THERMODYNAMICS OF FINITE VOLUME QUARK MATTER IN ANISOTROPIC MOMENTUM DISTRIBUTION

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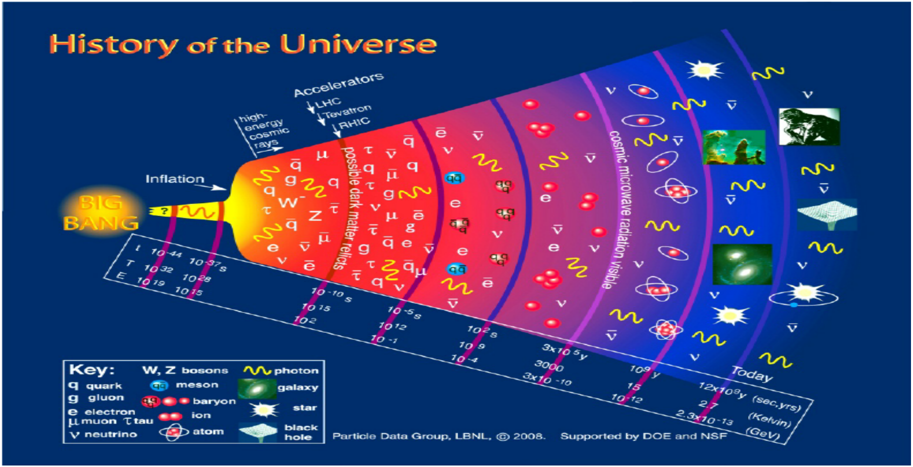
OUTLINE

In this presentation, we are going to discuss about,

- **Introduction**
  1. The Big-Bang
  2. QCD phase diagram
  3. Theoretical Approaches
- **Polyakov quark meson model**
  1. Lagrangian density
  2. Thermodynamic potential
  3. Polyakov loop
- **What do we need to study and why?**
  1. Finite volume effects
  2. Anisotropic momentum distribution
- **Results**
- **Conclusion**

The Big-Bang



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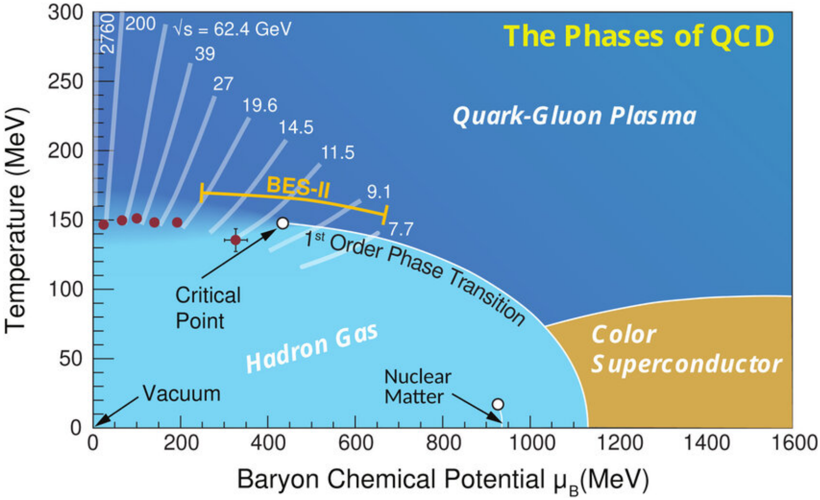
[1]Denis Perret-Gallix. In: vol. 454. 1. 2013, p. 012051.

QCD phase digaram



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[2] Ani Aprahamian et al. "Reaching for the horizon: The 2015 long range plan for nuclear science". In: *Reaching for the Horizon* (2015).

Theoretical Approaches

- **Lattice QCD simulations**: It is a non-perturbative application of field theory based on the Feynman path integral technique
- **MIT bag model**: Hadrons are considered to be composed of weakly interacting quarks confined within a finite region referred to as the "bag."
- **Nambu Jona Lasinio (NJL) and Polyakov NJL (PNJL) model**: focusing on the interaction between quarks and anti-quarks through a four-point interaction term in the Lagrangian density.
- **Chiral perturbation theory**: Includes the expansion in power of momentum and quark masses.

AND Many More.......

Polyakov Quark Meson model

- Quark meson model is an effective approach to studying the strong interactions between mesons and quarks.
- The total Lagrangian of the model for N_f flavors is given by[3]

$$\mathcal{L} = \bar{\Psi} i\gamma^{\mu}\partial_{\mu}\Psi + \mathrm{Tr}\left(\partial_{\mu}\varphi^{\dagger}\partial^{\mu}\varphi\right) - m^2\mathrm{Tr}\left(\varphi^{\dagger}\varphi\right) - \lambda_1\left[\mathrm{Tr}\left(\varphi^{\dagger}\varphi\right)\right]^2 - \lambda_2\left[Tr\left(\varphi^{\dagger}\varphi\right)^2\right] + c\left(\det(\varphi) + \det\left(\varphi^{\dagger}\right)\right) + \mathrm{Tr}\left[H\left(\varphi + \varphi^{\dagger}\right)\right] + \mathcal{L}_{qm} - \frac{1}{4}\mathrm{Tr}\left(V_{\mu\nu}V^{\mu\nu}\right) + \frac{m_1^2}{2}V_{a\mu}V_{\mu}^{a}.$$

[3] Thomas Beisitzer, Rainer Stiele, and Jürgen Schaffner-Bielich. In: *Phys. Rev. D* 90 (Oct. 2014), p. 085001.

Polyakov Quark Meson model

- The m_f^* represents the effective mass of constituent quarks given by

$$m_u^* = \frac{g_s}{2}\sigma_u, \quad m_d^* = \frac{g_s}{2}\sigma_d \quad \text{and} \quad m_s^* = \frac{g_s}{\sqrt{2}}\sigma_s. \tag{1}$$

- The effective chemical potential of the quarks is modified as a consequence of vector-meson interactions and is defined in terms of quark chemical potential, μ_q, isospin chemical potential, μ_I and strangeness chemical potential, μ_S as

$$\begin{aligned} \mu_u^* &= \mu_q + \mu_I - g_{\omega u}\omega - g_{\rho u}\rho \\ \mu_d^* &= \mu_q - \mu_I - g_{\omega d}\omega + g_{\rho d}\rho \\ \mu_s^* &= \mu_q - \mu_S - g_{\phi s}\phi. \end{aligned} \tag{2}$$

Polyakov Quark Meson model

- Polyakov loop
$$\Phi(\tilde{\mathrm{x}}) = (\mathrm{Tr_c L})/\mathrm{N_C},$$
and it's conjugate
$$\bar{\Phi}(\tilde{\mathrm{x}}) = (\mathrm{Tr_c L^\dagger})/\mathrm{N_C}.$$
- In the current work, we use the polynomial form of the Polyakov loop defined as[4]

$$\frac{\mathcal{U}_{\text{poly}}(\Phi, \bar{\Phi})}{T^4} = -\frac{b_2(T)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}\left(\Phi^3 + \bar{\Phi}^3\right) + \frac{b_4}{4}(\bar{\Phi}\Phi)^2,$$

and the temperature-dependent coefficient b_2 defined as
$$b_2(T) = a_0 + a_1\left(\frac{T_0}{T}\right) + a_2\left(\frac{T_0}{T}\right)^2 + a_3\left(\frac{T_0}{T}\right)^3.$$

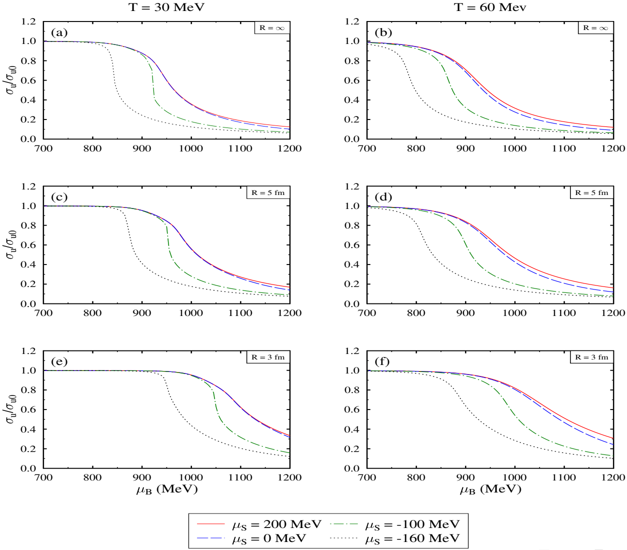
[4] Ana Gabriela Grunfeld and G Lugones. In: *The European Physical Journal C* 78 (2018), p. 640.

Finite Volume and Anisotropic momentum distribution

- A lower momentum cutoff, denoted as p_{min} [MeV], equal to π/R [MeV], where R signifies the length of a cubic volume (designated as Λ) is introduced.
- In the context of anisotropic quark matter, the modification of quasiparticle dispersion relations aligns with the anisotropic momentum distribution. In this case, the nontrivial dispersion relation for effective mass m_f^* is characterized by

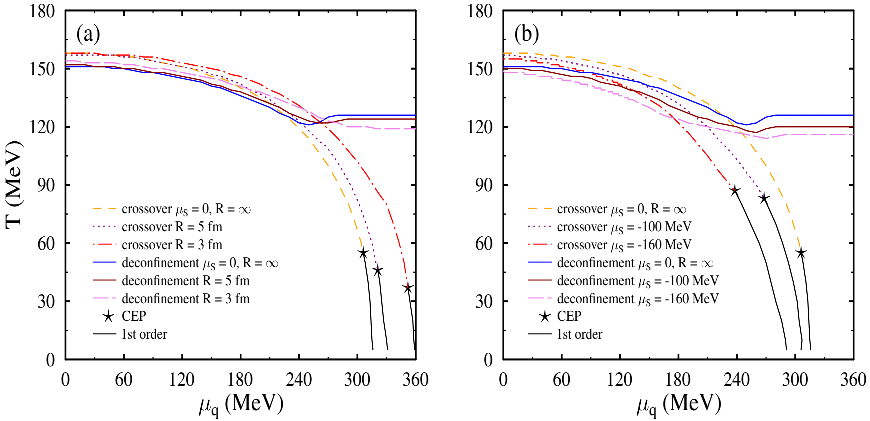
$$E_f^{*(aniso)} = \sqrt{p^2 + \xi(p.\hat{n})^2 + m_f^{*2}}. \tag{3}$$

Results



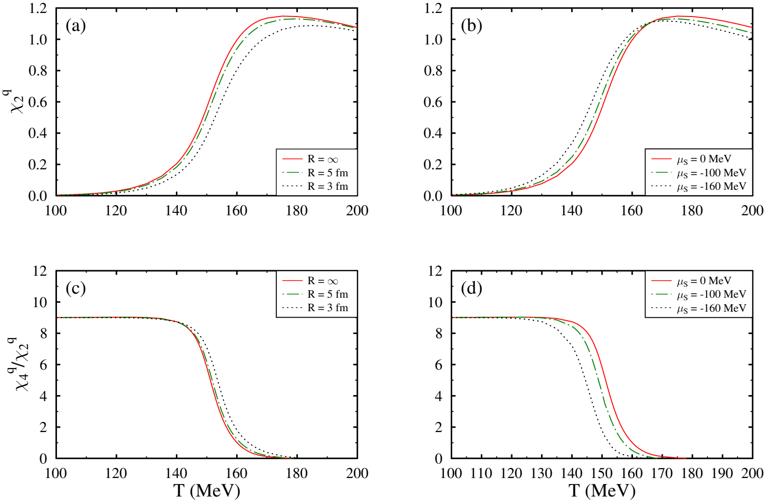
T = 30 MeV
T = 60 Mev
(a)
R = ∞
(b)
R = ∞
(c)
R = 5 fm
(d)
R = 5 fm
(e)
R = 3 fm
(f)
R = 3 fm
σ_u/σ_{u0}
μ_B (MeV)
μ_S = 200 MeV
μ_S = 0 MeV
μ_S = -100 MeV
μ_S = -160 MeV

Results



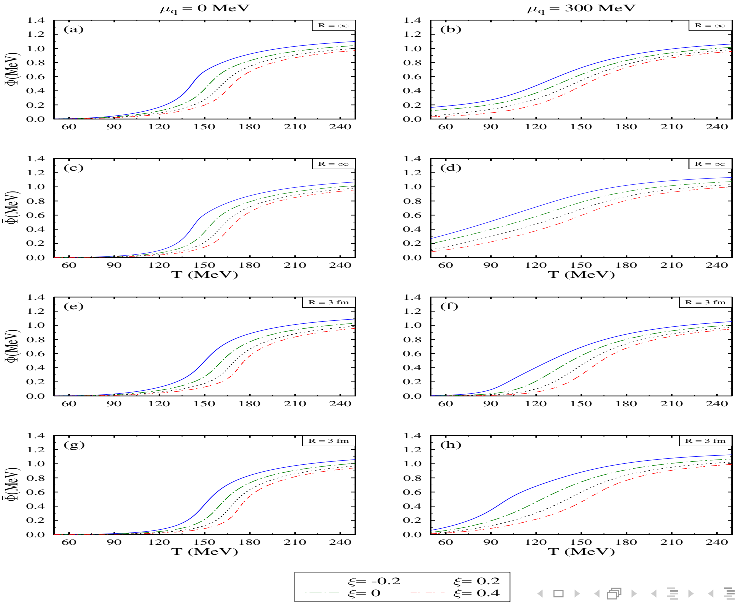
(a)
T (MeV)
μ_q (MeV)
crossover μ_S = 0, R = ∞
crossover R = 5 fm
crossover R = 3 fm
deconfinement μ_S = 0, R = ∞
deconfinement R = 5 fm
deconfinement R = 3 fm
CEP
1st order
(b)
crossover μ_S = 0, R = ∞
crossover μ_S = -100 MeV
crossover μ_S = -160 MeV
deconfinement μ_S = 0, R = ∞
deconfinement μ_S = -100 MeV
deconfinement μ_S = -160 MeV
CEP
1st order

Results



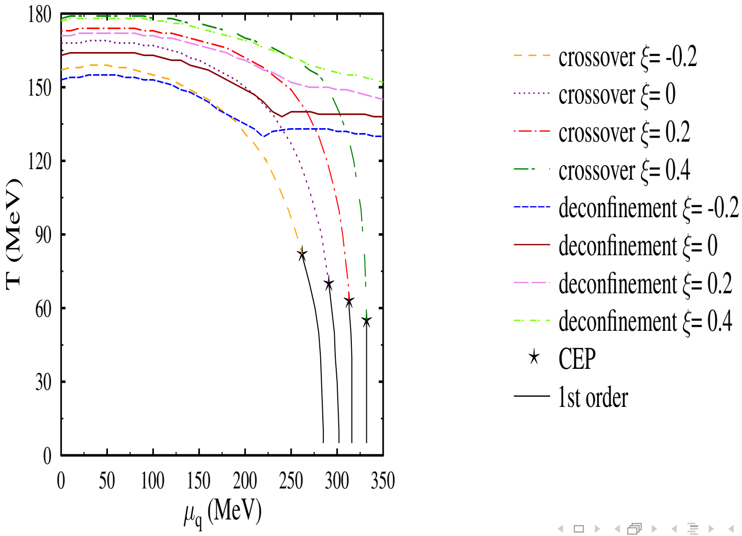
(a)
(b)
(c)
(d)
χ_2^q
χ_4^q/χ_2^q
R = ∞
R = 5 fm
R = 3 fm
μ_S = 0 MeV
μ_S = -100 MeV
μ_S = -160 MeV
T (MeV)
T (MeV)

Results



$\mu_q = 0$ MeV
$\mu_q = 300$ MeV
(a) R = ∞
(b) R = ∞
(c) R = ∞
(d) R = ∞
(e) R = 3 fm
(f) R = 3 fm
(g) R = 3 fm
(h) R = 3 fm
Φ(MeV)
$\bar{\Phi}$(MeV)
T (MeV)
ξ= -0.2
ξ= 0.2
ξ= 0
ξ= 0.4

Results



180
150
120
90
60
30
0
T (MeV)
0
50
100
150
200
250
300
350
μ_q (MeV)
crossover ξ= -0.2
crossover ξ= 0
crossover ξ= 0.2
crossover ξ= 0.4
deconfinement ξ= -0.2
deconfinement ξ= 0
deconfinement ξ= 0.2
deconfinement ξ= 0.4
CEP
1st order

Conclusion

- The effects of strangeness chemical potential, anisotropic momentum distribution, and finite system size have been investigated.
- The susceptibilities of conserved charges are enhanced in the transition region.
- In future work, susceptibilities can be calculated at finite chemical potential values and compared with STAR data.
- The model can be further improved by using the Functional Renormalization Approach (FRG).

thank you!