viscosity η/s from experimental data: using the first one tries to establish an ideal fluid benchmark for how much elliptic flow to expect and then extracts η/s from the experimentally observed suppression of $v_2(p_T)$ below this mark; in the second approach one studies the system size dependence of the p_T-integrated v_2 and determines η/s from its slope [106].

(4) First steps toward extracting η/s from RHIC data. With these first papers the path to an empirical extraction of the QGP viscosity from RHIC data was laid out, and a first attempt was published by Luzum and Romatschke soon after [PRC 78 (2008) 034915]. Intense discussions following that publication revealed, however, that a precise quantitative extraction of this key transport parameter requires much additional work [116]. Since η/s is to be derived from a typically $\mathcal{O}(25-30\%)$ suppression of the measured v_2 below the ideal fluid benchmark calculation, the latter must be known very precisely, with at most a few % theoretical uncertainty if η/s turns out to be small (of order $\frac{\eta}{s}\big|_{\rm KSS}=\frac{1}{4\pi}$ [Policastro et al., PRL 87 (2001) 081601) and the empirically extracted value is supposed to be accurate. A 20-30% uncertainty in the ideal fluid benchmark due to uncertainty in the initial source deformation ε of the fireball created in non-central collisions was pointed out by Luzum and Romatschke [PRC 78 (2008) 034915]. This largest of all uncertainties can be resolved by systematic studies of the centrality dependence of the eccentricity-scaled elliptic flow v_2/ε, as we pointed out in a paper written with undergraduate student Scott Moreland [130].

Two other almost equally large uncertainties (which, however, happen to partially cancel each other) arise from chemical and kinetic non-equilibrium effects in the late hadronic phase. At RHIC energies the highly viscous hadronic phase still plays a non-negligible role in how much elliptic flow is built, as we discovered in several papers written in collaboration with T. Hirano at Tokyo University [69,87,94]. Hadronic dissipation strongly suppresses v_2 in peripheral Au+Au collisions at RHIC and must be subtracted from the analysis in order to arrive at an accurate value for the QGP viscosity; this requires using a hybrid code that couples viscous hydrodynamics for the QGP above T_c to a microscopic hadronic cascade below T_c and allows for a rapid increase of η/s during the phase transition. Furthermore, the stable hadron yields decouple close to T_c, implying that the chemical composition of the hadron gas goes quickly out of equilibrium as the system continues to cool. This non-equilibrium chemical composition, together with the hardening of the p_T-spectra for heavy hadrons caused by radial flow, results in about 30% larger differential elliptic flow $v_2(p_T)$ for pions than in the chemically equilibrated case. At RHIC energies these two effects effectively cancel each other but this cancellation will disappear at the higher LHC collision energies [87].

Differences in the EOS, especially near the quark-hadron phase transition, contributed to the discrepancies between the early viscous calculations done in our group and elsewhere. In the near run it is unlikely that the temperature dependences of the QCD EOS and of the transport coefficients can be determined independently through phenomenological analysis of the experimental RHIC data. Fortunately, lattice QCD data are now becoming so precise that uncertainties in the EOS can be held to a minimum. In collaboration with P. Huovinen, who together with P. Petreczky fitted these lattice data and matched them to a chemically non-equilibrated hadron resonance gas as discussed above, undergraduate student Tom Riley and my new graduate student Shen Chun have recently implemented this state-of-the-art EOS into VISH2+1, in order to eliminate EOS uncertainties as much as possible from future studies with `VISH2+1` [C. Shen et al., PRC 82 (2010) 054904].

Last but no least, bulk viscosity also affects the build-up of elliptic flow. While shear viscosity directly acts again the development of flow anisotropies in and out of the reaction plane, bulk viscosity resists the build-up of transverse flow in general. Since transverse radial flow affects the slope of the spectra, it also affects the distribution of the total hydrodynamic momentum anisotropy over the transverse momentum space and thus $v_2(p_T)$. In contrast to shear viscous effects which are always largest at earliest times where the expansion rates are biggest, bulk viscosity develops a peak near the quark-hadron phase transition and is largest where the matter is close to T_c. In this shell of matter bulk viscosity can become larger than shear viscosity. However, the same growth of correlation lengths that is responsible for the critical behaviour leading to a peak of the bulk viscosity near T_c also leads to large relaxation times of the bulk viscous pressure near T_c. If the fireball expands explosively and the matter passes through T_c quickly, the bulk viscous pressure will never become large, and bulk viscous corrections to the shear viscous suppression of elliptic flow remain small. This is explored and described in detail in [131].

II.C.2 Radiative and elastic parton energy loss

(1) Heavy quark energy loss in dynamical media. With postdoc M. Djordjevic we performed a detailed analysis of recoil effects on radiative heavy quark energy loss in a *dynamical* QCD medium (a thermalized quark-gluon plasma) where the plasma constituents have finite mass [90,105,123]. Accounting for recoil is essential for calculating collisional energy loss [77], so it must be included in any consistent calculation of both elastic and radiative energy loss together. We found that, for a medium of given density and temperature, color magnetic effects caused by plasma recoil increase the radiative energy loss by up to a factor 2 compared to the static approximation, and that the relative increase in energy loss is about 10-20% larger for bottom quarks than for light quarks. Although the calculation was done only at lowest order in opacity, this indicates that (at least in a weakly interacting QGP) color magnetic effects may play an important role in understanding the surprisingly large suppression of c- and b-decay electrons and their large elliptic flow observed in Au+Au collisions. Djordjevic found a very simple substitution rule that translates the energy loss formula for a medium of static scatterers into that for a dynamical medium [90,105,123] which holds in all tested cases and may allow to easily generalize higher-order calculations by Gyulassy et al.

from a static to a dynamic medium.

(2) Comparing parton energy loss in different formalisms. With the arrival of Guang-You Qin, Abhijit Majumder and Will Horowitz as postdocs in 2008, our group got very actively involved in the activities of the Parton Energy Loss Working Group of the TECHQM collaboration. For the "QCD brick problem", a standardized setup where hard quarks lose energy traversing a slab of matter of prescribed properties, they contributed calculations representing the Arnold-Moore-Yaffe (AMY), Higher Twist (HT), and WHDG/ASW approaches which are presently compiled and written up as a report by the TECHQM Collaboration [Horowitz and Cole, PRC 81 (2010) 024909; Armesto et al., arXiv:1106.1106].

(3) Progress towards a comprehensive theory of parton energy loss. Together with H. Song, Qin and Majumder completed the first computation of the hydrodynamic response to parton energy loss in which the energy *lost* by the fast parent parton and the fraction of it *deposited* in the medium by showering and rescattering were calculated self-consistently within a single theoretical framework (the HT formalism) [121]. Their work improved on an earlier analysis by Neufeld that used a simpler model for the energy deposition. Both groups found that showering leads to an energy deposition rate that increases with time, enhancing the resulting hydrodynamic Mach cone signature by up to a factor 3 for realistic collision geometries. The work [121] made use of steep recent progress made by Majumder who added elastic collisional energy loss to the radiative one in the HT formalism [114], developed a resummation scheme with a single-gluon emission kernel to compute the in-medium virtuality evolution of a fast parton travelling through dense matter [120], and related the radiative and elastic parton energy loss transport coefficients $\hat{q}$ and $\hat{e}$ to non-perturbative medium expectation values of color electric field strength correlators that can be evaluated analytically in a perturbative QGP in Hard Thermal Loop approximation [122] or numerically on a lattice [Majumder, arXiv:1202.5295]. With the same formalism, Qin and Majumder demonstrated [132] that puzzling RHIC data on the suppression of light and heavy quarks in Au+Au collisions at high-p_T and its dependence on their azimuthal emission angle can be quantitatively described if one does not insist on a description of the fireball medium as a weakly coupled QGP but allows for it to be strongly coupled. Only the interaction of the hard quark with the medium, but not the medium itself, are required to be describable within perturbative QCD.

Most recently, Majumder generalized the kernel of the HT scheme to include single-gluon emission accompanied by multiple scatterings of both the emitting quark and emitted gluon [133] and compared with other multiple scattering schemes. With this work Majumder pushes the forefront of parton energy loss formalisms, by having developed the only formalism that simultaneously includes radiative and elastic energy loss, interference between vacuum and medium induced radiation, and virtuality evolution. The perfection of this approach and its implementation in a Monte Carlo event generator that can accomodate realistic space-time geometries of the expanding medium through which the parton travels are among the main research goals proposed for the coming grant cycle.

III. IMPACT:

The impact of the work of the OSU group can be assessed by the list of invited conference talks presented in the appendix and the citation statistics for papers published by the group. According to INSPIRE, the papers listed in Appendix A have collected (as of Nov. 1, 2012) more than 6,000 citations. Our work has impacted the experimental RHIC heavy-ion program (it motivated the 2012 run with uranium beams) and flowed into the 2007 NSAC Nuclear Physics Long Range Plan (which listed as one of the top priorities the exploration of the "perfect liquid" nature of the quark-gluon plasma). An OSU graduate student, Huichao Song, won the 2011 Dissertation Award in Nuclear Physics of the American Physical Society for her 2009 thesis on developing relativistic viscous fluid dynamics for heavy-ion collisions. Seven former postdocs, supported at one stage or another by this grant, are now faculty members elsewhere.

IV. APPENDIX: Research Output and Workforce Development 2001-2010

A. Publications by group members during the period 07/15/2001-08/14/2010

1. P. F. Kolb, P. Huovinen, U. Heinz and H. Heiselberg, *Elliptic flow at SPS and RHIC: From kinetic transport to hydrodynamics*, Phys. Lett. B 500 (2001) 232.
2. P. Huovinen, P.F. Kolb, U. Heinz, P.V. Ruuskanen and S.A. Voloshin, *Radial and elliptic flow at RHIC: Further predictions*, Phys. Lett. B 503 (2001) 58.
3. G. Aarts, *Spectral function at high temperature in the classical approximation*, Phys. Lett. B 518 (2001) 315-322.
4. P.F. Kolb, U. Heinz, P. Huovinen, K.J. Eskola, and K. Tuominen, *Centrality dependence of multiplicity, transverse energy, and elliptic flow from hydrodynamics*, Nucl. Phys. A696 (2001) 197-215.
5. M. Tilley, *Free streaming and hydrodynamic simulations of heavy-ion collisions at RHIC*, final report on work done as a an REU summer student at Ohio State University, August 2001.
6. U. Heinz, *From SPS to RHIC: Breaking the Barrier to the Quark-Gluon Plasma*, in *QCD@WORK – International Workshop on Quantum Chromodynamics: Theory and Experiment* (P. Colangelo and G. Nardulli, eds.), AIP Conf. Proc. 602 (2001) 281-292 [hep-ph/0109006].
7. G. Aarts, O. Kaczmarek, F. Karsch, and I.-O. Stamatescu, *1/M correction to quenched QCD with non-zero baryon density*, Nucl. Phys. B – Proc. Suppl. 106 (2002) 456-458.
8. G. Aarts, *Spectral function at high temperature*, Nucl. Phys. B – Proc. Suppl. 106 (2002) 534-536.
9. J. I. Kapusta and S. M. H. Wong, reply to *Comment on 'Modification of Z boson properties in the quark-gluon plasma' and 'Two-loop contribution to high mass dilepton production by a quark-gluon plasma'*, Phys. Rev. D 65 (2002) 038502.
10. J. I. Kapusta and S. M. H. Wong, *Possible evidence of Disoriented Chiral Condensates from the anomaly in* Ω *and* $\bar{\Omega}$ *abundances at the SPS*, Pramana 60 (2002)

1099-1102 [hep-ph/0201166].

11. B. Tomášik and U. Heinz, *Flow effects on the freeze-out phase-space density in heavy-ion collisions*, Phys. Rev. C 65 (2002) 031902(R) [4 pages].
12. S. M. H. Wong, *What exactly is a Skyrmion?*, arXiv:hep-ph/0202250 [4 pages].
13. G. Aarts, D. Ahrensmeier, R. Baier, I.-O. Stamatescu, and J. Serreau, *Far from equilibrium dynamics with broken symmetries from the 2PI – 1/N expansion*, Phys. Rev. D 66 (2002) 045008 [14 pages].
14. G. Aarts and J. M. Martinez Resco, *Transport coefficients, spectral functions and the lattice*, JHEP 0204 (2002) 053 [24 pages].
15. U. Heinz and P. F. Kolb, *Early thermalization at RHIC*, in: *Statistical QCD*, Nucl. Phys. A702 (2002) 269-280.
16. G. Aarts and J. M. Martinez Resco, *Ward identity and electrical conductivity in hot QED*, JHEP 0211 (2002) 022 [15 pages].
17. G. Aarts and J. M. Martinez Resco, *Transport coefficients and quantum fields*, in *Strong and Electroweak Matter 2002*, edited by M. G. Schmidt (World Scientific, Singapore, 2003), pp. 96-110 [arXiv:hep-ph/0212268, 15 pages].
18. J. I. Kapusta and S. M. H. Wong, *Anomalous production of* Ω *and* $\bar{\Omega}$ *is evidence for the formation of disoriented chiral condensates?*, J. Phys. G 28 (2002) 1929-1936.
19. B. Alessandro, U. Heinz, *et al.*, *ALICE Physics: Theoretical Overview*, CERN-ALICE-INTERNAL-NOTE-2002-025.
20. U. Heinz and P. F. Kolb, *Two RHIC puzzles: Early thermalization and the HBT problem*, in: Proceedings of the *18th Winter Workshop on Nuclear Dynamics*, R. Bellwied, J. Harris, and W. Bauer (eds.), pp. 205-216 (EP Systema, Debrecen, Hungary, 2002) [arXiv:hep-ph/0204061].
21. U. Heinz and S. M. H. Wong, *Elliptic flow from a transversally thermalized fireball*, Phys. Rev. C 66 (2002) 014907 [15 pages].
22. Enke Wang and U. Heinz, *A generalized fluctuation-dissipation theorem for non-linear response functions*, Phys. Rev. D 66 (2002) 025008 [17 pages].
23. U. Heinz, A. Hummel, M. A. Lisa, and U. A. Wiedemann, *Symmetry constraints for the emission angle dependence of HBT radii*, Phys. Rev. C 66 (2002) 044903 [8 pages].
24. U. Heinz and P. F. Kolb, *Emission angle dependent pion interferometry at RHIC and beyond*, Phys. Lett. B 542 (2002) 216-222.
25. U. Heinz, *The quark-gluon plasma at RHIC*, Nucl. Phys. A721 (2003) 30c-39c.
26. D. Molnár and M. Gyulassy, *Differential freezeout and pion interferometry at RHIC from covariant transport theory*, Phys. Rev. Lett. 92 (2004) 052301 [arXiv:nucl-th/0211017, 4 pages].
27. G. Aarts and J. M. Martinez Resco, *Transport coefficients from the lattice?*, Nucl. Phys. B – Proc. Suppl. 119 (2003) 505-507.
28. U. Heinz and S. M. H. Wong, *Elliptic flow from partially thermalized heavy-ion*

collisions, Nucl. Phys. A715 (2003) 649c-652c [4 pages].

29. P. F. Kolb and U. Heinz, *Emission angle dependent HBT at RHIC and beyond*, Nucl. Phys. A715 (2003) 653c-656c [4 pages].
30. S. M. H. Wong and J. I. Kapusta, *Baryonic coherent state formation from small domain disoriented chiral condensates*, Nucl. Phys. A715 (2003) 573c-576c [4 pages].
31. B. Tomášik, U. A. Wiedemann, and U. Heinz, *Reconstructing the freeze-out state in Pb+Pb collisions at 158 A GeV/c*, Heavy Ion Phys. 17 (2003) 105-143.
32. Enke Wang and U. Heinz, *Shear viscosity of hot scalar field theory in the real-time formalism*, Phys. Rev. D 67 (2003) 025022 [12 pages].
33. Defu Hou, M. E. Carrington, R. Kobes and U. Heinz, *Four-point spectral functions and Ward identities in hot QED*, Phys. Rev. D 67 (2003) 049902 [Erratum, 2 pages].
34. S. M. H. Wong, *Equivalence of classical Skyrmions and coherent states of baryons. I: Constrained quantization on the SU(2) and SO(3) manifolds*, arXiv:hep-ph/0207194 [16 pages].
35. S. M. H. Wong, *Equivalence of classical Skyrmions and coherent states of baryons. II: Baryonic coherent state construction on compact manifolds*, arXiv:hep-ph/0207195 [21 pages].
36. G. Aarts, *Quasi-fixed points in nonequilibrium field theory*, in The Monte Carlo Method in the Physical Sciences: Celebrating the 50th Anniversary of the Metropolis Algorithm, AIP Conf. Proc. 690 (2003) 367-368.
37. D. Molnár and S.A. Voloshin, *Elliptic flow at large transverse momenta from quark coalescence*, Phys. Rev. Lett. 91 (2003) 092301 [4 pages].
38. Zi-wei Lin and D. Molnár, *Quark coalescence and elliptic flow of charm hadrons*, Phys. Rev. C 68 (2003) 044901 [5 pages].
39. Zi-wei Lin and C.M. Ko, *Deuteron-nucleus collisions in a multi-phase transport model*, Phys. Rev. C 68 (2003) 054904 [8 pages].
40. G. Aarts and J. M. Martinez Resco, *Transport coefficients from the 2PI effective action*, Phys. Rev. D 68 (2003) 085009 [5 pages].
41. D. Molnár and M. Gyulassy, *The decoupling problem at RHIC*, Heavy Ion Phys. 18 (2003) 69-78.
42. U. Heinz, *Hydrodynamic emission of strange and non-strange particles at RHIC and LHC*, J. Phys. G 30 (2004) S251-S256.
43. Zi-wei Lin and C.M. Ko, *Kaon interferometry at RHIC from the AMPT model*, J. Phys. G 30 (2004) S263-S269.
44. D. Molnar, *Meson and baryon elliptic flow at high p_T from parton coalescence*, J. Phys. G 30 (2004) S235-S241.
45. U. Heinz, *Emission angle dependence of HBT radii: Theoretical background and interpretation*, Acta Phys. Pol. B35 (2004) 29-36 [arXiv:nucl-th/0311048].

46. P.F. Kolb and U. Heinz, *Hydrodynamic description of ultrarelativistic heavy-ion collisions*, in *Quark Gluon Plasma 3*, edited by R.C. Hwa and X.N. Wang (World Scientific, Singapore, 2004), pp. 634-714 [arXiv:nucl-th/0305084].

47. G. Aarts and J. M. Martinez Resco, *Shear viscosity in the O(N) model,* JHEP 0402 (2004) 061 [arXiv:hep-ph/0402192, 37 pages].

48. U. Heinz and P. F. Kolb, *Rapidity dependent momentum anisotropy at RHIC,* J. Phys. G 30 (2004) S1229-S1233 [arXiv:nucl-th/0403044].

49. D. Molnar, *Particle correlations at RHIC from parton coalescence dynamics: First results,* J. Phys. G 30 (2004) S1239-S1242 [arXiv:nucl-th/0403035].

50. G. Aarts and J. M. Martinez Resco, *Transport coefficients and the 2PI effective action in the large N limit,* in: Proceedings of "Strong and Electroweak Matter 2004 (SEWM04)", eds. K.J. Eskola et al., World Scientific Publ. Co., Singapore, 2005, pp. 231-240 [arXiv:hep-ph/0409090, 10 pages].

51. D. Molnar and P. Huovinen, *Dissipation and elliptic flow at RHIC,* Phys. Rev. Lett. 94 (2005) 012302 [arXiv:nucl-th/0404065, 4 pages].

52. D. Molnar, *Parton coalescence and spacetime*, Acta Phys. Hung. A22 (2005) 271-279 [arXiv:nucl-th/0406066].

53. U. Heinz, *Thermalization at RHIC,* AIP Conf. Proc. 739 (2004) 163-179 [arXiv:nucl-th/0407067].

54. U. Heinz, *Concepts of heavy-ion physics,* Lectures given at the 2nd Latin American School of High-Energy Physics (San Miguel Regla, Mexico, 1-14 Jun 2003), CERN Yellow Report CERN-2006-001, pp. 165-238 [arXiv:hep-ph/0407360, 74 pages].

55. D. Molnar, *Elliptic flow from quark coalescence: Mass ordering or quark number scaling?*, arXiv:nucl-th/0408044 [4 pages].

56. U. Heinz and A. Sugarbaker, *Projected three-pion correlation functions*, Phys. Rev. C 70 (2004) 054908 [arXiv:nucl-th/0408056, 6 pages].

57. D. Molnar, *Charm elliptic flow from quark coalescence dynamics,* J. Phys. G 31 (2005) S421-S428 [arXiv:nucl-th/0410041].

58. U. Heinz and A. Kuhlman, *Anisotropic flow and jet quenching in ultrarelativistic U+U collisions*, Phys. Rev. Lett. 94 (2005) 132301 [arXiv:nucl-th/0411054, 4 pages].

59. Z. W. Lin, C. M. Ko, B. A. Li, B. Zhang and S. Pal, *A multi-phase transport model for relativistic heavy ion collisions*, Phys. Rev. C 72 (2005) 064901 [arXiv:nucl-th/0411110, 29 pages].

60. U. Heinz, *Hydrodynamics at RHIC: How well does it work, where and how does it break down?*, J. Phys. G 31 (2005) S717-S724 [arXiv:nucl-th/0412094].

61. D. Molnar, *Novel mechanism of high-p_T production from an opaque quark-gluon plasma*, arXiv:nucl-th/0503051 [3 pages].

62. U. Heinz, *Equation of state and collective dynamics*, J. Phys. Conf. Ser. 50 (2006) 230-237 [arXiv:nucl-th/0504011].

63. A. K. Chaudhuri and U. Heinz, *Hydrodynamical evolution of dissipative QGP fluid*, J. Phys. Conf. Ser. 50 (2006) 251-258 [arXiv:nucl-th/0504022].

64. A. J. Kuhlman, *The scientific promise of a future uranium-uranium collision program at the Relativistic Heavy Ion Collider facility*, in: Proceedings of the "2005 Edward F. Hayes Graduate Research Forum" (Ohio State University, Columbus, Ohio, Apr. 16, 2005), Volume 5 (2005), pp. 323-338.

65. A. J. Kuhlman and U. Heinz, *Multiplicity distribution and source deformation in full-overlap U+U collisions*, Phys. Rev. C 72 (2005) 037901 [arXiv:nucl-th/0506088, 4 pages].

66. B. Kämpfer, M. Bluhm, R. Schulze, D. Seipt and U. Heinz, *QCD matter within a quasi-particle model and the critical end point*, Nucl. Phys. A 774 (2006) 757-760 [arXiv:hep-ph/0509146].

67. D. Molnar, *Parton cascade and coalescence*, Nucl. Phys. A 774 (2006) 257-266 [arXiv:nucl-th/0512001].

68. U. Heinz, H. Song and A. K. Chaudhuri, *Dissipative hydrodynamics for viscous relativistic fluids*, Phys. Rev. C 73 (2006) 034904 [arXiv:nucl-th/0510014, 12 pages].

69. T. Hirano, U. Heinz, D. Kharzeev, R. Lacey and Y. Nara, *Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions*, Phys. Lett. B 636 (2006) 299-304 [arXiv:nucl-th/0511046].

70. R. Chatterjee, E. S. Frodermann, U. Heinz and D. K. Srivastava, *Elliptic flow of thermal photons in relativistic nuclear collisions*, Phys. Rev. Lett. 96 (2006) 202302 [arXiv:nucl-th/0511079, 4 pages].

71. A. K. Chaudhuri and U. Heinz, *Effects of jet quenching on the hydrodynamical evolution of quark-gluon plasma*, Phys. Rev. Lett. 97 (2006) 062301 [arXiv:nucl-th/0503028, v3(10Nov2005), 4 pages].

72. U. Heinz, *Viscous relativistic hydrodynamics*, in: Proceedings of the International Workshop "Extreme QCD" (University of Wales, Swansea, Aug. 2-5, 2005), eds. G. Aarts, S. Hands et al. [arXiv:nucl-th/0512049, 9 pages].

73. U. Heinz, *'RHIC serves the perfect fluid' - Hydrodynamic flow of the QGP*, in: Proceedings of the International Workshop "Extreme QCD" (University of Wales, Swansea, Aug. 2-5, 2005), eds. G. Aarts, S. Hands et al. [arXiv:nucl-th/0512051, 10 pages].

74. S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, *Elastic, inelastic, and path length fluctuations in jet tomography*, Nucl. Phys. A784 (2007) 426-432 [arXiv:nucl-th/0512076].

75. M. Djordjevic, *Transition radiation in QCD matter*, Phys. Rev. C73 (2006) 044912 [arXiv:nucl-th/0512089, 13 pages].

76. M. A. Lisa, E. Frodermann, and U. Heinz, *Fitted HBT radii versus space-time variances in flow-dominated models*, Phys. Rev. C 73 (2006) 044908 [arXiv:nucl-th/0602023, 12 pages].

77. M. Djordjevic, *Collisional energy loss in finite size QCD matter*, Phys. Rev. C 74 (2006) 064907 [arXiv:nucl-th/0603066] (12 pages).

78. A. J. Kuhlman, U. Heinz, and Yu. V. Kovchegov, *Gluon saturation effects in relativistic U+U collisions*, Phys. Lett. B 638 (2006) 171-177 [arXiv:nucl-th/0604038].

79. M. Djordjevic, *An overview of the heavy quark energy loss puzzle at RHIC*, J. Phys. G 32 (2006) S333-S342 [arXiv:nucl-th/0610054].

80. U. Heinz, R. Chatterjee, E. S. Frodermann, C. Gale and D. K. Srivastava, *Elliptic flow of thermal photons and dileptons*, Nucl. Phys. A783 (2007) 379-386 [arXiv:nucl-th/0610014].

81. M. Djordjevic, *Heavy quark energy loss: collisional vs. radiative*, Nucl. Phys. A783 (2007) 197-204.

82. U. Heinz, *Universal chemical freeze-out as a phase transition signature*, PoS CPOD2006 (2006) 038 [nucl-th/0612105, 16 pages].

83. M. Baker, U. Heinz, *et al.*, *Future Science at the Relativistic Heavy Ion Collider*, White Paper of the RHIC II Science Working Group, resulting from a series of workshops held at BNL in 2004-2006, BNL, August 2006.

84. M. Lisa, E. Frodermann and U. Heinz, *Fitted HBT radii versus space-time variances in flow-dominated models*, Braz. J. Phys. 37 (2007) 903-914.

85. S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, *Heavy quark jet quenching with collisional plus radiative energy loss and path length fluctuations*, Nucl. Phys. A783 (2007) 493-496 [arXiv:nucl-th/0701063].

86. A. K. Chaudhuri and U. Heinz, *Effect of jet quenching on hydrodynamical evolution of QGP*, J. Phys. G 34 (2007) S689-S692.

87. T. Hirano, U. Heinz, D. Kharzeev, R. Lacey and Y. Nara, *Elliptic Flow from a Hybrid CGC, Full 3D Hydro and Hadronic Cascade Model*, J. Phys. G 34 (2007) S879-S882 [arXiv:nucl-th/0701075].

88. R. Chatterjee, D. K. Srivastava, U. Heinz and C. Gale, *Elliptic flow of thermal dileptons in relativistic nuclear collisions*, Phys. Rev. C75 (2007) 054909 [arXiv:nucl-th/0702039, 8 pages].

89. M. Bluhm, B. Kämpfer, R. Schulze, D. Seipt and U. Heinz, *A family of equations of state based on lattice QCD: Impact on flow in ultrarelativistic heavy-ion collisions*, Phys. Rev. C76 (2007) 034901 [arXiv:0705.0397 [hep-ph], 18 pages].

90. M. Djordjevic and U. Heinz, *Radiative heavy quark energy loss in a dynamical QCD medium*, Phys. Rev. C 77 (2008) 024905 [arXiv:0705.3439 [nucl-th], 18 pages].

91. E. Frodermann, R. Chatterjee, and U. Heinz, *Evolution of pion HBT radii from RHIC to LHC – predictions from ideal hydrodynamics*, J. Phys. G 34 (2007) 2249-2254 [arXiv:0707.1898 [nucl-th]].

92. H. Song and U. Heinz, *Suppression of elliptic flow in a minimally viscous quark-gluon plasma*, Phys. Lett. B658 (2008) 279-283 [arXiv:0709.0742 [nucl-th]].

93. U. Heinz and G. Kestin, *Jozso's Legacy: chemical and kinetic freeze-out in heavy-*

ion collisions, Eur. Phys. J. ST 155 (2008) 75-87,2008 [arXiv:0709.3366 [nucl-th]].

94. T. Hirano, U. Heinz, D. Kharzeev, R. Lacey and Y. Nara, *Mass ordering of differential elliptic flow and its violation for ϕ mesons*, Phys. Rev. C 77 (2008) 044909 [arXiv:0710.5795 [nucl-th], 13 pages].
95. M. Bluhm, B. Kämpfer and U. Heinz, *Transverse momentum spectra and elliptic flow: Hydrodynamics with QCD-based equations of state*, in: N. Armesto (ed.) *et al.*, *Heavy Ion Collisions at the LHC – Last Call for Predictions*, Sect. 2.1 (2 pages), J. Phys. G 35 (2008) 054001 [arXiv:0711.0974 [hep-ph]].
96. G. Kestin and U. Heinz, *From RHIC to LHC: Elliptic and radial flow effects on hadron spectra*, in: N. Armesto (ed.) *et al.*, *Heavy Ion Collisions at the LHC – Last Call for Predictions*, Sect. 2.4 (2 pages), J. Phys. G 35 (2008) 054001 [arXiv:0711.0974 [hep-ph]].
97. E. Frodermann, R. Chatterjee, and U. Heinz, *Evolution of pion HBT radii from RHIC to LHC – predictions from ideal hydrodynamics*, in: N. Armesto (ed.) *et al.*, *Heavy Ion Collisions at the LHC – Last Call for Predictions*, Sect. 4.6 (2 pages), J. Phys. G 35 (2008) 054001 [arXiv:0711.0974 [hep-ph]].
98. M. Djordjevic and U. Heinz, *Effect of dynamical QCD medium on radiative quark energy loss*, in: N. Armesto (ed.) *et al.*, *Heavy Ion Collisions at the LHC – Last Call for Predictions*, Sect. 6.6 (2 pages), J. Phys. G 35 (2008) 054001 [arXiv:0711.0974 [hep-ph]].
99. R. Chatterjee, E. Frodermann, U. Heinz, and D. K. Srivastava, *Elliptic flow of thermal photons from RHIC to LHC*, in: N. Armesto (ed.) *et al.*, *Heavy Ion Collisions at the LHC – Last Call for Predictions*, Sect. 8.3 (2 pages), J. Phys. G 35 (2008) 054001 [arXiv:0711.0974 [hep-ph]].
100. R. Tribble, U. Heinz, *et al.* (The Nuclear Science Advisory Committee), *The Frontiers of Nuclear Science – A Long Range Plan*, DOE/NSF NSAC Report, Jan. 2008.
101. B. Alver, U. Heinz, *et al.*, *Importance of correlations and fluctuations on the initial source eccentricity in high-energy nucleus-nucleus collisions*, Phys. Rev. C 77 (2008) 014906 [arXiv:0711.3724 [nucl-ex], 16 pages].
102. S. Turbide, C. Gale, E. Frodermann, U. Heinz, *Electromagnetic radiation from nuclear collisions at RHIC energies*, Phys. Rev. C 77 (2008) 024909 [arXiv:0712.0732 [hep-ph], 8 pages].
103. D. Anchishkin and U. Heinz, *Two-Particle correlations in the wave function and covariant current approaches*, Phys. Atom. Nucl. 71 (2008) 1632-1646 (2008) [arXiv:0712.1104 [hep-ph]].
104. H. Song and U. Heinz, *Causal viscous hydrodynamics in 2+1 dimensions for relativistic heavy-ion collisions*, Phys. Rev. C 77 (2008) 064901 [arXiv:0712.3715 [nucl-th], 25 pages].
105. M. Djordjevic and U. Heinz, *Radiative energy loss in a finite dynamical QCD medium*, Phys. Rev. Lett. 101 (2008) 022302 [arXiv:0802.1230 [nucl-th], 4 pages].

106. H. Song and U. Heinz, *Multiplicity scaling in ideal and viscous hydrodynamics*, Phys. Rev. C 78 (2008) 024902 [arXiv:0805.1756 [nucl-th], 14 pages].

107. U. Heinz, *From SPS to RHIC: Maurice and the CERN heavy-ion programme*, Phys. Scripta 78 (2008) 028005 [arXiv:0805.4572 [nucl-th], 6 pages].

108. T. Hirano, U. Heinz, D. Kharzeev, R. Lacey and Y. Nara, *Hadronic dissipative effects on transverse dynamics at RHIC*, J. Phys. G 35 (2008) 104124 [arXiv:0805.0064 [nucl-th], 4 pages].

109. U. Heinz and H. Song, *Causal relativistic hydrodynamics for viscous fluids*, J. Phys. G 35 (2008) 104126 [arXiv:0806.0352 [nucl-th], 4 pages].

110. C. Gale, S. Turbide, E. Frodermann and U. Heinz, *Photons from nuclear collisions at RHIC energies*, J. Phys. G 35 (2008) 104119 [arXiv:0806.0610 [hep-ph], 4 pages].

111. G. Kestin and U. Heinz, *Hydrodynamic radial and elliptic flow in heavy-ion collisions from AGS to LHC energies*, Eur. Phys. J. C 61 (2009) 545-552 [arXiv:0806.4539 [nucl-th]].

112. G. Y. Qin, J. Ruppert, C. Gale, S. Jeon and G. D. Moore, *Radiative and collisional energy loss, and photon-tagged jets at RHIC*, Eur. Phys. J. C 61 (2009) 819-823 [arXiv:0809.2030 [hep-ph]].

113. A. Majumder, *Characterizations of the medium in jet quenching calculations*, arXiv:0810.1367 [nucl-th] (8 pages). (Invited talk at *Hard Probes 2008.*)

114. A. Majumder, *Elastic energy loss and longitudinal straggling of a hard jet*, Phys. Rev. C 80 (2009) 031902(R) (2009) [arXiv:0810.4967 [nucl-th], 5 pages].

115. U. Heinz, *The strongly coupled quark-gluon plasma created at RHIC*, J. Phys. A: Math. Theor. 42 (2009) 214003 [arXiv:0810.5529 [nucl-th], 10 pages].

116. H. Song and U. Heinz, *Extracting the QGP viscosity from RHIC data – A status report from viscous hydrodynamics*, J. Phys. G 36 (2009) 064033 [arXiv:0812.4274 [nucl-th], 8 pages].

117. R. Chatterjee, D. K. Srivastava and U. Heinz, *Time evolution of thermal photon elliptic flow*, Nucl. Phys. A827 (2009) 1c-694c [arXiv:0901.3270 [nucl-th], 4 pages].

118. B. Schenke, C. Gale, G. Y. Qin, *The evolving distribution of hard partons traversing a hot strongly interacting plasma*, Phys. Rev. C 79 (2009) 054908 [arXiv:0901.3498 [hep-ph], 6 pages].

119. U. Heinz, *Early collective expansion: Relativistic hydrodynamics and the transport properties of QCD matter*, in Relativistic Heavy Ion Physics, edited by R. Stock, Landolt-Börnstein New Series, Vol. I/23, chapter 5 (Springer Verlag, Heidelberg, 2009) [arXiv:0901.4355 [nucl-th], 54 pages].

120. A. Majumder, *The in-medium scale evolution in jet modification*, arXiv:0901.4516 [nucl-th] (4 pages).

121. G. Y. Qin, A. Majumder, H. Song, U. Heinz, *Energy and momentum deposited into a QCD medium by a jet shower*, Phys. Rev. Lett. 103 (2009) 152303 [arXiv:0903.2255 [nucl-th], 4 pages].

122. A. Majumder, B. Müller and S. Mrowczynski, *Momentum broadening of a fast parton in a perturbative quark-gluon plasma*, Phys. Rev. D 80 (2009) 125020 [arXiv:0903.3683 [hep-ph], 9 pages].

123. M. Djordjevic, *Theoretical formalism of radiative jet energy loss in a finite size dynamical QCD medium*, Phys. Rev. C 80 (2009) 064909 [arXiv:0903.4591 [nucl-th], 27 pages].

124. G. Y. Qin, J. Ruppert, C. Gale, S. Jeon and G. D. Moore, *Jet energy loss, photon production, and photon-hadron correlations at RHIC*, Phys. Rev. C 80 (2009) 054909 [arXiv:0906.3280 [hep-ph], 10 pages].

125. E. Frodermann and U. Heinz, *Photon HBT interferometry for non-central heavy-ion collisions*, Phys. Rev. C 80 (2009) 044903 [arXiv:0907.1292 [nucl-th], 16 pages].

126. H. Song and U. Heinz, *Viscous hydrodynamics with bulk viscosity: uncertainties from relaxation time and initial conditions*, Nucl. Phys. A830 (2009) 467c-470c [arXiv:0907.2262 [nucl-th]].

127. G. Y. Qin, C. Gale, S. Jeon, G. D. Moore and J. Ruppert, *Jet energy loss and high p_T photon production in hot quark-gluon plasma*, Nucl. Phys. A830 (2009) 459c-462c [arXiv:0907.3898 [hep-ph]].

128. U. Heinz, *Can the energy dependence of elliptic flow reveal the QGP phase transition?*, Nucl. Phys. A830 (2009) 287c-290c [arXiv:0907.4256 [nucl-th]].

129. A. Majumder, *Jet medium interactions at Quark Matter 09*, Nucl. Phys. A830 (2009) 875c-882c [arXiv:0908.1747 [hep-ph]].

130. U. Heinz, J. S. Moreland and H. Song, *Viscosity from elliptic flow: clearing the path towards precision*, Phys. Rev. C 80 (2009) 061901(R) [arXiv:0908.2617 [nucl-th], 5 pages].

131. H. Song and U. Heinz, *Interplay of shear and bulk viscosity in generating flow in heavy-ion collisions*, Phys. Rev. C 81 (2010) 024905 [arXiv:0909.1549 [nucl-th], 12 pages].

132. G. Y. Qin and A. Majumder, *A pQCD-based description of heavy and light flavor jet quenching*, Phys. Rev. Lett. 105 (2010) 262301 [arXiv:0910.3016 [hep-ph], 4 pages].

133. A. Majumder, *Hard collinear gluon radiation and multiple scattering in a medium*, Phys. Rev. D 85 (2012) 014023 [arXiv:0912.2987 [nucl-th], 30 pages].

134. M. Asakawa, A. Majumder, and B. Müller, *Electric Charge Separation in Strong Transient Magnetic Fields*, Phys. Rev. C 81 (2010) 064912 [arXiv:1003.2436 [hep-ph], 18 pages].

135. A. Majumder and M. van Leeuwen, *The theory and phenomenology of perturbative QCD based jet quenching*, Prog. Part. Nucl. Phys. 66 (2011) 41-92.

136. A. Majumder and B. Müller, *Hadron mass spectrum from Lattice QCD*, Phys. Rev. Lett. 105, 252002 (2010) (4 pages).

B. Unpublished talks and posters presented by group members in the period 07/15/2001-08/14/2010:

1. S. M. H. Wong, *Bremsstrahlung as a probe of collision dynamics in a microscopic transport model of heavy-ion collisions*, RIKEN/High Energy Physics Seminar, Brookhaven National Laboratory, July 18, 2001.
2. U. Heinz, *Initial geometry in hydrodynamic calculations*, invited talk, RHIC Topical Workshop on *Estimating $N_{\rm part}$ and $N_{\rm coll}$*, Brookhaven National Laboratory, July 19, 2001.
3. U. Heinz, *Early thermalization*, invited talk, Workshop on *Thermalization and Chemical Equilibration in Heavy-Ion Collisions at RHIC*, Brookhaven National Laboratory, July 20-21, 2001.
4. S.M.H. Wong, *How to get rapid thermalization from perturbative QCD in heavy-ion collisions*, Workshop on *Thermalization and Chemical Equilibration in Heavy-Ion Collisions at RHIC*, Brookhaven National Laboratory, July 20-21, 2001.
5. P. Kolb, *Applicability of hydrodynamics and the HBT riddle at RHIC*, poster, Gordon Research Conference in Nuclear Physics "QCD in Extreme Conditions: High Temperature, High Density and Small-x", Newport (Rhode Island), July 22-27, 2001.
6. G. Aarts, *Quantum fields far from equilibrium: a quantitative approach*, seminar, CERN, Geneva (Switzerland), Aug. 9, 2001.
7. G. Aarts, *Spectral function at high temperature*, contributed talk, International Conference *Lattice 2001*, Berlin (Germany), Aug. 19-24, 2001.
8. P. Kolb, *Hydrodynamics at RHIC*, invited talk, 222nd ACS National Meeting, Chicago (Illinois), Aug. 30, 2001.
9. P. Kolb, *Source function and HBT from hydrodynamics*, Heavy Ion Tea Seminar, Lawrence Berkeley Laboratory, Sep. 11, 2001.
10. S. M. H. Wong, *Anomalous production of Omega and antiOmega is evidence for the formation of disoriented chiral condensates?*, contributed talk, 6th International Conference on "Strange Quarks in Matter" (SQM2001), Frankfurt (Germany), Sep. 24-29, 2001.
11. P. Kolb, *Indications for hydrodynamic expansion in ultrarelativistic heavy-ion collisions*, Triangle Nuclear Theory Colloquium, Duke University, Oct. 2, 2001.
12. P. Kolb, *Azimuthally sensitive HBT analysis from hydrodynamics*, seminar, 2001 Midwest Nuclear Theory Get-Together, Argonne National Laboratory, Oct. 5, 2001.
13. P. Kolb, *Anisotropic observables from non-central collisions*, invited talk, *STAR ÜberFit-Workshop*, Lawrence Berkeley Laboratory, Oct. 10, 2001.
14. G. Aarts, *Classical aspects of nonequilibrium quantum fields*, seminar, Ohio State University, Oct. 12, 2001.
15. G. Aarts, *Classical aspects of nonequilibrium quantum fields*, seminar, Purdue Uni-

versity, Nov. 27, 2001.

16. G. Aarts, *Classical aspects of nonequilibrium quantum fields*, Nuclear Theory Seminar, MIT, Dec. 4, 2001.
17. U. Heinz, *Spatial and momentum anisotropies and the thermalization problem at RHIC*, seminar, Wayne State University, Dec. 12, 2001.
18. J. M. Martinez Resco, *Transport coefficients in hot gauge theories*, seminar, Ohio State University, Dec. 14, 2001.
19. P. Kolb,
Spectra, elliptic flow and HBT radii from hydrodynamics, invited talk, INT/RHIC Winter Workshop 2002 on *Correlations and Fluctuations in Heavy-Ion Collisions at RHIC*, INT Seattle (Washington), Jan. 4-6, 2002
20. U. Heinz, *Two RHIC puzzles: Early thermalization and the HBT problem*, invited talk, 18th Winter Workshop on *Nuclear Dynamics*, Nassau (Bahamas), Jan. 20-27, 2002.
21. U. Heinz, *Two RHIC puzzles: early thermalization and HBT and the HBT problem*, seminar, Yale University, April 2, 2002.
22. U. Heinz, *Flow and early thermalization at RHIC*, invited talk, International Conference on *QCD in the RHIC Era*, Santa Barbara (California), April 8-12, 2002.
23. P. Kolb, *Hydrodynamic flow at RHIC*, invited talk, *APS Spring Meeeting 2002*, Albuquerque (New Mexico), April 20-23, 2002.
24. G. Aarts, *Transport coefficients and spectral functions from the lattice?*, invited talk, Workshop on *QCD and Gauge Theory Dynamics in the RHIC Era*, KITP, Santa Barbara, CA, April 27-May 18, 2002.
25. J. M. Martinez Resco, *Transport coefficients, spectral functions and the lattice*, contributed talk, *DPF 2002*, Williamsburg, Virginia, May 24-28, 2002.
26. U. Heinz, *RHIC and the Quark-Gluon Plasma*, Theory Colloquium, CERN, Aug. 21, 2002.
27. U. Heinz, *Emission angle dependent pion interferometry*, Heavy Ion Forum seminar, CERN, Aug. 27, 2002.
28. U. Heinz, *Concepts of Heavy Ion Physics*, two 75' lectures given at the *2002 European School of High Energy Physics*, Pylos, Greece, Aug. 31 and Sep. 2, 2002.
29. U. Heinz, *RHIC and the Quark-Gluon Plasma*, Colloquium, Washington University, St. Louis, Sept. 18, 2002.
30. U. Heinz, *Soft particle production at RHIC – thermalization and statistical hadronization*, theoretical overview talk given at the *RHIC & AGS Annual Users' Meeting*, Brookhaven National Laboratory, Sept. 20-21, 2002.
31. D. Molnar, *Solving nonlinear dynamical equations with QCDOC horsepower*, invited talk, QCDOC Workshop on *Large-Scale Computations in Nuclear Physics using the QCDOC*, RIKEN/BNL Research Center, Upton, NY, September 26-28, 2002.

32. U. Heinz, *RHIC and the Quark-Gluon Plasma: What's New from Quark Matter 2002*, Nuclear Physics Seminar, Ohio State University, Sep. 27, 2002.

33. U. Heinz, *The Quark-Gluon Plasma at RHIC*, plenary overview talk, XVI Particles and Nuclei International Conference *(PANIC02)*, Osaka, Japan, Sept. 30 – Oct. 4, 2002.

34. J.M. Martinez Resco, *The Ward identity for the electrical conductivity at leading-log in hot QED*, poster, International Workshop on *Strong and Electroweak Matter (SEWM 2002)*, Heidelberg, Germany, Oct. 2-5, 2002.

35. Amy Hummel, *Symmetry constraints for azimuthally-sensitive HBT interferometry*, contributed talk, APS Division of Nuclear Physics Fall Meeting 2002, Michigan State University, Oct. 12, 2002.

36. G. Aarts, *Electrical conductivity in hot QED*, contributed talk, APS Ohio Section Fall Meeting 2002, Columbus, OH, Oct. 18-19, 2002.

37. U. Heinz, *Emission angle dependent pion interferometry at RHIC and beyond*, contributed talk, APS Ohio Section Fall Meeting 2002, Columbus, OH, Oct. 18-19, 2002.

38. Amy Hummel, *Symmetry constraints for azimuthally-sensitive HBT interferometry*, contributed talk, APS Ohio Section Fall Meeting 2002, Columbus, OH, Oct. 18-19, 2002.

39. D. Molnar, *Decoupling phenomena and the opacity of the gluon plasma in Au+Au at RHIC*, contributed talk, APS Ohio Section Fall Meeting 2002, Columbus, OH, Oct. 18-19, 2002.

40. U. Heinz, *Hydrodynamic behaviour and elliptic flow at RHIC*, invited talk, INT/RHIC Winter Workshop 2002 on *The First Two Years of RHIC: Theory versus Experiments*, Institute for Nuclear Theory, University of Washington, Seattle, Dec. 13-15, 2002.
This presentation won the prize for "The quantitatively most successful prediction for RHIC phenomena" in the RHIC Predictions Competition *announced at an INT Workshop in 1998. Coauthor of this presentation was Peter Kolb.*

41. Ziwei Lin, *Open charm and Drell-Yan at RHIC*, invited talk, INT/RHIC Winter Workshop 2002 on *The First Two Years of RHIC: Theory versus Experiments*, Institute for Nuclear Theory, University of Washington, Seattle, Dec. 13-15, 2002.
At this meeting, Zi-Wei Lin and his co-authors Che-Ming Ko and Bin Zhang were awarded the prize for "The most successful RHIC prediction from a microscopic model" in the RHIC Predictions Competition *announced at an INT Workshop in 1998.*

42. D. Molnar, *Parton cascade predictions: 1999-2002*, invited talk, INT/RHIC Winter Workshop 2002 on *The First Two Years of RHIC: Theory versus Experiments*, Institute for Nuclear Theory, University of Washington, Seattle, Dec. 13-15, 2002.

43. J. M. Martinez Resco, *Transport coefficients in hot gauge theories*, seminar, Lawrence Berkeley Laboratory, Jan. 29, 2003.

44. U. Heinz, *Constraints on transverse dynamics from emission angle dependent*

HBT measurements, invited talk, Workshop on *Transverse Dynamics at RHIC*, Brookhaven National Laboratory, March 3-6, 2003.

45. Ziwei Lin, *Ordering of elliptic flow at high p_T*, invited talk, Workshop on *Transverse Dynamics at RHIC*, Brookhaven National Laboratory, March 3-6, 2003.
46. D. Molnar, *Elliptic flow at high p_T from quark coalescence*, invited talk, Workshop on *Transverse Dynamics at RHIC*, Brookhaven National Laboratory, March 3-6, 2003.
47. G. Aarts, *Transport coefficients in hot field theory*, seminar, University of Virginia, Charlottesville (VA), March 19, 2003.
48. D. Molnar, *Quark coalescence - a possible solution to the RHIC elliptic flow puzzle?*, Nuclear Physics Seminar, Brookhaven National Laboratory, April 15, 2003.
49. D. Molnar, *Quark coalescence and elliptic flow at RHIC*, invited talk in the program *The First Three Years of Heavy-Ion Physics at RHIC*, Institute for Nuclear Theory, Seattle, Washington, April 28, 2003.
50. Ziwei Lin, *Quark coalescence and charm elliptic flow*, invited talk in the program *The First Three Years of Heavy-Ion Physics at RHIC*, Institute for Nuclear Theory, Seattle, Washington, April 2003.
51. U. Heinz, *The Quark-Gluon Plasma at RHIC*, seminar, University of Regensburg, Germany, May 16, 2003.
52. D. Molnar, *Quark coalescence: a possible solution to the RHIC v2 puzzle?*, Nuclear Theory Seminar, Columbia University, May 22, 2003.
53. U. Heinz, *Hydrodynamic behaviour and elliptic flow at RHIC*, Nuclear Theory Seminar, Columbia University, May 26, 2003.
54. D. Molnar, *The abyss between parton transport and hydrodynamics regarding elliptic flow at RHIC*, Nuclear Theory Seminar, Columbia University, May 2003.
55. Ziwei Lin, *Results at SPS Energies from AMPT*, invited talk at the International Workshop on *Transport Theories for Heavy Ion Reactions*, ECT*, Trento, Italy, May 2003.
56. Ziwei Lin, *Meson HBT at RHIC*, Nuclear Theory Seminar, Columbia University, June 2003.
57. G. Aarts, *Transport coefficients in hot field theory*, seminar, Los Alamos National Laboratory, June 6, 2003.
58. G. Aarts, *Quasi-fixed points in nonequilibrium field theory*, poster presented at *The Monte Carlo Method in the Physical Sciences: Celebrating the 50th Anniversary of the Metropolis Algorithm*, Los Alamos National Laboratory, June 9-11, 2003.
59. G. Aarts, *Issues in nonequilibrium field theory*, seminar, Los Alamos National Laboratory, June 12, 2003.
60. U. Heinz, *Concepts of Heavy Ion Physics*, three 75' lectures given at the *2nd Latin American School of High Energy Physics*, San Miguel Regla, Mexico, June 1-14, 2003.

61. D. Molnar, *Charm hadrons from parton coalescence - elliptic flow and spectra*, contributed talk, Conference on *Topics in Heavy Ion Collisions (HIC'03)*, McGill University, Montral, Canada, June 25-28, 2003.
62. U. Heinz, *The Quark-Gluon Plasma at RHIC*, Nuclear Theory Seminar, Brookhaven National Laboratory, July 8, 2003.
63. D. Molnar, *Parton coalescence and elliptic flow at RHIC*, Heavy Ion Forum seminar, CERN, July 22, 2003.
64. Ziwei Lin, *A Multiphase Transport Model for high energy heavy ion collisions*, seminar, the National Space Science and Technology Center at the University of Alabama at Huntsville, August 2003.
65. Ziwei Lin, *Quark coalescence for RHIC*, seminar, Peking University, China, September 2003.
66. Ziwei Lin, *Charm from quark coalescence*, seminar, Purdue University, West Lafayette, September 2003.
67. G. Aarts, *Non-equilibrium quantum fields and transport coefficients*, seminar, Ohio University, Athens, Ohio, Sep. 18, 2003.
68. G. Aarts, *Non-equilibrium quantum fields and transport coefficients*, seminar, Ohio State University, Sep. 26, 2003.
69. G. Aarts, *Non-equilibrium quantum fields and transport coefficients*, seminar, Kent State University, Oct. 3, 2003.
70. Ziwei Lin, *d+Au Collisions from a MultiPhase Transport Model*, contributed talk, Mid-West Theory Get-Together, Argonne National Laboratory, Argonne, Illinois, Oct 10-11, 2003.
71. D. Molnar, *Elliptic flow and parton coalescence at RHIC*, contributed talk, Mid-West Theory Get-Together, Argonne National Laboratory, Argonne, Illinois, Oct 10-11, 2003.
72. D. Molnar, *Elliptic flow at RHIC and parton coalescence*, Physics Seminar, Wayne State University, Oct 24, 2003.
73. U. Heinz, *Thermalization and quark-gluon plasma formation at RHIC: The evidence from hadron multiplicities, spectra, and HBT correlations*, invited talk, Workshop on *QCD, Confinement and Heavy-Ion Collisions*, 2003 Fall Meeting of the Division of Nuclear Physics of the APS (DNP03), Oct. 29, 2003.
74. D. Molnar, *Parton coalescence and elliptic flow*, contributed talk, 2003 Fall Meeting of the Division of Nuclear Physics of the APS (DNP03), Oct. 31, 2003.
75. U. Heinz, *Hydrodynamics, freeze-out, and blast wave fits to flow spectra*, introductory lecture, RIKEN/BNL Workshop on *Collective Flow and QGP Properties*, Brookhaven National Laboratory, Nov. 17-19, 2003.
76. D. Molnar, *What the parton cascade tells us about RHIC*, invited talk, RIKEN/BNL Workshop on *Collective Flow and QGP Properties*, Brookhaven National Laboratory, Nov. 17-19, 2003.

77. Ziwei Lin, *Strong and positive x-t correlation and its effect on* $R_{\rm out}/R_{\rm side}$, invited talk, RIKEN/BNL Workshop on *Collective Flow and QGP Properties*, Brookhaven National Laboratory, Nov. 17-19, 2003.

78. D. Molnar, *Quark coalescence and elliptic flow*, invited talk, Quark Recombination Mini-Workshop, Institute for Nuclear Theory, Seattle, Washington, December 8-9, 2003.

79. J. M. Martinez Resco, *Transport coefficients in field theory at high temperature*, seminar, UCM, Madrid, Spain, Dec. 17, 2003.

80. G. Aarts, *Quantum and classical fields far from equilibrium: an overview*, invited talk, International Workshop on *Field Theories Near Equilibrium*, Mumbai, India, Dec. 15-19, 2003.

81. G. Aarts, *Close to equilibrium: transport coefficients and spectral functions*, invited talk, International Workshop on *Field Theories Near Equilibrium*, Mumbai, India, Dec. 15-19, 2003.

82. D. Molnar, *Dissipation and momentum anisotropy in heavy-ion collisions at RHIC*, contributed talk, APS Ohio Section Spring Meeting (Athens, Ohio, April 17, 2004).

83. A. Kuhlman, *Computation of the HBT spatial correlation tensor using VEGAS*, contributed talk, APS Ohio Section Spring Meeting, (Athens, Ohio, April 17, 2004).

84. D. Molnar, *Meson vs. baryon elliptic flow from hadronization via quark coalescence*, contributed talk, International Workshop on "Creation and Flow of Baryons in Hadronic and Nuclear Collisions" (ECT*, Trento, Italy, May 3-7, 2004).

85. D. Molnar, *Parton coalescence and flow*, *invited talk*, "2004 RHIC/AGS Users Meeting", Brookhaven National Laboratory, May 11-15, 2004.

86. A. Kuhlman, *Computation of the HBT spatial correlation tensor using VEGAS*, student presentation, Nuclear Physics Summer School, Bar Harbor, Maine, 15 June 2004.

87. U. Heinz, *The Quark-Gluon Plasma at RHIC*, *invited talk*, Gordon Research Conference on "Nuclear Chemistry", Colby Sawyer College, New London, NH, June 13-18, 2004.

88. D. Molnar, *Parton coalescence - a unique window on the strucure of the partonic phase at RHIC*, *invited talk*, Gordon Research Conference on "Nuclear Chemistry", Colby Sawyer College, New London, NH, June 13-18, 2004.

89. D. Molnar, *Charm elliptic flow from parton coalescence dynamics*, contributed talk at "Hot Quarks 2004 Workshop" (Taos, NM, July 18-25, 2004).
This presentation won the **Klaus Kinder-Geiger Award** for the best talk given at the workshop.

90. D. Molnar, *Heavy flavor elliptic flow in nuclear collisions*, *invited talk*, VIIIth International Conference on "Strangeness in Quark Matter (SQM2004)" (Cape Town, South Africa, Sep. 15-20, 2004).

91. A.J. Kuhlman, *Why one should collide Uranium on Uranium at RHIC*, contributed

talk, APS Division of Nuclear Physics Fall Meeting (DNP04), Chicago, 30 Oct. 2004.

92. U. Heinz, *Properties of Hot Dense Matter from Colliding Nuclei*, invited talk, Workshop on "The Physics of Nuclei with 12 GeV Electrons", William T Jefferson National Laboratory, Nov. 1-5, 2004.
93. D. Molnar, *Momentum anisotropies and the quark-gluon plasma in heavy-ion collisions*, Nuclear Physics Seminar, Ohio University, Athens, OH, Oct. 12, 2004.
94. D. Molnar, *The strongly coupled plasma at RHIC and soon LHC*, Physics Seminar, Lawrence Livermore National Laboratory, Dec. 6, 2004.
95. D. Molnar, *Probing the strongly coupled plasma at RHIC and soon LHC*, Physics Seminar, SUNY Stony Brook, Jan. 27, 2005.
96. U. Heinz, *Ideal fluid dynamics at RHIC: successes and limitations*, invited talk, International Conference on "Contemporary Issues in Nuclear and Particle Physics (CINPP-05)" (Jadavpur University, Kolkata, 4-7 Feb. 2005).
97. D. Molnar, *Finding the quark-gluon plasma in the Little-Bang*, Physics Seminar, Lawrence Livermore National Laboratory, Feb. 7, 2005.
98. U. Heinz, *RHIC, The Little Bang and the Quark-Gluon Plasma*, Colloquium, Vanderbilt University, Feb. 17, 2005
99. D. Molnar, *New form of quark and gluon matter created at RHIC*, Physics Seminar, Purdue University, Mar. 6, 2005.
100. D. Molnar, *High-pT correlations from parton transport*, invited talk, RIKEN/BNL Workshop on "Jet Correlations", Brookhaven National Laboratory, March 10, 2005.
101. U. Heinz, *The Quark-Gluon Plasma at RHIC*, Seminar, Los Alamos National Laboratory, March 16, 2005.
102. A. J. Kuhlman, *Anisotropic flow and jet quenching in ultra-relativistic U+U collisions*, contributed talk, APS Ohio Section Spring Meeting, Dayton, OH, April 9, 2005.
103. E. Frodermann, *Towards photon intensity interferometry in relativistic heavy-ion collisions*, contributed talk, APS Ohio Section Spring Meeting, Dayton, OH, April 9, 2005.
104. A. J. Kuhlman, *Anisotropic flow and jet quenching in ultra-relativistic U+U collisions*, invited talk, "RHIC II Science" Workshop, Brookhaven National Laboratory, April 29, 2005.
105. U. Heinz, *Soft probes of relativistic heavy-ion collisions*, 2 invited lectures presented at the International School on "Quark-Gluon Plasma and Heavy-Ion Collisions: Past, Present and Future", Torino (Italy), May 11-17, 2005.
106. D. Molnar, *Collectivity from covariant transport*, invited lecture, "Berkeley RHIC School", Lawrence Berkeley National Laboratory, May 19-27, 2005.
107. U. Heinz, *RHIC, the Little Bang, and the Quark-Gluon Plasma*, Colloquium, INFN

and University of Florence, Florence, Italy, May 23, 2005.

108. U. Heinz, *Physics at RHIC*, *invited talk* at “Cortona 2005: Convegno Informale di Fisica Teorica”, Cortona, Italy, May 25, 2005.

109. U. Heinz, *RHIC Physics*, *2 invited lectures*, International Conference and School on “Frontiers in Contemporary Physics 2005”, Vanderbilt University, Nashville, TN, May 27, 2005.

110. D. Molnar, *Transport properties of the plasma at RHIC*, Physics Seminar, Los Alamos National Laboratory, June 8, 2005.

111. E. Frodermann, *Towards photon intensity interferometry in relativistic heavy-ion collisions*, student presentation at the “National Nuclear Physics Summer School 2005”, UC Berkeley, June 2005.

112. U. Heinz, *Dynamics of the Quark-Gluon Plasma Liquid*, *invited lecture*, International Summer School on “QCD Theory and RHIC Physics”, Huazhong Normal University, Wuhan, China, June 19-20, 2005.

113. D. Molnar, *Open issues at RHIC*, *invited talk*, “2005 RHIC/AGS Users Meeting”, Brookhaven National Laboratory, June 20, 2005.

114. D. Molnar, *Correlations from transport theory*, *invited talk*, “2005 RHIC/AGS Users Meeting”, Brookhaven National Laboratory, June 21, 2005.

115. D. Molnar, *The opaque plasma and charm*, *invited talk*, “2005 RHIC/AGS Users Meeting”, Brookhaven National Laboratory, June 21, 2005.

116. U. Heinz, *The promise of a U+U collision program at RHIC*, *invited talk*, CCAST Workshop on “QCD Theory and RHIC Physics”, Huazhong Normal University, Wuhan, China, June 21-24, 2005.

117. U. Heinz, *Heavy-ion collisions and the Quark-Gluon Plasma: Theoretical perspective*, *invited talk*, Gordon Research Conference on “Today’s Frontiers in Nuclear Physics”, Bates College, Lewiston, Maine, July 10-15, 2005.

118. A. J. Kuhlman, *Anisotropic flow and jet quenching in ultra-relativistic U+U collisions*, poster, Gordon Research Conference on “Today’s Frontiers in Nuclear Physics”, Bates College, Lewiston, Maine, July 10-15, 2005.

119. U. Heinz, *’RHIC serves the perfect fluid’: Hydrodynamic flow and other properties of the Quark-Gluon Plasma*, Nuclear Physics Seminar, Technische Universität München, Munich, Germany, July 27, 2005.

120. A. J. Kuhlman, *Using uranium-uranium collisions to probe the quark-gluon plasma*, Ice Cream Seminar, The Ohio State University, August 22, 2005.

121. M. Djordjevic, *Heavy Flavor Suppression Pattern at RHIC*, HIT Seminar, Lawrence Berkeley National Laboratory, Oct. 11, 2005.

122. M. Djordjevic, *Single Electron Puzzle at RHIC*, *invited talk*, “STAR HFT Workshop”, Lawrence Berkeley National Laboratory, Oct. 13-15, 2005.

123. M. Djordjevic, *Hard Probes at RHIC and LHC*, *invited presentation*, “ALICE-USA Collaboration Meeting”, Lawrence Berkeley National Laboratory, Oct. 15, 2005.

124. A. J. Kuhlman, *What can we learn from a U+U program at RHIC?*, "Midwest Critical Mass Workshop (MCM2005)", Toledo, Ohio, October 21-22, 2005.

125. Huichao Song, *Introduction to viscous hydrodynamics*, "Midwest Critical Mass Workshop (MCM2005)", Toledo, Ohio, October 21-22, 2005.

126. U. Heinz, *A plan for an integrated research and graduate education program in RHIC physics at midwestern universities*, "Midwest Critical Mass Workshop (MCM2005)", Toledo, Ohio, Oct. 21-22, 2005.

127. U. Heinz, *Is the quark-gluon plasma a 'perfect fluid'?*, Theoretical Physics Seminar, University of Kentucky, Lexington, KY, Oct. 31, 2005.

128. A. J. Kuhlman, *What can we learn from a U+U program at RHIC?*, Nuclear Physics Seminar, Brookhaven National Laboratory, Nov. 8, 2005.

129. M. Djordjevic, *Heavy Quark Energy Loss in Nucleus-Nucleus Collision*, *invited talk*, "Heavy Flavor Workshop", Brookhaven National Laboratory, Dec, 12-14, 2005.

130. U. Heinz, *Is the Quark-Gluon Plasma a "perfect fluid"?*, Nuclear Physics Seminar, BNL, Jan. 17, 2006.

131. U. Heinz, *Hydrodynamics at RHIC – successes, failures, and perspectives*, *invited talk*, RBRC Workshop "Strangeness in Collision", BNL, Feb. 15, 2006.

132. U. Heinz, *Euler vs. Navier-Stokes hydro of the sQGP at RHIC*, *invited talk*, "Columbia-Yale RHIC Physics Fest on Dissipation in the 'Perfect sQGP Fluid"', Columbia University, Feb. 24, 2006.

133. U. Heinz, *Hydrodynamics at RHIC – successes, failures, and perspectives*, *invited talk*, "STAR Collaboration Meeting", BNL, March 1, 2006.

134. E. Frodermann, *Elliptic flow of photons in heavy-ion collisions using hydrodynamics*, cointributed talk, Spring Meeting of the Ohio Section of the APS, Wayne State University, April 1, 2006.

135. A. J. Kuhlman, *Gluon saturation effects in ultra-relativistic U+U collisions*, contributed talk, Spring Meeting of the Ohio Section of the APS, Wayne State University, April 1, 2006.

136. M. Djordjevic,
Collisional and radiative energy loss mechanisms at RHIC,
seminar, Kent State University, April 11, 2006.

137. G. Kestin and U. Heinz, *The quark-gluon plasma to hadron phase transition in ultra-relativistic heavy-ion collisions*, poster presented at the "MAPS Undergraduate Research Forum" of the OSU College of Mathematical and Physical Sciences, OSU, May 10, 2006, and at the "Denman Undergraduate Research Forum", The Ohio State University, May 17, 2006.

138. U. Heinz, *Quark-Gluon Plasma Physics at RHIC and at the LHC*, *invited overview talk*, "Hadron Collider Physics Symposioum 2006", Duke University, May 25, 2006.

139. E. Frodermann, *Elliptic flow of thermal photons from hydrodynamics*, *invited talk*, 2006 RHIC/AGS Users Meeting, Workshop on "How perfect is this matter? – The

success and new challenges of hydrodynamics at RHIC", BNL, June 7, 2006.

140. U. Heinz, *Viscous relativistic hydrodynamics*, invited talk, 2006 RHIC/AGS Users Meeting, Workshop on "How perfect is this matter? – The success and new challenges of hydrodynamics at RHIC", BNL, June 7, 2006.

141. U. Heinz, *Mach cones from parton energy loss? A hydrodynamic study*, invited talk, 2006 RHIC/AGS Users Meeting, Workshop on "Interactions between hard probes and the bulk", BNL, June 7, 2006.

142. U. Heinz, *Elliptic flow of thermal photons and dileptons*, invited plenary talk, 2nd International Conference on "Hard and Electromagnetic Probes of High Energy Nuclear Collision (Hard Probes 2006)", Asilomar, June 9-16, 2006.

143. M. Djordjevic, *Zeroth order energy loss in a QCD medium: radiative vs. collisional*, invited plenary talk, 2nd International Conference on "Hard and Electromagnetic Probes of High Energy Nuclear Collision (Hard Probes 2006)", Asilomar, June 13, 2006.

144. U. Heinz, *Universal chemical freeze-out as a phase transition signature*, invited talk, International Workshop on "Heavy Ion Reactions at Ultrarelativistic Energies", ECT* Trento, Italy, June 26 - July 1, 2006.

145. M. Djordjevic, *Heavy flavor physics at RHIC*, invited talk ("mini-lecture") at the "STAR Collaboration Meeting", MIT, July 10, 2006.

146. M. Djordjevic, *Open questions in heavy flavor physics*, invited talk, RBRC Workshop "Future Prospects in QCD at High Energy", BNL, July 17-21, 2006.

147. U. Heinz, *Fast equilibration and almost perfect liquidity of the QGP at RHIC – fact or fiction?*, opening talk, INT Workshop "Non-Equilibrium Quark-Gluon Plasma", Institute for Nuclear Theory, University of Washington, Seattle, Sep. 25-29, 2006.

148. M. Djordjevic, *Heavy quark energy loss*, invited talk, INT Program "From RHIC to the LHC: Achievements and Opportunities", Institute for Nuclear Theory, University of Washington, Seattle, Oct. 23, 2006

149. U. Heinz, *Theoretical initiatives related to the RHIC program*, invited talk, QCD Town Meeting, Rutgers University, Jan. 12-14, 2007.

150. A. J. Kuhlman, *What can we learn from a U+U program at RHIC?* Nuclear Physics Seminar, Purdue University, West Lafayette, IN, 02/23/2007.

151. A. J. Kuhlman, *What can we learn from a U+U program at RHIC?* Nuclear Theory Seminar, Lawrence Berkeley National Laboratory, 03/15/2007.

152. U. Heinz, *Quarksuppe – die 'perfekte' Flüssigkeit?* Colloquium, Universität Tübingen, Tübingen, Germany, 04/16/2007.

153. M. Djordjevic, *Heavy quark energy loss in a strongly interacting quark-gluon plasma*, invited talk, APS April Meeting, Jacksonville, FL, April 14-17, 2007.

154. G. Kestin, *Elliptic flow in ultrarelativistic heavy-ion collisions*, poster, Mathematical and Physical Sciences Undergraduate Research Forum, Ohio State University, 05/09/2007.

155. U. Heinz, *PHOBOS @ RHIC and the perfect QGP fluid*, invited talk, Symposium in honor of R. Betts' 60th Birthday, University of Illinois, Chicago, IL, 05/10/2007.

156. G. Kestin, *Elliptic flow in ultrarelativistic heavy-ion collisions*, poster, Denman Undergraduate Research Forum, Ohio State University, 05/16/2007 (winner).

157. U. Heinz, *'RHIC Serves the Perfect Fluid' – fact or fiction? Successes and puzzles from 5 years of RHIC experiments*, invited opening talk, Conference on *Exotic States of Hot and Dense Matter and their Dual Description*, Perimeter Institute, Waterloo, Ontario, 05/22/2007.

158. U. Heinz, *Recent results on spectra and v_2 from (2+1)-d viscous hydrodynamics*, invited talk, CERN Theory Institute program *Heavy Ion Collisions at the LHC*, CERN, 06/05/2007.

159. M. Djordjevic, *Effect of dynamical QCD medium on radiative heavy quark energy loss*, invited talk, 2007 RHIC & AGS Annual Users' Meeting, BNL, Upton, NY, June 18-22, 2007.

160. E. Frodermann, *Elliptic flow of thermal photons and dileptons in heavy-ion collisions*, student seminar, Gordon Research Conference on Nuclear Physics, Salve Regina University, Newport, RI, July 15-20, 2007.

161. M. Djordjevic, *Heavy quark energy loss in a dynamical QCD medium*, invited talk, international conference on *Early Time Dynamics in Heavy Ion Collisions*, McGill University (Montreal, Canada), July 16-19, 2007.

162. H. Song, *Viscous hydrodynamics for relativistic heavy-ion collisions*, student seminar, 2007 National Nuclear Physics Summer School, Florida State University, Jacksonville, FL, July 8-21, 2007.

163. U. Heinz, *Viscous hydrodynamics for relativistic heavy-ion collisions*, invited talk, *Workshop on Particle Correlations and Femtoscopy (WPCF 2007)*, Santa Rosa, CA, Aug. 1-3, 2007.

164. U. Heinz, *From SPS to RHIC: Maurice and the CERN heavy-ion programme*, invited talk, *Maurice Jacob Memorial Meeting*, CERN, 09/11/2007.

165. E. Frodermann, *Elliptic flow of thermal photons and dileptons in heavy-ion collisions*, contributed talk, 2007 Midwest Theory Get-Together, Argonne National Laboratory, October 5-6, 2007.

166. H. Song, *Viscous hydrodynamics for relativistic heavy-ion collisions*, contributed talk, 2007 Midwest Theory Get-Together, Argonne National Laboratory, October 5-6, 2007.

167. U. Heinz, *Quark soup – the perfect liquid*, TH Theoretical Seminar, CERN, 10/10/2007.

168. M. Djordjevic, *Heavy quark energy loss in a finite size dynamical QCD medium*, contributed talk, 2007 Fall Meeting of the APS Division of Nuclear Physics (DNP2007), Newport News, Oct. 10-13, 2007.

169. G. Kestin, *The quark-hadron phase transition in ultrarelativistic heavy-ion collisions*, contributed talk, 2007 Fall Meeting of the APS Division of Nuclear Physics (DNP2007), Newport News, Oct. 10-13, 2007.

170. G. Kestin, *Elliptic flow in ultrarelativistic heavy-ion collisions*, CEU poster, 2007 Fall Meeting of the APS Division of Nuclear Physics (DNP2007), Newport News, Oct. 10-13, 2007.

171. U. Heinz, *Elliptic flow from a transversally thermalized fireball*, seminar, CERN Heavy Ion Forum, CERN, 11/06/2007.

172. M. Djordjevic, *Heavy quark energy loss in a dynamical QCD medium*, Nuclear Physics & RIKEN Theory Seminar, Brookhaven National Laboratory, 11/16/2007.

173. M. Djordjevic, *Effect of dynamical QCD medium on radiative heavy quark energy loss*, Nuclear Physics Seminar, Iowa State University, Ames, IA, 11/27/2007.

174. M. Djordjevic, *Heavy quark energy loss in a dynamical QCD medium*, Nuclear Physics Seminar, Los Alamos National Laboratory, 12/10/2007.

175. U. Heinz, *Quarksuppe – die 'perfekte' Flüssigkeit?*, Colloquium, Universität Regensburg, Regensburg, Germany, 01/07/2008.

176. M. Djordjevic, *Heavy quark energy loss in a dynamical QCD medium*, Physics Seminar, Arkansas State University, 01/10/2008.

177. Guangyou Qin, *Jet energy loss and high-p_T photons in hot QGP*, Nuclear Physics Seminar, The Ohio State University, Columbus, OH, 01/15/2009.

178. H. Song, *Extracting the QGP viscosity from RHIC data - a status report from viscous hydrodynamics*, Nuclear Physics Lunch Seminar, LBNL, 01/21/2009.

179. U. Heinz, *Viscous hydrodynamics for heavy-ion collisions*, invited talk, *25$^{\text{th}}$ Winter Workshop on Nuclear Dynamics*, Big Sky, Montana, 02/03/2009.

180. A. Majumder, *Hard jets as probes of dense matter: SCET, Glauber gluons and factorization*, invited talk, SCET workshop 2009, MIT, 03/25/2009.

181. U. Heinz, *Viscous hydrodynamics and QGP viscosity*, invited talk, STAR Collaboration Meeting, BNL, 03/26/2009.

182. U. Heinz, *Hydrodynamics and transport properties of the Quark-Gluon Plasma*, invited student lecture, *Quark Matter 2009* Conference, Knoxville, TN, 03/29/2009.

183. H. Song, *Extracting the QGP viscosity from RHIC data – a status report from viscous hydrodynamics*, Nuclear Physics Seminar, LANL, 05/05/2009.

184. A. Majumder, *Jets and Jet correlations: where we are and where we want to be*, Nuclear Seminar, Wayne State Univ., Detroit, MI, 05/08/2009.

185. J. S. Moreland, *Shear viscosity of the quark-gluon plasma*, poster, *2009 Denman Undergraduate Research Forum*, The Ohio State University, 05/14/2009 (winner)

186. A. Majumder, *Jet quenching across all energies*, invited parallel talk, CIPANP 2009, San Diego, CA, 05/06/2009.

187. Guang-You Qin, *Direct Photons – theoretical overview*, invited talk, Workshop 9 on *Early Time Measurement*, 2009 RHIC & AGS Annual Users' Meeting, BNL, 06/02/2009.

188. Guang-You Qin, *Jet Quenching: probing arbitrary media perturbatively*, invited talk, *TECHQM Collaboration Meeting*, CERN, 07/08/2009.

189. U. Heinz, *Azimuthally sensitive photon HBT interferometry – a difficult, but very interesting measurement*, seminar, *Heavy Ion Forum*, CERN, 07/15/2009.

190. H. Song, *Viscous hydrodynamics with shear and bulk viscosities*, invited talk, APS DPF meeting, Detroit, MI, Jul. 27 - 31, 2009.

191. H. Song, *Extracting the QGP viscosity from RHIC data – a status report from viscous hydrodynamics*, TNT Colloquium, Duke University, 09/01/2009.

192. U. Heinz, *Hydrodynamic modeling of heavy ion collisions – status and open issues*, invited opening talk, Workshop on *Flow and Dissipation in Ultrarelativistic Heavy Ion Collisions*, ECT*, Trento, Italy, 09/14/2009.

193. H. Song, *Viscous hydrodynamics: interplay of shear and bulk viscosity*, invited talk, Workshop on *Flow and Dissipation in Ultrarelativistic Heavy Ion Collisions*, ECT*, Trento, Italy, 09/17/2009.

194. U. Heinz, *RHIC & LHC and the Quark-Gluon Plasma – from discovery to quantitative characterization*, TH Colloqium, CERN, 10/14/2009.

195. U. Heinz, *Azimuthally sensitive photon HBT interferometry at RHIC*, *V Workshop on Particle Correlations and Femtoscopy (WPCF 2009)*, CERN, 10/15/2009.

196. A. Majumder, *Jet quenching in the higher twist method*, seminar, Duke University, Durham, NC, 10/15/2009.

197. A. Majumder, *A pQCD based approach to jet modification in dense matter*, Nuclear Physics Seminar, The Ohio State University, Columbus, OH, 10/22/2009.

198. A. Majumder, *A factorization-based approach to jet modification in an arbitrary medium*, Hadronic Physics Seminar, McGill University, 12/01/2009

199. A. Song, *QGP viscosity from RHIC data – a hydrodynamic perspective*, invited talk, Joint CATHIE/TECHQM Workshop, BNL, Dec. 14-18, 2009.

200. A. Majumder, *Hydrodynamic response to a weakly coupled fast parton*, invited talk, Joint CATHIE/TECHQM Workshop, BNL, Dec. 14-18, 2009.

201. A. Majumder, *Energy loss in cold nuclear matter – a jet quenching lab*, invited talk, Joint CATHIE/TECHQM Workshop, BNL, Dec. 14-18, 2009.

202. H. Song, *QGP viscosity from RHIC data – a hydrodynamic perspective*, invited overview talk at the *Joint CATHIE/TECHQM Workshop*, BNL, Dec. 14-18, 2009.

203. A. Majumder, *Energy loss in cold nuclear matter – a jet quenching lab*, invited talk, *Joint CATHIE/TECHQM Workshop*, BNL, Dec. 14-18, 2009.

204. A. Majumder, *Hydrodynamic response to a weakly coupled fast parton*, contributed talk, *Joint CATHIE/TECHQM Workshop*, BNL, Dec. 14-18, 2009.

205. A. Majumder, *Using factorization to construct a consistent theory of jet-modification in an arbitrary medium*, Nuclear Seminar, Iowa State University, Jan. 28, 2010.

206. H. Song, *Extracting QGP shear viscosity from RHIC data – current uncertainties from viscous hydrodynamics*, HIT seminar, Lawrence Berkeley National Laboratory, Feb. 2, 2010.

207. U. Heinz, it Quark soup – the perfect liquid?, Colloquium, Physics Department,

Texas A&M University, Feb. 25, 2010.

208. U. Heinz, *Viscous hydrodynamics for relativistic fluids and heavy-ion collisions*, invited talk at the international workshop *Dense Matter 2010*, Stellenbosch, South Africa, April 6-9, 2010.

209. A. Majumder, *Higher twist energy loss, in-medium evolution and the EIC, or: What do nuclei look like to a microscopic colored probe*, invited talk, Workshop on *Nuclear Chromodynamics at a Future EIC*, Argonne National Lab, Apr. 8, 2010.

210. U. Heinz, *Hydrodynamics at RHIC (ideal and viscous): Where it works, where and how it breaks down, and why*, invited talk at the Workshop on *Critical Examination of RHIC Paradigms*, UT Austin, TX, April 14-17, 2010.

211. U. Heinz, *Hydrodynamics at RHIC (ideal and viscous): Where it works, where and how it breaks down, and why*, invited lecture at the *Berkeley School on Collective Dynamics in High-Energy Collisions*, LBNL, June 7-11, 2010.

212. J. S. Moreland, *Viscosity from elliptic flow – study of fKLN and Glauber initializations*, seminar, J. W.-Goethe Universität, Frankfurt, Germany, 6/7/2010.

213. A. Majumder, *Alternate mechanisms of charge separation in heavy-ion collisions*, invited talk, Workshop on *Local Strong Parity Violation*, 2010 RHIC & AGS Annual Users' Meeting, BNL, 6/7/2010.

214. W. A. Horowitz, *Theory update on energy loss*, invited talk, 2010 RHIC & AGS Users' Meeting, BNL, 6/8/2010.

215. Guang-You Qin, *Gamma-jet correlations*, invited talk, 2010 RHIC & AGS Annual Users' Meeting, BNL, June 7-11, 2010.

216. H. Song, *Results from viscous hydrodynamics coupled to UrQMD*, invited talk, INT Workshop on *Quantifying the Properties of Hot QCD Matter*, Institute for Nuclear Theory, University of Washington, 6/14/2010.

217. A. Majumder, *The factorized approach to jet modification*, invited talk, Symposium on *Jet and Electromagnetic Tomography of Dense Matter*, LBNL, 6/18/2010.

218. H. Song, *Viscous hydrodynamics + UrQMD – medium for JET*, report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

219. W. A. Horowitz, *Theory comparisons*, report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

220. Guang-You Qin, *Fluctuating initial conditions from Glauber and CGC models*, report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

221. A. Majumder, *The Higher Twist approach*, report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

222. A. Majumder, *Heavy-flavor suppression in Higher Twist*, report, 1st JET Collaboration Meeting, LBNL, 6/19/2010.

223. H. Song, *Parton shower simulation in the Higher Twist formalism*, report, 1st JET Collaboration Meeting, LBNL, 6/20/2010.

224. W. A. Horowitz, *RHIC challenges and LHC Outlook*, invited talk, INT Workshop

on *Quantifying the Properties of Hot QCD Matter*, Institute for Nuclear Theory, University of Washington, 6/21/2010.

225. A. Majumder, *The Higher twist approach to jet modification*, invited talk, INT Workshop on *Quantifying the properties of Hot QCD Matter*, Institute for Nuclear Theory, University of Washington, 6/21/2010.
226. Guang-You Qin, *Perturbative description of jet-medium interaction*, invited talk, INT Workshop on *Quantifying the properties of Hot QCD Matter*, Institute for Nuclear Theory, University of Washington, 6/24/2010.
227. J. S. Moreland, *Statistical fluctuations and correlations in hadronic equilibrium systems*, seminar, J. W.-Goethe Universität, Frankfurt, Germany, 7/12/2010.
228. W. A. Horowitz, *Energy loss mechanisms and jet physics*, invited talk, PHENIX Collaboration Meeting, Iowa State University, 7/12/2010.
229. W. A. Horowitz, *Heavy ion physics at RHIC and LHC*, seminar, University of Tennessee, Knoxville, TN, 7/16/2010.
230. Guang-You Qin, *Interactions between jets and the hot, dense medium*, hadronic physics seminar, McGill University, 7/27/2010.
231. W. A. Horowitz, *Heavy ion physics and Electron Ion Colliders*, Electron-Ion Collider Collaboration Meeting, Catholic University of America, 7/29/2010.
232. A. Majumder, *A factorized approach to hard jet modification in dense matter*, invited talk at the International Workshop on *High Energy Strong Interactions (HESI 2010)*, Yukawa Institute, Kyoto University, Kyoto, Japan, 8/2/2010.
233. U. Heinz, *The QCD brick problem*, invited talk, International Workshop on *Jets in Proton-Proton and Heavy-Ion Collisions*, Prague, Aug. 12-14, 2010.

C. Special volume edited during the period 07/15/2001-08/14/2010:

1. L. Alvarez-Gaume and U. Heinz (eds.),
Memories of Maurice Jacob (1933-2007),
Proceedings of the Maurice Jacob Memorial Meeting (CERN, 11 September 2007),
Phys. Scr. 78, No 2 (30 July 2008) 020301 (6 articles and a preface, 26 pages total)

D. Workshop organization during the period 07/15/2001-08/14/2010:

1. U. Heinz, M. Lisa, S. Panitkin, ans S. Pratt (organizers), RHIC Winter Workshop 2002 on *Correlations and Fluctuations in Heavy-Ion Collisions at RHIC (RWW02)*, Institute for Nuclear Theory, January 4-6, 2002.
2. U. Heinz and K. Zalewski (convenors), *International Workshop on Multiparticle Dynamics 2003 (ISMD 2003)*, session on *HBT Correlations*, Krakow, Poland, Sep. 5-11, 2003.
3. S. Bass, S. Esumi, U. Heinz, P. Kolb, E. Shuryak and Nu Xu (organizers), RIKEN/BNL Workshop on *Collective Flow and QGP Properties*, Brookhaven National Laboratory, Nov. 17-19, 2003.
4. U. Heinz and R. J. Furnstahl (organizers), Ohio Center for Theoretical Science

Workshop *From Nano to Tera: Effective Field Theories in Physics*, Ohio State University, June 13-17, 2005.

5. U. Heinz, Y. Kovchegov, J. Jalilian-Marian, L. McLerran (organizers), *From RHIC to LHC: Achievements and Opportunities*, INT Program INT06-03, Sep. 25 - Dec. 8, 2006.
6. U. Heinz (convenor/discussion leader), *2007 Gordon Research Conference on Nuclear Physics*, session on *Quarks, Gluons, and Spin*, Salve Regina University, Newport, RI, July 15-20, 2007.
7. U. Heinz, H. Specht, and U. A. Wiedemann (organizers), *Electromagnetic Radiation in Nuclear Collisions*, CERN TH Workshop, CERN, Dec. 17-19, 2007.
8. B. Cole, U. Heinz, P. Jacobs, B. Müller, J. Nagle, P. Petreczky, X.-N. Wang, and U. Wiedemann (organizers), *Theory meets Experiment: Theory-Experiment Collaboration for Hot QCD Matter (TECHQM)*, inaugural workshop of the TECHQM Collaboration, Brookhaven National Laboratory, May 6-7, 2008.
9. B. Cole, U. Heinz, P. Jacobs, B. Müller, J. Nagle, X.-N. Wang, and U. Wiedemann (organizers), *Second TECHQM Workshop*, Lawrence Berkeley National Laboratory, Dec. 15-17, 2008.
10. B. Cole, U. Heinz, P. Jacobs, B. Müller, J. Nagle, X.-N. Wang, and U. Wiedemann (organizers), *Third TECHQM Workshop*, CERN, July 6-10, 2009.
11. Kevin Dusling, Ulrich Heinz, Peter Jacobs, Dima Kharzeev, Berndt Müller, Jamie Nagle, Peter Petreczky, Raju Venugopalan, and Urs Wiedemann (organizers), *Joint CATHIE/TECHQM Workshop*, Brookhaven National Laboratory, Dec. 14-18, 2009.
12. Brian Cole, Ulrich Heinz, Peter Jacobs, Yuri Kovchegov, Berndt Müller and Jamie Nagle (organizers), *Quantifying the Properties of Hot QCD Matter*, INT Program INT-10-2a, May 24 - July 16, 2010.

E. Theses completed during the period 07/15/2001-08/14/2010:

1. Peter Kolb,*Early thermalization and hydrodynamic expansion in nuclear collisions at RHIC*, **PhD Thesis**, University of Regensburg & The Ohio State University, March 2002.
2. Amy Hummel, *Hanbury Brown-Twiss interferometry for deformed sources*, **M.Sc. Thesis**, The Ohio State University, March 2003.
3. Anthony J. Kuhlman, *A VEGAS Monte Carlo code for computing HBT radii and their dependence on the azimuthal emission angle for model sources*, **M.Sc. Thesis**, The Ohio State University, August 2004.
4. Anthony J. Kuhlman, *The beginning and end of relativistic heavy-ion collisions: Using uranium beams and Bose-Einstein correlations as probes of the collision fireball*, **PhD Thesis**, The Ohio State University, August 2004.
5. Evan Frodermann, *A view of heavy-ion collision dynamics and geometry through electromagnetic signatures*, **PhD thesis**, The Ohio State University, August 2008.

6. Michael Wong, *Evolution of anisotropies in asymmetric heavy-ion collisions*, undergraduate **Senior Honors Thesis**, The Ohio State University, May 2009.
7. Huichao Song: *Causal viscous hydrodynamics for heavy-ion collisions*, **PhD thesis**, The Ohio State University, August 2009.
   This thesis won the **2011 Dissertation Award in Nuclear Physics** of the American Physical Society.

F. Former postdocs funded through the grant who are now faculty members elsewhere:

Gert Aarts: left OSU in 2004 for a position as Reader at Swansea University, Wales, United KIngdom. Present position there: Professor of Physics.

Denes Molnar: left OSU in 2005 for a tenure track position as Assistant Professor at Purdue University. Present position there: Associate Professor of Physics.

Zi-Wei Lin: presently Assistant Professor of Physics and Health Sciences, East Carolina University, Greenville, North Carolina.

Magdalena Djordjevic: left OSU in 2008 for a tenure track position as Assistant Professor at Arkansas State University. Present position: Research Associate Professor at the Institute of Physics, University of Belgrade, Serbia.

William A. Horowitz: left OSU in 2010 for a tenure track position as Lecturer in Physics at the Uiversity of Cape Town.

Abhijit Majumder: Left OSU in 2011 for a tenure track position as Associate Professor of Physics at Wayne State University, Detroit, MI.

Huichao Song: left OSU in Sep. 2012 for a tenure track position as Research Assistant Professor at Beijing University, Beijing, China.