Towards understanding QCD phase diagram from the fluctuations of conserved charges

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Bielefeld-BNL-CCNU collaboration

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Outline

1. The QCD phase diagram: outstanding issues

2. Fluctuations and the physics near chiral crossover transition

3. QCD medium for $T > T_c$

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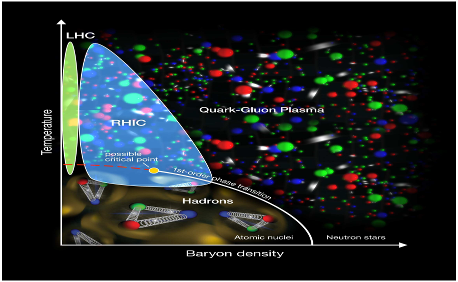

[http://www.bnl.gov/rhic/news]

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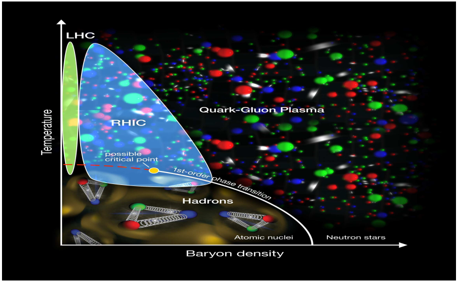

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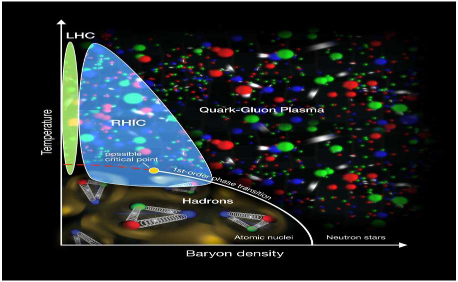

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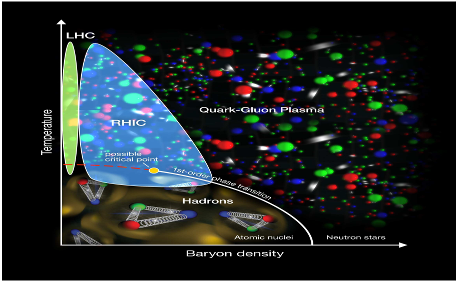
- Lattice calculations also provide a baseline for the observations of fluctuations of conserved charges from Heavy Ion collision experiments.



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Basic observables: Fluctuations of conserved charges

- Measure the fluctuations of conserved charges in a Grand Canonical ensemble

$$\chi_{ij}^{XY} = \frac{\partial^{i+j}}{\partial \hat{\mu}_i^X \partial \hat{\mu}_j^Y} P_{QCD}(\mu_x, T)/T^4 \ , \ \chi_i^X = \frac{\partial^i}{\partial \hat{\mu}_i^X} P_{QCD}(\mu_x, T)/T^4$$

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- The derivatives of pressure can be written in terms of trace of D and its derivatives: Like: $\chi_2^u = \langle Tr[D^{-1}D'' - D^{-1}D'D^{-1}D'] \rangle + \langle Tr[D^{-1}D']^2 \rangle$.

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- No. inversions increases for higher fluctuations$\rightarrow$ numerically expensive. Techniques developed like analytic continuation from imaginary chemical potential data [S. Borsanyi, 15] and recent advances in programming [P. Steinbrecher's, Kate Clark's Talk] to address these issues.

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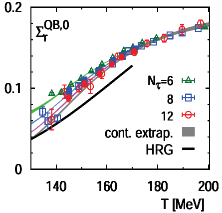
- Ratios of fluctuations $\Sigma_r^{QB} = 0.4\frac{\chi_2^B}{\chi_2^Q}$ are the simplest to compute.
- Even these simple observables already show a deviation from Hadron Resonance Gas (HRG) Model at $T > 140$ MeV. [Bielefeld-BNL collaboration, 15]



Is Hadron Resonance Gas a good approximation for QCD below T_c?

- When there are no inelastic collisions $\Rightarrow$ the ensemble can be described by a gas of all measured hadrons and possible resonances (HRG) [Dashen, Ma and Bernstein, 69,71]

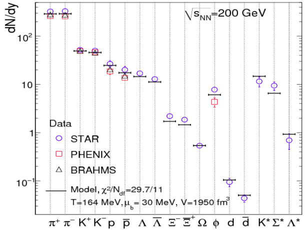
$$\ln \mathcal{Z} = \pm \sum_i g_i \frac{V}{2\pi^2} \int_0^\infty dp p^2 \ln\left(1 \pm \mathrm{e}^{\beta(\epsilon_i - \mu_i)}\right) ,$$

$$\epsilon_i = \sqrt{p^2 + m_i^2} \simeq m_i \quad \& \quad \mu_i = \mu_B B_i + \mu_S S_i + \mu_C C_i + \mu_I I_i \ .$$

- Residual interactions $\propto n_i n_j \sim \mathrm{e}^{-(m_i+m_j)/T}$ suppressed.
- A virial expansion can be used to estimate the effect of interactions.
- Scattering phase shifts from expt used to calculate interaction cross-section.
- HRG a good approximation if resonances very near to two particle threshold. [Prakash & Venugopalan, 92]
- For light hadrons validity of HRG needs to be checked! For charm it is expected to work.

HRG and Freezeout data from experiments

- Chemical freezeout $\Rightarrow$ the hadrons do not scatter inelastically.
- Compare the ratio of particle yields from theory and experiments and perform a χ^2 minimization in the $T - \mu_B$ plane.
- If indeed a thermalized medium is formed $\Rightarrow$ get T^f and μ_B^f corresponding to the collision energy of two heavy nuclei.
- Caveats: Issues about thermalization, expanding system, momentum cut etc..



Freezeout curve for a thermalized medium

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$\Sigma_r^{QB} = \Sigma_r^{QB}(0) + \left[\Sigma_r^{QB,2} - \kappa_2^f \; T_{f,0} \frac{d\Sigma_r^{QB,0}}{dT}\Big|_{T_{f,0}}\right] \frac{\mu_B^2}{T^2} \; .$

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- As a result $\Sigma_r^{QB} = \Sigma_r^{QB}(0) \left[1 + c_{12} \; \left(R_{12}^B\right)^2\right] + \mathcal{O}\left(R_{12}^B\right)^4$.

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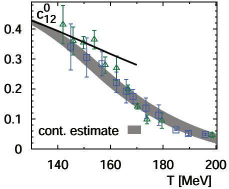
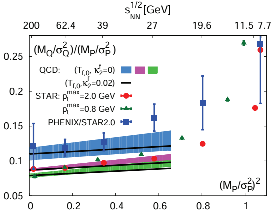
- An estimate of Σ_r^{QB} and R_{12}^B from experiments allows us to calculate c_{12}. [Bielefeld-BNL collaboration, 15]

- Caveat: In experiments one measures protons Σ_r^{Qp}, R_{12}^p.
- Additionally take into account also corrections due to finite range of momenta of detected particles [Karsch, Morita and Redlich, 15].
- From the 2 independent expressions of Σ_r^{QB} we extract $c_{12}(T_{f,0}, \kappa_2^f) = c_{12}(T_{f,0}) - \kappa_2^f D_{12}$.





- This excercise give $T_{f,0} = 147$ MeV consistent with expectation that its at or below T_c.
  Curvature: $\kappa_2^f < -0.012(15) \rightarrow$ near to chiral curvature $\kappa_2^B = 0.007$.

When do the open-charm hadrons melt

- We want to understand when heavy quarks deconfine looking at the properties of heavy-light hadrons.
- The analysis of bound states through the study of spectral functions difficult on the lattice.
- If the charm hadron ensemble near the freezeout well described as a hadron resonance gas characterized by T, μ_B, μ_C,

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

- The ground state $m_{C=2} - m_{C=1} = 1$ GeV : effect on thermodynamics of $C = 2, 3$ baryons is negligible.

- It is comparatively easy to calculate the fluctuations +correlations of B, C

$$\chi_{ij}^{BC} = \frac{\partial^{i+j}}{\partial \hat{\mu}_i^B \partial \hat{\mu}_j^C} P_{tot}/T^4$$

- The partial pressures can be constructed out of χ_2^C, χ_{11}^{BC} and $\chi_4^C, \chi_{31}^{BC}, \chi_{22}^{BC}, \chi_{13}^{BC}$. [Bielefeld-BNL collaboration, 13]

- Setting $\mu = 0$ one can rewrite the partial pressures in terms of these quantities like

$$P_M = \chi_2^C - \chi_{22}^{BC}\ , P_{B,C=1} \sim \chi_{mn}^{BC}\ , m+n=4$$

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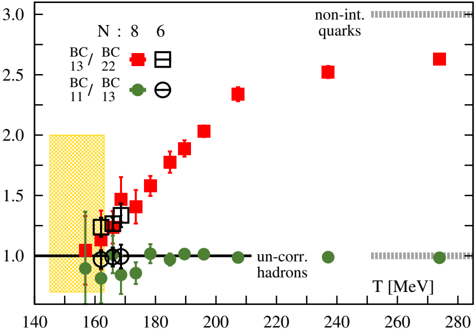
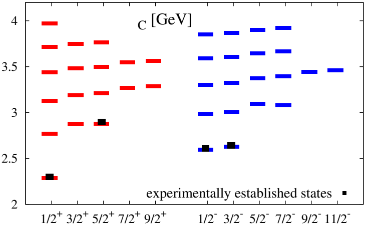
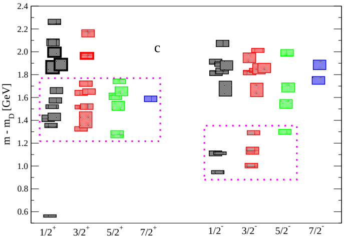
- Baryons with charm and light degrees of freedom melt at T_c independent of the details of the hadron spectrum. [Bielefeld-BNL collaboration, PLB 14]



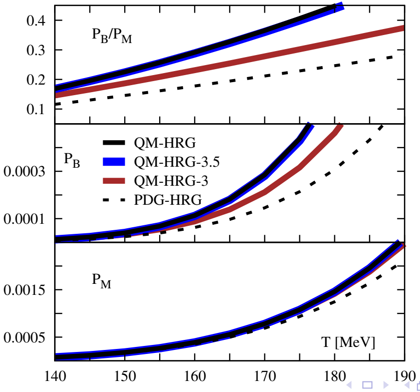
- The charm meson sector is measured experimentally to quite good precision.
- Many charm baryons states not measured yet predicted from lattice and quark models [Ebert et. al, 10, Padmanath et. al., 13]
- Even spin-parity of ground state Λ_c not measured!





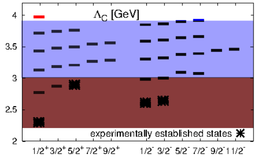
Relevance for QCD thermodynamics

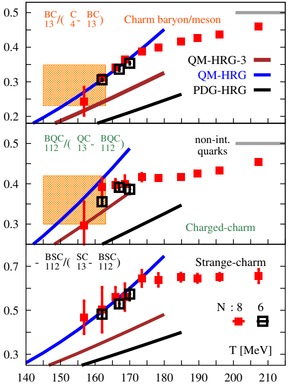
- We construct hadron resonance gas model with experimentally known states: PDG-HRG
- Compare with HRG with experimental+additional states: QM-HRG
- The partial pressure of mesons are similar
- In the baryon sector the difference starts showing up near T_c [Bielefeld-BNL collaboration, 14]



Our results

- Our methodology allows us to look at charm baryon sector exclusively
- Also look into the specific quantum number channels
  - all hadrons: $\frac{P_B}{P_M} = \frac{\chi_{13}^{BC}}{\chi_4^C - \chi_{13}^{BC}}$
  - S=1,2 hadrons: $\frac{\chi_{112}^{BSC}}{\chi_{13}^{SC} - \chi_{112}^{BSC}}$
  - Q=1,2 hadrons : $\frac{\chi_{112}^{BQC}}{\chi_{13}^{QC} - \chi_{112}^{BQC}}$





QCD data seems to support the contribution of these additional baryon states to thermodynamics near T_c. [Bielefeld-BNL collaboration, 14]

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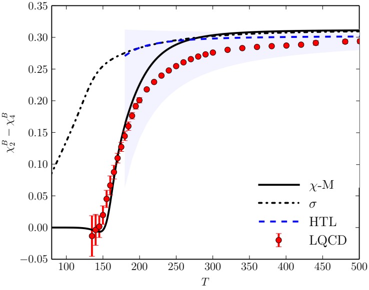
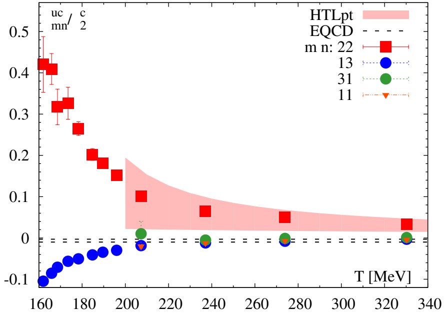
Non-perturbative nature of the QCD medium

- Above T_c, deconfinement of the color degrees of freedom occur.
- However the nature and/or existence of quasi-particles not well known for $T < 2T_c \Rightarrow$ any new insight to lattice data is clearly important.
- Matrix model for $SU_c(3)$ with non-trivial Polyakov loop potential could explain some of the essential features of strongly coupled pure gauge theory above T_d [Y. Hidaka and R. D. Pisarski, 08,09]
- Extension to chiral matrix model [R. D. Pisarski and V. Skokov, to appear] by adding 2+1 f quarks coupled to a meson nonet of both parities through Yukawa coupling + Potential for scalar fields symmetric under $SU(3)_L \times SU(3)_R \times Z(3)_A$ to mimic QCD.

- $\chi_2^B - \chi_4^B = 0$ in hadron phase, non-zero values signal deconfinement of quasi-particles carrying fractional B. [BI-BNL collaboration, 13]
- The Chiral Matrix model predictions for $\chi_2^B - \chi_4^B$ [R. D. Pisarski and V. Skokov, to appear] seems to agree with the continuum extrapolated lattice data [Budapest-Wuppertal collaboration, 14] for $T_c < T < 2T_c$.
- The Hard thermal loop perturbation theory agreement with lattice data only for $\sim 3\ T_c$.
- Naive quark-meson model do not capture the physics $\Rightarrow$ non-trivial eigenvalues or holonomy of the Polyakov loop seems to play a significant role for $T < 2T_c$.



Does it hold true for charm too?



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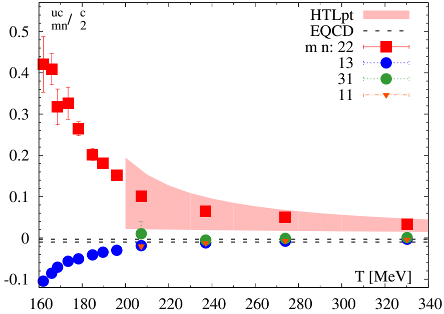

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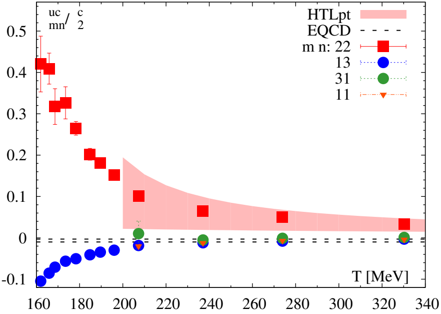

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- Pressure for broad "quasi-particles" considerably lower than small width QP [Biro & Jakovac, 14]

Degrees of freedom beyond T_c?

- We look specifically at the sector of strange and charm hadrons where S and C quantum numbers are correlated only in the hadron phase.
- Upto 4th order derivatives additionally one has 3 more measurements $\chi^{BSC}_{[112]}$ apart from χ^{SC}_{n+m} and

$$p_{SC}(T,\mu_B,\mu_C,\mu_C) = \sum_{j=0}^{1} p_{B,S=j}(T)\cosh\left(\frac{\mu_C+\mu_B-j\mu_S}{T}\right) + p_M(T)\cosh\left(\frac{\mu_C+\mu_S}{T}\right) + (p_D(T)?).$$

- $p_D = \chi^{BSC}_{[211]} - \chi^{BSC}_{[112]} = 0$ for our data. Di-quarks carry color quantum number... should disappear when quark d.o.f start dominating.

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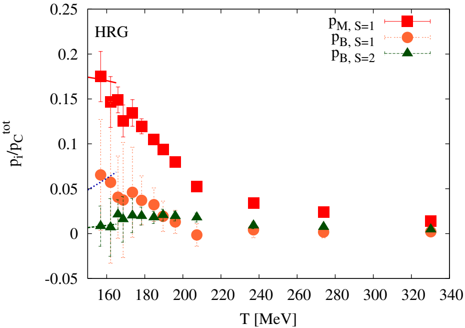
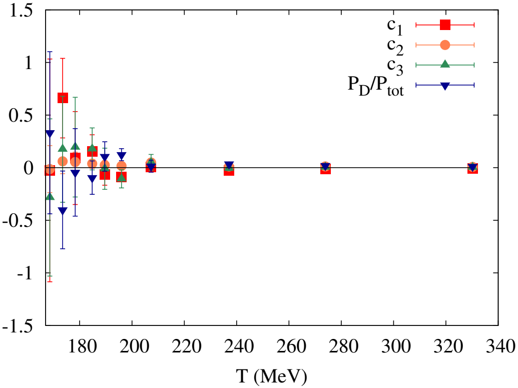


- Meson and baryon like excitations survive upto $1.2\ T_c$.
- Quark-quasiparticles start dominating the pressure beyond $T \gtrsim 200$ MeV $\Rightarrow$ hints of strongly coupled QGP [S. Mukherjee, P. Petreczky, SS, 15].
- Strange baryon-like excitations suppressed than meson-like excitations.
- These studies consistent with screening mass of sc-mesons [Y. Maezawa et. al., 15].

Degrees of freedom beyond T_c?

- For these calculations to be valid one should satisfy constraint relations $\rightarrow$ smoothly connect to HRG and free gas at low and high T.



- Lattice data agree with the constraints imposed by our proposed model [S.Mukherjee, P. Petreczky, SS, 15].

What we learnt till now

- For many fluctuation related observables the prediction from a hadron Resonance gas already breaks down at $T \sim 140$-145 MeV.
- We took the lattice data and tried to constraint the experimental freezeout curve assuming thermalization. The result for freezeout $T_f = 147$ MeV at small baryon density consistent with expectation $T_f < T_c$.
- For heavy quarks we observe that charm baryons too melt near T_c.
- Additional charm baryons and resonances will contribute to thermodynamics near T_c.
- A similar contribution of these additional strange baryons and excitations $\Rightarrow$ allows for a reduction of T_f by $5 - 8$ MeV [Bielefeld-BNL collaboration, 14] contrary to the flavour hierarchy picture at T_c.

Perspectives

- The QCD medium at $T > T_c$ is non-perturbative, non-trivial holonomy plays a role in explaining the fluctuation data.
- For the charm sector, we observe baryon and meson like excitations surviving in the medium till $1.2\ T_c$.
- Open charm hadrons melt at $T_c \Rightarrow$ freezeout temperature for D_s is now well known
  Input for heavy flavour transport models [A. Beraudo et. al., 12]
- Additional baryons may contribute to hadronic interactions near the freezeout $\rightarrow$ can it explain the discrepancy for between flow and suppression for D mesons?
- Our study more in favour for resonant scattering of heavy quarks in the medium [M. He, R. J. Fries, R. Rapp, 12].