Questions Emerging from Discussions at the INT Program
Quantifying the Properties of Hot QCD Matter

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A eight-week program entitled "Quantifying the Properties of Hot QCD Matter" was held at the Institute for Nuclear Theory in May-July 2010 (Program 10-2a). The workshop website, including agenda and talks, can be found at: *http://www.int.washington.edu/PROGRAMS/10-2a/*. Each week was devoted to discussion in a specific area, as follows: (1) New results from LHC and RHIC; (2) Initial conditions, small x; (3) Viscous hydrodynamics I; (4) Viscous hydrodynamics II; (5) Jet quenching; (7) Heavy flavor and quarkonium; (8) Electromagnetic probes. This document is a list of questions and challenges assembled by the organizers of the program, compiled at the end of each week. No attempt has been made to unify the presentation of topics or to resolve conflicting statements, and only minor editing has been applied. This document should be regarded as a snapshot of the field in summer 2010, as seen through the biased lenses of the organizers.

I. WEEK ONE: NEW RESULTS FROM LHC AND RHIC

- *p+p collisions:* Is it possible to put rigorous upper limits on collective flow (elliptic, triangular, etc.) in p+p collisions? Can one formulate a model independent strategy for both RHIC and LHC energies? Are very high multiplicity p+p collisions dominated by "jetty" contributions?

- *p+p and A+A event generators:* Existing Monte-Carlo event generators such as PYTHIA that have been tuned to e^+e^- and pp collisions at lower energies fail to reproduce basic global characteristics of pp collisions at $\sqrt{s} = 7\,\text{GeV}$ at the LHC. Can they be retuned to simultaneously reproduce RHIC and LHC data for pp, or are they missing essential physics ingredients that begin to play a role at LHC energies? Can they be retuned in order to be used for a meaningful analysis of upcoming LHC Pb+Pb data for nuclear effects in the initial state and collective effects in the final state?

- *Pion spectra in p+p:* The π^0 yields measured by PHENIX and the $\pi^\pm$ yields measured by STAR differ by more than 50% in the momentum range $8 - 10$ GeV/c. Is this difference real or an experimental artifact? Do state-of-the-art pQCD calculations yield a comparable difference? How can the difference be confirmed or ruled out?

- *Data comparison across experiments:* The ongoing efforts in the heavy ion physics community to extract quantitative information about QCD matter properties from the data engenders the need for a comprehensive comparison of measurements from different experiments with statistical and systematic uncertainties, as well as a clear explanation of their meaning. It would also be desirable to have the data sets available in a common format in an open data base (not as randomly formatted *ascii* files on the collaboration web pages).

- *Strong coupling:* Is a definitive experimental check whether the matter created at RHIC is a strongly coupled QGP or a quasi-particle QGP possible?

- *Perfect fluid:* Is there a significant change in the density-density correlation function between the hadron "gas" near, but below T_c and the QGP above T_c? Is the reason why the QGP has such a small kinematic viscosity that it is a "supercritical" fluid? [Supercritical fluids are fluids in the domain of the phase diagram beyond, i.e. at higher temperature and pressure than, the critical point. If the phase diagram of QCD matter exhibits a first-order transition line that ends in a critical point, QCD matter at $T \geq T_c$ and $\mu \approx 0$ lies in this supercritical region.]

- *Hydrodynamics – theory data comparison:* Can one identify a set of common ingredients that all viscous hydrodynamics calculations must share in order to allow systematic comparison with experimental data and a reliable description (i.e. with quoted uncertainties) of the QCD fluid properties?

- *Hadronic freeze-out:* Does a comparison with Cooper-Frye freeze-out make sense at all, or are hybrid calculations with hadronic Boltzmann freeze-out absolutely required? If calculations are made with Cooper-Frye freeze-out, does the freeze-out temperature need to be adjusted for different centrality bins?

- *Knudsen number fits:* The Knudsen number fits with parametrized functional form constitutes a very simple averaging over many aspects of the expansion. Can such fits give any quantitatively reliable results about the transport properties of the QCD matter? Can the "average" shear viscosity or the "average" speed of sound deduced from such fits be sufficiently well defined to yield useful information?

- RHIC – SPS comparison: It would be interesting to revisit the lower SPS energy hydro comparisons

with state-of-the-art updates on participant eccentricities and new transport tools. Given that STAR and PHENIX will are making new comprehensive measurements spanning from RHIC to SPS such an effort would be very timely.

- *v_2 fluctuations:* Experimentalists conclude that the initial state eccentricity fluctuations exhaust the elliptic flow fluctuations seen in the final state and that there is not much room for additional dynamical fluctuations generated at later times. Does this observation rule out a first-order phase transition or cavitation?

- *Triangular flow:* Are di-hadron correlation analyses that do not include a triangular flow term in the background model now obsolete? Are there any conclusions from previous analyses that did not consider triangular flow, which have become part of the common "folklore" but must now be considered wrong?

- *Ridge-like correlations:* What do realistic dynamical model calculations predict for the effect of initial event-by-event shape fluctuations on the angular and rapidity correlations between finally observed hadrons? PHOBOS has measured a large third-order flow coefficient $v_3/v_2 \sim 0.2 - 0.3$, claimed to be consistent with hydrodynamic-like evolution of initial-state tringularity fluctuations. When all initial shape fluctuation effects on the final two- and three-particle correlations are accounted for, do any "Mach cone" signatures survive in the experimental data? Can the theoretical uncertainties in the spectrum and strength of event-by-event fluctuations in the shape and magnitude of the initial energy density distribution be quantified? Can theoretical tools be developed that allow to distinguish final-state event fluctuations created by initial state fluctuations from those generated during the dynamical evolution between initial and final state (e.g. by passage through a first-order phase transition or by cavitation of a rapidly expanding viscous fluid)?

- *Critical fluctuations:* Critical fluctuations due to a critical point at the end of a line of first order phase transitions at large net baryon density are difficult to measure, not least because in the experiment one must hit the right initial conditions that allow the expanding fireball to pass in sufficient proximity of the critical point as it evolves through the QCD phase diagram. Wouldn't it be significantly easier to establish the existence of a critical end point by first demonstrating that at large net baryon density (low collision energies) the phase transition is indeed of first order, by measuring non-critical fluctuations caused by the thermodynamic discontinuities across such a transition? Can the magnitude and spectrum of such non-critical fluctuations (as caused by a first-order transition) be calculated? Can the absence of such fluctuations be established with sufficient reliability to exclude a first-order phase transition at RHIC energies?

- *Jets:* How would one go about showing that perturbative QCD factorization into initial-state parton distributions, hard scattering, and final-state fragmentation works for jet production in nuclear collisions in kinematic regions where jet quenching is important? Can factorization be demonstrated by comparison with data? Can we experimentally distinguish between perturbative jets in a strongly coupled medium and nonperturbative, strongly coupled jets in a strongly coupled medium (e.g., one in which the $q \rightarrow qg$ splitting function no longer peaks at small gluon-z)?

- *Jets:* Is it true that jet quenching measures the medium parameter $\hat{q}$ and nothing else? If jets can yield more information about the medium, which information would this be, and how would one go about extracting it from the data? If no general answer can be given, is an answer possible under additional assumptions? If so, can these be justified or experimentally confirmed?

- *Spontaneous breaking of P/CP:* Are the fluctuation signatures observed by STAR compatible with predictions based on the *chiral magnetic effect*? Can these predictions be made quantitative? Are there alternate explanations of the experimental data? Can one find ways to experimentally distinguish between these alternate explanations of the STAR data and the chiral magnetic effect?

- *Thermal photons:* Hydro simulations reproducing the hadron and photon spectra measured in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions require temperatures in the center of the fireball in excess of 300 MeV. Can it be shown that contributions from matter with $T > 200, 250, 300$ MeV are essential for bringing the thermal photon spectrum in agreement with the spectra measured by PHENIX?

- *First LHC p+p data:* What has been learned from the initial LHC measurements of charged particle multiplicity and pT distributions? What, if any, physics discrimination does the success or failure of the various MC "tunes" provide?

- *Future RHIC physics program:* What are the essential measurements at RHIC that cannot be carried out by STAR and PHENIX with their currently planned upgrades?

II. WEEK TWO: INITIAL CONDITIONS, LOW X

- *Initial Conditions:* Color Glass Condensate (CGC)

is a formalism which may describe the initial state dynamics in heavy ion collisions at RHIC. CGC degrees of freedom are strong (classical) gluon fields, dipole scattering amplitude, along with higher order correlators of Wilson lines. Can one construct a connection between the CGC approach and the transverse momentum distributions (TMD) formalism developed in recent years? Is such connection necessary to develop both subfields (or one of the subfields) further?

- *Testing CGC with Two-Particle Correlations in d+Au:* The PHENIX and STAR data on suppression of back-to-back hadron correlations in d+Au collisions (as compared to p+p) when both particles are in the forward rapidity direction is in rough qualitative agreement with CGC predictions. However, can one perform a more quantitative comparison of the data and CGC theory? Namely, constructing two-particle correlations in CGC numerically following existing theoretical predictions appears to be a daunting task. Can one make controllable realistic approximations of the exact CGC formula to generate phenomenological predictions? (*Note:* It is possible that some progress on the issue has been made recently.)

- *Ridge and Other Correlations:* Due to long rapidity extend of the ridge it seems natural to assume that ridge correlations originate in the initial state. This is the causality argument. What is the nature of these correlations? There are three possible explanations: (i) CGC classical fields have long-range rapidity correlations; (ii) non-perturbative QCD effects such as QCD strings also introduce long-range rapidity correlations; (iii) initial-state radiation in perturbative QCD scattering processes can have a wide rapidity distribution. However, the ridge is both long-range in rapidity and short-range in azimuth, so each of these scenarios must be supplemented with a mechanism that induces azimuthal focussing. Are there unique experimental tests which could distinguish the underlying mechanisms?

- *Strongly-Coupled Initial Conditions:* If the medium created at RHIC is strongly-coupled, it is probable that strongly-coupled dynamics plays an important role in thermalization. Can we understand thermalization in a purely strongly-coupled framework, i.e., using anti-de Sitter space/conformal field theory (AdS/CFT) correspondence? Since the early stages of the collision are likely to be weakly-coupled and described by either CGC or pQCD, how do we describe the transition from weak to strong coupling at later times? Is it even possible to construct such matching uniquely?

III. WEEK THREE: VISCOUS HYDRO I

- *Mach cones:* Hydrodynamic calculations that evolve event-by-event fluctuating initial energy density profiles have shown that string-like initial state-fluctuations can generate (by hydrodynamic "shadowing") ridge-like structures in two-particle $\Delta\phi - \Delta\eta$ correlations, with an angle $\Delta\phi \approx 120°$ between the "near-side" and each of two "away-side" peaks in the angular correlation function. Furthermore, they also show the characteristic 3-particle angular correlations measured by STAR and have been cited as evidence for a Mach cone structure in the away-side hemisphere. Can systematic studies of the effect (e.g. its dependence on the sound speed and viscosity of the fluid and on the collision centrality) help to further solidify this "hydrodynamic shadowing" scenario? Can one find other experimentally accessible correlation measures that allow to unambiguously distinguish Mach cone structures related to parton energy loss from such shape-fluctuation-driven hydrodynamic correlations?

- *Triggered ridge or Mach cone:* The most detailed correlation measurements, in which complex structures in the recoil distribution have been identified, have until recently been carried out at RHIC with triggers in the range $p_T \sim 3 - 4$ GeV/c, where the mechanisms underlying hadron production in nuclear collisions are unclear. Recent measurements with higher p_T triggers do not exhibit such structures. Does this systematic behavior argue against jet energy loss and subsequent medium response as the origin of such structures?

- *Initial state shape fluctuations:* Recent experimental and theoretical studies have shown that event-by-event fluctuations in the shape and magnitude of the initial density profile of the collision fireball have a strong influence on final-state two- and three-particle correlations, and that a quantitative understanding of their dynamical evolution from initial to final state is crucial for any program that attempts to quantitatively extract transport properties of the fireball medium (e.g. its viscosity) from experimental data. The theoretical description of the dynamical evolution of strongly inhomogeneous ("lumpy") initial conditions is technically demanding and presently not under full control. To what extent is it possible to replace the average over many fluctuating events of the final state obtained by evolving each event individually ("$\langle IC + \text{evolution} \rangle$") by the final state resulting from a single evolution of a smooth initial condition obtained by averaging over many fluctuating initial states ("$\langle IC \rangle + \text{evolution}$")? Which observables can be reliably calculated by the (much easier) second approach, for which observables can the (more demanding) first approach not be circumvented?

How does the averaging procedure $\langle IC \rangle$ over initial conditions have to be done for the simpler second approach to be phenomenologically useful?

- *Collective hydrodynamic response vs. parton energy loss:* At low transverse momenta the elliptic flow v_2 is believed to reflect the collective hydrodynamic response of hadron momentum distributions to anisotropic pressure gradients in the initial state of the medium, whereas at high transverse momentum it is expected to result from anisotropic parton energy loss in a spatially deformed medium. How can one experimentally explore the transition between these two mechanisms? Can the azimuthal ϕ-dependence of the "rise and fall" of $R_{AA}(p_T)$ (or, equivalently, of the ratio between AA and pp collisions of the p_T-spectra) of identified hadrons shed light on the answer to this question?

- *2nd order viscous hydrodynamics vs. kinetic theory:* Second-order (Israel-Stewart) hydrodynamics breaks down when the the viscous corrections $\sim \frac{\eta}{sT}\frac{1}{\tau}$ become too large – in heavy-ion collisions at RHIC and LHC this limits the shear viscosity $\eta/s < (3-4) \times \frac{1}{4\pi}$ at early times $\tau \sim 1\,\mathrm{fm}/c$. Boltzmann kinetic theory, on the other hand, fails for strongly coupled systems, i.e. at small values of $\eta/s < 3$ where it gives spetral functions for the transport coefficients that are incompatible with 2nd order viscous hydrodynamics. Does this mean that the validity of Israel-Stewart hydrodynamics at early times in RHIC collisions cannot be tested by comparing it with Boltzmann kinetic theory (i.e. parton cascades)? If the answer is "yes", what other options exist for assessing the validity and accuracy of 2nd order viscous hydrodynamics at early times?

- *v_4 and v_4/v_2^2 scaling:* Empirically, the ratio v_4/v_2^2 appears to be constant in RHIC collisions, independent of collision centrality, particle species and transverse momentum. Hydrodynamics with sudden Cooper-Frye freeze-out appears to be unable to explain this scaling: for ideal hydrodynamics, the scaling works only for a judicious choice of the decoupling temperature, and then only for $p_T > 500\,\mathrm{MeV}$, and adding viscous corrections destroys the scaling for all choices of T_{dec}. What is the origin of the experimentally observed scaling? It seems improbable that replacing the idealized Cooper-Frye procedure by a more realistic freeze-out can restore the scaling. Since it refers to a ratio between two typically very small numbers, it is very sensitive to all kinds of scale-breaking effects, which makes the observed scaling surprising. Is the observed scaling experimentally robust, i.e. can artificial scaling effects reflecting details of the experimental analysis procedure be convincingly excluded?

IV. WEEK FOUR: VISCOUS HYDRO II

- *Initial state fluctuations:* Several effects contribute to event-by-event fluctuations in the initial density distribution of a heavy-ion collision fireball: (1) The fluctuating distribution of nucleons within the colliding nuclei results in fluctuations of the positions of the wounded nucleons and the binary collision points, resulting in fluctuations of the shape and orientation of what one might call the nuclear overlap zone; (2) in the Glauber model, both the *amount* of energy per wounded nucleon or nucleon-nucleon collision that is deposited near the transverse positions of the nucleon collision points, and the *spatial width* of the region around these points into which this energy is deposited, fluctuate from one nucleon-nucleon collision event to the next; analogously, in the case of the CGC model, the number of gluons produced in a transverse region (cell) characterized by a given value Q_{sat} of the saturation momentum fluctuates from event to event; (3) finally, the width of the energy deposition region per nucleon-nucleon collision must be finite, due to quantum mechanical uncertainty. So far, model simulations for the event-by-event fluctuations in the initial entropy or energy density distribution take into account only the shape and orientation fluctuations of type (1). How important are the contributions (2) and the correct implementation of the consideration (3) for final state observables?

- *Micro-macro hybrid codes:* With the availability of first examples of hybrid models that couple *viscous* hydrodynamics for the QGP stage with a hadron cascade for microscopic kinetic evolution of the late hadronic stage, a correct implementation of the non-equilibrium chemistry in the hadronic through a chemical non-equilibrium EOS, and the ability to study viscous hydrodynamic evolution with temperature-dependent viscosities without running into numerical instabilities, we have arrived at the threshold of being able to extract the QGP viscosities from experimental data, by separating QGP effects from unavoidable strong viscous corrections in the late hadronic phase. Are the hydro-to-hadron converters and the available hadron cascade algorithms consistent with each other, i.e. do they, for identical hydrodynamic input at the end of the QGP evolution, yield the same input into the hadron cascade and (within statistical errors) the same output for the final hadron spectra? Developing and implementing a suitable comparison and verification protocol for hydro+cascade hybrid codes appears to be a matter of priority.

- *Macro–micro transition:* Some calculations (e.g. H. Song, slide 27-33) explore the systematic dependence of v_2 and extracted η/s on the switching temperature T_{sw} between hydro and UrQMD,

whereas others (e.g. T. Hirano, slide 12) simply fix $T_{sw} = 160$ MeV. Is there theoretical guidance about the allowed T_{sw} range over which hydro and cascade should both be under control, and how are we to understand the systematic uncertainties over this range?

- *Spinodal and other mechanical instabilities in viscous hydrodynamics:* First order phase transitions in ideal fluid dynamics, and strong bulk viscous effects near a rapid cross-over transition in viscous fluid dynamics, can lead to regions of mechanical instability and the exponential growth of unstable modes inside such regions. Can the second type of instabilities (e.g. cavitation inception in a rapidly expanding viscous fluid) be described with similar methods as developed to describe spinodal decomposition near a first-order phase transition in ideal fluid dynamics? Would the resulting instabilities lead to measurable event-by-event fluctuations caused by the *dynamical evolution* of the fireball, and if yes, how can such *dynamical fluctuations* be distinguished from a deterministic collective response to initial state shape fluctuations of the collision fireball?

- *Correcting elliptic flow signals for fluctuation effects:* Art Poskanzer showed a method for correcting elliptic flow measurements for non-flow and fluctuation effects. These corrections can be applied to the elliptic flow v_2 relative to the participant plane (which fluctuates relative to the reaction plane from event to event) or to the reaction plane (which is fixed by the direction of the impact parameter).

Which of these is theoretically more useful? It is the deformation and orientation of the initial participant distribution which drives the collective elliptic flow event by event. Proper implementation of this concept requires theoreticians to study and implement event-by-event fluctuations in the initial energy density and pressure distribution. Most theoretical studies so far calculated elliptic flow in the reaction plane, by using a smooth (event-averaged) initial energy density distribution aligned with the reaction plane. However, to compare with Poskanzer's non-flow corrected v_2 relative to the reaction plane, the event average underlying the smooth theoretical initial profile that is aligned with the event plane still needs to be computed from many events that, event by event, fluctuate in shape and orientation around the reaction plane. This has so far not been done in many calculations; furthermore, the amount of work needed to do this seems to be identical for both methods (participant plane eccentricity and event-plane eccentricity), except for the additional step of rotating each event to the same axis of alignment in the first method, as long as one uses event-averaged initial distributions for a 1-shot hydrodynamic evolution. (Whether or not one needs to rotate the event may affect the experimental errors, however, so it appears safer to do the rotation on the theory side and use the experimental v_2 with non-flow corrections relative to the participant plane.) When considering event-by-event hydrodynamic evolution of each fluctuating initial state, with the average over events only taken at the end when calculating observables, correcting to the experimental data (which measure elliptic flow in the participant plane) to the event plane seems to make little sense. Taken together, these consideration appear to favor experimental analyses that apply non-flow and fluctuation corrections relative to he participant plane, not the reaction plane.

Additional comment (A. Poskanzer): The new, direct 4-particle cumulant method is free of non-flow contributions and will give the results in the reaction plane except for the most peripheral collisions.

- *Boltzmann tests of viscous hydrodynamics:* Comparisons of microscopic parton cascade and viscous (Israel-Stewart) hydrodynamic simulations of systems undergoing 1-dimensional boost-invariant expansion are giving valuable insights into the applicability of both approaches. Existing studies by the Purdue and Frankfurt groups agree that, for sufficiently small viscosity, the two approaches agree very well; from the pattern and magnitude of the remaining discrepancies one wants to learn about failures and possible improvements of the Israel-Stewart viscous hydrodynamic approach (or, as pointed out by Teaney, possibly of the cascade approach in the limit of very small viscosity). It appears, however, that the Frankfurt and Purdue groups report a different sign for the observed deviations between the parton cascade and hydrodynamic simulations. This calls for clarification.

- *Separating QGP and hadronic viscosities:* The viscosity of a hadron resonance gas is expected to be significantly larger than that of a QGP. In every collision, the fireball formed in the reaction zone has a dilute hadronic corona which, in viscous hydrodynamics, causes very strong dissipative effects especially at early times when the expansion rate is large. To which extent do such hadronic viscous effects cover up experimental signatures of QGP viscosity? Will hadronic viscous effects preclude the observation of a possible increase of $(\eta/s)_{\mathrm{qgp}}$ at higher initial temperatures as probed at the LHC? Is the description of the hadronic corona by viscous hydrodynamics during the early stage of the collision warranted, or are the strong early viscous effects caused by this corona an unphysical artifact caused by using an inapplicable evolution model?

The shape of the finally observed transverse momentum spectra is influenced by viscous effects in

two conceptually distinct ways: (1) Viscous effects are present throughout the fireball evolution and accumulate over its entire history in the finally established collective flow pattern at freeze-out. This viscous modification of the flow pattern is accounted for in the local equilibrium part of the distribution function at decoupling, which gives rise to exponential spectra modified by a flow-induced blue-shift factor that has been affected by earlier viscosity. (2) At decoupling, the local distribution function is distorted away from equilibrium by viscous effects *at freeze-out* by an amount $\delta f(x,p)$ $(f_{\rm fo}(x,p) = f_{\rm eq}(x,p) + \delta f(x,p))$ that measures the strength of viscous effects *at freeze-out* (or slightly before). This deviation δf grows with p_T (somewhere between linearly and quadratically) but is only sensitive to late viscosity near decoupling and not to early viscosity, say, during the QGP phase. The p_T-dependence of δf and its dependence on hadron masses is theoretically not yet fully clarified; it depends on the structure and energy dependence of the hadronic scattering cross sections just before freeze-out. Assuming that this issue can be theoretically resolved, can the shape of $v_2(p_T)$ for identified hadrons at intermediate p_T $(1 < p_T < 2\,{\rm GeV}/c)$ be used to measure δf and thus the late hadronic viscosity, allowing us to distinguish it from early QGP viscous effects?

- *Higher-order anisotropic flow:* With the discovery of the practical importance of initial-state eccentricity fluctuations of higher than second order (quadrupole fluctuations) for the observed final state flow anisotropies, a more systematic study of the higher order coefficients v_n $(n > 2)$ and their evolution as a collective response to the initial-state shape eccentricities ϵ_n $(n > 2)$ has become a priority. Initial studies suggest that higher order flow coefficients are degraded more strongly by viscous effects than v_2. Can this observation be developed into a new quantitative too to extract the QGP viscosities? Do the higher order v_n's react to shear and bulk viscosity differently from v_2, and might this allow to separate bulk from shear viscosity experimentally?

- *Global fits of experimental data with hybrid evolution models:* Experimental data for hadron yields, spectra, elliptic flow, and two-particle correlations have very different statistical errors: data points for momentum distributions are numerous and accurate, those for anisotropic flow coefficients and HBT radii are much sparser and have larger errors. How does one account for this disparity in a meaningful fashion when attempting global model fits to the experimental data? How does one avoid the fits to be entirely dominated by accurately measured spectra, thereby involuntarily homing in on secondary model features that happen to influence

details of the shape of the precisely measured azimuthally averaged spectra while not having much influence on the much less precisely known v_2 and HBT radii?

V. WEEK FIVE: JET QUECHING

- *Fake jet removal:* STAR and PHENIX presently use different algorithms to identify and reconstruct jets and to account for "fake" jets caused by the presence of the bulk background. STAR estimates the spectrum of fake jets and subtracts them on a statistical basis; PHENIX uses an algorithm that detects "fake" jets individually and removes them from their jet sample. Some participants in the discussion viewed the STAR estimate of the fake jet spectrum as a *lower* bound; it would be important to obtain an *upper* bound, as well.

- *False Jet Analysis:* The discussion of jet reconstruction focussed primarily on the crucial question of the Fake or False Jet rate. On a qualitative level, False Jets arise from low p_T objects due to soft production, that are boosted to high apparent jet energy in the observed heavy ion jet spectrum due to the very broad distribution of background fluctuations. The discussion showed that the False Jet rate estimate is inseparable from the estimate of underlying event fluctuations and the unfolding of it to obtain the physical jet spectrum - perfect knowledge of the unfolding matrix and jet spectrum shape would result in no "False Jet" yield in the corrected inclusive spectrum. At present, STAR and PHENIX have significantly different approaches to estimating the False Jet rate in practice, which give very different answers.

  General arguments were made that, since the parton spectrum diverges at low p_T and the background fluctuation distribution is very broad, the False Jet rate *must* in fact be very large even at $20 - 30$ GeV. However, such arguments do not account for the finite size of jets returned from practical jet algorithms, which will significantly tame the divergence in per-event jet rate in the experimental acceptance. Some algorithms (in particular, k_t) do in fact allow very small area jets relative to $\pi * R^2$, but for such jets the background fluctuation spectrum will be much narrower than that underlying high E_T, large area jets. Both effects need to be properly accounted for to obtain a realistic estimate of False Jet rates, and such studies are in progress as a result of this week's discussions.

  In the current analyses, STAR estimates the False Jet rate by means of azimuthal scrambling of events and elimination of high p_T leading hadrons, which will destroy all multi-particle correlations and eliminate real jet fragments. This provides a lower

bound to the False Jet rate, and it remains to be shown to what extent multi-hadron correlations contribute to the False Jet rate. Proposals to study this were discussed and the work is in progress.

PHENIX estimates the False Jet rate based on a cut on jet shape, with guidance from simulations.

In order to facilitate convergence between the experiments, the PHENIX has promised to provide their sample of HIJING events with hard partons removed to STAR. The PHENIX representatives also indicated that they will make their jet finding algorithm publicly available soon. It is desirable that the STAR group applies the same algorithm to their data. It would also be helpful if PHENIX would apply their jet finder to the Au+Au data.

- *Event-by-event fluctuations and jet quenching:* It has been shown that the difference between the shape (eccentricity) of the binary collision distribution of the jet production points and the shape (eccentricity) of the matter distribution (Glauber or CGC) affects the azimuthal dependence of jet quenching and thereby the elliptic flow coefficient at high p_T. Jets probe the space-time evolution of the matter distribution which is, among other effects, affected by the viscosity of the medium. Jet quenching (more accurately: parton energy loss) probes this distribution through the opacity integral which enters in the exponent of the jet attenuation factor, thereby emphasizing small differences between models. It appears clear that, in view of significant event-by-event fluctuations and local inhomogeneities in the evolving density distribution of real heavy-ion fireballs, the representation of the event-averaged parton energy loss in terms of a ϕ-dependent attenuation factor calculated from a smooth (event-averaged) density distribution is dangerous. A toy model in which the calculation was done both ways (J. Jia), using the rotated event and averaging many events and taking each event with local path density fluctuations, found very small differences. Does this observation hold up in more realistic jet quenching simulations?

This discussion suggests that it will be important to calculate jet quenching with bulk simulations of ideal or viscous hydrodynamics on an event-by-event basis, with initial state fluctuations propagated in the hydro evolution. In order to facilitate this for all jet quenching formalisms, hydro output for fluctuating events should be made available in a standardized form, e.g. as proposed by the TEC-HQM collaboration.

- *Jet quenching in a hadronic gas:* Several studies indicate that the hadronic final state medium contributes significantly to jet quenching. More theoretical estimates of jet quenching in a thermal hadronic medium would be desirable.

- *Differences and similarities between parton energy loss formalisms:* The discussion revealed that the various relationships between the approximations and assumptions made in different theoretical approaches to parton energy loss, and the implications on their respective domains of validity still need further clarification. A serious effort should be made to fully map the various approaches onto each other. Good first steps in this direction were reported during this week, but a systematic comparison between all of the approaches, that cuts away differences in language and choices of reference frame and focusses on the differences in physics and, perhaps more importantly, on the location and shape of regions of mutual agreement (even if they lie outside the phenomenologically relevant parameter space), is still missing. (*Note:* Recent work by S. Caron-Huot (arXiv:1006.2379) has elucidated the differences between some of the existing approaches.)

- *Z+jet at the LHC:* Member of the Los Alamos theory group presented a new, fully consistent NLO calculation of the Z+jet coincidence process at LHC energies. This process, together with γ+jet at both RHIC and LHC, is in principle the most precise and controlled way to measure Fragmentation Functions and their modification in p+p and heavy ion collisions, since (at LO) the Z/γ and recoiling jet energies balance precisely. The new calculations reveal that in fact the energy balance is broadened when the process is considered at NLO. The impact of this insight on the LHC heavy ion program needs to be assessed, and may not be small. A similar NLO calculation for γ+jet is urgently needed at both RHIC and LHC energies, work in progress.

VI. WEEK SIX: STRONG VS. WEAK COUPLING

- *Parton energy loss and strong coupling:* Jet tomography is based on the idea that hard partons are a calibrated probe whose interaction with the medium can be factored into a hard part that depends on the probe and can be reliably calculated (e.g. within perturbative QCD), and a soft part that describes properties of the medium that may be difficult to compute but can be extracted experimentally through tomography. The program of QGP tomography does not rely on the *medium* properties being perturbatively calculable (even though many existing studies make this assumption), but it appears to rely on the probe interacting perturbatively with the medium. Is there a way to generalize the idea of jet tomography in a meaningful way to jets that couple strongly with the medium? In other words, if the probe itself is strongly coupled, can its medium modification in

heavy-ion collisions still be used to extract meaningful information about the medium that holds true independent of the probe?

- *Parton energy loss in fluctuating media:* Given the now widely accepted view that the energy density distributions created in heavy-ion collisions are strongly inhomogeneous and fluctuate widely from event to event, and that jet and electromagnetic tomography rely on rare probes that yield only statistical information by summing over many collision events, but can not meaningfully characterize an individual collision event, what is the correct interpretation of experimental data on parton energy loss and jet modification? Which "average" properties of the medium are accessible to tomographic measurements? Discussions during this week seem to indicate that these questions need to be reconsidered and re-thought.

- *Path length dependence of parton energy loss:* AdS/CFT-based calculations of the average distance traveled by energetic light quarks and gluons before losing all their energy suggest an L^3-dependence of the average energy loss ΔE, but also show that the energy loss rate changes along the trajectory, with a strong Bragg peak just before the parton stops. Since partons used for jet tomography are by definition partons that escape the collision and thus do *not* lose all their energy, they do not experience this Bragg peak. What is, hence, the average path length dependence of the energy loss for strongly coupled light partons that *escape* the medium?

- *Completely absorbed partons:* Even for partons that are entirely absorbed in the medium, the energy deposited must emerge as flow of the medium in the direction of the jet. What are the expectations for the manifestation of the jet energy and momentum in this case? Will conventional jet algorithms be sensitive to it?

- *Required precision of suppression measurements:* As for pion suppression, one of the primary tools for the study of jets is the comparison of production cross section in nuclear and proton-proton collisions. What precision in the measurement of jet R_{AA} is required to distinguish different theoretical scenarios? What is the role of different jet algorithms?

- *Strongly coupled partons and jet finding algorithms:* At strong coupling, jet and medium are inseparable. Can jet finding algorithms be constructed that can actually find strongly coupled jets? Or, if this is not possible and all jet reconstruction algorithms suffer from an inevitable bias towards finding unmodified jets emitted from the fireball sur-

face, which physics properties could be quantitatively determined by a theory–data comparison?

- *Strongly coupled vs. weakly coupled jets:* Which kind of experiments would allow to distinguish between a scenario where hard partons are strongly coupled to a strongly coupled medium and the alternative where hard partons are weakly coupled to a strongly coupled medium?

- *Path from strong to weak coupling:* Can a path be found that shows the way from AdS/CFT-based calculations at infinitely strong coupling to weakly coupled perturbative QCD at asymptotically high energies and temperatures? In the absence of such a path, is there a way to falsify the AdS/CFT paradigm experimentally?

- *Lattice QCD equation of state:* The Budapest-Wuppertal collaboration appears to see an excess above the hadron resonance gas expectation for the "interaction measure" $(\epsilon - 3p)/T^4$ at temperatures between 140 MeV and T_c. Can this be understood in terms of residual interactions in the hadron resonance gas that are not captured by including all resonances and, if yes, what is the nature of these residual interactions? Or can the excess possibly be accounted for by including additional massive resonances that have so far escaped detection due to their large widths?

VII.   WEEK SEVEN: HEAVY FLAVOR AND QUARKONIUM

- *Cold nuclear matter effects on J/ψ production:* The theoretical uncertainties in the charm production cross section due to presently explored independent variations of theory parameters such as charm quark mass, the factorization and renormalization scales, intrinsic k_T, and initial state energy loss appear too large. Can a strategy be devised which allows to narrow down the allowed ranges for these parameters separately, by studying charm and charmonium production in certain kinematic limits or under certain systematic changes of experimental conditions (such as collision energy) in which one or the other of these parameters enters most sensitively?

- *Initial state energy loss:* More generally, is there experimental evidence for initial state energy loss in hard QCD reactions? Do existing Drell-Yan data from p+A reactions present unambiguous evidence for this effect? If so, can it be determined whether the energy loss is due to elastic or inelastic interactions with the nucleons in the nuclear target?

- *Heavy quark potential at finite temperature:* Can the systematic real-time pNRQCD–HTL effective

theory be generalized to heavy quarkonia moving at high velocity through a thermal medium or to quarkonia embedded in a non-equilibrium medium?

- *T-matrix and EFT approaches to charmonium melting:* What is the relationship between the T-matrix theory pursued by Rapp et al. and the pN-RQCD effective field theory developed by Ghiglieri et al.? How do their respective regions of applicability compare with each other?

- *Charmonium flow:* Can hydrodynamic model comparisons with experimental p_T-spectra clarify whether J/ψ mesons measured at RHIC participate in the collective flow of the hot quark-gluon liquid created in heavy-ion collisions?

- *Charmonium recombination:* In Rapp's calculation, the recombination is predominantly between "diagonal" $c-\bar{c}$ pairs, *i.e.* as pairs produced together in a hard process, but not initially having the right kinematics to form a J/ψ, however later recombining due to rescattering in the medium). This has large implications for the scaling of such recombination effects to the LHC. It also seems to go in the wrong direction for explaining the larger forward-rapidity J/ψ suppression at RHIC (in contradiction to earlier calculations by Thews).

VIII.   WEEK EIGHT: EM PROBES

- *NA60 above-ρ-mass di-muon data:* There has been a debate whether the excess in the di-muon spectrum in the $1.0-1.4\,\mathrm{GeV}/c^2$ invariant mass range is due to hadronic or partonic processes. The m_T- dependence of the excess indicates that the di-leptons are emitted at a time when the collective flow velocity of the medium is still small. Is the value $T_c = 160 - 165$ MeV, to which the lattice calculations are converging, compatible with the assumption of a hadronic source? What is the participant number dependence of the excess?

- *Low-mass di-muon data:* A new calculation of the low-mass di-lepton yields in SPS (In+In) and RHIC (Au+Au and Cu+Cu)experiments with state-of-the-art bulk evolution models (hydro plus hadronic cascade) would be desirable. In particular, for the In+In data it would be of interest to determine to what extent a shift of the ρ-meson in medium, in addition to its broadening, can be ruled out.

- *Di-lepton production in $p + n$ collisions:* The HADES data show that the di-lepton yield from $p + n$ collisions is substantially different from the yield from $p + p$ collisions. This strong isospin dependence does not seem to be well understood theoretically. Existing calculations may suffer from

lack of gauge invariance; a theoretically consistent calculation would be highly desirable.

- *Low-mass di-lepton excess in Au+Au:* The large excess of di-leptons at low invariant mass seen by PHENIX in central Au+Au collisions has two components: one with a slope of 92 MeV and one with a slope of 258 MeV. While no credible theoretical explanation of the 92 MeV slope component is known, the question is whether the 258 MeV slope component can be reproduced quantitatively by theories of a broadened in-medium ρ-meson. Also, the difference between the Au+Au and Cu+Cu data is striking. Does any scenario exist which could explain this difference? Since the hadron-blind detector only ran for Au+Au, but not Cu+Cu, will existing data be able to resolve this puzzle?

- *Low-mass cutoff of the $\rho-$ contribution to the vacuum di-lepton spectrum:* Often the contribution of the vacuum-ρ to the di-lepton spectrum is cut off abruptly at $2m_\pi$ invariant mass. Is this procedure correct when the ρ is produced as a virtual state in, e.g. $\pi - N$ scattering?

- *ϕN cross section:* The small value of the slope of the ϕ spectrum is usually taken as a sign that the ϕ-meson decouples early from the medium, shortly after hadronization. Is this explanation compatible with reports of a large ϕN cross section from photo-production experiments on deuterium at JLab and SPring-8? (See e.g. T. Mibe, et al, PRC76, 052202 (2007) or Titov et al, PRC76, 048202 (2007)).

- *Elliptic flow of identified hadrons at large p_T:* Can the elliptic flow of identified hadrons other than the π^0, e.g. strange hadrons, be measured at $p_T > 6$ GeV/c? Such a measurement would help assess the role of chemical reactions in jet fragmentation, such as flavor conversion of the leading parton.

- *Consistent weak-coupling scenario for heavy-ion reactions at RHIC:* Is there a consistent weak-coupling scenario for quark-gluon plasma dynamics at RHIC? Such a scenario would invoke field-driven transport processes in the presence of strong color fields, either as remnants of the glasma or generated by plasma instabilities. Elliptic collective flow would be generated by repulsion of glasma flux tubes in an anisotropic geometric configuration. In such a scenario, bulk "equilibration" of the hadronic final state would only occur at hadronization. Would such a scenario be compatible with data, e.g. on two-particle correlations at low and intermediate p_T, and with strangeness equilibration?