Exploring the Phase Diagram of Nuclear Matter with Relativistic Heavy Ion Collisions

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Abstract. I will review the present status of relativistic heavy ion collisions at RHIC and the LHC with special emphasis on the most recent discoveries, which characterize the deconfined phase of matter and the phase diagram itself.

1. Introduction
Since the discovery of the deconfined, strongly interacting phase of matter at RHIC in 2005 [1], the experiments at RHIC and the LHC have focussed on characterizing this new phase and determining the features of the QCD transition phase diagram at lower energies. The deconfined phase, which was originally termed the Quark Gluon Plasma (QGP) turned out to show quite unexpected features, in particular a strong collective behaviour which is characterized by a very small mean free path between interactions. This led to the rather dramatic announcement that the partonic matter phase behaves more like an ideal liquid than a weakly interacting plasma. Ideal hydrodynamics came close to describing the collective flow patterns, and after small viscous corrections were added, the data could be described well enough to make first estimates of state variables [2], such as the shear viscosity over entropy ratio ($\eta/s$), which showed that the produced fluid indeed features a minimal viscosity ratio, very close to the conjectured quantum limit of $\eta/s = 1/4\pi$ [3].

Since these discoveries, which are almost a decade old, the experiments have evolved by a.) increasing the collision energy range by almost a factor 30 to the LHC energies in order to characterize the deconfined in more detail and with newer detector technology, and b.) decreasing the collision energy in order to determine the exact temperature and density when the QCD transition sets in, and to determine whether the phase diagram of nuclear matter features a critical point on the deconfinement line. The nature of the phase diagram at high temperatures and low densities has come into focus due to continuum extrapolated lattice QCD results which were, for the first time, conducted with realistic quark and pion masses and with very small lattice spacings [4,5]. These first principle calculations show unambiguously that at LHC and the highest RHIC energies where the baryon density (as described by the quark chemical potential) is negligible, the QCD transition is an analytic crossover rather than a transition of first or second order [6]. Effective models such as Dyson-Schwinger chiral theory [7] or PNJL [8] have indicated that at finite density the transition should become first order, which means that the transition line will feature a critical point. These postulates have not yet been confirmed by lattice QCD calculations, since the so-called sign problem, makes it impossible to

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cleanly calculate the transition at higher quark chemical potential. Several methods to approximate the finite density behaviour on the lattice have been attempted, either through Taylor expansion or imaginary chemical potentials, but none of them have yielded conclusive evidence for a critical point [9,10]. Still, since in particular the RHIC machine is capable to lower the collision energy to study the baryon densities in question, a significant experimental program, labelled the Beam Energy Scan (BES) program, has been initiated and its first phase was concluded in the past year.

At the higher LHC energies the main questions that have been addressed are whether one can a.) determine the shear viscosity to textbook accuracy and b.) show directly that hydrodynamics and strong interactions are indeed the proper model to describe the behaviour above the transition. This picture deviates significantly from the original belief that the deconfined phase consists, even near the phase transition, of weakly interacting, asymptotically free quark and gluons. Early lattice QCD calculations showed that from about 1.5-2 Tc on the chosen order parameters approach the Stefan Boltzmann limit and show deviations of at most 20% from the limit, which characterizes an asymptotically free phase. Since the latest calculations show more of an analytic crossover the limit is approached slightly slower. Still, the fact that in this crossover region the phase acts like a strongly coupled plasma requires us to rethink the properties of the relevant degrees of freedom in the deconfined phase near the hadronization temperature. Fluctuation measurements are sensitive to the chiral, confinement and flavour properties of the relevant particle state in the transition region and they can be directly related to susceptibility calculations on the lattice [11]. Regarding the interaction strength between the degrees of freedom, several parton based transport models (BAMPS [12], PHSD [13], non-Abelian bremsstrahling [14]) taking into account multi-parton interactions in the dense regime have been proposed to describe the collective features of the emitting system without invoking parton hydrodynamics. This has become more relevant since some of the hadron correlation structures, which have been attributed to collective flow, have now also been measured in proton-nucleus (pA) and even proton-proton (pp) collisions at the LHC. More detailed measurements are needed to sort out whether the hydrodynamical approach is also valid for even the smallest interaction system, where no thermalization is historically expected, or whether multi-parton interactions in a non-equilibrium system can explain correlation structures even in heavy ion collisions.

On a broader scale these measurements will relate to cosmology by studying the evolution of the universe during the QCD transition, which leads to correlations and flavour patterns during the hadronization, that might still be imprinted in the hadronic cosmological matter in the core of stars and cosmic rays today.

In the following I will first discuss the latest LHC measurements in the context of determining collectivity in the heavy ion systems, then I will briefly review the most dramatic measurements of the RHIC-BES program, before ending with some interesting observations from collision energy dependent fluctuation measurements. I will end with a short conclusion that relates these measurements to the QCD transition and its role in the evolution of matter in the universe.

2. LHC measurements on collective behaviour

Over the past three years the LHC has successfully completed a program that included proton-proton, proton-Pb and Pb-Pb collisions at various beam energies, all of which correspond to a regime very near zero baryon density on the nuclear phase diagram. This program enables us to study the source of collective behaviour as a function of the system size. Furthermore the high multiplicity achievable at these beam energies allows a very precise determination not only of the higher harmonics in the Fourier decomposed moment spectrum of the emitted charged particles, but also of the features of multi-particle correlations for a given harmonic.
2.1. Heavy Ion Collision Measurements

The realization that collectivity in a heavy ion collision can be measured by determining how much an asymmetry in the original coordinate system of the produced fireball causes an anisotropy in the momentum spectrum of the emitted particles was realized during the early days of the fixed target relativistic heavy ion programs at the BEVALAC and the AGS [15,16]. As expected the ideal hydrodynamic limit was never reached at these low energies. Still, a certain level of collectivity could be shown, in particular in the lowest harmonic \( v_2 \) in the Fourier decomposed momentum spectrum (elliptic flow) in non-central collisions. During the analysis of the RHIC data it became also apparent that the energy density fluctuations in the fireball, which are largely caused by the distribution of nucleons, and subsequently quarks and gluons in the initial state, will cause higher harmonics in the Fourier series to occur on an event-by-event basis [17].

Early measurements at RHIC energies indicated that the higher harmonics, which are more sensitive to the initial conditions, might be used to constrain the viscosity ratio by distinguishing the contribution from asymmetries caused by the initial density profile. In particular the early PHENIX results showed that \( v_3 \) can be used to show that an initial profile based on a highly saturated gluon density (Color Glass Condensate) does not describe that data [18]. Since then, though, models that merge reasonable assumptions of the initial parton densities with a hydrodynamic evolution of the system have proven to be very successful in describing the higher harmonics and constraining the \( \eta/s \) value [19].

This has become possible due to the tremendous wealth of higher order harmonic data from all three LHC experiments. Fig.1 shows a comparison of \( v_2 \) data as a function of transverse momentum from ATLAS [20], ALICE [21], and CMS [22]. The data are in excellent agreement and reach out to almost 20 GeV/c for all experiments. Fig.2 shows the latest \( v_3 \) and \( v_4 \) results from ATLAS based on four-particle correlations [20].

![Figure 1. Comparison of ATLAS [20] and CMS [22] (top panel), and ATLAS [20] and ALICE [21] (bottom panel) measurements of \( v_2 \{4\} \) for selected centrality intervals at \( |h| < 0.8 \) (from [20]).](image-url)
The transverse momentum dependence of $v_3$ calculated with two- and four-particle cumulants and with the event-plane method $v_3\{\text{EP}\}$ for the centrality interval 0–25% (left plot) and 25–60% (middle plot). The right plot shows the same results for $v_4$ for the centrality interval 0–25% (from [20]).

The argument to measure more than two-particle correlations for a given harmonic is relatively simple: the more particles contribute to a collective effect, the less likely it is that this effect can be caused by fundamental non-equilibrium gluon exchange processes. The latest transport calculations expanded the basic 2 to 2 processes to include 2 to 3 and 3 to 2 processes [12], but it is difficult to imagine that exchange processes can be extended to more than a few particles. Therefore any collective effect that includes more than four particles can be viewed as a likely sign for collective dynamics outside of multi-parton interactions. I will come back to this point when discussing the results from the small system measurements. In order to constrain the initial conditions and ultimately the precise value of the viscosity over entropy ratio, the data have been analysed up to $v_5$ in the context of a hybrid model taking into account initial gluon densities and hydrodynamical evolution. Fig.3 show the $p_T$-dependence as measured by ATLAS [23] and Fig.4 shows the centrality dependence as measured by ALICE [24] in comparison to a MUSIC model calculation which yields a $\eta/s=0.2$ or roughly 2.5 times the quantum limit [19]. This is still many times smaller than one would expect in a perturbative QCD calculation.

**Figure 2.** The transverse momentum dependence of $v_3$ calculated with two- and four-particle cumulants and with the event-plane method $v_3\{\text{EP}\}$ for the centrality interval 0–25% (left plot) and 25–60% (middle plot). The right plot shows the same results for $v_4$ for the centrality interval 0–25% (from [20]).

**Figure 3.** RMS anisotropic flow coefficients $(v_n^2)^{1/2}$, computed as a function $p_T$, compared to experimental data of $v_n\{2\}$, $n \in \{2, 3, 4\}$, by the ATLAS collaboration [23]. Results are for 200 events per momentum bin with bands indicating statistical errors (from [19]).

**Figure 4.** RMS anisotropic flow coefficients $(v_n^2)^{1/2}$, computed as a function of centrality, compared to experimental data of $v_n\{2\}$, $n \in \{2, 3, 4\}$, by the ALICE collaboration [24]. Results are for 200 events per centrality with bands indicating statistical errors (from [19]).
The viscous corrections are not negligible but they are small and well within the capabilities of existing viscous hydrodynamical models. If one applies the same model to the existing RHIC data the $\eta/s$ reduces to 0.12 [25], so as expected the very strong coupling reduces as a function of collision energy but the pQCD limit is still far away and we are seemingly still dominated by strongly coupled degrees of freedom above the QCD transition.

2.2. \textit{pPb} and \textit{pp} Collision Measurements

The analysis of the first year of proton-proton collisions at the LHC led to a very surprising result, when CMS announced that they found long-range two particle correlations in very high multiplicity events that are consistent with elliptic flow. Historically proton-proton collisions were considered reference data obtained in a system that is distinctly non-equilibrium and shows no collective effects from emission from a thermalized fireball. Since then certain multi-parton interactions, if properly included in fragmentation models, such as PYTHIA, have given rise to long-range correlations. In particular final state effects, characterized as color reconnection, seem to be able to at least qualitatively confirm the correlation trends observed in high multiplicity proton proton collisions. A definitive test of either theory (collective or non-equilibrium) should be possible by studying nucleon-nucleus collisions, such as p-Pb or d-Au, where we expect again no collective behaviour but a significant sensitivity to the initial gluon density, since the nucleon system is isolated in the incoming channel. In this case the most relevant flow measurement is the multi-particle correlation probability for a fixed harmonic. Since the charged particle multiplicity is limited in the small systems only the lowest collective harmonic ($v_2$) has been fully analysed at this time. Fig.5 shows the rather dramatic result based on the preliminary CMS analysis [25]. As can be seen, although the flow in pPb is about a factor 2 smaller than in PbPb collisions, the multi-particle correlations up to $v_2\{8\}$ are finite for the small system.

![Figure 5](image_url)

\textbf{Figure 5.} The $v_2$ results obtained from multi-particle cumulants, and LYZ method, averaged over the particle $p_T$ range of 0.3–3.0 GeV/c, as a function of number of tracks recorded in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV (left) and pPb at $\sqrt{s_{NN}} = 5.02$ TeV (right). Shaded areas denote systematic uncertainties (from [25]).
All $v_2$ measurements in both systems are consistent from $v_2\{4\}$ to $v_2\{8\}$. $v_2\{2\}$ is generally larger because non-flow effects cannot be fully suppressed when only two particles are correlated. The measurement gives rise to an interpretation based on hydrodynamics, even for very small collision systems that lead to a sufficiently large charged particle multiplicity. At this point it seems very difficult to reconcile these results with just fundamental gluon exchange processes. If small systems indeed show a high level of collectivity then it might be possible to determine potentially a sub-structure in the proton from the flow patterns since they will be, as in the large systems, dependent on the initial distribution of the energy density in the colliding system. The question on how such a small system, or even a large system, can thermalize in such a short time is still not fully answered. Several ideas have been proposed, but need to be verified with more experimental data [26,27].

3. Beam Energy Scan Results from RHIC

The discovery of a deconfined phase and the realization that at high collision energies the QCD transition is an analytic crossover makes it very interesting to study the phase diagram as a function of collision energy, i.e. as a function of finite density ($\mu_B$). One needs to remember, though, that all previous fixed target experiments at the BEVALAC, SIS, AGS and SPS have yielded a significant wealth of data on temperature and density dependence of the measured particle properties. They are well described by statistical hadronization models (SHM), which assume emission from a chemically and kinetically equilibrated source. The models yield a chemical freeze-out curve, which is very close to QCD transition curve, at least for the small densities at which lattice can yield definitive results on the transition temperature based on Taylor expansion calculations. Fig.6 shows the long established chemical freeze-out curve based on measured particle yields and ratios [28].

![Figure 6. Chemical freeze-out curve in SHM based on data from RHIC (black and red), SPS (blue), AGS (red) and SIS (green) (from [28]).](image)

The questions to answer with the BES are: a.) can we determine the collision energy, and thus the energy density, for which the transition is not achieved and the system stays in the hadronic phase. b.) can we determine the existence of a critical point on the nuclear phase diagram, and c.) can we show that the chemical freeze-out temperature coincides with the hadronization temperature and is common for all hadrons?

3.1. Flow measurements as a function of energy

The discrepancy between realistic hydrodynamical calculations and the data from the AGS and SPS is contrasted by the near perfect agreement between the same models and the highest energy RHIC and
LHC data. This difference gives rise to the assumption that the onset of small viscosity over entropy ratios will coincide with the transition to the deconfined phase. STAR has measured the elliptic flow as a function of transverse momentum at five different energies ranging from \( \sqrt{s_{NN}} = 7.7 \) GeV to 200 GeV, as shown in Fig.7 [29]. The results show that a decrease in the \( v_2 \) strength is measured below \( \sqrt{s_{NN}} = 39 \) GeV and the flow is weakest at the lowest energy. This might indicate that the minimum collision energy required to deconfine the matter is in the \( \sqrt{s_{NN}} = 10-40 \) GeV range.

Another interesting flow measurement, which was suggested early on as a possible signature for the transition energy density, is directed flow (\( v_1 \)). In the early models the directed flow changes from a ‘bounce off’ type of interaction to a ‘squeeze-out’ interaction [30, 31], which means \( v_1 \) would change sign, reach a minimum and then continue to grow again as a function of increasing collision energy. Such behaviour would signal a softest point in the equation of state, i.e. a system of maximum compressibility. The measurement by STAR, conducted for the net-protons emitted from the interaction, is shown in Fig.8 [32] and shows a remarkable likeness to the predicted effect. In theory the softest point coincides with the energy necessary to convert from a dense hadronic system to a deconfined partonic system. Based on this measurement this would occur at collision energies between \( \sqrt{s_{NN}} = 10-20 \) GeV.

The two aforementioned measurements are only examples of a whole series of studies initiated to determine the transition conditions. In the final analysis one needs to assume that all measurements, which can be related to the QCD transition show a consistent collision energy dependence. The early results are intriguing but they will require additional consistency test of dynamic variables in the probed energy regime.

### 3.2. Fluctuation measurements as a function of energy

Dynamic fluctuation measurements have a long history of controversy in the field of relativistic heavy ion measurements, in part because they are very sensitive to critical effects near the phase transition and to quantum number dependent patterns, which might allow us to study various aspects of the transition in a first principle approach. On the flip side, fluctuations can often be artificially generated.
through experimental limitations, such as geometrical acceptance and reconstruction efficiencies, and they are prone to background from trivial sources, such as detector response effects [33].

The main goal of the BES study of fluctuations is to find evidence for a critical point in the QCD phase diagram. Although the lattice QCD results on this subject are at best inconclusive, many effective models predict the existence at finite chemical potential. Semi-quantitative predictions of actual measurable quantities are largely based on non-linear sigma model simulations [34, 35]. The exact correspondence of susceptibilities on the lattice, which are the derivatives of the pressure with respect to the chemical potential of a specific quantum number, to higher moments of the measured particle multiplicity, allows, for the first time, to relate a measured quantity to a calculated quantity on the lattice as long as the measurement reflects uniquely the behaviour of a conserved quantum number [11]. For example it can be shown that net-protons are a good proxy for the net-baryon number [36] and net-charges obviously reflect the behaviour of the electric charge. Fluctuations in these moments of multiplicities are predicted near a critical point in the sigma model. Generally, the higher the moment the more pronounced the non-Poissonian fluctuation. The order of the moment also determines the required statistics for a significant measurement, though. At this time, STAR was able to determine the first four moments (mean ($c_1$), variance ($c_2$), skewness ($c_3$) and kurtosis ($c_4$)) of the net-proton and the net-charge particle distributions [37, 38].

In particular the shape and the magnitude of the kurtosis over variance ratio was proposed as a sensitive signature for critical behaviour. A moment ratio has the advantage that volume effects that are significant in a limited acceptance detector cancel out. The sigma model has predicted two unique effects near the critical point: a.) the ratio should go negative (compared to a Poissonian baseline) and b.) the magnitude should rise significantly above the Poissonian baseline at the critical point. The figures above show the collision energy dependence of moment ratios for net-protons, (Fig.9) and net-charges (Fig.10).

![Figure 9](image1.png)

**Figure 9.** Beam-energy dependence of net-proton $S_0$ and $\kappa \sigma^2$, after all corrections, for most central (0-5%) and peripheral (70-80%) bins. The error bars are statistical and the caps represent systematic errors. Results from URQMD and independent production are superimposed (from [37]).

![Figure 10](image2.png)

**Figure 10.** Beam-energy dependence of net-charge $\sigma^2/M$, $S_0$, and $\kappa \sigma^2$, after all corrections, for most central (0-5%) and peripheral (70-80%) bins. The error bars are statistical and the caps represent systematic errors. Results from the Poisson and the NBD baselines are superimposed (from [38]).
A slight dip in the $c_2/c_4$ ($\kappa\sigma^2$) ratio is observed in the net-proton but no significant rise can yet be established. The net charges show no effect which can be understood since the charges are a combination of pions, kaons and protons, pre-dominantly, and the sigma model predicts that the strength of the critical behaviour is hadron mass dependent [39]. More measurements in particular below $\sqrt{s_{NN}} = 20$ GeV are planned for phase II of the RHIC-BES which is scheduled for 2017/2018.

Quantum number fluctuations can also be used for a slightly more mundane, but nevertheless very important measurement, regarding the dynamic evolution of the system through the hadronization process. As was stated earlier the particle yields determined in statistical hadronization models with a single freeze-out temperature describe the measured yield extremely well over many orders of magnitude. The model is a static model, though, which can only determine the yields assuming a fixed temperature. If confirmed by more sensitive measurements, namely fluctuations, one would have to conclude that the hadron yields and fluctuations tell us very little about the hadronization mechanism and the relevant degrees of freedom above the transition temperature. If, though, specific patterns arise, depending on which quantum number is studied, then we might be able to determine a quantum number specific evolution through the phase transition. This topic has garnered considerable interest recently when it was shown that at least for some fluctuation measures on the lattice one can determine a flavour specific freeze-out temperature based on differences in susceptibility ratio between light and strange quarks [40]. It was shown that the continuum extrapolated $c_2/c_4$ ratio exhibits a 20 MeV temperature difference between the two quark flavors. This difference in the chemical freeze-out is not necessarily expected since the statistical fits to the particle yields describe all species reasonably well with a single temperature. A closer look, though, shows that at the highest RHIC and LHC energies the proton yields are consistently over estimated when assuming a common temperature of 164 MeV. The best fits to the proton/pion ratios yield a temperature of 148 MeV. A compromise of 152 MeV slightly overestimates the protons and underestimates the strange baryons by 2-3$\sigma$. Studies of the net-proton and net-charge fluctuations, independently performed in the framework of lattice QCD [41] and a hadron resonance gas (HRG) approach [42], shows that for fluctuations, which are dominated by light flavour particles, the preferred freeze-out temperature is less than 150 MeV.

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**Figure 11.** Comparison between HRG model results and experimental data for the most central collisions (0-5%) (from Refs. [37, 38]) for $\sigma^2/M$ of net-electric charge (blue symbols) and net protons (red symbols). The experimental data have been used in the HRG model in order to extract $T$ and $\mu_B$ for each collision energy (from [42]).

**Figure 12.** Freeze-out parameters in the $T-\mu_B$ plane: comparison between the curve obtained in Ref. [28] (grey band) and the values obtained from the combined analysis of $\sigma^2/M$ for net-electric charge and net protons in the HRG model (blue symbols) and in lattice QCD (Ref.[41]) (from [42]).
Fig. 11 shows the HRG fit to the experimental $c_2/c_1$ data, Fig. 12 shows a comparison of the obtained freeze-out temperature from lattice and HRG with the freeze-out properties from fits to the yields.

If it can be established that strange particle fluctuations require a higher temperature then one could deduce that the chemical freeze-out is flavour dependent. In other words during the dynamic expansion of the system in the crossover region the system is likely emitting strange particles at a higher temperature than light quark particles. There will be a finite time window during which the system will predominantly produce strange matter, which could lead to higher mass strange baryon configurations as postulated by the quark model [43] or even exotic strange quark matter configurations as suggested for the core of neutron stars [44].

4. Summary
The study of the deconfined matter produced at RHIC and LHC energies in heavy ion collisions has reached a level of sophistication that allows us to determine the properties of the high temperature phase just above the phase transition. It turns out that this phase is very strongly interacting with ideal liquid like features. The viscosity over entropy ratio is near the quantum limit at RHIC and only rises slightly when reaching LHC energies. The system is still well below the pQCD limit and therefore cannot be described with weakly interacting quarks and gluons. Whether quasi-particles or color-neutral bound states dominate the system between 1-2 $T_c$ remains to be seen, but there are first indications that the de-excitation to hadronic matter might be flavour dependent, which opens the possibility of a phase of mixed degrees of freedom which follows a flavour specific pattern during the hadronization process. Exotic states could be formed during this time in the cosmological evolution and might be found in relativistic heavy ion collisions as well as the interior of stars.

The search for a critical point is still ongoing, but it seems likely that the minimum required energy density to achieve a deconfined state is somewhere in the $\sqrt{s_{NN}} = 10-30$ GeV range. It might be that a critical point, which should exist at finite chemical potential, is located at such a high quark density and temperature that it cannot be reached with accelerator based experiments.

Finally, the phenomena that enable us to quantify the collective behaviour of the deconfined parton phase also seem to be achievable in the collision of very small systems at energies that produce high particle multiplicities in the final state. If true, then the paradigm of proton-proton collision reference data needs to be revised and distinctly non-perturbative effects in the system, such as hadronization and equilibration, could be an explanation for effects in elementary particle collisions within the same framework that is presently used to describe large multi-particle initial state systems such as heavy ion collisions. This would also allow us to study the Quark Gluon Plasma in collisions that are generally reserved for the study of Higgs Bosons or exotic phenomena beyond the Standard Model.

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