Fluctuations of strangeness and charm from lattice QCD

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For Bielefeld-BNL collaboration
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Outline

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Introduction

- The fluctuations of the conserved numbers are good probes of the properties of QGP [Gottlieb et. al. 88, Koch, 08]

- In a heavy ion experiment the net Baryon number(B), Strangeness(S), electric charge(Q) are good quantum nos.

- The strange particles are produced in the thermalized QGP $\rightarrow$ enhancement of strangeness.

- The fluctation of S shows a smoother behaviour at the crossover $\rightarrow$ Strange hadron bound states beyond T_c? [Ratti et. al, 11]

- At LHC, strange quark production would saturate and large production of $D_s(c\bar{s})$ mesons.

Introduction

- The charm quarks and charmed hadrons are created early before QGP is formed
- The temperature of QGP: 350 MeV(RHIC), 500 MeV(LHC)
- No additional charm quarks produced in the medium
- These are expected to be in thermal equilibrium with QGP
  [Gupta & R. Sharma, 14]
- The melting of J/ψ, η_c act as thermometer of the QGP [Matsui & Satz, 86]
  However statistical regeneration of charmed hadrons important at LHC energies [Braun-Munziger & Stachel 2000]

Outline

The issues addressed

- What are the most important coordinates that characterize the curve for chemical freezeout in the phase diagram
- How do the open heavy hadrons behave at the freezeout
- How the fluctations of heavier quarks allow us to understand the QCD medium at freezeout
- Information about the sign problem from analysis of fluctuations
- We use Taylor series approach [Allton et. al., 02, Gavai & Gupta, 03] to circumvent the sign problem and extract some useful information in heavy quark sector

Our tools

- We compute the second order diagonal and off-diagonal strangeness and charm quark number susceptibilities at zero and finite $\hat{\mu}_X$ for QCD
- Expanding as a Taylor series about $\hat{\mu}_X = 0$,$\hat{\mu}_X = \mu_X/T, X = B, C, S, Q$

$$\chi_2^{C(S)}(\hat{\mu}_B, \hat{\mu}_C, \hat{\mu}_S, \hat{\mu}_Q) = \chi_2^{C(S)}(0,0,0,0) + \frac{\hat{\mu}_X^2}{2}\chi_{22}^{XC(S)}(0,0,0,0) + ..$$

$$\chi_{11}^{XC(S)}(\hat{\mu}_B, \hat{\mu}_C, \hat{\mu}_S, \hat{\mu}_Q) = \chi_{11}^{XC(S)}(0,0,0,0) + \frac{\hat{\mu}_X^2}{2}\chi_{31}^{XC(S)}(0,0,0,0) + ..$$

where the susceptibilities are

$$\chi_{ijkl}^{BQSC} = -\frac{1}{VT^3}\frac{\partial^{i+j+k+l}\ln \mathcal{Z}_{QCD}}{\partial \hat{\mu}_i^B \hat{\mu}_j^Q \hat{\mu}_k^S \hat{\mu}_l^C}$$

- Each of these correlations can be expressed in terms of quark number susceptibilities

$$\frac{\partial}{\partial \hat{\mu}^Q} = \frac{1}{3}\left(2\frac{\partial}{\partial \hat{\mu}^u} - \frac{\partial}{\partial \hat{\mu}^d} - \frac{\partial}{\partial \hat{\mu}^s} + 2\frac{\partial}{\partial \hat{\mu}^c}\right)$$

Computational Details

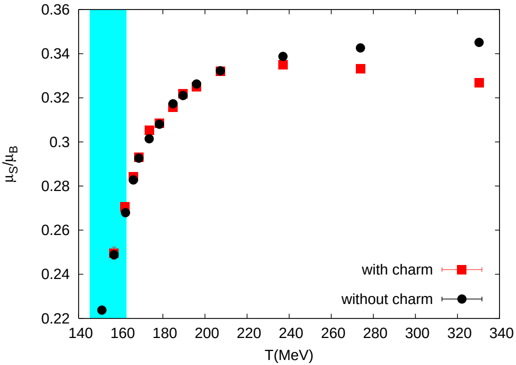
- The lattice used: $24^3 \times 6$,$32^3 \times 8$
- 2+1 flavour configurations with Highly Improved Staggered Quarks(HISQ) quarks $\rightarrow$ taste breaking effects minimal on a finite lattice
- The charm quarks are external probes $\rightarrow$ quenched
- The strange quark mass is physical.
- The light quark mass $m_l = m_s/20 \Rightarrow m_\pi = 160$ MeV.
- The charm mass determined by setting spin averaged $\frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ mass to its physical value
- 1500-6000 stochastic estimators used to determine the traces of Dirac operator and its derivatives for the susceptibilities.
- Statistical errors controlled by analyzing 5000 configurations at lower T

The freezeout curve

- The coordinates that characterize freezeout curve: $T, \mu_B, \mu_S, \mu_C, \mu_Q$.
- The freezeout conditions at RHIC: $r = \frac{\langle n_p \rangle}{\langle n_p + n_n \rangle} = \frac{\langle n_Q \rangle}{\langle n_B \rangle} = 0.4$ $\langle n_C \rangle = \langle n_S \rangle = 0$
- To lowest order in chemical potentials $\hat{\mu}_X = \mu_X / T, X = B, C, S, Q$

$$\begin{pmatrix} \langle n_B \rangle \\ 0 \\ 0 \\ r\langle n_B \rangle \end{pmatrix} = \begin{pmatrix} \chi_2^B & \chi_{11}^{BS} & \chi_{11}^{BC} & \chi_{11}^{BQ} \\ \chi_{11}^{BS} & \chi_2^S & \chi_{11}^{SC} & \chi_{11}^{SQ} \\ \chi_{11}^{BC} & \chi_{11}^{SC} & \chi_2^C & \chi_{11}^{QC} \\ \chi_{11}^{BQ} & \chi_{11}^{SQ} & \chi_{11}^{QC} & \chi_2^Q \end{pmatrix} \begin{pmatrix} \mu_B \\ \mu_S \\ \mu_C \\ \mu_Q \end{pmatrix}$$

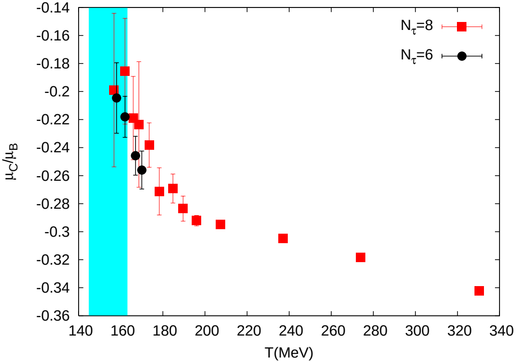
The freezeout curve



- The $|\mu_S/\mu_B| \sim 0.2 - 0.3$ is not affected significantly at the freezeout.
- At $T > 250$ MeV the effect of the charm quarks shows up.
- The contribution of μ_Q order of magnitude smaller than μ_S

[Bielefeld-BNL collaboration, 12]

The freezeout curve



- The $|\mu_C/\mu_B| \sim 0.2 - 0.3$ behaves similarly as μ_S/μ_B.
- Conclusion: T, μ_B are the most important coordinates characterizing freezeout.

The partial pressures of strange hadrons

- We study the second order susceptibilities of Strangeness sector as a Taylor series in μ_B.
- Using the second order susceptibilities and its leading order Taylor coefficients at $\mu_B = 0$ we ask:
- Do deconfinement of the open heavy flavours occur at the chiral crossover?

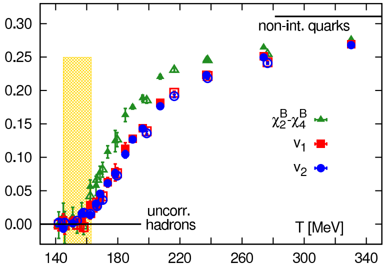
The partial pressures of strange hadrons

- The total pressure of an ensemble of non-interacting strange hadrons and resonances is given as,

$$\begin{aligned} P(\hat{\mu}_S, \hat{\mu}_B) &= P_M \cosh(\hat{\mu}_S) + P_{B,S=1} \cosh(\hat{\mu}_B + \hat{\mu}_S) \\ &+ P_{B,S=2} \cosh(\hat{\mu}_B + 2\hat{\mu}_S) + P_{B,S=3} \cosh(\hat{\mu}_B + 3\hat{\mu}_S) \end{aligned}$$

- The partial pressures can be constructed out of the second order χ_2^S, χ_{11}^{BS} and their leading order Taylor coefficients at $\hat{\mu}_{B,S} = 0$.
- 6 variables: $\chi_2^S, \chi_{11}^{BS}, \chi_4^S, \chi_{13}^{BS}, \chi_{31}^{BS}, \chi_{22}^{BS}$
- 4 independent partial pressures and 2 constraints can be constructed out of these 6 quantities.
- The constraints in the HRG phase are $v_1 \equiv \chi_{31}^{BS} - \chi_{11}^{BS} = 0$ and $v_2 \equiv \frac{1}{3}(\chi_S^4 - \chi_S^2) - 4\chi_{22}^{BS} + 2\chi_{31}^{BS} + 2\chi_{13}^{BS} = 0$. [Bielefeld-BNL collaboration, 13]

The partial pressures of strange hadrons



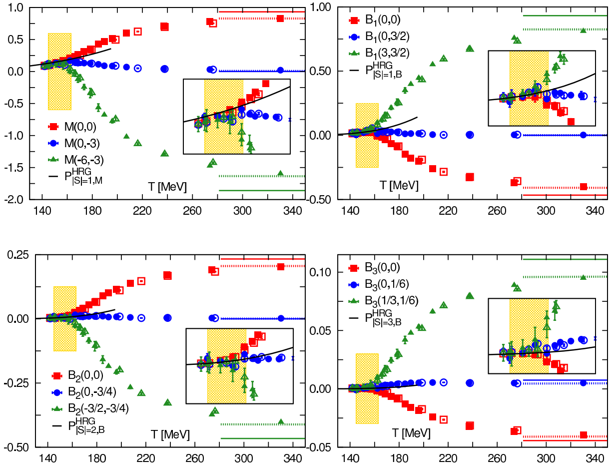
[Bielefeld-BNL collaboration, 13]

- The Hadron resonance gas(HRG) description of the strange quarks breaks down already at the chiral crossover
- Deconfinement of strangeness takes place at the crossover region

The partial pressures of strange hadrons

- In the HRG regime: the partial pressures can be expressed in terms of fluctuations
- The meson partial pressure: $P_M(c_1, c_2) = \chi_2^S - \chi_{22}^{BS} + c_1 v_1 + c_2 v_2$
- The baryons with different strangeness contents: $P_{B,S=1}(c_1, c_2) = \frac{1}{2}(\chi_4^S - \chi_2^S + 7\chi_{22}^{BS} + 5\chi_{13}^{BS}) + c_1 v_1 + c_2 v_2$

The partial pressures of strange hadrons

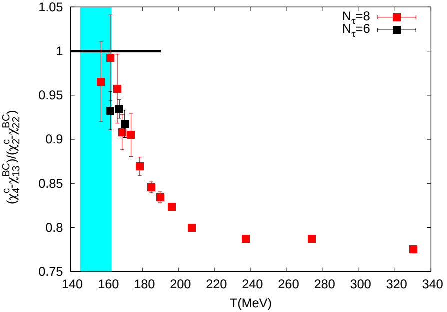


- The HRG description for strange baryons, mesons break down at crossover
- The values tend towards the Hard Thermal loop results for $T > 250$ MeV
- Intermediate $T \rightarrow$ strongly interacting quasi-particles [Bielefeld-BNL collaboration, 13]

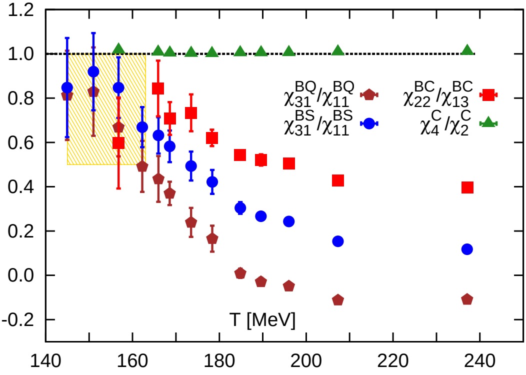
The fate of charmed hadrons

- Two different construction of the charmed sectors $P_M = \chi_2^C - \chi_{22}^{BC}$ or equivalently $P_M = \chi_4^C - \chi_{13}^{BC}$.
- Departure of the ratio from unity $\Rightarrow$ melting of mesons.
- The HRG description breaks down at the crossover region

[Bielefeld-BNL collaboration, in preparation].

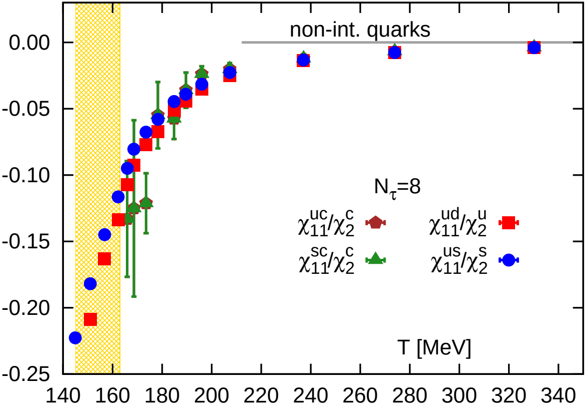


The fate of charmed hadrons



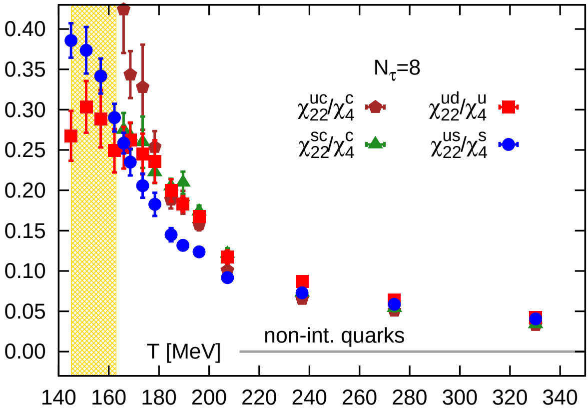
The conclusions well summarized in terms of the ratios of susceptibilities.

The susceptibilities at high temperatures



The correlations between different flavours are identical beyond $T > 200$ MeV

The susceptibilities at high temperatures



The higher order correlators more sensitive to gluon interactions. Do not reach free gas limit even at 2 T_c.

Outline

Summary

- We used Taylor expansion to circumvent the Sign problem and extract some useful information about the heavy quark sector
- $T, \ \mu_B$ are the most relevant coordinates at the chemical freezeout
- The second order diagonal and off-diagonal susceptibilities for charm and strangeness and their first Taylor coefficient in μ_B used to extract partial pressures of open heavy hadrons
- Deconfinement of strangeness occur at the chiral crossover

Thank You.