Nuclear and quark matter: exploring the QCD phase diagram

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Phase diagrams

- Maps showing the state of a substance in equilibrium conditions
- Phase boundaries: phase transitions
- 1st order:
 - Latent heat
 - 2nd order:
 - Fluctuations
 - Cross over:

Continuous

Smooth transition



Cross over

Matter in "unusual conditions" Enrico Fermi (1953)

70 - Matter in musual conditions 70 a $10^{12}\,\mathrm{K}$ 25 12 Election proton gas 10 Non deg Degenerate $10^{32} \, {\rm Atm}$ 2 6 8 10 127 14 10 to 14 12 18 26 28 30 32 Log plat Start from ordinary condensed matter with "



Matter at the extreme

- Densest and hottest substances being studied
 - Nuclear/Quark Matter: interior of nuclei, neutron stars (cold and dense)



Univers

arlv

 Quark-Gluon plasma: ultra-relativistic nucleus-nucleus collisions, early universe (hot and dense)

Nucleus-nucleus collisions



Quantum Chromo Dynamics

- Describes the interaction between quarks and gluons, the strong interaction
- Quarks and gluons carry color charge
- Symmetries of QCD
 - Color SU(3): confinement of colored dof's
 - Chiral symmetry: right & left handed light quarks do not mix, spontaneously broken in vacuum
 - Expect two transitions @ large T: deconfinement + chiral restoration

A. The pressure in (2+1)-flavor QCD for $\mu_B > 0$, $\mu_S = \mu_Q = 0$

= $\mu_S = 0$ the Taylor series for the person of the perso

$$\begin{split} \Delta \left(P/T^4 \right) &= \frac{P(T,\mu_B) - P(T,0)}{T^4} = \sum_{\substack{n=1\\2}}^{\infty} \frac{\chi_{2n}^B(T)}{(2n)!} \left(\frac{\mu_B}{T} \right)^{2n} \\ &= \frac{1}{2} \chi_2^B(T) \hat{\mu}_B^2 \left(1 + \frac{1}{12} \frac{\chi_4^B(T)}{\chi_2^B(T)} \right) \frac{\chi_4^B(T)}{\chi_2^B(T)} \hat{\mu}_B^4 + \dots \end{split}$$

we have $\#a\overline{c}tdrad$ but the leading $\mathcal{O}(\hat{\mu}_{B}^{2})$ contribution to the μ_{B} -dependent part of the pressure a feeling for the importance of higher order contributions. Note that all ratios $\chi_{2n}^{2}/\chi_{2}^{2}$ are unit $3^{0.35}_{-2} = 2/(3\pi^{2}) \simeq 0.468$ is the only non-vanishing higher order coefficient in a massless, 3 flavor idea heoleading order coefficient χ_{2}^{2} (flow and the ratio $\chi_{4}^{B}/\chi_{2}^{W^{2}}$ in Fig.h2droffhasdefice. and shows a part of the f order contribution χ_{2}^{B} . Here we used additional data from simulations on $48^{3} \times 12$ lattices the the continuum extrapolation performed in [26]. As can be seen in the right hand part of this μ_{2}^{D} becomes small in the region where the leading correction is large. The notion of the next-to-feading order correction thus is the set in the hadronic phase, where $\chi_{4}^{B}/\chi_{2}^{B}$ egion, 0.4 = 155 MeV, $\chi_{4}^{B}/\chi_{2}^{B} \simeq 0.88$ We thus find that the relative contributiofflow of the method of the persure in the crossover region and below is about 8% at $\mu_{B}/T = 1$ and ris T = 20 At the pressure in the crossover region and below is about 8% at $\mu_{B}/T = 1$ and ris T = 20 At the pressure in the crossover region and below is about 8% at $\mu_{B}/T = 1$ and ris 0.2

to estimate the truncation error arising from a Taylor series truthcated at $O(\mu_B^4)$ we use $\chi_6^B/2 \chi_2^B$ hop histing in $Q_1^2 \chi_2^B$ we use $\chi_6^B/2 \chi_2^B$ hop histing in $Q_2^2 \chi_2^B$ is a statistical for all temperatures T > 180 MeV. In fact, for $\chi_6^B/\chi_2^B \leq 0$ 4 that the correction to the leading order result is less than $Q_2^2 \chi_2^B/\chi_2^B = 180$ MeV. In fact, for $\chi_6^B/\chi_2^B \leq 0$ 4 that the statistical errors on current results for χ_6^B/χ_2^B are still large. However, a crude of the statistical errors on current results for χ_6^B/χ_2^B are still large.

Phases of QCD matter?





Freeze-out curve



Finding a smooth cross over?

- Explore phase diagram using critical fluctuations
- Fluctuations diverge @ critical point



Measuring derivatives?

• $Z = \operatorname{Tr} e^{-(\hat{E} - \mu \hat{N}_B)/T} \qquad p = \frac{T}{V} \ln Z$

$$\langle N_B \rangle = \frac{1}{Z} \operatorname{Tr} \hat{N}_B e^{-(\hat{E} - \mu \hat{N}_B)/T} = \frac{\partial}{\partial \mu/T} \ln Z$$
$$\chi_B^2 = \langle (\Delta N_B)^2 \rangle = \langle N_B^2 \rangle - \langle N_B \rangle^2 = \left(\frac{\partial}{\partial \mu/T}\right)^2 \ln Z$$

$$\Delta N_B = N_B - \langle N_B \rangle$$
$$\chi_B^n = \langle (\Delta N_B)^n \rangle - \dots = \left(\frac{\partial}{\partial \mu/T}\right)^n \ln Z$$

• Cumulants of baryon number fluctuations measure μ derivatives — cross over transition!

- Specific heat near critical point of H₂O
- Fluctuation of Entropy diverges at CP!

$$C_p = \langle S^2 \rangle - \langle S \rangle^2$$

- Fluctuations peaked at cross over trans.
- Explore fluctuations to localize continuous phase transitions



Where is the snag?

- Higher cumulants probe the tail of the distribution
 - Need high statistics both in experiment & theory
- Experiments don't measure neutrons
- Finite size & time effects: no diverg. Need to understand <u>all</u> other (non-critical) sources of fluctuations!
- Other complications: momentum space cuts, non-equilibrium effects





Dependence on freeze-out line 4₁ Kurtosis = χ_B^4 / χ_B^2 Kurtosis χ^4_B \sqrt{s} , GeV T [MeV] Critical point μ_q [MeV]

STAR data on fluctuations

- Transport theory (no criticality) yields only suppression!
- Can enhancement at low energies be due to the chiral critical point?
- Are other cumulants consistent?



Self consistent freeze-out

- Freeze-out line determined by fitting χ_B^3/χ_B^1 to data
- Yields good description of χ^1_B/χ^2_B and χ^3_B/χ^2_B
- Enhancement of χ_B^4/χ_B^2 not reproduced!



Lattice extrapolation

- Freeze-out line determined by fitting χ_B^3/χ_B^1 to data
- Yields good description of χ^1_B/χ^2_B and χ^3_B/χ^2_B
- Enhancement of χ_B^4/χ_B^2 not reproduced!



Summary

- Prospects for exploring the phase diagram of QCD in nuclear collisions with fluctuations
- Low cumulants described by model/lattice $(n \leq 3)$
- χ_B^4/χ_B^2 cannot be reproduced in model
- Numerous effects not yet understood:
 - Non-critical sources of fluctuations (e.g. volume)
 - Non-equilibrium effects?
 - Momentum cuts
 - Protons vs. baryons?