# The phase diagram of QCD at finite temperature and density

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Under ordinary conditions, quarks are confined inside hadrons. When matter is heated or compressed, hadrons start to overlap, and assigning a quark to one hadron or another becomes ambiguous. Quark confinement gives way to a plasma of deconfined quarks and gluons. Our goal is to determine the boundary between these two regimes as a function of temperature $T$ and baryon chemical potential $\mu$. At the same time an experimental search for quark-gluon plasma formation in Heavy-Ion collisions is ongoing at RHIC (Brookhaven) and soon at LHC (CERN).

Monte Carlo simulations at non-zero chemical potential are afflicted by the notorious "sign problem": the fermion determinant is complex, which prevents its interpretation as a probability density. To circumvent this problem, we perform simulations at imaginary $\mu = i\mu_I$ where the sign problem is absent, fit our phase boundary $T_c(i\mu_I)$ by a truncated Taylor expansion, then analytically continue this polynomial back to real $\mu$. Control over systematic errors is possible for $\mu \leq \pi T$, which covers the range of Heavy Ion experiments [1, 2].

For a QCD-like theory with 2 light $u, d$ quarks ($m_u = m_d = m_{u,d}$) and 1 strange quark of mass $m_s$, the order of the phase transition at $\mu = 0$ depends on the quark masses. We have determined the line in the plane ($m_{u,d}, m_s$) which separates crossover and first-order transition behaviours, and where the transition is second-order. This is illustrated in Fig. 1.

Then, we have determined in which direction this line moves under the effect of a small chemical potential. It turns out that, according to our present simulations on small, coarse lattices, the first-order region shrinks when the chemical potential is turned on. This implies that, if the behaviour is crossover at $\mu = 0$ as believed for the physical values of the quark masses, then it remains a crossover for any small $\mu$, as shown Fig. 2. There is no special point ($\mu_E, T_E$) at small $\mu_E$, as currently searched for in Heavy-Ion experiments, where the crossover becomes a second-order transition.

We are currently checking this provocative finding by repeating our simulations on finer lattices. RCNP provides a small but greatly appreciated fraction of our computer resources for this ambitious project.

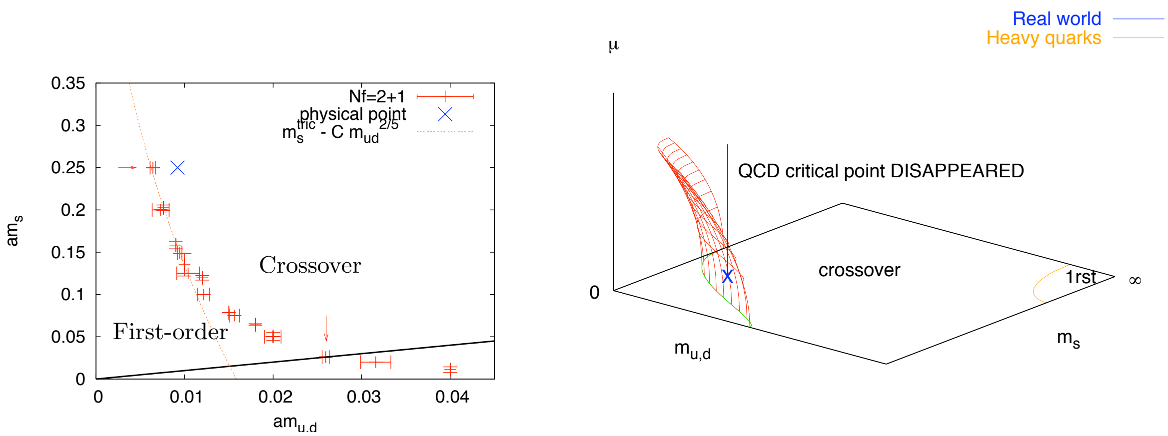


Figure 1: Left: Line of second-order finite-temperature transitions, at $\mu = 0$, in the plane of quark masses ($m_{u,d}, m_s$). The data are consistent with the existence of a tricritical point ($0, m_s^*$), with a rather heavy mass $m_s^* \sim 500$ MeV. Right: Observed behaviour of the previous line of second-order transitions, as a small chemical potential $\mu$ is turned on. For physical values of the quark masses, the transition remains crossover at any small $\mu$, and there is no second-order critical point; from [3].

## References

[1] P. de Forcrand and O. Philipsen, "The QCD phase diagram for small densities from imaginary chemical potential," Nucl. Phys. B **642** (2002) 290 [arXiv:hep-lat/0205016], **214** citations.

[2] P. de Forcrand and O. Philipsen, "The QCD phase diagram for three degenerate flavors and small baryon density," Nucl. Phys. B **673** (2003) 170 [arXiv:hep-lat/0307020], **96** citations.

[3] P. de Forcrand and O. Philipsen, "The chiral critical line of N(f) = 2+1 QCD at zero and non-zero baryon density," JHEP **0701** (2007) 077 [arXiv:hep-lat/0607017], **21** citations.