

Exploring the QCD phase diagram through high energy nuclear collisions: An overview

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We present an overview of the status of the studies related to the phase diagram of strong interactions through high-energy nuclear collisions. We discuss both the theoretical and experimental status of establishing the various QCD phase structures in the phase diagram, such as, quark-gluon phase, quark-hadron crossover, crossover temperature, phase boundary and critical point.

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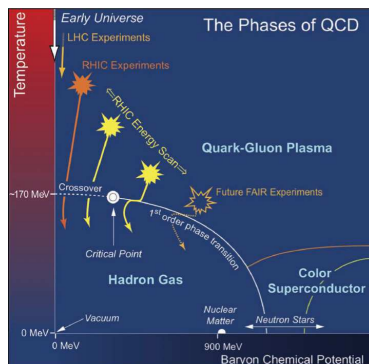


Figure 1: (Color online) The conjectured phase diagram of strong interactions [4].

1. Introduction

A phase diagram displays information on the structure of the matter as it manifests various degrees of freedom under different external conditions. One of the most widely studied phase diagram in science is that of water. In this case the underlying interaction is electromagnetic, one of the four basic interactions that occur in nature. The goal of high-energy nuclear collisions is to establish a similar phase diagram for a system whose underlying interaction is due to the strong force. The phase diagram of strong interaction on one hand displays the interplay of the chiral and center symmetry as a function of quark masses [1], on the other hand can be represented as a graph which shows variation of temperature (T) versus the chemical potential (μ) [2] associated with conserved charges like baryon number (B), electric charge (Q) and strangeness number (S). The later is the one which can be experimentally studied.

In the heavy-ion colliding systems, it is found that values of μ_Q and μ_S are small [3] and hence the phase diagram of strong interaction reduces to a two dimensional graph of T vs. μ_B as shown in Fig. 1. Further, the analysis of particle yields in the heavy-ion collisions and their comparison to statistical models suggests that T and μ_B vary in opposite manner with center of mass energy ($\sqrt{s_{NN}}$) at the chemical freeze-out [5]. The μ_B decreases with $\sqrt{s_{NN}}$ while T increases with increase in $\sqrt{s_{NN}}$ [6]. Thus changing the $\sqrt{s_{NN}}$ one can vary the two axes of phase diagram, T and μ_B , and experimentally get access to a large part of the phase space. The Beam Energy Scan (BES) program has been designed based on this idea for the study of the phase structure of the quantum chromodynamic (QCD) phase diagram [7, 8]. The phase diagram in Fig. 1 shows the experimentally accessible parts using heavy-ion collisions at the Large Hadron Collider (LHC), Relativistic Heavy Ion Collider (RHIC) and through future experiments (like CBM at GSI and NICA at JINR). The phase diagram displays a rich phase structure, however the experimentally accessible part corresponds to some of the following distinct structures: de-confined phase of quarks and gluons, hadronic phase, critical point, crossover line and a crossover at low μ_B . We discuss in the sections below the progress towards establishing these phase structures, both theoretically and experimentally.

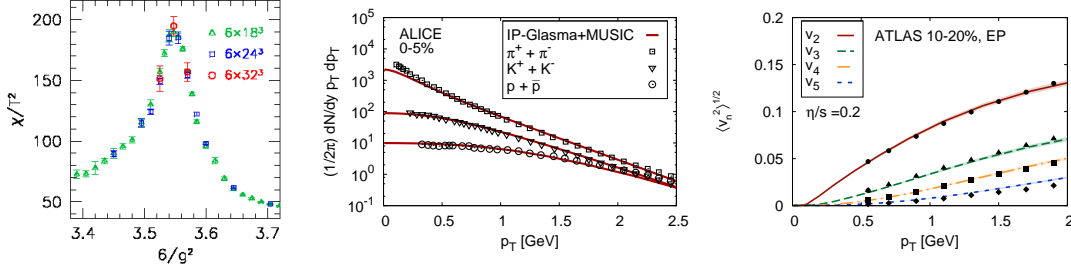


Figure 2: (Color online) Left panel: chiral susceptibility versus $6/g^2$ (g is the gauge coupling) [9]. Middle panel: Hydrodynamical calculation of identified hadron transverse momentum compared to experimental data from the ALICE collaboration, and Right panel: Root-mean-square anisotropic flow co-efficients as a function of transverse momentum compared to experimental data by the ATLAS collaboration [10].

Table 1: Crossover temperature at $\mu_B = 0$ MeV along with the references.

Observable	Transition temperature	Ref
$\chi_{\bar{\psi}\psi}$	151(3)(3) MeV	[11]
$\chi_{\bar{\psi}\psi}$	154(9) MeV	[12]
χ_s	175(2)(4) MeV	[11]
L	176(3)(4) MeV	[11]
Baryon correlations	175(1)(7) MeV	[13]

2. Crossover and Crossover temperature

2.1 Crossover

QCD calculations on lattice at high temperature and $\mu_B = 0$ MeV have established the quark-hadron transition to be a crossover [9]. Figure 2 shows the lattice chiral susceptibility $\chi(N_s, N_t) = \partial^2 / (\partial m_{ud}^2) (T/V) \cdot \log Z$, where m_{ud} is the mass of the light u,d quarks, N_s is the spatial extension, N_t euclidean time extension, and V the system volume. The susceptibility plotted as a function of $6/g^2$ (g is the gauge coupling and T grows with $6/g^2$) shows a pronounced peak around the transition temperature (T_c). The peak and width are independent of volume (varied by a factor 8) thereby establishing the transition to be an analytic cross-over [9]. For a first-order phase transition the height of the susceptibility peak should have been $\propto V$ and the width of the peak $\propto 1/V$, while for a second-order transition the singular behaviour should have been $\propto V^\alpha$, α is a critical exponent. Using the crossover equation of state for the quark-hadron transition in a hydrodynamic based model, the experimental data on invariant yields of charged hadrons and various order azimuthal anisotropy as a function of transverse momentum at LHC are nicely explained (shown in Fig 2) [10]. Lending indirect support to the transition being a crossover at small μ_B .

2.2 Crossover temperature

The point of sharpest change in temperature dependence of the chiral susceptibility ($\chi_{\bar{\psi}\psi}$), the strange quark number susceptibility (χ_s) and the renormalized Polyakov-loop (L) are used to estimate the crossover temperature in the lattice calculations. There is a clear agreement between

Table 2: Observables reflecting quark-gluon phase (QGP) formation in heavy-ion collisions at RHIC and LHC along with the references.

Observable	Observation	Remark	Reference
Nuclear modification factor	< 1	at high p_T for hadrons	[28, 29, 30]
Temperature	> 300 MeV	direct photons	[31]
Strangeness enhancement	> 1	crucial role by ϕ mesons	[20]
Constituent quark scaling	for hadrons and nuclei	elliptic flow	[21, 22]
Dynamical charge correlations	observed	same and opposite charges	[33, 34]
Quarkonia suppression	observed	J/Ψ and Υ	[25, 32]

various lattice QCD estimates of chiral crossover temperature using $\chi_{\bar{\psi}\psi}$ [11, 12]. The observables (χ_s and L) that provide important insights into deconfining aspects of the crossover shows a slightly higher transition temperature. But with a width of around 15 MeV in temperature estimates, it is difficult to make a concerted statement on the difference between deconfinement and chiral crossover temperatures. Moreover there are unresolved discussions on the establishment of Polyakov loop expectation and strange quark number susceptibilities to critical behaviour in the light quark mass regime [12]. The crossover temperature situation is summarised in the table 1.

3. Quark-Gluon Phase

The results from heavy-ion collisions at relativistic high energies have clearly demonstrated the formation of a de-confined system of quarks and gluons at RHIC [14, 15, 16, 17, 18] and LHC [19]. The produced system exhibits copious production of strange hadrons [20], shows substantial collectivity developed in the partonic phase [21, 22], exhibits suppression in high transverse momentum (p_T) hadron production relative to $p+p$ collisions [23, 24], suppression in quarkonia production relative to $p+p$ collisions [25], and small fluidity as reflected by a small value of viscosity to entropy density ratio (η/s) [26]. All these at temperatures and energy densities much larger than predicted by lattice QCD calculations for a quark-hadron transition. Some of these clear signatures are given in the table 2.

Here we only discuss one observable called the nuclear modification factor (R_{AA}). R_{AA} is defined as $\frac{dN_{AA}/d\eta d^2p_T}{T_{AB}d\sigma_{NN}/d\eta d^2p_T}$, here the overlap integral $T_{AB} = N_{binary}/\sigma_{inelastic}^{pp}$ with N_{binary} being the number of binary collisions commonly estimated from Glauber model calculation and $d\sigma_{NN}/d\eta d^2p_T$ is the cross section of charged hadron production in $p+p$ collisions. R_{AA} value of less than one is attributed to energy loss of partons in QGP and phenomenon is referred to as the jet quenching in a dense partonic matter [27]. It is one of the established signature of QGP formation in heavy-ion collisions.

Figure 3 shows the R_{AA} of various particles produced in heavy-ion collisions at RHIC and LHC. In Fig. 3(a), we observe that the values $R_{AA} < 1$ and at RHIC are higher compared to those at LHC energies up to $p_T < 8$ GeV/c [29, 30]. In Fig. 3(b), we observe that the nuclear modification factors for $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV [35] and $p+Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV [36] are greater than unity for the $p_T > 2$ GeV/c. The nuclear modification factor value in $p(d)+A$ collisions not being below unity strengthens the argument (from experimental point of view) that a

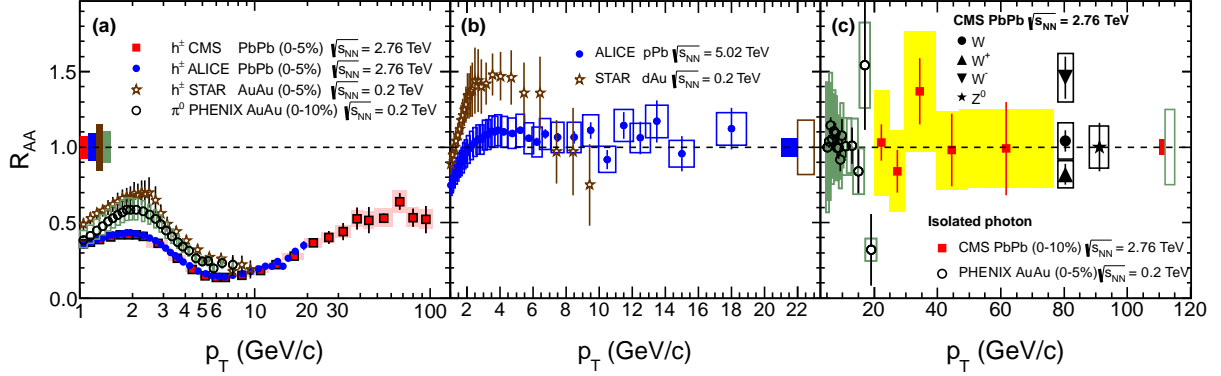


Figure 3: (Color online) (a) Nuclear modification factor R_{AA} of charged hadrons measured by ALICE [29] and CMS [30] experiments at midrapidity. Also shown the R_{AA} of charged hadrons at midrapidity measured by STAR [35] and R_{AA} of π^0 at midrapidity measured by PHENIX [28]. (b) Comparison of nuclear modification factor for charged hadrons versus p_T at midrapidity for minimum bias collisions in d +Au collisions at $\sqrt{s_{NN}} = 200$ GeV [35] and p +Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [36]. (c) The nuclear modification factor versus p_T for isolated photons in central nucleus-nucleus collisions at $\sqrt{s_{NN}} = 200$ GeV [37] and 2.76 TeV [38]. Also shown are the R_{AA} of W^\pm [39] and Z bosons [40] at LHC energies. The boxes around the data denote p_T -dependent systematic uncertainties. The systematic uncertainties on the normalisation are shown as boxes at $R_{AA} = 1$.

hot and dense medium of color charges is formed in A+A collisions at RHIC and LHC. In Fig. 3(c), we show the R_{AA} of particles that do not participate in strong interactions and some of them are most likely formed in the very early stages of the collisions. These particles (photon [37, 38], W^\pm [39] and Z [40] bosons) have a $R_{AA} \sim 1$, indicating that the $R_{AA} < 1$, observed for hadrons in A+A collisions, are due to the strong interactions in a dense medium consisting of color charges.

4. Crossover line

4.1 Theory estimates

The quark-hadron transition at $\mu_B = 0$ is a crossover [9] and one of the important aspects of the phase diagram is to trace out the crossover temperature as we increase μ_B . Besides the actual value of the curvature of the crossover line a particularly interesting question is whether the transition becomes weaker or stronger as μ_B grows (does it lead to a real phase boundary?) and how close it is to the chemical freeze-out line. A recent lattice estimate is shown in Fig. 4 [41]. Two crossover lines are defined with two quantities, the chiral condensate and the strange quark number susceptibility. The width of the bands represent the statistical uncertainty of $T_c(\mu)$ for the given μ coming from the error of the curvature for both observables. The dashed line is the freeze-out curve from heavy ion experiments [42]. It appears that the freeze-out line is quite close to the transition line for a large range of values of μ_B . The right panel of Fig. 4 shows the estimates of chemical freeze-out temperature (T_{ch}) and μ_B using a statistical model from the RHIC BES program [43]. One observes interesting dependence of T_{ch} vs. μ_B unfolding at lower beam energies.

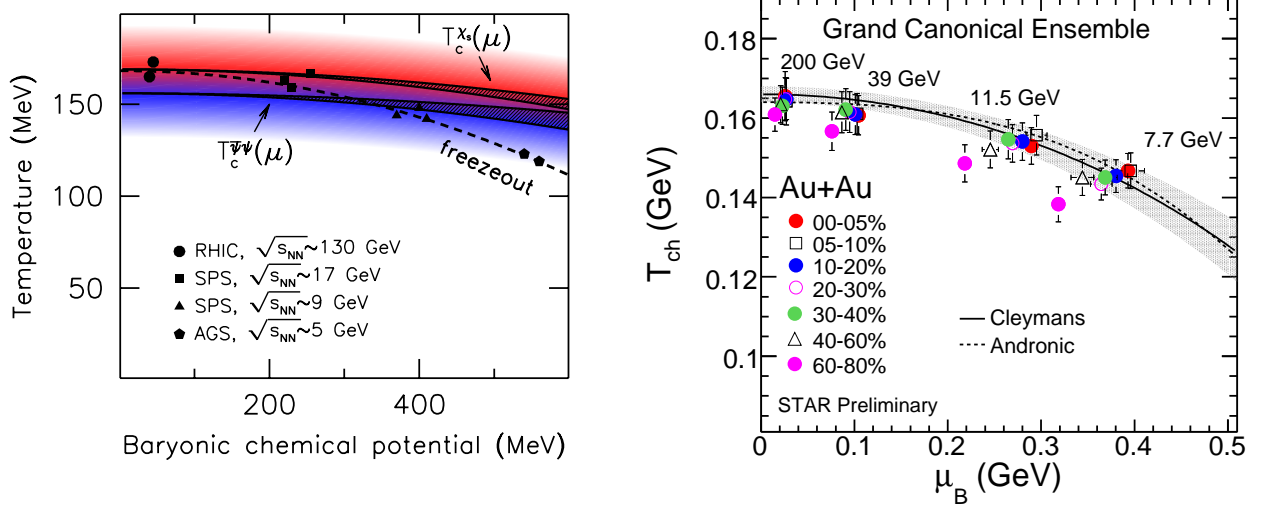


Figure 4: (Color online) Left panel: The crossover line between the quark-gluon and hadronic phases is represented by the coloured area (blue and red correspond to the transition regions obtained from the chiral condensate and the strange susceptibility, respectively) [41]. Right panel: Variation of T_{ch} with μ_B for different energies and centralities. The curves represent the theoretical calculations.

4.2 Turn-off of QGP signatures

An experimental way to demonstrate the quark-hadron transition is to show the turn-off of QGP signatures (like those discussed in section 3) as the collision energy is dialed down. This interesting test is being carried out at the BES program in RHIC. Two such results are shown in Fig. 5. For collision energies around 11.5 GeV the nuclear modification factor for K_S^0 mesons becomes > 1 at $p_T > 2$ GeV/c, whereas it gradually goes below unity for higher beam energies [44]. The baryon-meson splitting of azimuthal anisotropy parameter v_2 (which is the basis for the claim of partonic collectivity at RHIC) reduces as the beam energy is dialed down and vanishes for $\sqrt{s_{NN}} = 11.5$ and 7.7 GeV [45]. These are an experimental indication that for $\sqrt{s_{NN}} = 11.5$ GeV and below hadronic interactions dominate as signatures associated with QGP phenomena seem smoothly getting turned-off.

5. Critical Point

Several QCD based models predict the existence of an end point or critical point (CP) at high μ_B for the first order phase transition in the QCD phase diagram. However the exact location depends on the model assumptions used [46]. Given the ambiguity in predictions of CP in models, studies on lattice was expected to provide reliable estimates [47]. However lattice calculations at finite μ_B are difficult due to *sign problem*. There are several ways suggested to overcome this issue. (i) Reweighting the partition function in the vicinity of transition temperature and $\mu = 0$ [48], (ii) Taylor expansion of thermodynamic observables in μ/T about $\mu = 0$ [49] and (iii) Choosing the chemical potential to be imaginary will make the fermionic determinant positive [50]. The first two

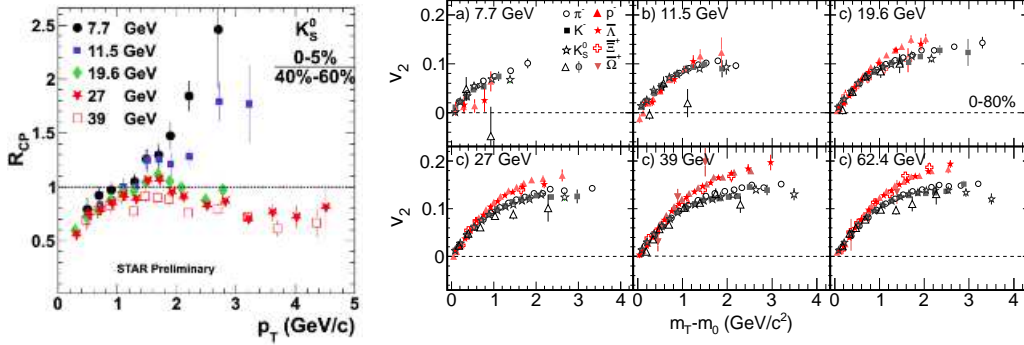


Figure 5: (Color online) Left panel: Nuclear modification factor for K_S^0 mesons as a function of transverse momentum for various $\sqrt{s_{NN}}$ [44]. Right panel: Azimuthal anisotropy parameter, v_2 as a function of transverse mass (m_T) minus the mass of the hadrons for various $\sqrt{s_{NN}}$ [45].

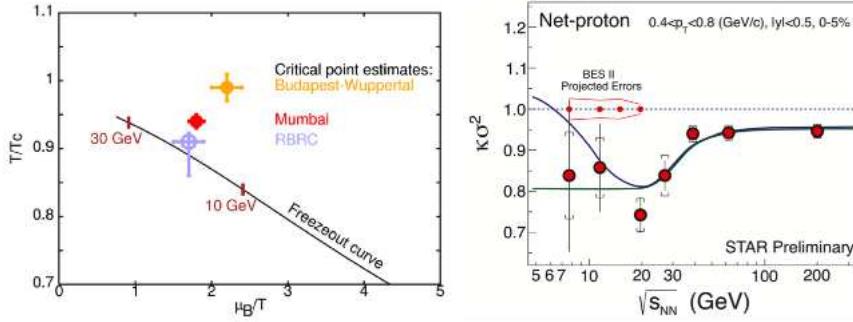


Figure 6: (Color online) Left panel: Estimates of position of critical point from various lattice QCD calculations [51, 52, 53]. Right panel: $\kappa\sigma^2$ for net-proton distributions as a function of $\sqrt{s_{NN}}$ in RHIC BES program [54]. Also shown are the projected statistical error in 2nd phase of BES program.

methodologies yield an existence of CP, whereas the third procedure gives a CP only when the first co-efficient in the Taylor expansion of generic quark mass on the chiral critical surface (m_c) as a function of μ/T ($\frac{m_c(\mu)}{m_c(0)} = 1 + \sum_{k=1} c_k \left(\frac{\mu}{\pi T_c}\right)^{2k}$) is positive. The lattice calculations which yield a CP on phase diagram are shown in Fig. 6 [51, 52, 53]. However these calculations have to overcome some of the common lattice artifacts like, lattice spacing, physical quark masses, volume effect and continuum limit extrapolation.

In the experimental side, the characteristic signature of CP is large fluctuations in event-by-event conserved quantities like net-charge, net-baryon number and net-strangeness. The variance of these distributions ($\langle(\delta N)^2\rangle$) are proportional to square of the correlation length (ξ). The finite size and finite time effects attained in high energy heavy-ion collisions, limits the value of the ξ achieved in the collisions, thereby making it extremely challenging to measure in the experiments. Motivated by the fact that non-Gaussian features in above observables increase if the system freezes-out closer to QCP, it has been suggested to measure higher moments (non-zero skewness and kurtosis indicates non-Gaussianity) of net-charge or net-baryon number distributions. Further it has been shown that higher moments ($\langle(\delta N)^3\rangle \sim \xi^{4.5}$ and $\langle(\delta N)^4\rangle \sim \xi^7$) have stronger depen-

dence on ξ compared to variance and hence have higher sensitivity [55, 56, 57]. In addition the moments are related to susceptibilities [58]. Motivated by all these, experiments are studying the variable $\kappa\sigma^2$ of net-proton distributions (a proxy for net-baryon), to search for the CP. The $\kappa\sigma^2$ will be constant as per the CLT and have monotonic dependence with $\sqrt{s_{NN}}$ for non-CP scenarios. However as it is related to the ratio of baryon number susceptibilities in QCD models: $\kappa\sigma^2 = \frac{\chi_B^{(4)}}{\chi_B^{(2)}/T^2}$ [59], close to CP it is expected to show a non-monotonic dependence on $\sqrt{s_{NN}}$. Preliminary experimental results on $\kappa\sigma^2$ value for net-proton distributions measured in RHIC BES program is shown in right panel of Fig. 6 [54]. Interesting trends are observed indicating CP if exists in the phase diagram, have to be below $\sqrt{s_{NN}} = 39$ GeV [60].

6. Summary

Significant progress has been made towards establishing the QCD phase diagram. From the QCD calculations on lattice it is now established theoretically that the quark-hadron transition at $\mu_B = 0$ MeV is a crossover. This is indirectly supported by the experimental data, as models using the lattice based equation-of-state explain various measurements at RHIC and LHC. Lattice QCD calculations are in agreement that the chiral crossover temperature is around 154 MeV. Other observables of quark-hadron crossover give a slightly higher values of crossover temperature with large uncertainties.

High energy heavy-ion collision experiments have seen distinct signatures which suggest that the relevant degrees of freedom at top RHIC and LHC energies in the initial stages of the collisions are quark and gluons and the system quickly approaches thermalization. The underlying mechanism for the fast thermalization is currently under study. Dialling down the beam energies to 11.5 GeV and below leads to a smooth turning-off of the QGP signatures, indicating that hadronic interactions dominate. These observations in turn further support the formation of partonic matter at higher energy collisions. Lattice QCD calculations of the crossover line indicates that they are close to freeze-out line for a substantial part of the phase diagram. The experimental measurements of freeze-out parameters in RHIC BES program reveals interesting temperature versus baryonic chemical potential dependences at lower beam energies.

Most calculations on lattice continue to indicate the possible existence of critical point for $\mu_B > 160$ MeV, this possibility have not been ruled out from the data at RHIC. The exact location is not yet known unambiguously. The experimental measurements though encouraging are inconclusive.

New phase structures are being proposed, like the existence of a quarkyonic phase around μ_B values corresponding to FAIR energies [61]. This is in addition to the confined and de-confined phases. The matter in such a phase is expected to have energy density and pressure that of a gas of quarks, and yet is a chirally symmetric confined matter. Baryon-Baryon correlations to look for nucleation of baryon rich bubbles surrounded by baryon free regions could be a signature of such a phase. A summary of the status of QCD phase diagram studies in theory and experiments is given in Table 3.

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Table 3: QCD phase structure: Theory and Experiment status.

Phase structure	Theory	Experiment	Remark
De-confined phase	Yes	Yes	RHIC and LHC
Cross over	Yes	Indirectly	$\mu_B \sim 0$ MeV
Crossover temperature	Yes	Yes	$\mu_B \sim 0$ MeV
Crossover line	Uncertain	Indications	RHIC BES
Critical Point	Uncertain	Inconclusive	$\mu_B > 200$ MeV
QGP properties	Progress	Progress	Temperature, density, η/s
Hadronic phase properties	Progress	Progress	Freeze-out dynamics
New phases	Proposed	Lack of proper observables	Quarkyonic phase

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