Science Meeting – Scientific report

Proposal Title: QCD Phase Diagram and Holography
(FIAS, Frankfurt, July 27-28 2013)

Application Reference N^o: HoloGrav - Science Meeting 4784

Summary For a few years now, gauge/gravity correspondence has been claimed to be a tool for studying non-perturbative QCD, or at least its more symmetric "cousin", theories which are strongly coupled and conformally invariant (either at all scales, in the simplest AdS/CFT model, or in the UV, as its more complicated cousins).

However, whether such models really share enough similarities with QCD to be a useful "tool" is somewhat open to question. While features "similar" to QCD (confinement, chiral symmetry breaking, Regge trajectories and so on) can be described qualitatively with gauge/gravity techniques, QCD is fundamentally different from its "cousins" with string theory duals in several important ways. It is of course weakly coupled in the UV, and only exhibits strongly coupled, not necessarily conformal behavior, in the IR. The number of colors is 3, very far quantitatively from the "planar limit", a "large" number of colors.

These are very important questions, yet they are seldom discussed in both the gauge/gravity and the QCD community. Instead, rather unfortunate tendencies exist, to either work on $\mathcal{N} = 4$ theory as a given, or to ignore it completely as *a priori* irrelevant. The aim of this workshop is to challenge both these attitudes. We gave an opportunity to leading practitioners of this field to "ask each other tough questions", voice their arguments for believing or disbelieving the holographic approach, and discuss what aspects of QCD could be clarified by holographic methods, or, inversely, what aspects of holographic theory could be meaningfully compared to experimental heavy ion data or theoretical approaches.

In this workshop we focused our investigation on the QCD phase diagram, and generally the thermal and statistical aspects of strongly interacting matter. The "phenomenological" part of the workshop was centered around numerical studies on the lattice, various non-perturbative approaches and the interpretation of heavy ion experimental data, either the high energy frontier at RHIC and the LHC or the high density frontier at FAIR. The holographic part attempted to determine what relevance theories with gravity duals had on the Ansätze described above.

Description of the scientific content of and discussions at the event The meeting was opened by Robert Pisarski, who gave an overview talk on questions in confinement phenomenology which a holographic approach could clarify. He started by discussing pure Yang-Mills theory on the lattice, and the apparent scaling, around the critical temperature T_c, of the "soft bag constant", given by $(e - 3p)/(T_c T)^2$. This quantity, extending from T_c to $\sim 5T_c$, exhibits a near-constant behavior, independent of N_c. Dimensional analysis, and comparison to a 2+1 dimensional lattice, suggests this to be the behavior of a "string".

Pisarski also discussed thermalization in small systems, in reference to the recent results of RHIC and LHC pA collisions, asking to what extent can "a lower limit to thermal behavior" be obtained from holographic methods.

This was followed by the overview of important results from holography given by Andreas Karch. He highlighted the success and limitations of holography as a tool in applications to particle physics. He reviewed holography's impact on our understanding of hydrodynamics (including anomaly effects), on energy loss mechanisms in plasma, and on thermalization. In particular, he linked the thermalization issue raised by Pisarski, showing works by Chesler and Yaffe in 1+1 dimension that seem to indicate that near-hydrodynamic behavior precedes thermalization.

Steve Gubser discussed a family of "bottom-up" approaches capable of capturing both the zero temperature cross-over behavior and the critical point appearing at finite chemical potential. He concluded by pointing out that his leading large N analysis suggests a critical point at $\mu_c = 783MeV$ and $T_c = 143MeV$ with mean field and Model B critical exponents (according to the classification scheme by Hohenberg and Halperin). Such a picture of the phase diagram is possible, but not guaranteed, to occur in QCD.

Jan Pawlowski described an alternative approach capable of investigating physics in this region, functional renormalization group techniques, capable of enforcing self-consistency to an empirically derived non-perturbative propagator. This approach can perhaps form a conceptual "bridge", as it is capable of describing both holographic approaches and non-perturbative QCD physics. To what extent does such an approach match holography, and the implications for the phase diagram of the validity of this approach, are however still open questions.

Krystof Redlich showed a phase diagram where such a critical point was present, while Kenji Fukushima (in direct response during Redlich's presentation) mentioned results of models where there was no critical point. Krystof Redlich also gave an overview of how the approach critical point, both on the lattice and in experimental data, could be investigated by looking at higher cumulants (variance, skewness and kurtosis) of conserved charges.

Misha Stephanov gave an overview of the theory of hydrodynamics and hydrodynamic fluctuations. In particular, he showed a 1+1 dimensional solution incorporating both a fluctuation and a dissipation term.

Continuing the theme of modern hydrodynamics and its applications Karl Landsteiner gave a comprehensive overview of all the known transport effects which are induced by anomalies. Prominent examples are the chiral vortical and chiral magnetic effect, but there are many more effects and by now well-understood relations among them, for example the relation of gravitational anomalies to the chiral vortical and chiral magnetic effect. Landsteiner described how these effects may be seen in heavy-ion-collisions or alternatively in Weyl-semimetals. He thus provided a bridge to condensed matter physics.

Johanna Erdmenger reviewed a top-down approach to QCD utilizing probe branes. She showed results for holographic vector spectral functions comparing these to results from lattice gauge theory and effective field theory calculations. In a comment Redlich pointed out possible reasons for the close resemblence. Erdmenger continued to discuss regions of the phase diagram at large chemical potential where the holographic analogs of the ρ mesons condense. Subjected to external magnetic fields these condensates develop lattice structures. Which structure is energetially favored depends on chemical potential, temperature, magnetic field and possibly other parameters resembling the situation found in various superfluids and superconductors known experimentally and theoretically in the context of condensed matter physics.

While the primary focus of this workshop was QCD, holographic methods are also widely applied to strongly coupled condensed matter systems. Indeed, such systems are not irrelevant to this workshop also because materials such as Graphene, strongly interacting metals and ultracold atoms have been claimed to be analogous to QCD. Talks by Hofstetter, on the condensed matter theory side, and Johanna Erdmenger, on the holographic side, discussed this issue.

Hofstetter gave a comprehensive review of the recent experimental control and refinement of quantum simulations based on ultracold atoms. Major recent developments are the realization of synthetic gauge fields for neutral atoms, allowing the simulation of topologically nontrivial phases of matter, and the creation of frustrated lattice geometries such as triangular or Kagome. Particularly rich physics arises in the presence of multiple atomic species and strong interactions, which he highlighted for several examples. Hofstetters talk was received very well, as a large number of questions during and after his presentation showed.

Finally, Derek Teaney discussed the problem of thermalzation from a holographic fluctuation-dissipation aspect, showing how the equilibrium of a forming event horizon with Hawking radiation could be mapped to an approach to equilibrium similar to the Keldysh-Schwinger formalism used in quantum field theory. This approach also suggests that "hydrodynamic evolution" happens parametrically slower than thermalization.

During the discussion, an impromptu talk was given by Marco Panero, regarding the recently made attempts to calculate the jet quenching parameter $\hat{q}$ from the lattice. As made clear in talks by Gubser and Karch, this parameter can be calculated within holographic theories, and is also of interest to QCD phenomenology.

Assessment of the results and impact of the event on the future directions of the field Note that we have already assesed some of the scientific results of the meeting above. In addition to that, from the intense discussions between the different specialists, we can say the proposed goal of this workshop was amply achieved. Questions which are usually ignored by practitioners of both sides of the field were widely discussed.

Discussion was lively, and disagreements were deep, but a very high scientific level was maintained. It seems several "interdisciplinary" collaborations, between string theorists and QCD phenomenologists, might develop as a result of this workshop. While it is too early to tell where this work might lead, it is beyond doubt that this workshop forced everyone involved to question their assumptions and confront non-trivial unresolved issues. In theoretical physics, this can only be a good thing.

ANNEX 4. a) Final program of the meeting

Day	Time	Topic
Sat	08.30-09.00	Coffee & Registration (payment, site access, info)
	09.00-09.15	Welcome & Introduction (participants introduction)
	09.15-10.45	**First session**
		Pisarski –*Open questions in nuclear theory*
		Karch –*Answers from holography*
	10.45-11.15	Coffee break
	11.15-12.45	**Second session**
		Gubser –*Holographic models of the QCD phase diagram*
		Pawlowski –*Structure of the QCD phase diagram*
	12.45-14.30	Lunch at "Lahmer Esel"
	14.30-16.00	**Third session**
		Stephanov –*Hydrodynamics & hydrodynamic noise*
		Landsteiner –*Anomalous Transport: From the Quark Gluon Plasma to Weyl Semi-Metals on a Superstring*
	16.00-16.45	Coffee break
	16.45-18.15	**Fourth session**
		Erdmenger –*Transport, magnetic fields, and condensates from holography*
		Discussion: *Holography & heavy ions* (Gubser & Pisarski)
	19.00-22.00	
Sun	09.00-09.30	Coffee
	09.30-11.00	**Fifth session**
		Hofstetter –*Quantum Simulations with Ultracold Atoms: Beyond Standard Optical Lattices*
		Redlich –*Probing QCD phase transtions with fluctuations in theory and experiment*
	11.00-11.30	Coffee break
	11.30-13.00	**Sixth session**
		Teaney –*Heavy ions and string theory*
		Discussion: *Nonequilibrium* (Redlich & Teaney)
	13.00-14.00	Lunch catering & open discussion
	14.00-18.00	**Open discussion:**
		Future directions for testing holography
	19.00-21.00	Dinner

ANNEX 4.b) List of participants Note that the institutions are written in brackets following the corresponding name. Names of cities specify the corresponding university.

- Johanna Erdmenger (MPI Munich)
- Steven Gubser (Princeton)
- Walter Hofstetter (Frankfurt)
- Andreas Karch (UW Seattle)
- Karl Landsteiner (IFT Madrid)
- Jan Pawlowski (Heidelberg)
- Rob Pisarski (BNL)
- Krzysztof Redlich (Wroclaw)
- Misha Stephanov (Illinois)
- Derek Teaney (Stony Brook)
- Timo Alho (Helsinki)
- Martin Ammon (Jena)
- Nele Callebaut (Gent)
- Nick Evans (Southampton)
- Carlo Ewerz (Heidelberg)
- Antonia Frassino (Frankfurt)
- Kenji Fukushima (Kyoto)
- Michal Heller (Amsterdam)
- Mei Huang (CAS Beijing)
- Stefan Janiszewski (UW Seattle)
- Shu Lin (BNL)
- Andy O'Bannon (Cambridge)
- Marco Panero (Helsinki)
- Dawei Pang (MPI Munich)
- Hannah Petersen (Frankfurt)
- Adam Ritz (Victoria)
- Andreas Samberg (Heidelberg)

- Chihiro Sasaki (Frankfurt)
- Andreas Schaefer (Regensburg)
- Thomas Schaefer (NCSU)
- Martin Sprenger (DESY Hamburg)
- Stefan Stricker (Vienna)
- Nan Su (Bielefeld)
- Sascha Vogel (Frankfurt)