Open heavy flavor from lattice studies

Sayantan Sharma

BROOKHAVEN NATIONAL LABORATORY

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BNL-Bielefeld collaboration, Physics Letters B 737, 210, (2014),
S. Mukherjee, P. Petreczky, SS Phys. Rev. D 93, 014502 (2016).

Outline

1. Puzzles for open heavy flavor
2. Open charm mesons at freezeout
3. Relevance of our studies

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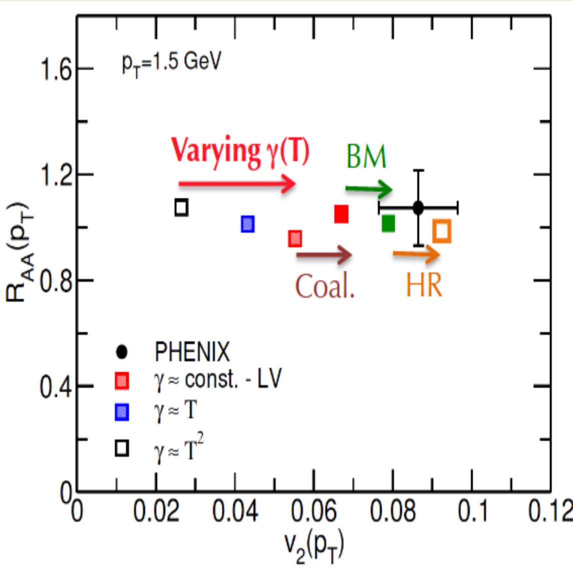
Open heavy flavors: challenges

- Heavy quarks are created in the initial stages of heavy-ion collisions.
- Exchange energy and momenta with the medium $\rightarrow R_{AA}$ quantifies the suppression of high p_T heavy hadrons due to the interaction.
- v_2 generated due to interactions.
- Tension between R_{AA} and v_2. Can be understood for RHIC energies but still unresolved for LHC energies? [Courtesy, V. Greco, QM 2017]



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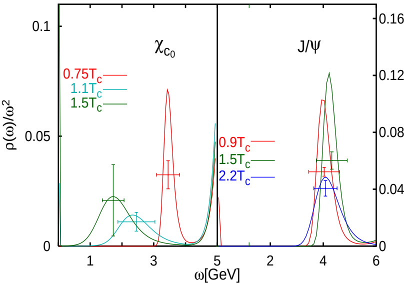
- What is the melting temperature of heavy hadrons T_c?
- Dynamic quantities like the diffusion constant D and η/S.

Melting temperature of heavy quark bound states

- The $c\bar{c}$ mesons like J/ψ, η_c are created early in HIC.
- If thermalized QGP is formed the number of J/ψ produced is much reduced due to screening of inter quark potential [Matsui & Satz, 86]
- First principles study of the spectral functions [S. Datta et. al., 04, Ding et. al, 12, Swansea collaboration, 07,10, H. Ohno, 13] and variational method [H. Ohno et. al, 11] shows melting of J/ψ at $T > 1.5\ T_c$.



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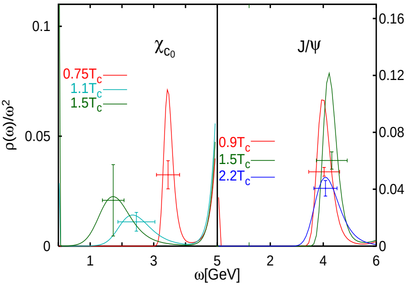
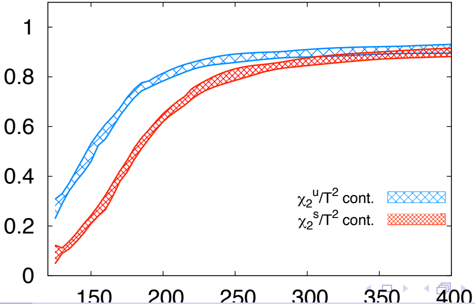
- Bottomonium states [H. Ohno, et. al. 13,14, Swansea 14] show sequential melting above T_c.



Is there really a flavor hierarchy?

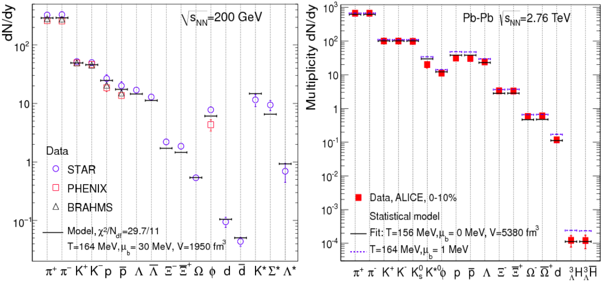
- Deconfinement : Releasing of colored degrees of freedom
- Pure gauge theory: phase transition due to deconfinement has an order parameter Polyakov loop L_{ren}
- In QCD with physical masses: no exact order parameter
- Looking at the fluctuations of s and u quark numbers in the thermal medium gives an apparent impression of different T_d [C. Ratti et. al, 12, Bellweid, 12]
- Important to look at good "order parameters" that clearly separates the deconfined phase.



Outline

Characterization of freezeout surface

- If a thermalized medium is formed $\Rightarrow$ characterized by T, μ_B, V
- Compare the ratio of particle yields from theory and experiments and perform a χ^2 minimization in the $T - \mu_B$ plane.
- Obtain T^f and μ_B^f corresponding to the collision energy
- Issues about acceptance cut, low momentum particles left out



Motivation for HRG

- At freezeout no more 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]

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

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

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- 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]

Is it a good approximation?

- Summary: any residual hadron interactions at the freezeout is taken into account by considering all known resonances [Braun-Munzinger, Cleymans, Oeschler, Redlich, 02].

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- Residual interactions $\propto n_i n_j \sim \mathrm{e}^{-(\mathrm{m_i}+\mathrm{m_j})/\mathrm{T}}$ suppressed for heavy quarks $\rightarrow$ HRG is a better approximation of QCD medium near freezeout for heavy hadrons.

Why charm?

- The heavy charm quarks produced before QGP is formed.
- Maximum $T \sim 500$ MeV at the LHC
- $m_c > T$: charm is not thermally generated in the hot medium
- Have a near thermal distribution of momenta [S.Gupta & R. Sharma, 14]
- At LHC energies charm abundances are quite high $\rightarrow$ statistical hadronization similar to the light quarks?[Braun-Munzinger, Redlich, Stachel, 06]
- Hadronization would imply existence of deconfined medium

Our Setup

- We want to understand where heavy quarks deconfine from properties of heavy-light hadrons. $c\bar{c}$ states not considered.
- 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.

Our Setup

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

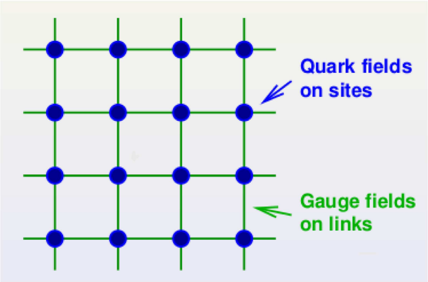
$$\chi_{ij}^{BC} = \frac{\partial^{i+j}}{\partial \hat{\mu}_i^B \partial \hat{\mu}_j^C} P_{tot}/T^4$$

- The partial pressures can be constructed out of 6 fourth order susceptibilities:
  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

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

A glimpse of what goes into computations



- Two different lattice $24^3 \times 6$, $32^3 \times 8$ to check the cut-off effects
- Large enough for thermodynamic limit
- The light and strange quarks are dynamical $\rightarrow$ nearly-physical
- Charm quarks are like external probes $\rightarrow$ quenched
- m_c determined by setting $1/4\left(3m_{J/\psi} + m_{\eta_c}\right)$ to its physical value

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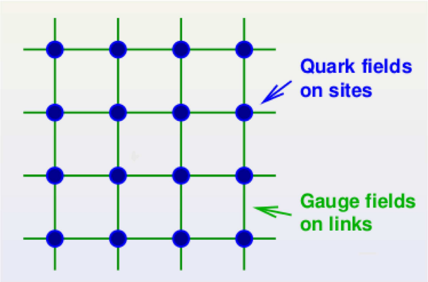

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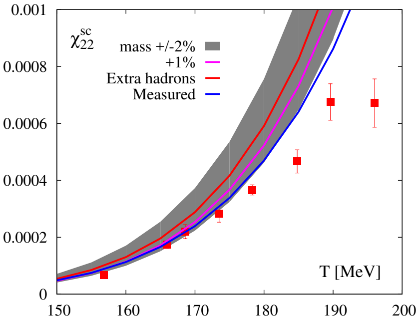
- m_c determined by setting $1/4\left(3m_{J/\psi} + m_{\eta_c}\right)$ to its physical value
- On the lattice measuring susceptibilities is complimentary to the spectral function method.

What do we need to consider

- An "order parameter" to characterize deconfinement of heavy quarks



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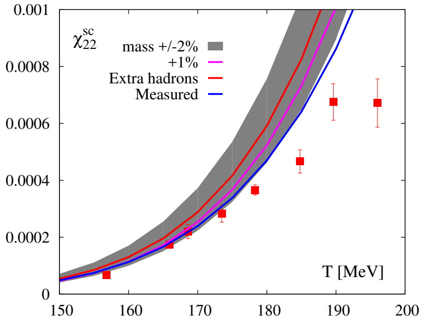
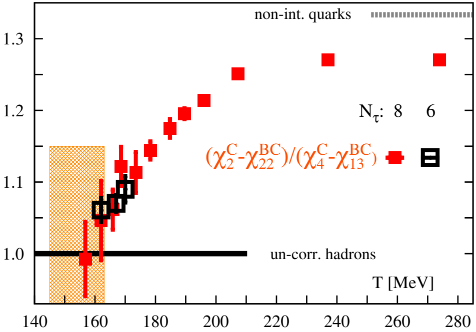
- For heavy quarks the mass dependent cut–off effects are severe $\rightarrow$ need to make our order parameter free from such effects.



Open charm mesons at freezeout

- We consider two equivalent definitions of $P_M = \chi_2^C - \chi_{22}^{BC} = \chi_4^C - \chi_{13}^{BC}$
- Ratio is like an order parameter
- Insensitive to lattice cut-off, mass effects
- Diagonal fluctuations dominated by mesons $\rightarrow$ not a good observable.



- Open charm mesons melt at T_c independent of the details of the hadron spectrum [Bielefeld-BNL collaboration, PLB, 14]

Fate of Charm baryons

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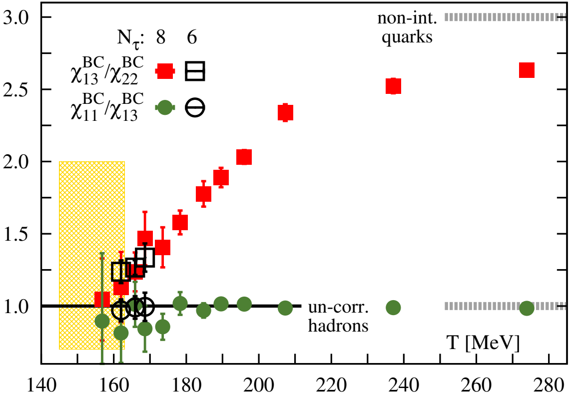

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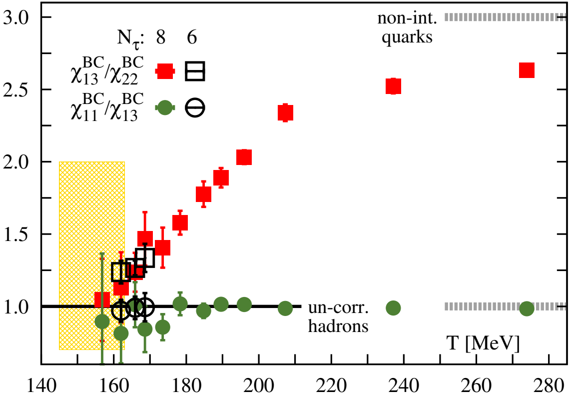

- These melt near T_c too!

[Bielefeld-BNL collaboration, PLB 14]

Summary till now

- Do the heavy baryons and mesons have a different freezeout surface than the others? $\Rightarrow$ look at the melting of hadrons of heavy and light quarks

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- What does it imply for the medium properties?

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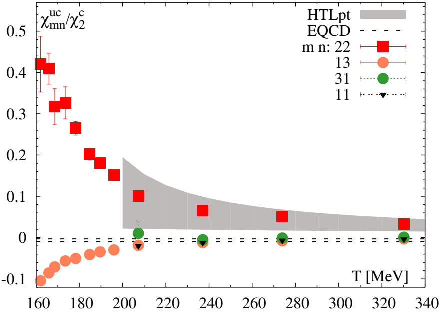

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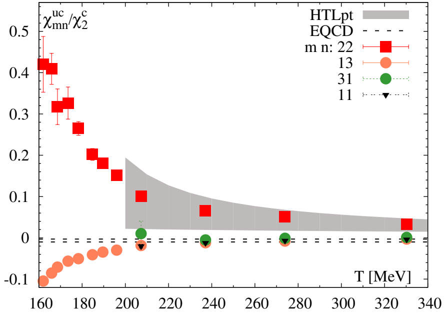

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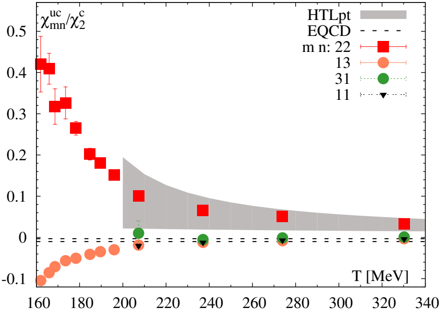

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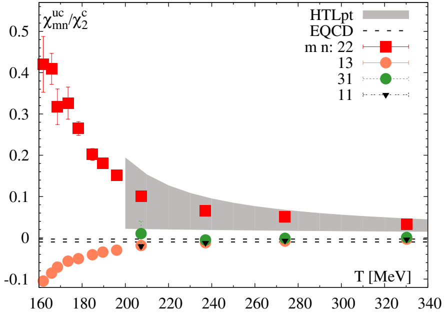

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- Hadrons melt but may survive as broad excitations till $1.2\,T_c$
- Pressure for broad "quasi-particles" considerably lower than small width QP [Biro & Jakovac, 14]
- Charm may also exist as a broad resonance with asymmetric peak in spectral function$\rightarrow$ not a good quasi-particle.

Charm d.o.f at deconfinement

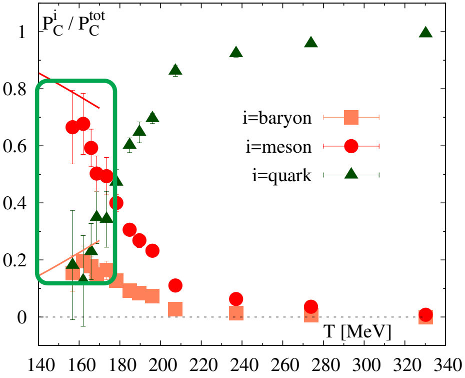
- Considering charm mesons+baryon+quark-like excitations

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

- Considering fluctuations upto 4th order we have 2 trivial constraints $\chi_4^C = \chi_2^C \; , \; \chi_{11}^{BC} = \chi_{13}^{BC}$.
- A more non-trivial constraint: $c_1 \equiv \chi_{13}^{BC} - 4\chi_{22}^{BC} + 3\chi_{31}^{BC} = 0$.

[Mukherjee, Petreczky, SS, PRD 2015]

Charm d.o.f at deconfinement



- 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 [Mukherjee, Petreczky, SS, PRD 2015]

Do diquarks exist beyond T_c?

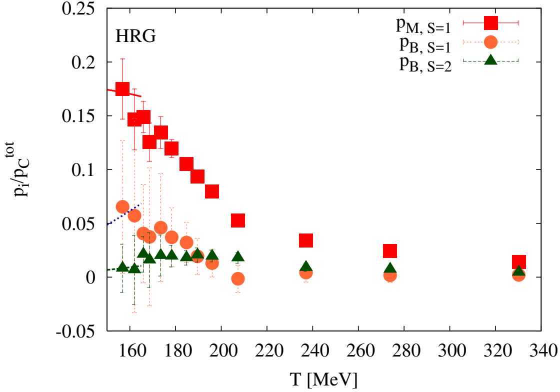
- We look specifically at the sector of strange and charm hadrons.
- Upto 4th order derivatives additionally one has 3 more measurements $\chi^{BSC}_{[112]}$

$$p_{SC}(T, \mu_B, \mu_C) = \sum_{j=0}^{1} p_{B,S=j}(T) \cosh\left(\frac{\mu_C + \mu_B - j\mu_S}{T}\right) + p_M(T) \cosh\left(\frac{\mu_C + \mu_S}{T}\right) + p_D(T) \cosh\left(\frac{\mu_C + \mu_B/3 - \mu_S}{T}\right).$$

- Di-quarks carry color quantum number...should disappear when quark d.o.f start dominating around 200 MeV.

Do diquarks exist beyond T_c?

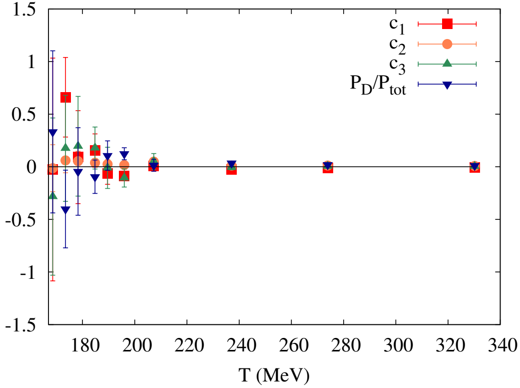
- $p_D = \chi^{BSC}_{[211]} - \chi^{BSC}_{[112]} = 0$ for our data.



- Strange baryon-like excitations suppressed than meson-like excitations.
- These studies consistent with screening mass of sc-mesons [Y. Maezawa et. al., PRD 2015] and also from recent spectral function study [I Kelly, J.I. Skullerud, 2017]

Do diquarks exist beyond T_c?

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



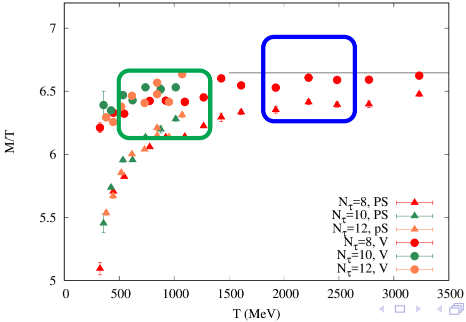
- LQCD data agree with the constraints imposed by our proposed model.

How perturbative is the QGP medium

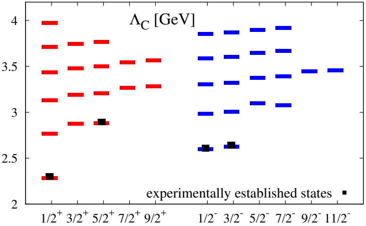
- Screening masses can show how perturbative is the medium → less IR sensitive, more perturbative than gluonic observables.

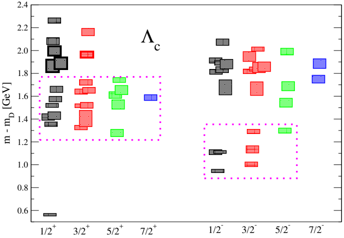
$$C(z) = \int_0^{1/T} d\tau dx dy \langle \mathcal{O}^\dagger(x,y,z,\tau)\mathcal{O}(0,0,0,0)\rangle \sim \mathrm{e}^{-m_{\mathcal{O}} z}, z \to \infty,$$

- Vector like excitations $\mathcal{O} = \bar{\psi}\gamma_\mu\psi$ reach the perturbative estimate quickly than pseudo-scalar excitations $M/T = 2\pi + \frac{g^2 C_F}{2\pi}(E_0 + 1/2)$ [Bi-BNL collaboration, preliminary].



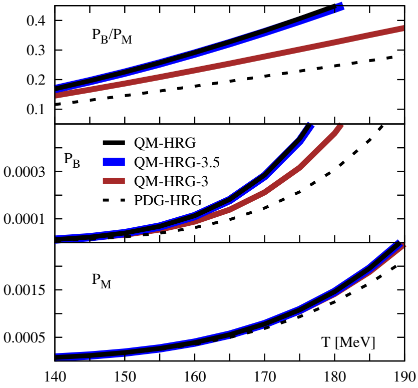
- The charm meson sector is measured experimentally to high precision.
- Many charm baryons states not measured yet predicted from lattice and quark models [Ebert et. al, 10, Padmanath et. al., 13]
- Even spin-parity of ground state Λ_c not measured!





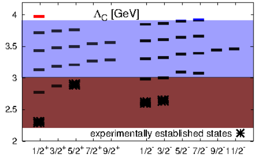
Relevance for QCD thermodynamics

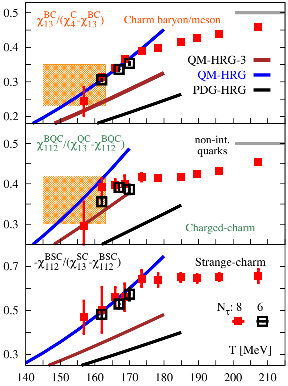
- We construct hadron resonance gas model with experimentally known states: PDG-HRG
- Compare with HRG with experimental+additional states: QM-HRG
- The partial pressure of mesons are similar
- In the baryon sector the difference starts showing up [Bielefeld-BNL collaboration, 14]



Our results

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



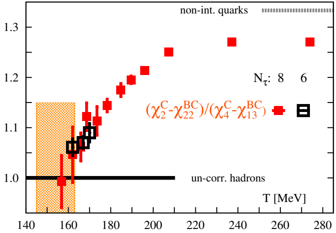


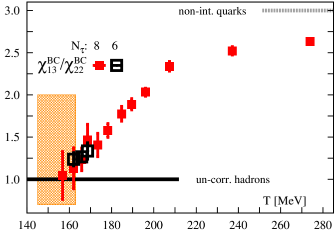
Our data from QCD seems to support the existence of these additional baryon states!

Outline

Conclusions

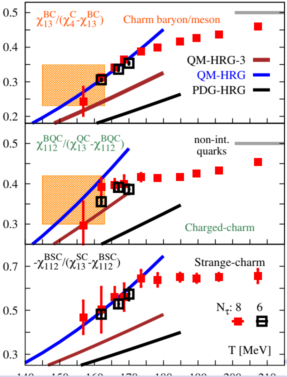
- We could for the first time distinctly investigate the baryon and the meson sectors for heavy-light systems
- The charm mesons and baryons melt near T_c $\rightarrow$ similar to the light quarks.





Many more charm baryons at freezeout?

- Interpret experiments to theory it is crucial to account for hadron abundances correctly
- Found evidence for the thermodynamic imprint of yet to be measured charm baryons
- These resonances should be taken into account for feed-down corrections.



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- Our study supports the picture of a broad D-meson resonance immediately beyond T_c as predicted from T-Matrix approach. [M. He, R. J. Fries, R. Rapp, 12].

Conclusions

- Open charm hadrons melt at $T_c \Rightarrow$ freezeout temperature for D_s is now well known
  Input for heavy flavour transport?

- Additional baryons may contribute to hadronic interactions near the freezeout $\rightarrow$ can it explain the R_{AA} for open-charm mesons?

- Our study supports the picture of a broad D-meson resonance immediately beyond T_c as predicted from T-Matrix approach. [M. He, R. J. Fries, R. Rapp, 12].

- Can one find the 3D effective potential that decides the screening mass and heavy quark number fluctuations from T-Matrix approach?