The $O(4)$ criticality in the net-baryon number probability distribution*

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Relativistic heavy-ion collisions provide a unique opportunity to explore possible phase transitions in Quantum Chromodynamics (QCD) at finite temperature and baryon density. Current lattice QCD simulations show, that at vanishing and small density the transition is of the crossover type. However, near the transition temperature the higher order fluctuations of conserved charges reflect the underlying second order chiral phase transition, expected in QCD in the chiral limit.

Fluctuations of the net-proton number, as a proxy for the net-baryon number, have been recently measured by the STAR collaboration in Au+Au collisions at RHIC for a wide range of beam energies [1]. The fluctuation measurements yield event-by-event multiplicity distributions.

Assuming that the event-by-event fluctuations are governed by the grand canonical (GC) ensemble, the probability distribution of the net-baryon number reads

$$P(T,V,N,\mu) = \frac{Z(T,V,N)e^{\mu N/T}}{\mathcal{Z}(T,V,\mu)}, \qquad (1)$$

where $Z(T,V,\mu)$ is the canonical and $\mathcal{Z}(T,V,\mu)$ the GC partition function.

While higher order fluctuations are often characterized by the behavior of cumulants of the probability distribution (1), we directly compute $P(N)$ and discuss its properties near the chiral crossover [2].

In the chiral limit, the critical behavior of QCD at finite temperature is expected to belong to the $O(4)$ universality class, as conjectured by Pisarski and Wilczek and recently supported by lattice QCD simulations. The sixth order cumulant of the net baryon number exhibits a change of sign at the crossover transition. This is a remnant of the $O(4)$ criticality, since in the chiral limit the sixth and the higher order cumulants diverge.

In the following, we utilize the chiral quark-meson (QM) model as an effective approach to describe the $O(4)$ chiral phase transition and employ the functional renormalization group method to account for critical fluctuations in $P(N)$. We introduce the Skellam distribution $P^S(N)$ as a reference for a non-critical behavior. Since criticality in the $O(4)$ transition lies in the higher order fluctuations, except in the vicinity of the $Z(2)$ critical point, we employ a Skellam distribution $P^S(N)$ with the same second cumulant as the $P(N)$ obtained in the model calculation, and compare the two by examining their ratio.

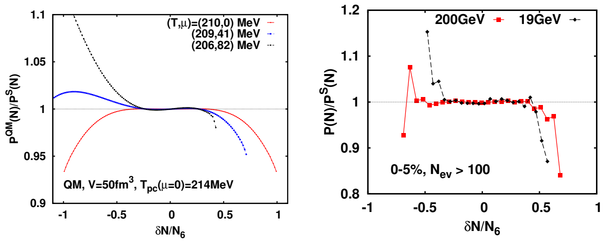

Figure 1: Ratio of probability distribution to the reference Skellam distribution. Left: model calculation. Right: experimental data.

Figure 1-left displays the ratio of these probability distributions as a function of the net baryon number δN normalized by a constant factor N_6 [2], at vanishing and at finite chemical potentials along an approximate freeze-out line. There are some interesting features of this ratio. At $\mu = 0$, $P(N)$ exhibits a narrower tail than $P^S(N)$ at large δN. This property is directly connected with the negative values of the sixth order cumulant, which is a consequence of $O(4)$ criticality.

Moreover, there is asymmetry in the ratio at $\mu > 0$. We note that at $\delta N > 0$ the narrowing of the tail begins at smaller δN than at $\mu = 0$, reflecting a stronger influence of criticality at non-zero net baryon density. This is consistent with the fact that at $\mu \neq 0$ already the third cumulant exhibits critical behavior.

The same ratio can be constructed for the experimental data. In Fig. 1-right, we show the ratio of the *efficiency uncorrected* data to the corresponding Skellam distribution for the most central bin in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and at $\sqrt{s_{NN}} = 19$ GeV. Clearly, the overall behavior is consistent with that expected near the $O(4)$ pseudocritical line. However, before drawing firm conclusions on the presence of critical fluctuations in data, the influence of efficiency corrections and of non-critical effects on $P(N)$ must be carefully examined.

References

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