Searching for the QCD Critical End Point

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1410.5454, 1509.04968
The location of the critical point (CEP) is still unknown.
Th: Difficult to apply LQCD to the low T / high chemical potential region.
Phase Transitions

2nd-order phase transition

1st-order phase transition
Exp: Energy Scan

Fire ball expansion, fast or slow?
Signatures of CEP

• Assuming slow expansion (thermal equilibrium)

• Correlation length diverges at the CEP, so are fluctuations, e.g. event by event variations of baryon number \( \langle (\delta N)^2 \rangle, \delta N = N - \langle N \rangle \)

• If correlation length is finite at freeze out, higher (nongaussian) moments could be useful:

\[
\kappa_3 \propto \langle (\delta N)^3 \rangle,
\kappa_4 \propto \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2
\]
Universality

• In the scaling region, physics is the same within the same universality class---an effective field theory argument.

• QCD near CEP $\sim$ Ising model

(Stephanov)
Universality

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• QCD near CEP $\sim$ Ising model
What is going on?
What is going on?

Robust!
Mapping: model dependent

\[ T, \text{ GeV} \]

- QGP
- critical point
- hadron gas
- nuclear matter

\[ \mu_B, \text{ GeV} \]

Inset:

- \[ T/\mu \]
- \[ \mu/\mu \text{ } \]
Our Works

• Mapping and diagram power counting w/ effective potential: more diagrams equally important

• Explicit model calculations: (a) 1+1 dim Gross-Neveu model in the large N limit (b) 3+1 dim 3 flavor NJL model (\(\mu_s = \mu_I = 0\)), complete set of susceptibilities up to 4 derivatives.
$$m_2 = \frac{4^{th} \text{ moment}}{2^{nd} \text{ moment}}$$
\( m_2 = \frac{4^{\text{th}} \text{ moment}}{2^{\text{nd}} \text{ moment}} \)
$m_2 = 4^{th}$ moment$/2^{nd}$ moment

CPOD 2014

Au+Au Collisions
Net-proton
$0.4 < p_T < 2$ (GeV/c), $|y| < 0.5$

- 0-5%
- 5-10%
- 30-40%
- 70-80%

STAR Preliminary

R. Gavai, S. Gupta, PLB 2011
$m_1 = 3^{rd}$ moment/$2^{nd}$ moment

CPOD 2014

STAR Preliminary Au+Au Collisions
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$S_\sigma$

$\sqrt{S_{NN}}$ (GeV)

$0-5\%$
$5-10\%$
$30-40\%$
$70-80\%$

R. Gavai, S. Gupta, PLB 2011

$m_1(B)$

$T$ (MeV)

$\mu_q$ (MeV)
m2 vs m1
Counter clockwise, also seen in Ising model, maybe robust even w/ non-thermal effects
\[ T_{\text{min}, m_2} > T_{\text{max}, m_1} > T_{\text{max}, m_2} > T_{\text{CEP}} \]
Flavor Dependence

• $\mu_s = \mu_I = 0$, complete set of susceptibilities:

$\chi_{qq}, \chi_{II}, \chi_{ss},$

$\chi_q^{(3)}, \chi_{qss}, \chi_{qII},$

$\chi_q^{(4)}, \chi_{qqII}, \chi_{qqss}, \chi_I^{(4)}, \chi_{IIss}, \chi_s^{(4)}$
Flavor Dependence

- $\mu_s = \mu_I = 0$
Flavor Dependence

- $\mu_s = \mu_I = 0$

- B, Q, S basis, proton and kaon susceptibilities
Summary

- It is encouraging to see non-monotonic $m_1$ and $m_2$ at RHIC.
When the Imaginary is a Real Alternative

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From the hottest to the coolest, and back?

$$h = \frac{(\mu_\uparrow - \mu_\downarrow)}{2}$$

$$\bar{\mu} = \frac{(\mu_\uparrow + \mu_\downarrow)}{2}$$
When Mr. Berry Meets Mr. Wigner

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JWC, Shi Pu, Qun Wang, Xin-Nian Wang
Flavor Structure of the Nucleon Sea from Lattice QCD

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Collaborators: Huey-Wen Lin, Saul D. Cohen, Xiangdong Ji
Backup slides
Parton Physics on a Euclidean Lattice

X. Ji, PRL, 2013

\[ q(x, \mu^2) = \int \frac{d\xi^-}{4\pi} e^{-ix\xi^- P^+} \langle P | \bar{\psi}(\xi^-) \gamma^+ \]
\[ \times \exp \left( -ig \int_0^{\xi^-} d\eta^- A^+ (\eta^-) \right) \psi(0) | P \rangle \]

\[ q(x, \mu^2, P^z) = \int \frac{dz}{4\pi} e^{izk^z} \langle P | \bar{\psi}(z) \gamma^z \]
\[ \times \exp \left( -ig \int_0^{z} dz' A^z (z') \right) \psi(0) | P \rangle \]
\[ + \mathcal{O} \left( \frac{\Lambda^2}{(P^z)^2}, \frac{M^2}{(P^z)^2} \right), \]