Finite size scaling as a tool in search for the QCD critical point in heavy ion data

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1. Introduction and Motivation

Given the short lifetime and the reduced volume of the quark-gluon plasma formed in high-energy heavy ion collisions (HIC's), a possible critical endpoint (CEP) will be blurred in a region and the effects from criticality severely smoothened. A direct consequence of this fact is that all signatures of the second-order CEP based on the non-monotonic behavior [1] or sign modifications [2] of particle correlation fluctuations will probe a *pseudocritical endpoint* that can be significantly shifted from the genuine (unique) CEP by finite-size corrections and will be sensitive to boundary effects [3]. This feature, together with the even more crucial limitation on the growth of the correlation length due to the finite (short) lifetime of the plasma and critical slowing down [4], makes the experimental searches of signatures of the presence of a critical point at lower energies very challenging. Rounding and smoothening of fluctuation peaks tend to hide them behind the background.

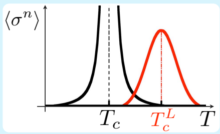
Nevertheless, the non-monotonic behavior of correlation functions near criticality for systems of different sizes, given by different centralities in heavy ion collisions, must obey finite-size scaling. We apply the predicting power of scaling plots to the search for the CEP of strong interactions in heavy ion collisions using data from RHIC and SPS [5]. The results of our data analysis exclude a critical point below chemical potentials μ ≈ 450 MeV. Extrapolating the analysis, we speculate that criticality could appear slightly above μ ≈ 500 MeV. Using available data we extrapolate our scaling curves to predict the behavior of new data at lower center-of-mass energy, currently being investigated in the Beam Energy Scan program at RHIC [6]. If it turns out that the QGP phase is no longer achievable in heavy ion experiments before the CEP is reached, FSS might be the only way to experimentally estimate its position in the phase diagram.

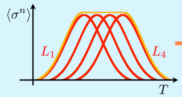
2. How the finite size of the system affects the CEP [3]

Most signatures will probe *pseudocritical quantities*, with smoothened divergences and shifted peaks. The correlation-length (ξ) dependence of the cumulants $\langle\sigma^n\rangle$ of the order parameter are:

$$\boxed{\langle\sigma^n\rangle_L \sim \xi^{p_n}\ f_n(\xi/L)}$$

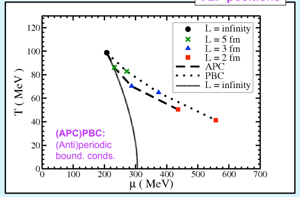
Superposition of different peaks





The pseudocritical chiral phase diagram within the linear sigma model with constituent quarks: SIZABLE CORRECTIONS for length scales probed at current HIC's.

CEP positions



3. Finite size scaling (FSS) and the CEP

CEP ⇒ 2ND ORDER PHASE TRANSITION → { **DIVERGENT CORRELATION LENGTH**; **SCALE INVARIANCE ON THE CRITICALITY** }

These features imply the existence of finite size scaling [7] for finite systems in the vicinity of the CEP (rigorous proof through RG analysis):

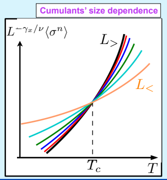
$$\boxed{X(t,L) = L^{\gamma_x/\nu}\ f_x(tL^{1/\nu})}$$

$t = (T - T_c)/T_c$ (distance to the *genuine* CEP)

X ⇒ (any) correlation function of the order parameter

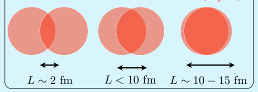
ν ⇒ universal critical exponent (div. of corr. length)

Cumulants' size dependence



4. FSS analysis of HIC data

The system created in HIC's is FINITE, and its size is CENTRALITY-DEPENDENT, $L(N_{\rm part})$:



→ **HIC data:** ***an ensemble of media of different sizes.***

LOCATE THE CEP BY IDENTIFYING FSS BEHAVIOR IN THE CENTRALITY DEPENDENCE OF HIC DATA!

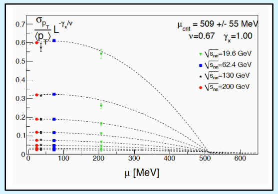
- **Distance to the CEP:** **constrained by the freeze-out curve, parameterized by the chemical potential μ or the center-of-mass energy $\sqrt{s_{nn}}$.**
- **Observables:** **transverse momentum fluctuations, pion multiplicity fluctuations, ...**
- **Size:** **from HBT analysis.**

5. Scaling plots for RHIC and SPS data [5]

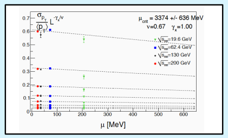
We analyze pragmatically the available transverse momentum fluctuation data from RHIC and SPS [8] through the FSS prism, assuming the existence of a CEP.

STAR data for center-of-mass energies 19.6, 62.4, 130 and 200 GeV:

- **Restricted data → extrapolations using fits**
- **Scaling function should be smooth → polynomial fit for each L**
- **Enforce the condition that all the curves cross at some critical μ (adjustable parameter)**



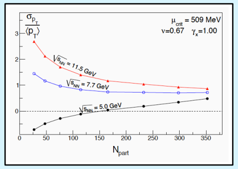
Data seems to favor values of the critical chemical potential above 450 MeV



- **Estimated position of the CEP based on FSS of current data still highly dependent on the assumed functional form of f.**
- **The small energy dependence of the curves for a given L indicates within the FSS assumption that the CEP should be at values well above those currently available.**
- **For the current set of data, full scaling plots are still not very enlightening.**

FSS predictions for different energies, based on STAR data:

- **We use the quadratic polynomial fit of STAR data and assume the critical point is at 509 MeV to make predictions at lower RHIC energies for the Beam Energy Scan Program [8].**
- **The centrality dependence changes once one moves to the other side of the critical point - a generic signal for having reached the first-order phase transition side of the CEP.**



Outlook: **The fact that FSS prescinds from the knowledge of the details of the system under consideration, providing information about its criticality based solely on its most general features, makes it a very powerful and pragmatic tool for data analysis in the search for the CEP. From a very limited data set in energy spam, we have used FSS to exclude the presence of a critical point at values of the chemical potential below 450 MeV. We have also used the scaling function to predict the behavior of data with system size at lower energies. We are looking forward to compare our predictions to the outcome of data analysis from the Beam Energy Scan program at RHIC.**

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