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What is the Quark-Gluon Plasma (QGP) and How Do We Find Out?

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We present a panel discussion about our current state of knowledge about the Quark-Gluon Plasma. The nine panelists were asked to address the question: What do we want to know about the quark-gluon plasma, and how can we find the answers? The contributions illuminate our present understanding and highlight various aspects of the ongoing debate about the future directions of relativistic heavy-ion collision research.

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1. Introduction

The round table discussion was opened by the chairs, Yiota Foka and Berndt Müller, who briefly introduced the subject and the members of the panel.

First, the round table discussion in the last Confinement IX [1] in Madrid, August 30 – September 3, 2010, was recalled where, waiting for the LHC heavy-ion data, the discussion focused on the understanding of heavy-ion collisions and expectations from LHC [2].

Now with the Pb–Pb LHC data in hand and further results from RHIC, the panel members were invited to discuss what we have learnt about the QGP and what the open questions are. More specifically: How do we want to characterize the properties of the QGP? Do we know which set of observables serves us best to do so? Are we able to establish the link between experimental observables and QGP properties? If so, which measurements still need to be done? If not, what kind of theoretical developments are needed to establish the links? Ultimately, what will it make into the textbooks?

A wealth of experimental data and theoretical developments were presented in the Quark Matter Conference in Washington [3], August 13–18, 2012. Highlights and overview talks were presented during this conference, Confinement X, which is in fact the first one of this series where LHC heavy-ion data were presented.

LHC has offered us vastly extended p_{T} range, which means that the so-called "rare probes" become abundant and high-p_{T} accessible. However, we still want to first characterize the bulk looking at low-p_{T} observables and assess the status of "classical QGP probes". One of the first papers on QGP signatures, on "strangeness enhancement" was authored by the chair Berndt Mueller together with Jan Rafelski, back in 1982 [4] while the round table discussion in Madrid concluded that the observable that could unambiguously confirm or otherwise the current conventional understanding of heavy-ion collisions will be the elliptic flow measurement [2].

The present panel of experts, including theorists and experimentalists working in the field from AGS to LHC discussed the questions addressed by the chairs but also from the audience:

John: How do we want to characterize the QGP? What are the best observables?

Wojciech: Is fluid dynamics sufficient to describe the evolution of the QGP?

Zoltan: What do we KNOW about the QGP equation of state?

Harvey: How can we compute the dynamics of the QGP?

Dirk: How quantitative can viscous hydrodynamics become?

Peter: What can jet quenching tell us about the QGP ?

Sasha: How has the LHC revolutionized jet probes of the QGP?

Andre: What can we learn from heavy quarks?

Mike: What have we learned (or failed to learn) from the beam energy scan? What more do we need?

A compilation of this discussion is presented below.

2. Characterizing the QGP: key directions for experiment to pursue

With regard to characterizing the QGP, here are a few key directions for experiment to pursue.

The observable that presently delivers the most information on the properties of the medium is the harmonic composition of the final state momentum distributions. Depending upon the transport properties of the medium, the fluctuations in the initial state eccentricities and the subsequent hydrodynamic transport of the medium will determine the final state momentum anisotropies. The transport of light and heavy flavors can be measured by harmonic decomposition of final state momentum distributions, providing information on the shear viscosity (η) to entropy density (s) ratio η/s or alternatively the sound attenuation length. Furthermore, any nonlinear fluctuations would shed light on the Reynolds number of the medium. Perhaps most generally, measurement of various observables over a large range of c.m. energy (e.g. from RHIC to LHC ion energies) would help to determine whether the coupling changes over the range of energies and interactions, as one might think that the coupling strength to be temperature dependent. Again, comparisons with LQCD results may help.

In order to probe the structure of the QGP on a more microscopic level, it is essential to understand at a fundamental level the propagation and energy loss of a parton in the medium. This will in turn allow a study of the response of the medium to large energy deposition from fast partons and a study of properties of the medium. To investigate parton energy loss, it is important to obtain measurements of identified particles with large transverse momenta and to separate heavy from light flavors to determine the mass and flavor dependence of parton energy loss. It would be enlightening to be able to distinguish quark from gluon jets. Quark jets can be distinguished by those that contain leading heavy quarks (e.g. b-jets) or those on the away-side of a high momentum photon in Υ-jet correlations, while the abundance of jets at RHIC and the LHC are gluon jets.

Analogous to the study of the energy loss (or dE/dx) of charged particles traversing a QED medium, it is important to obtain measurements of the parton energy loss per unit pathlength as it traverses the QCD medium. An initial approach to this is to measure the jet energy loss relative to the reaction plane and thus deduce an average pathlength (or a total pathlength for di-jets). The geometry and path length can be further constrained by selecting on values and orientations of other observables such as specific Fourier components of the shape in momentum space, such as large elliptic flow. Particle-particle, jet-particle, Υ-jet and di-jet correlations will further constrain the geometry and path lengths traversed by the subject parton(s) in the medium. It is also important to cover a large parton energy range and span a range of virtualities of partons used to probe the medium. This should indicate the sensitivity of parton energy loss to the parton energy and thus its virtuality, and lead to determination of the coupling strength of the medium, and the relative roles of collisional and radiative energy loss of the parton. It is also imperative that theory determine the time evolution of the parton-medium interactions as a function of parton energy as the parton propagates through the medium. Once parton energy loss begins to be understood at a fundamental level, then the response of the medium to energy deposition of a fast parton can be pursued further to determine various transport parameters of the medium.

Perhaps, the best opportunity to determine whether the system is deconfined is a measurement of the sequential "melting" of quarkonium states. Due to the Debye screening of color charge in the colored medium, formation of the various quarkonium states will be suppressed with the suppression dependent upon the strength of binding of the state. Thus, comparison of the yields of various charmonium and bottomonium ground states and excited states as a function of momentum and centrality of the collision will provide essential data with which to compare to lattice QCD calculations. The results of calculations on the lattice establish whether the system is deconfined or not as a function of temperature, with the yield of unbound/bound states providing a direct comparison with experiment.

To make further progress in determining properties of the medium, it is imperative to pursue measurements of differential quantities. This entails a detailed investigation of variables such as parton attenuation and QGP transport properties as a function of centrality (both impact parameter and shape of the final state) and event plane directionality, in order to constrain (and have knowledge of) the directions of pressure gradients and to better determine path lengths through the medium. Then measurements and correlations (for differences of the initial state configurations) of parton propagation and transport properties and their dependence on the momentum of the probe will provide differential quantities that will constrain models.

3. Hydrodynamics and the QGP evolution

The subject of our Round Table discussion is "What is the Quark-Gluon Plasma (QGP) and how do we find it out". On the general grounds, I think, that we can answer this question if 1) we have the data that suggests creation of a new state of matter in relativistic heavy-ion collisions, 2) we have an appropriate theory that may be used to interpret the new experimental findings, and finally 3) our theory is successful in the description of the collected data. Then, the concepts and parameters used in the theory define the physical properties of the produced matter, which we intend to call the quark-gluon plasma (clearly, at high beam energies the energy densities of the created systems are so high that the concept of systems formed from individual hadrons breaks down and we deal with a quark-gluon system, called QGP).

The first decade of the XXI century has brought us a remarkable set of different experimental data collected at the Relativistic Heavy-Ion Collider (RHIC). This time will be, for sure, regarded as a "Golden Era" of the field of (ultra) relativistic heavy-ion collisions. Hopefully, the"Golden Era" will continue for a couple of the next years with the heavy-ion program performed at the Large Hadron Collider (LHC). On the theoretical side, it has turned out that most of the RHIC soft hadronic observables may be well explained by the relativistic hydrodynamics (with a very small shear viscosity to entropy ratio) [20, 21]. In this respect, I think, we were very lucky that such complicated processes found a relatively simple way of understanding. Following E. Shuryak's opinion, I want to add that hydrodynamics is more than a model; this is a theory of strongly interacting matter. The successful applications of relativistic hydrodynamics have allowed us to define the properties of the plasma. As mentioned earlier, the most successful achievement in this activity is the conclusion about the very low shear viscosity of the plasma [15, 22].

One may ask now the question where the place for QCD is in this scheme? The natural answer is that QCD should explain now the "measured" properties, for example, the values of the kinetic coefficients such as the shear and bulk viscosity. This is known to be a difficult problem for the first-principle QCD calculations. There are, however, other examples. In my opinion, an excellent example for the convergence of experimental analyses, phenomenology, and basic theory were

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studies of the HBT correlations combined with more popular studies of the hadron spectra and flow [16, 17]. Such studies ended with the conclusion that the equation of state (EOS) of QCD matter used in relativistic hydrodynamics should be like that predicted by the lattice simulations of QCD (see Z. Fodor's contribution). The absence of a first order phase transition implies the absence of a significant soft point in the QCD EOS, and this, in turn, implies short timescales necessary to get a correct description of the HBT radii. This example shows the importance of the analyses where several observables are studied at the same time and the aim of theoretical modeling is reaching a uniform picture of the whole collision processes.

Several theoretical investigations showed that naive interpretations of the lattice results might be misleading, for example, the convergence to the Stefan-Boltzmann limit does not necessarily mean that the system becomes weakly interacting (the opinion we shared for many years in our searches for the quark-gluon plasma understood as an asymptotically free state). In this context, and also in the studies of the QGP viscosity, illuminating results are delivered by the AdS/CFT correspondance. We have to remember, however, that this framework does not connect the gravity with QCD, hence, the AdS/CFT results must be accepted with appropriate skepticism. This we learnt also directly from J. Maldacena at this conference.

From my personal perspective I think that one of the most important issues to be solved in the future is the problem of early thermalization or, in other words, the problem of justification of the hydrodynamic description of the evolution of matter at the very early stages of collisions (at the time being a fraction of the fermi). An equivalent problem is matching of hydrodynamic description with a microscopic QCD description of the early stages. Similar opinions have been expressed by D. Rischke during this discussion. It would be interesting to find observables which are sensitive to the details of the early stage. Can "standard" early-stage observables like photons, dileptons, and jet quenching deliver us this kind of information? The hadronic observables seem to be completely insensitive to the early stage dynamics, due to the freedom of choosing different initial conditions [18, 19]. However, thinking more positively, such freedom may be used just for the proper matching of the hydrodynamic evolution with QCD theories of the early stages.

My last remarks concern the experiments at lower energies (BES etc.). Amazingly, we find many regularities in the data which are very much similar to those observed at higher energies (where the baryon chemical potential is zero). On the other hand, we do not have a reliable theory in this regime — EOS cannot be determined by the lattice simulations. This makes comparisons between theory and experiment quite difficult and speculative. Can we infer new properties of matter by looking at the data alone? I would agree with M. Lisa that this might be possible (after the U-bahn discussion I think that Mike opts for this) but only if a very striking new phenomenon is observed which has a straightforward physical interpretation.

4. The QGP equation of state

Generic remarks for lattice results. When we analyze the absolute scale, the equation of state or any other question related to the T>0 QCD transition for the physically relevant case two ingredients are quite important. First of all, one should use physical quark masses. Whereas it is relatively easy to reach the physical value of the strange quark mass m_s in present day lattice simulations, it is much more difficult to work with physical up and down quark masses m_{ud}, because

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they are much smaller: $m_s/m_{ud} \approx 28$. In calculations with m_s/m_{ud} smaller than 28 the strange quark mass is usually tuned to its approximate physical value, whereas the average up and down quark masses are larger than the physical value. Secondly, the nature and other characteristics of the T>0 QCD transition are known to suffer from discretization errors. Therefore, the only way to get rid of these errors is to take smaller and smaller lattice spacings and systematically extrapolate to vanishing lattice spacings (thus to the continuum limit).

It is numerically very demanding to fulfill both conditions. There are only a few cases, for which this has been achieved. Within the staggered formalism of lattice QCD thermodynamics there are full results such as the nature of the transition [5], the transition temperature for vanishing and small chemical potential [6, 7, 8, 9], equation of state [10] and fluctuations [11, 12].

Status of equation of state. The first step to obtain any trustworthy result in QCD thermodynamics is to determine the overall scale of the QCD transition. Its value was disputed for some years, but it is a great succes of lattice QCD that the field has reached now a point at which the results from different groups completely agree [6, 7, 8]. The next important step is the determination of the equation of state. There are various calculations with different fermion formulations. Far the most precise results have been obtained by staggered quarks. In these calculations the quark masses (light and strange) take their physical (or approximately physical) values. There is still a discrepancy for the equation of state in the literature. The Wuppertal-Budapest group obtained in 2005 [13] a value around 4 for the peak height of the trace anomaly (ε–3p), which was confirmed in 2010 [10] (at three characteristic temperatures the continuum result was given; it pinned down the result for the equation of state, which is also given as a simple parametrization). The hotQCD collaboration typically receives higher values for the peak height of the trace anomaly (for a recent summary see e.g. Ref. [14]). The left panel of Fig. 1 shows the comparison of the results of the two groups. Obviously, more work is needed to clarify the source of the difference. The equation of state for small non-vanishing temperatures is also known [10].

Susceptibilities from lattice. Fluctuations and correlations of conserved charges are important probes of various aspects of deconfinement. This is because fluctuation of conserved charges are sensitive to the underlying degrees of freedom which could be hadronic (in the low temperature phase) or partonic (in the high temperature phase). Fluctuations of conserved charges have been studied using different staggered actions (though some results with Wilson fermions are also available). The two most complete calculations have been carried out by the Wuppertal-Budapest group and by the hotQCD Collaboration [11, 12]. As an illustration the right panel of Fig. 1 shows the comparison of the results of the two groups for the strange quark number susceptibility. Fluctuations are small at low temperatures because strangeness is carried by massive strange hadrons (in this case mostly by kaons). This part of the figure is well described by the Hadron Resonance Gas (HRG) model. Strangeness fluctuations sharply rise in the transition region, in which quarks get more and more free. The susceptibility approaches the value one for infinitely large temperatures. Note that the strange susceptibility is the quantity, which was determined with a high precision. Other quantities and particularly higher cumulants are under investigation by many lattice groups and high quality results are expected in the near future.

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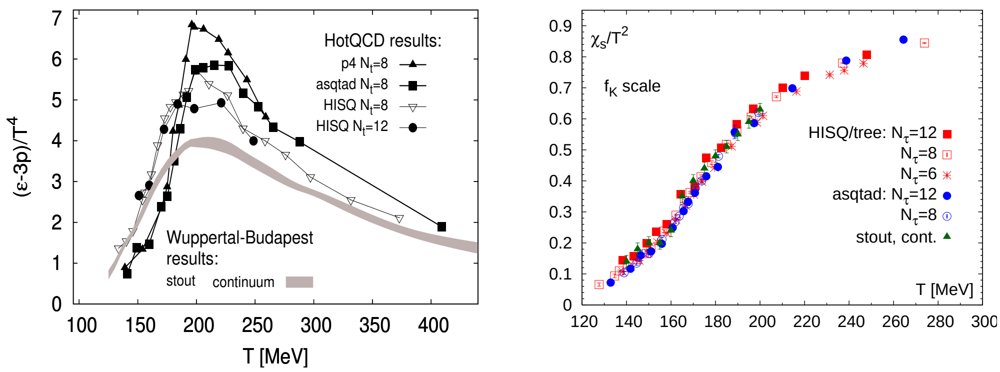

Figure 1: Left: comparison of the equation of states obtained by the Wuppertal-Budapest group (stout action) and the hotQCD Collaboration. There is still a sizable discrepancy. Right: comparison of the strange susceptibilities. In the continuum limit the two results agree.

5. Computing the dynamics of the QGP

Non-equilibrium quantities such as transport coefficients and the dilepton pair production rate represent a particular theoretical challenge. Fully resummed leading-order perturbative calculations are available in all channels of interest, but the convergence and reliability in the range of temperatures accessible in current heavy-ion collisions is questionable. Beyond perturbation theory, no general framework exists to handle these quantities. Important results have been obtained via the gauge/gravity correspondence, and provide a sharp contrast with the paradigm of kinetic theory that is based on quasiparticles, but no theory dual to QCD has been found so far.

The lattice QCD framework has been demonstrated to deliver the equation of state and other equilibrium quantities with reliable uncertainty estimates. Since it is formulated in the Euclidean formalism of thermal field theory, non-equilibrium quantities are accessible only via an analytic continuation. The central quantity of interest, which encodes the dynamics of the medium and from which e.g. the dilepton rate can be predicted, is the spectral function. When the Euclidean correlation functions are known numerically rather than analytically, this analytic continuation can be reformulated as an inverse problem for the spectral function. Such inverse problems are known to be numerically ill-posed.

Specifically, in one commonly used formulation one has to solve the integral equation

$$G(\tau,\vec{k},T) = \int_0^\infty d\omega\, \rho(\omega,\vec{k},T)\, \frac{\cosh[\omega(1/(2T)-\tau)]}{\sinh[\omega/(2T)]}, \tag{5.1}$$

for the spectral function ρ, given the Euclidean correlator G at a discrete set of points τ with a finite statistical accuracy. Compared to non-relativistic systems, QCD has the added difficulty that the correlation functions are strongly divergent at short distances. In spite of these difficulties, with good data and with the help of prior analytic information on the spectral function (including effective field theory predictions, sum rules and the operator-product expansion), its gross features can be determined. The reliable resolution of detailed (but physically essential) features such as peaks substantially narrower than the temperature is probably impossible. Nevertheless an accurate and reliable calculation of the Euclidean correlators remains an important goal for lattice QCD, not least because they can be used to test analytic methods.

The question remains, how one could possibly go beyond this indirect method within the framework of lattice QCD. In specific, individual cases, a formulation of the problem of calculating a real-time quantity in a clean way in lattice QCD exists. A simple example is the speed of sound, which through the hydrodynamic equations is related to thermodynamic potentials. This example illustrates a more general strategy, applicable when an effective field theory description of the medium exists: determine the low-energy coefficients of the effective field theory by matching to stationary properties which can be computed in lattice QCD, and then use the effective field theory to calculate the time-dependent quantities. At zero temperature, universal relations due to Luescher allow one to relate the stationay states of QCD in a box to the parameters of the S-matrix. These relations can be exploited to calculate the vector spectral function in lattice QCD without an explicit analytic continuation. For the time being, this method is restricted to low energies where only two pions can be produced.

The common theme of these examples is to establish a one-to-one correspondence between the real-time quantities of interest and stationary observables that can be computed reliably in lattice QCD. Such correspondences can presumably only build on a deeper understanding of the underlying physics, and more effort should be devoted to developing computational methods for the non-equilibrium properties of the quark-gluon plasma along these lines.

6. Viscous hydrodynamics

Hot and dense matter created in heavy-ion collisions shows a remarkable degree of collectivity, commonly quantified by the harmonic flow coefficients v_n in the Fourier decomposition of the single-inclusive particle spectra with respect to the polar angle in the transverse plane. This observation has firmly established fluid dynamics as the main theoretical tool to describe the collective flow in nuclear collisions. Currently, researchers apply second-order dissipative fluid dynamics for modelling nuclear collision dynamics. Besides an equation of state, this theory requires several transport coefficients as input parameters, foremost among them the shear-viscosity-to-entropy-density ratio η/s. Given some initial condition, fluid dynamics is then applied to model the expansion of matter created in nuclear collisions until freeze-out, i.e., where interactions between particles cease and they stream freely towards the detectors.

It has been found that, for what is believed to be reasonable initial conditions, good agreement with the finally observed particle spectra can be achieved with a surprisingly small value of η/s, giving rise to the notion that the QGP is the "most perfect liquid" ever created. The good agreement between fluid-dynamical modelling and data has also nurtured the hope that one will be able to extract the value of η/s of the QGP from experimental flow data.

However, for two reasons this is, at least at the present stage, an ill-posed problem. Firstly, η/s is certainly not constant in the QGP, but a function of the thermodynamic variables and the strong coupling constant. Thus, only an "average" value of η/s can be extracted from a comparison of fluid-dynamical calculations with flow data. This argument can be made more explicit. Consider, for example, the various parametrizations for $\eta/s(T)$ shown in the left panel of Fig. 2. It has been demonstrated in Ref. [23] that the elliptic flow coefficient at RHIC energies is not at all sensitive

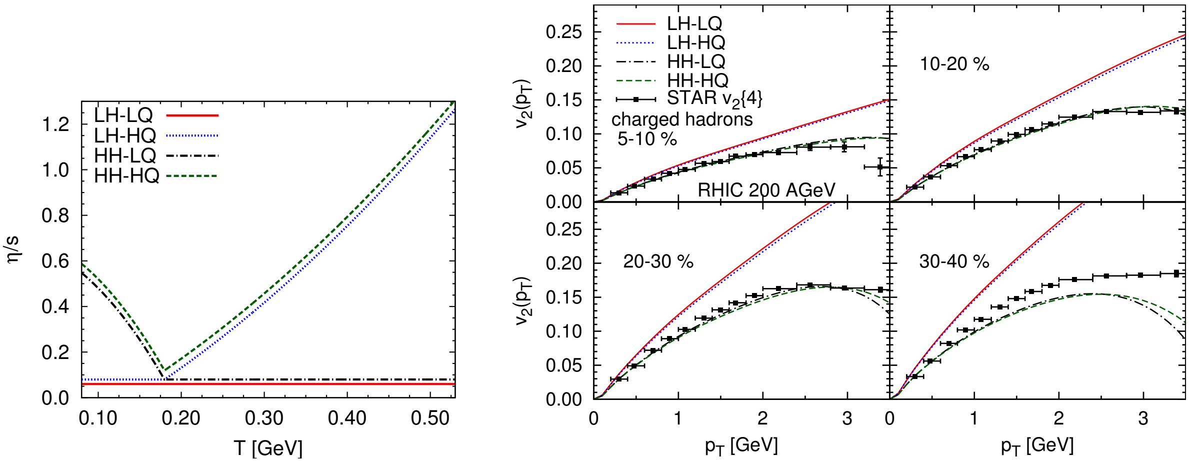

Figure 2: Left: various parametrizations of η/s as a function of temperature T, from Ref. [23]. Right: elliptic flow coefficient v_2 as a function of transverse momentum for various centralities, from Ref. [23].

to the value of η/s in the QGP phase, but only to its minimum (which is presumably close to the transition between QGP and hadronic phase), cf. right panel of Fig. 2. As was also demonstrated in Ref. [23], only at the highest LHC energies, the functional dependence of η/s on T starts to have an impact on v_2.

But even if η/s were constant, as predicted in the framework of some strongly coupled theories following the AdS/CFT correspondence, there is a second reason why an attempt to extract the value of η/s from flow data is, at least at the present stage, bound to fail (and thus an ill-posed problem). Fluid dynamics is a theory which solves conservation equations for the energy-momentum tensor and charge currents, which are coupled partial differential equations that require initial conditions on some space-time hypersurface. These initial conditions are not very well known at present. Remarkable progress has been made in recent years in describing the initial parton production (from longitudinally coherent color fields) immediately after the two nuclei collide. However, where we have to make further progress are calculations based on non-equilibrium quantum-field theory that show how the initially produced matter approaches a state which is close to thermodynamical equilibrium, because only then dissipative fluid dynamics may be applied for the further evolution of the system. Thus, in present fluid-dynamical models, a "miracle" has to be invoked by assuming that, after initial copious parton production, these partons rapidly approach thermodynamical equilibrium. Understanding this equilibration process is the remaining piece of the puzzle. Simply invoking a "miracle" and imposing some initial conditions for fluid dynamics (which are merely deemed realistic) introduces an uncontrollable uncertainty in the extraction of any microscopic observable (such as the equation of state or the transport coefficients).

Let me conclude by referring to the non-equilibrium field-theoretical calculations of Ref. [24], cf. Fig. 3, which constitute a first step in the above mentioned direction. Here, it is shown that, for a scalar conformal field theory, an equation of state is rapidly established (indicated by the equality of energy density ε with the sum of twice the transverse pressure and the longitudinal pressure $2p_T + p_L$), while the approach to mechanical equilibrium (indicated by $p_T = p_L$) takes a much longer time. Therefore, it may be more appropriate to model the fluid-dynamical stage of the system

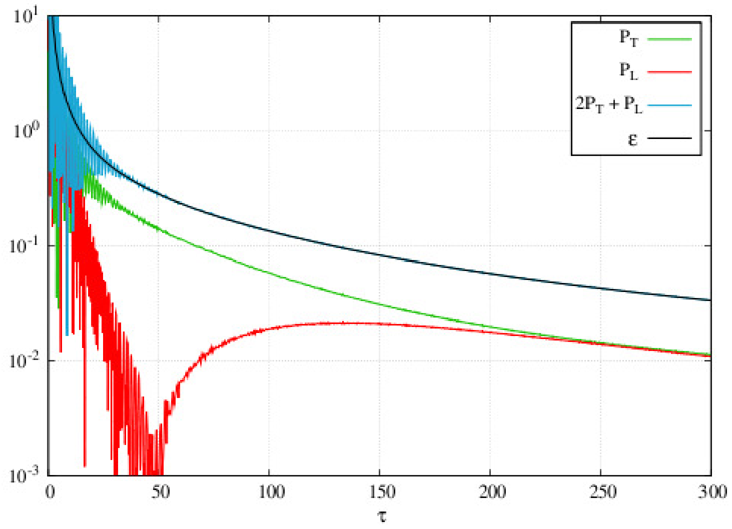

Figure 3: Components of the energy-momentum tensor as a function of time, from Ref. [24].

by a theory like anisotropic fluid dynamics developed by Florkowski, Strickland, and coworkers [25]. Such a theory (in its fully dissipative form) involves several additional transport coefficients (and most likely more than one shear-viscosity coefficient), so the question of "extracting η/s of the QGP from flow data" becomes moot and will most likely be replaced by more sophisticated questions with well- (or at least better-) defined answers.

7. Probing QGP through jet quenching

Energetic partons injected into the QCD vacuum decay into jets of hadrons. These jets get modified when the parton initially propagates through a dense QCD medium, such as a quark-gluon plasma. The amount of modification can tell us something about the structure and the properties of the QGP. The fundamental quantity that controls the medium modification of jets is the energy loss of partons as a function of path length in the medium. Partons can lose energy either by gluon radiation or simply by transferring energy to the medium in elastic collisions with particles contained in the matter. The transport coefficient that controls radiative energy loss – the dominant energy loss mechanism at high energies – is called $\hat{q}$.

There is a lot of rich data from RHIC and LHC concerning jet quenching, with the promise of much more. To give an idea of one of the open problems in the theory of jet quenching, let us oversimplify a bit[1] and focus on one characteristic parameter of the plasma, known as $\hat{q}$. The parameter $\hat{q}$ characterizes the rate at which a high-energy parton traversing the plasma gets random momentum kicks transverse to its direction of motion: $\hat{q} = d\langle Q_\perp^2 \rangle / dx$. What does this have to do with energy loss? Small momentum kicks cause small changes in the high-energy parton's direction

[1]One of the oversimplifications is that we will think about plasmas that are thick enough that the quantum mechanical duration of an individual bremsstrahlung process (the formation time) is small compared to the time that the high-energy parton spends in the plasma. Cases where this is not true are important and relevant to jet quenching, but the simplified case is adequate as an example for the theory question we want to address here.

of motion. Such changes are a form of acceleration and so cause bremsstrahlung radiation, and hence the parton loses energy through bremsstrahlung and related processes. As an example, the formula for the stopping distance of a high-energy massless parton in the plasma is related to $\hat{q}$ through a formula schematically of the form[2]

$$\ell_{\text{stop}} = \frac{\#}{\alpha_{\text{s}}} \left(\frac{E}{\hat{q}} \right)^{1/2} . \tag{7.1}$$

Whenever one sees an α_{s}, one has to wonder what running momentum scale it is evaluated at. There are two relevant scales in this problem. The plasma is characterized by its temperature T, and the most common momentum transfer from the plasma to a high-energy particle in a single collision is of order T. As a result, the calculation of $\hat{q}$ involves interactions[3] of strength $\alpha_{\text{s}}(T)$. On the other hand, for bremsstrahlung, there is also the α_{s} associated with the explicit vertex at which the high-energy particle radiates a hard gluon. The scale of this vertex turns out to be characterized by the relative transverse momentum $Q_\perp$ of the two daughter particles, which turns out to grow very mildly with energy as $Q_\perp \sim (\hat{q}E)^{1/4}$. The explicit factor of α_{s} in (7.1) is such a factor of $\alpha_{\text{s}}(Q_\perp)$, while the implicit factors of α_{s} in $\hat{q}$ involve $\alpha_{\text{s}}(T)$.

The formula (7.1) assumes that $\alpha_{\text{s}}(Q_\perp)$ is small, but it is believed to make no assumptions about the size of $\alpha_{\text{s}}(T)$. A natural question is whether the formula (7.1) is universal? What are the corrections to it for values of $\alpha_{\text{s}}(Q_\perp)$ that are not arbitrarily small? This is a case where we can learn some important field theory lessons by using AdS/CFT to look at QCD-like plasmas that are solvable at strong coupling, such as large-N_{c} $\mathcal{N}$=4 super Yang Mills and its cousins. For $\alpha_{\text{s}}(Q_\perp) = \alpha_{\text{s}}(T)$ very large, one finds[4] [29, 30, 31, 32, 33]

$$\ell_{\text{stop}} \propto E^{1/3}, \tag{7.2}$$

as reviewed in Jorge Cassalderry Solana's excellent plenary talk, instead of (7.1). The power-law is different, and there is no known relation between this strong-coupling result and the corresponding value of $\hat{q}$.

Moral: AdS/CFT teaches us something we didn't know, which is that the exponent in $\ell_{\text{stop}} \propto E^{\nu}$ depends on the size of the $\alpha_{\text{s}}(Q_\perp)$ associated with the bremsstrahlung vertex.

Problem: How reliable are small $\alpha_{\text{s}}(Q_\perp)$ results such as (7.1) [and anything else we might want to compute related to energy loss] for realistic values of $Q_\perp \sim (\hat{q}E)^{1/4}$? What is the first correction to (7.1) and related results? We don't know! This is an example of the sort of basic field theory problem that the field would like to make progress with.

[2] The physics behind this formula goes back to the work in the 1990s of Baier, Dokshitzer, Mueller, Peigne, and Schiff and of Zakharov. For a review, see, for example, [27], or the list of reviews cited in the introduction of [28]. For explicit results for stopping distance, see [26].

[3] Technical note: at weak coupling, the relevant scale is really the inverse Debye screening length $\sim gT$, and so the relevant coupling is $\alpha_{\text{s}}(gT)$. But the difference between this and $\alpha_{\text{s}}(T)$ is small at weak coupling, so we just say $\alpha_{\text{s}}(T)$ for simplicity.

[4] Technically, this is the *maximal* stopping distance. But the technical details are not relevant for the point that we want to make.

8. Jet probes at LHC

Studying hard processes is crucial for understanding the properties of the medium created in HI collisions. Experiments at the LHC operate at a new energy regime where jets are produced at high rates, which makes them one of the most interesting observables. Jets carry important information about the properties of the medium they are propagating. Making quantitative measurements of the jet energy loss is one of the central items of the heavy-ion experimental programs at the LHC and RHIC.

The first LHC result revealed a strong violation of the jet energy balance in the most central HI collisions [34, 35] while jets still remained back-to-back in azimuth at any centrality. This measurement strongly suggested that the jets energy loss happens at the level of partons propagating in the medium. Further measurements were needed to understand the phenomenon.

The modification of measured observables in HI collisions can be expressed in terms of the nuclear modification factor, the ratio of yields measured in HI collisions to that measured in pp (R_{AA}) or peripheral HI collisions (R_{CP}), taking into account the geometric factor of nuclei. Measurements of inclusive jets demonstrate a suppression by a factor of 2 in the most central collisions at the LHC energy as it is shown in the left panel of Fig. 4.

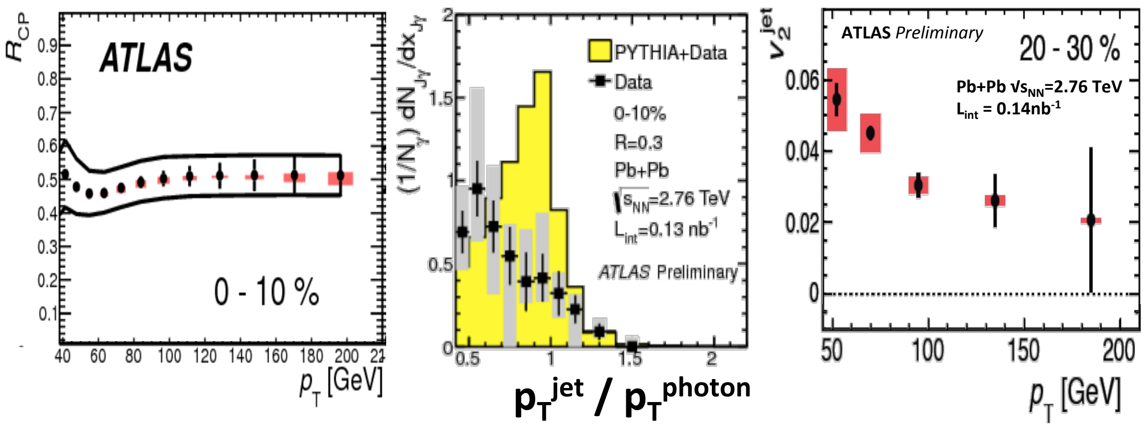

Figure 4: Left: The fully reconstructed R_{CP} [36] as a function of reconstructed jet p_{T}. Middle: jet distribution of ratio of jet p_{T} divided by the p_{T} of isolated photon reconstructed back-to-back [37]. Right: v_2 measured for fully reconstructed jets [38]. Data by the ATLAS Collaboration. The layouts of some plots have been modified to satisfy the space constrains. For unmodified plots refer to original publications mentioned in figure captions.

Measuring inclusive jets provides only limited information, because the initial energy of the jet is not known. A way to measure the amount of the energy lost by each jet is by studying boson-jet correlations, assuming that the boson may serve as a proxy for the initial momentum of the jet. Bosons, or their decay products, not carrying colour charges leave the collisions unaffected, and therefore carry information about the initial state of the collision. It was established, that the production rates of photons, Z and W bosons [39, 40, 41] scales with the nuclear thickness function of the colliding nuclei and that the shapes of the p_{T} and rapidity distributions of the bosons are not modified in Pb–Pb compared to pp.

The measurement of the p_T ratios of reconstructed jet to the boson [37] is shown in the middle panel of Fig. 4 for the most central events. The experimental points differ from the simulation which does not take into account any nuclear modification effects. The average ratio in the data is significantly smaller in the central events compared to peripheral and compared to the model. Similar results are measured in [42, 43].

The LHC results also allows estimating the path length dependence of the energy loss by the parton traversing the medium. The right panel of Fig. 4 shows the second azimuthal anisotropy coefficient (v_2) measured for fully reconstructed jets [38]. The jet suppression is stronger in the direction where the parton has to travel longer path inside the medium.

Due to the fact that jets are complex objects, an important information can be extracted by studying the structure of the jets and comparing different jet types. Figure 5 on the left shows the fraction of b-jets in the inclusive jets sample as a function of centrality. This fraction does not

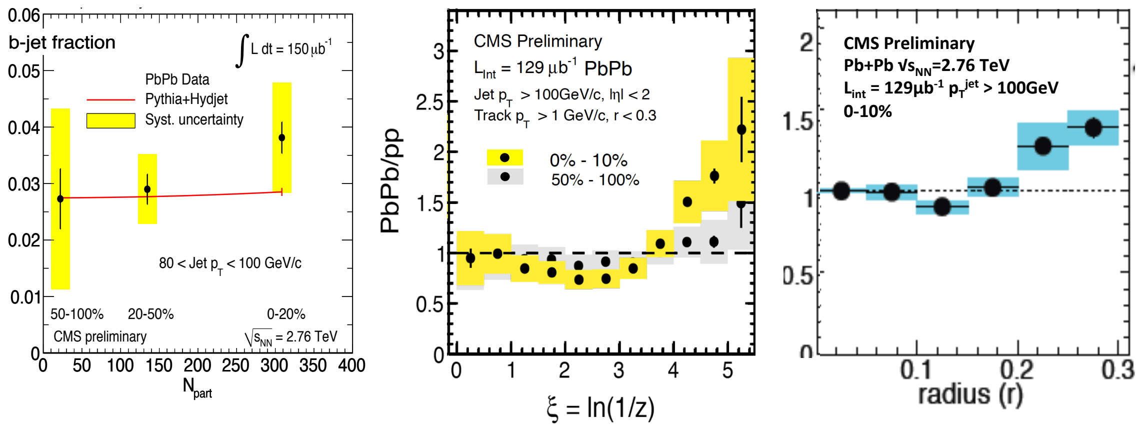

Figure 5: Left: fraction of b-jets in different centrality bins [44]. Middle: ratios of fragmentation functions measured in two centrality bins to the same in pp [45]. Right: the ratio of the Pb–Pb and pp jet shapes [45]. Data by the CMS Collaboration.

change with centrality within the uncertainties of the measurements. It indicates that the magnitude of suppression is similar for b-jets and inclusive jets.

The middle panel of Fig. 5 shows the ratios of the fragmentation functions measured in Pb–Pb and in pp systems at the same energy. The fragmentation is measured with respect to the jet momentum after the energy loss. The figure shows that the longitudinal structure of the jet does to change at the high p_T, but an overall trend suggests softening of the fragmentation function in the most central collisions.

The right panel of the figure shows the ratio of transverse jet shape as a ratio of the radial density measured in central Pb–Pb collisions to that measured in pp [45]. The shape of the curve suggest that the jet energy is redistributed from the central part of the jets to higher radii as the centrality increases. For an update on recent developments in high-p_T see [46].

9. Heavy quarks as QGP probes

Heavy quarks (charm and beauty) are sensitive penetrating probes allowing to study the dynamical properties of the Quark-Gluon-Plasma (QGP) that is created in ultra-relativistic heavy-ion collisions. Due to their large mass (larger than about 1.3 GeV/c^2), they are predominantly produced in the early stage of the collision by gluon-fusion processes, so that they provide information about the hottest initial phase.

The dissociation of quarkonium states (hidden charm and beauty) due to colour screening in the QGP is one of the "classic signatures" of deconfinement [47]. A sequential suppression of the quarkonium states, such as Υ(1S), Υ(2S) and Υ(3S), depends on their binding energy and the temperature of the surrounding medium, thus providing a so-called "QCD thermometer" [48]. However, it has been shown that yield enhancement via subsequent regeneration in QGP or at chemical freeze-out of quarkonium states due to the large heavy-quark multiplicity might play an important role at LHC energies [49, 50, 51, 52].

The nuclear modification factor R_{AA} for different quarkonium states at mid-rapidity in head-on lead-lead collisions at 2.76 TeV centre-of-mass energy per nucleon-nucleon pair indicates indeed a sequential melting of these states [53] (cf. Figure 6, left). The inclusive J/ψ production is less suppressed at low transverse momentum at LHC collision energy, which was not observed at RHIC collision energy [54] (cf. Figure 6, right). Comparison with transport and statistical model calculations suggest that a sizeable regeneration component is needed to describe the data at low transverse momentum.

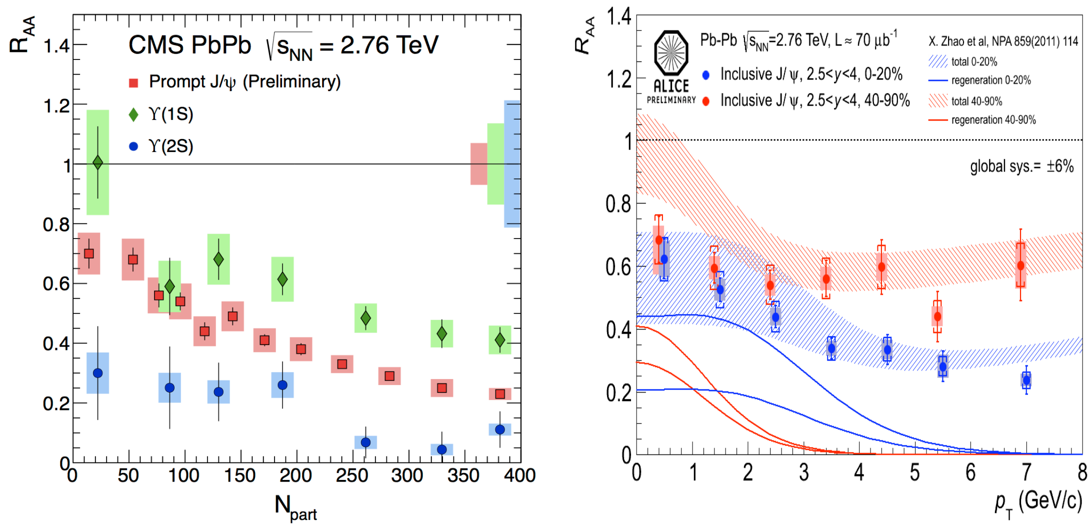

Figure 6: Left: Nuclear modification factor R_{AA} for different quarkonium states at mid-rapidity as a function of number of participants in head-on lead-lead collisions at 2.76 TeV centre-of-mass energy per nucleon-nucleon pair [53]. Right: R_{AA} for inclusive J/ψ production at forward rapidity for two different centralities [54]. The curves show transport model calculations.

Moreover, the scattered heavy quarks loose energy when traversing through the QGP by medium-induced gluon radiation and elastic collisions with the light quarks in the QGP. This interaction provides more insight on the transport properties of the QGP and thus on the energy loss mechanisms. Theoretical models based on perturbative QCD predicted that heavy quarks should experience smaller energy loss than light quarks due to the suppression of gluon radiation at small angles (so-called "dead-cone effect") [55]. Since this angle is mass dependent one expects less energy loss for charm hadrons at low transverse momentum compared to light quark hadrons (e.g. pions). Moreover, beauty is expected to be less suppressed than charm.

Figure 7–left presents the R_{AA} for prompt D-mesons, calculated as the average of the relevant factors for D^0, D^+ and D^{*+} mesons [56], for central Pb–Pb collisions measured at mid-rapidity [57, 58]. To test the predicted hierarchy of suppression, the results are compared to the R_{AA} of charged particles and pions also measured at mid-rapidity, and found to be very similar. At $p_{\mathrm{T}} < 8$ GeV/c the average R_{AA} for prompt D-mesons is slightly higher than the charged-particle R_{AA} (however, still within the systematic uncertainties) while at higher p_{T} the D-mesons R_{AA} is compatible to the one of charged particles. This strong suppression of charmed hadrons confirms observations at RHIC and seems to indicate that the energy loss rate depends less strongly on the parton mass than expected for radiative energy loss. While energy loss models currently describe the observed suppression at high transverse momentum reasonably well the description at low transverse momentum (≤ 2 GeV/c) is more challenging. Higher statistics and detailed comparisons with models is required to see how this small, and within current statistics not very significant, difference can be accommodated by theory. Figure 7–right presents the R_{AA} measurements [59] based on secondary, non–prompt J/Ψ mesons, mostly originating from B decays, at $p_{\mathrm{T}} > 6.5$ GeV/c, compared to charged hadrons, indicating a smaller energy loss for beauty than for light quarks. In general, while the results give a hint about the expected hierarchy of suppressions, the current precision of the measurements makes it difficult to conclude with respect to the predicted colour charge and mass hierarchy of parton energy loss [60]. Detailed studies based on the analysis of the p–Pb data at 5.02 TeV are needed to clarify the issues of the initial state effects and measure the contribution from cold nuclear matter effects such as nuclear shadowing and Cronin enhancement.

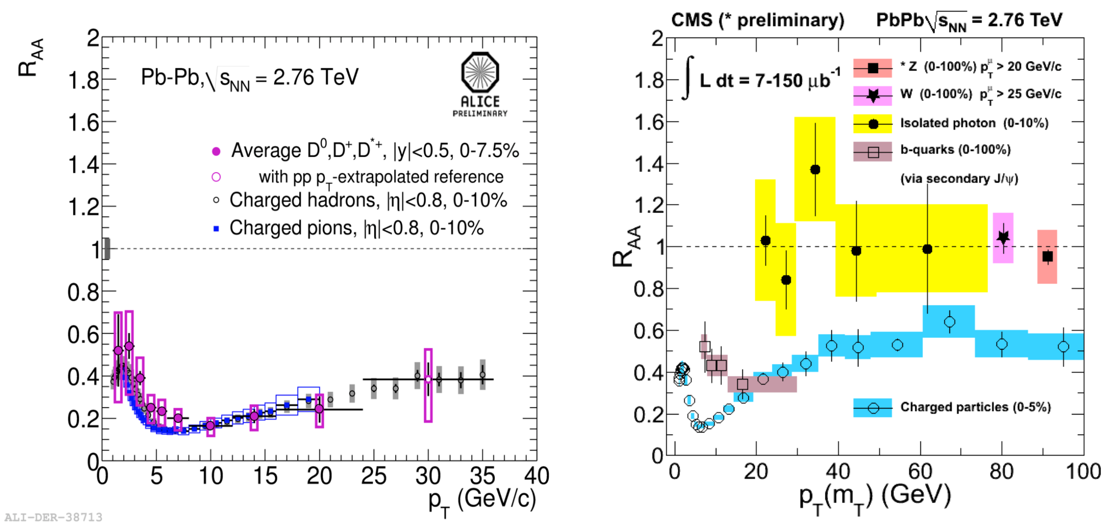

Figure 7: Transverse momentum dependence of the nuclear modification factor R_{AA} for different particle species at mid-rapidity in head-on lead-lead collisions at 2.76 TeV centre-of-mass energy per nucleon-nucleon pair.

Furthermore, measurements of the momentum distribution of emitted particles and comparison with hydro-dynamic model calculations have shown that the outward streaming particles move collectively, with the patterns arising from variations of pressure gradients early after the collision. This phenomenon is called azimuthal anisotropy or elliptic flow and is analogous to the properties of fluid motion. The study of the elliptic flow (or azimuthal anisotropy) of heavy-quark particles is particularly interesting as it provides information on the degree of thermalisation (interactions) of heavy quarks in the QGP. Sensitive measurements of the azimuthal anisotropy of electrons from heavy-flavour decays and prompt open charmed mesons in peripheral heavy-ion collisions indicate a sizable flow of heavy quarks [62]. A simultaneous description of the nuclear modification factor and elliptic flow heavy-quark particles is challenging for the currently available theoretical model calculations.

In summary we can conclude that the matter created at RHIC and LHC is dense and dissipative.

10. The RHIC Beam Energy Scan

The exploratory phase-I of the Beam Energy Scan (BES) program at Brookhaven Relativistic Heavy-Ion Collider (RHIC) was completed in 2011, with data sets at $\sqrt{s_{NN}} = 39$, 27, 19.6, 11.5 and 7.7 GeV. Together with larger data sets at 62, 130 and 200 GeV, these measurements provided an initial look into the uncharted territory of the QCD phase diagram. All data taken by the STAR (Solenoidal Tracker At RHIC) detector below the RHIC injection energy $\sim$ 20 GeV are affected by large statistical errors, steeply increasing with decreased energy. Nevertheless, the BES Phase-I measurements allowed for the first time a direct search for the anticipated critical point and phase transition signatures.

The BES program goals [63] are focused on three areas. The first one, and arguably the least complicated, is to scan the phase diagram with varying collision energy (different μ_B and T) to find whether (and where in $\sqrt{s_{NN}}$) the key QGP signatures reported at the top RHIC energy are no longer observed. This may suggest that the system remains in the hadron gas phase throughout the collision process. The disappearance of a single signature would not be convincing evidence of the onset of deconfinement, because there are other phenomena not related to deconfinement which may cause a similar effect, or our sensitivity to the phenomenon of interest could be reduced at lower energies. However, the modification or disappearance of several signatures simultaneously would constitute a more compelling case. The particular observables identified as the essential drivers of this part of the run are: constituent quark number scaling, hadron suppression in central collisions characterized by R_{CP}, untriggered pair correlations in the space of pair separation in azimuth and pseudorapidity, and correlations associated with the Chiral Magnetic Effect.

The second goal is to search for critical fluctuations associated with a strong increase in the susceptibilities, which are expected in the vicinity of a critical end point. However, finite size effects could wash out this critical behavior. The search for evidence of a softening of the Equation Of State as the system enters a mixed phase region was proposed as a third goal of the BES program. Such an effect is implicitly associated with crossing a first-order phase transition. Promising observables in this search are: elliptic and directed flow of charged particles and of identified protons, net protons, and pions, azimuthally-sensitive femtoscopy, and fluctuations indicated by large jumps in baryon, charge, and strangeness susceptibilities, as a function of system temperature.

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The BES Phase-I results, although still considered preliminary, already have allowed STAR to close-in on some of the goals outlined above, and what is particularly important, these Phase-I results specify a clear path for Phase-II which should lead to a conclusion regarding all of the BES goals. Phase-I of the BES program allowed STAR to extend the μ_B reach of RHIC from a few tens of MeV up to approximately 400 MeV. The critical region in μ_B has been predicted to span on the order of 100 MeV [64, 65, 66, 67, 68, 69, 70], which suggests that the overall program of BES measurements to date offers reasonable coverage below $\mu_B \sim 400$ MeV. It has been very encouraging that the performance of both the collider and the experiments were excellent throughout the entire energy range explored to date.

As expected, some highly promising preliminary results have been report. Highlights were also presented in this conference and summarized in [71]. The statistics collected during BES Phase-I are not sufficient to reach a confident conclusion on the three goals explained above. Therefore, the STAR Collaboration proposes the BES phase-II program of precision measurements to map out the QCD phase diagram with an order of magnitude increase in data samples. BES phase-II is planned to take data around 2017. Results of Phase-I allow STAR to focus Phase-II on a narrower energy window, where signatures of sQGP seems to change or even disappear, i.e. below $\sqrt{s_{NN}} \sim 20$ GeV. Additionally, there is a plan to run STAR in fixed-target mode concurrently with collider mode during BES Phase-II. This would allow the extension of the range of accessible baryon chemical potential from the current maximum of just above $\mu_B \sim 400$ MeV up to ~ 800 MeV, corresponding to a collision energy $\sqrt{s_{NN}} \sim 2.5$ GeV. This wide-ranging experimental effort must be accompanied by advances in theory. Some topics where theoretical developments are particularly needed were also outlined in [71].

11. Conclusions

To conclude, after more than a decade of experiments at RHIC and recently at LHC, a consistent picture of the quark-gluon plasma as a strongly coupled gauge plasma with extraordinary transport properties has emerged. The challenge now is to quantify the qualitative conclusions drawn from the experiments. The framework for this endeavour is still developing, but many of its central aspects are becoming visible, as our roundtable discussion has shown. More data from RHIC and LHC will be forthcoming soon; detector upgrades at RHIC and the coming p+Pb run at LHC promise a wealth of new insights. The development of rigorous theoretical frameworks for comparison with experimental data is also making rapid progress, in viscous hydrodynamics, jet quenching, as well as in the theory of heavy-quarkonium interactions in the QGP.

The uncertainties of the shear viscosity of the QGP have been narrowed to within a factor two, and it is becoming clear that the QGP produced at RHIC is more a “perfect” liquid than that produced at LHC. Theory-data comparisons of jet quenching also indicates that the effective coupling constant controlling jet-medium interactions is smaller at LHC than at RHIC. Rapid progress is being made on all aspects discussed by the Roundtable experts, and we can expect that many of the questions discussed here will be answered at the time of the next *Confinement* conference.

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