Recent results on QCD thermodynamics from lattice

Sayantan Sharma

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Outline

1. The QCD phase diagram: outstanding issues
2. Symmetries
3. Degrees of freedom in QCD
4. Realistic modelling of the heavy ion experiments and lattice
The QCD phase diagram: outstanding issues

- Understanding QCD phase diagram is one of the most challenging problems in the recent years.
- The underlying physics of confinement and chiral symmetry breaking is not yet completely understood.
  
  [Schaefer and Shuryak, 96]
- Challenges bring in new opportunities!
- Major new insights from Lattice QCD in last two years.
- It is also important in view of the BESII program at RHIC in 2019-2020.
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  - QCD thermodynamics at finite density.
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- The exciting news about developments in heavy quark potentials and color screening would be covered in the following talks:
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The phase diagram at $\mu_B = 0$

- For finite quark masses, no unique order parameter.
- It is now well established that $\mu_B = 0$ chiral symmetry restoration occurs via crossover transition with a $T_c = 154(9)$ MeV.
  [Budapest-Wuppertal collaboration, 1309.5258, HotQCD collaboration, Bazavov et. al, 1407.6387]
- The EoS for $2 + 1$ QCD is measured in the continuum and different lattice groups agree.[See Alexie Bazavov’s talk, Wed 11:25AM].
- The dynamical effects of charm quarks included till 1 GeV → important as degrees of freedom and EoS during cosmological evolution.
  [Borsanyi et. al, 1606.07494]
The phase diagram at $\mu_B = 0$

- However since $m_u, m_d \ll \Lambda_{QCD}$ there is an approximate $U_L(2) \times U_R(2)$ symmetry of QCD Lagrangian.

- $U_L(2) \times U_R(2) \rightarrow SU(2)_V \times SU(2)_A \times U_B(1) \times U_A(1)$

- At chiral crossover transition:
  $SU(2)_V \times SU(2)_A \times U_B(1) \rightarrow SU(2)_V \times U_B(1)$.

- Is $U_A(1)$ effectively restored at $T_c$? → can change the universality class of the second order phase transition at $\mu_B = 0$.

  Either $O(4)$ or $U_L(2) \times U_R(2)/U_V(2)$

  [Pisarski & Wilczek, 84, Butti, Pelissetto & Vicari, 03, 13, Nakayama & Ohtsuki, 15]
The phase diagram at $\mu_B = 0$

- Not an exact symmetry $\rightarrow$ what observables to look for? Degeneracy of the 2-point correlators [Shuryak, 94] $\rightarrow$ higher point correlation functions imp.

$$\chi_\pi - \chi_\delta \overset{\nu \rightarrow \infty}{\rightarrow} \int_0^\infty d\lambda \frac{4 m_f^2 \rho(\lambda, m_f)}{\lambda^2 + m_f^2}$$

- Observables non-analyticities + analytic part of the eigenvalue spectrum.

[Aoki, Fukaya & Taniguchi, 1209.2061, HotQCD collaboration, 1205.3535, V. Dick et. al. 1502.06190]

- Independent hints from study of screening masses (excitations) for $\pi, \eta$.

[Y. Maezawa et. al. 1411.3018, B. Brandt et. al. 1608.06882]

- Non-analytic part still needs careful study. Analytic part of the spectrum strongly suggest that $U_A(1)$ is broken!

[V. Dick, et. al, 1602.02197]
Near-zero modes of QCD Dirac operator at $1.5 \ T_c$ due to a weakly interacting instanton-antiinstanton pair!
Microscopic origin of $U_A(1)$ breaking?

- Near-zero modes of QCD Dirac operator at $1.5 \, T_c$ due to a weakly interacting instanton-antiinstanton pair!
- The density $\approx 0.147(7)\, fm^{-4}$. This is much more dilute than an instanton liquid with density $1\, fm^{-4}$.

[ V. Dick, F. Karsch, E. Laermann, S. Mukherjee and S.S, 1502.06190 ]
Independent confirmation: Topological susceptibility

- Topological susceptibility measurement at high $T$ on the lattice suffers from rare topological tunneling, lattice artifacts.
- Going towards continuum limit difficult due to freezing of topology.
- New fermionic observables developed to crosscheck the standard definition of $\chi_t = \int d^4x \langle \tilde{F}(x)F(0) \rangle$. [P. Petreczky, H-P Schadler, SS, 1606.03145].
- Continuum extrapolated results now available for QCD!
Independent confirmation: Topological susceptibility

- Fit ansatz: $\chi_t^{1/4} = AT^{-b}$.
- $b = 0.9 - 1.2$ for $T < 250$ MeV. Agrees well with [Bonati et. al, 1512.06746]
- $T > 300$ MeV: Continuum extrapolated $b = 1.85(15)$ in agreement with dilute instanton gas.
  confirmed also in an independent study with improved topological tunneling techniques at high temperatures [Borsanyi et. al, 1606.07494]

- Dilute gas prediction: $b = 4 - \frac{11N_c}{3} - \frac{2N_f}{3}$.
Lattice QCD studies can now address long standing problem on anomalous $U_A(1)$ symmetry and it’s fate near chiral crossover transition.
Summary till now

- Lattice QCD studies can now address long standing problem on anomalous $U_A(1)$ symmetry and it’s fate near chiral crossover transition.
- Most lattice studies hint that $U_A(1)$ is broken significantly near and even beyond $T_c$. 
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Underlying microscopic origin is being studied in quite detail. → hints to interplay between topology in QCD and chiral phase transition as suggested from studies by Shuryak and his collaborators

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Topological susceptibility has been measured in lattice QCD → suggests non-trivial top-fluctuations in hot QCD medium even at 1 GeV, consequences for axion cosmology.
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**Challenges** Is is possible to understand the intricate connection between chiral symmetry breaking and confinement through a detailed study of the topological constituents of QCD near $T_c$? What are the topological constituents near $T_c$?
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Basic observables: Fluctuations of conserved charges

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- Conventional Monte-Carlo algorithms at finite $\mu$ in Lattice QCD suffer from sign problem.
- One of the methods to circumvent sign problem: Taylor expansion of physical observables around $\mu = 0$ in powers of $\mu/T$

[Bielefeld-Swansea collaboration, 02]

$$\frac{P(\mu_B, T)}{T^4} = \frac{P(0, T)}{T^4} + \frac{1}{2} \left( \frac{\mu_B}{T} \right)^2 \chi_2^B(0, T) + \frac{1}{4!} \left( \frac{\mu_B}{T} \right)^4 \chi_4^B(0) + ...$$

Different orders of fluctuations appear as Taylor coefficients
Challenges for Lattice computations

- The fluctuations of conserved charges can be expressed in terms of Quark no. susceptibilities (QNS).
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- Higher derivatives $\rightarrow$ more inversions
  Inversion is the most expensive step on the lattice!

- Why extending to higher orders so difficult?
  - Matrix inversions increasing with the order
  - Delicate cancellation between a large number of terms for higher order QNS.
Introducing $\mu$ such that it appears as a linear term multiplying the conserved number [Gavai & Sharma, 1406.0474] as in the continuum instead of conventional $e^\mu$.

$$D(0)_{xy} - \frac{\mu a}{2} \eta_4(x) \left[ U_4^\dagger(y) \delta_{x,y+\hat{4}} + U_4(x) \delta_{x,y-\hat{4}} \right].$$

No divergences exist for sixth order susceptibilities and beyond. [Gavai & Sharma, 1406.0474]

Number of inversions significantly reduced for 6th and higher orders. For 8th order QNS the no. of matrix inversions reduced from 20 to 8.

Calculate $n_B$ in imaginary $\mu$ and extract higher order fluctuations. [See Szabolcs Borsanyi’s talk, Fri, 14:25 PM].

Current state of the art: 6th order fluctuations known with very good precision: [Gunther et. al, 1607.02493, D’Elia et. al., 1611.08285, Bielefeld-BNL-CCNU, 1701.04325]
Possible ways out

- Heavy-ion experiments at different collision energies sets non-trivial constraints: \( n_s = 0, \frac{n_B}{n_Q} \) = constant.
- Can be implemented easily within Taylor series method. [Bielefeld-BNL-CCNU, 1701.04325]. Also implemented in imaginary \( \mu \).
- \( \chi_B^6 \) has very distinct structure \( \rightarrow \) deviates from Hadron Resonance gas picture for \( T < T_c \). Weak coupling results cannot predict the dip at \( T > T_c \) \( \rightarrow \) signatures of a strongly coupled medium?

[Gunther et. al, 1607.02493, Bielefeld-BNL-CCNU, 1701.04325]
Can we understand degrees of freedom in hot QCD medium?

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- Look at a simple system: correlation between charm and light quarks
- Deviation from Hard Thermal Loop results between $160 – 200$ MeV.
- Charm quarks not a good quasi-particle below 200 MeV? What happens after charm hadron melts at $T_c$. [Mukherjee, Petreczky, SS, 1509.08887.]
What are the microscopic constituents beyond $T_c$?
Model charm d.o.f in QCD medium as charm meson+baryon+quark-like excitations.

\[ p_C(T, \mu_B, \mu_C) = p_M(T) \cosh \left( \frac{\mu_C}{T} \right) + p_{B,C=1}(T) \cosh \left( \frac{\mu_C + \mu_B}{T} \right) + p_q(T) \cosh \left( \frac{\mu_C + \mu_B/3}{T} \right). \]

Considering fluctuations upto 4th order there are 6 measurements and thus 2 trivial constraints $\chi_C^4 = \chi_C^2$, $\chi_{BC}^{11} = \chi_{BC}^{13}$.

A more non-trivial constraint:
\[ c_1 \equiv \chi_{13}^{BC} - 4\chi_{22}^{BC} + 3\chi_{31}^{BC} = 0. \]

Non-trivial check: LQCD data agree with the constraints in the model thus validating it. [Mukherjee, Petreczky, SS, 1509.08887].
Meson and baryon like excitations survive up to $1.2 T_c$.

Quark-quasiparticles start dominating the pressure beyond $T \gtrsim 200$ MeV $\Rightarrow$ hints of strongly coupled QGP [Mukherjee, Petreczky, SS, 1509.08887].

Introduce more sophistications: it is now possible to rule out di-quark excitations at least for the charm sector for $T > T_c$.

**Challenge**: Understand microscopics in strange sector. Fate of Kaon fluctuations reported. [Noronha-Hostler et. al., 1607.02527]
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Basic issues and requirements

- Do the expanding fireball formed in most central heavy-ion collisions attain local thermal equilibrium? → can be modelled by viscous hydrodynamics.

- Equation of state from lattice QCD indispensable input for the hydrodynamic evolution.

- For most RHIC energies: $n_S = 0$, $n_Q/n_B = 0.4$ need to calculate EOS for the constrained case.

- In order to disentangle the thermal fluctuations from non-thermal ones, need to measure suitable fluctuations of conserved charges on the lattice → then perform dynamical evolution in rapidity and relate to experimental measurements. [Asakawa & Kitazawa 1512.05038].

Dynamical evolution of fluctuations near critical point in model studies show interesting patterns Mukherjee, Venugopalan, Yin, 1605.09341
EoS away from criticality

- The pressure already well determined by $\chi_B^6$ for $\mu_B/T \leq 2.5$ [Bielefeld-BNL-CCNU, 1701.04325]. [See H. Ohno’s talk, Fri 14:00 PM].
- Extension to $\mu_B/T \sim 3$ is in progress to cover all the allowed range for energies of heavy-ion collisions to be probed in Beam Energy Scan II experiments → need to measure $\chi_B^8$? Control errors on such measurements.

![Graph showing the pressure at different $\mu_B/T$ ratios](image)

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Critical-end point search from Lattice

- The series for $\chi^B_2$ should diverge at the critical point. On finite lattice ratios of Taylor coefficients equal, indep. of volume [Gavai & Gupta, 03]

- Radius of convergence from Taylor expansion: $r_{2n} \equiv \sqrt{2n(2n - 1)} \left| \frac{\chi^B_{2n}}{\chi^B_{2n+2}} \right|$.

- Definition is true for $n \to \infty$. How large $n$ could be on a finite lattice?

- New studies from Taylor expansions and imaginary $\mu$ sets a current bound for CEP to be $\mu_B/T > 2$ [Bielefeld-BNL-CCNU, 1701.04325, D’Elia et. al., 1611.08285] though some studies point to a lower bound. [Datta et. al., 1612.06673, Fodor and Katz, 04]

![Diagram showing $r^2_2$ and $r^4_4$ estimators for $\mu_B/T$ versus $T$ in MeV, with disfavored region for the location of a critical point highlighted in yellow.](image)
Fluctuations measured at freezeout: Are these thermalized?

- Ratios of cumulants are independent of the volume of the fireball.
- First to second moment:
  \[ \frac{M_B}{\sigma_B^2} = \frac{\mu_B}{T} + \mathcal{O}\left(\frac{\mu_B}{T}\right)^3 \]
- \( S_B\sigma_B = \frac{\mu_B}{T} \frac{\chi_4}{\chi_2} + \mathcal{O}\left(\frac{\mu_B}{T}\right)^3 \)
- \( \mu_B \) is unknown parameter and model dependent.

Clear deviation from Hadron Resonance gas description in experimental data!
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- \(S_B\sigma_B = \frac{\mu_B}{T} \frac{\chi_4^B}{\chi_2^B} + O\left(\frac{\mu_B}{T}\right)^3\)
  \(\mu_B\) is unknown parameter and model dependent.
- Instead \(S_B\sigma_B = \frac{M_B}{\sigma_B^2} \frac{\chi_4^B}{\chi_2^B} + \ldots\)
  removes model uncertainties!

[Refs: Karsch et. al., arxiv:1512.06987]

Clear deviation from Hadron Resonance gas description in experimental data!
Fluctuations at freezeout and lattice

\[ R_{31}^B = \frac{S_B \sigma_B^3}{M_B} = \frac{\chi_4^B}{\chi_2^B} + \frac{1}{6} \left[ \frac{\chi_6^B}{\chi_2^B} - \left( \frac{\chi_4^B}{\chi_2^B} \right)^2 \right] \left( \frac{M_B}{\sigma_B^2} \right)^2 \]

[Karsch et. al., arxiv:1512.06987]

- Experimental data tantalizingly close to QCD prediction \( \rightarrow \) Accidental coincidence or hints of thermalization?

- **Challenges** Need to perform dynamical evolution of the ratios of cumulants.

- **Caveat:** In experiments only charged baryons (protons) measured \( n_P \neq n_B \!), take into account \( p_t \) cuts in the data. Look for suitable observables!
Preparing for BES-II runs: QCD EoS for $\frac{\mu_B}{T} < 2 \rightarrow \sqrt{s}_{NN} \geq 20$ GeV already under control. Need to extend it for $\frac{\mu_B}{T} = 3$. 
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Fluctuations data suggest QCD medium beyond $T_c$ non-perturbative. Quasi-particle picture valid $\sim 1.5T_c$ and beyond. Existence of broad resonance atleast in charm sector observed $\rightarrow$ crucial for dynamical modelling of hot QCD medium.