Charm degrees of freedom above deconfinement

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. The story about charm so far
2. Open charm mesons at freezeout
3. Relevance of our studies

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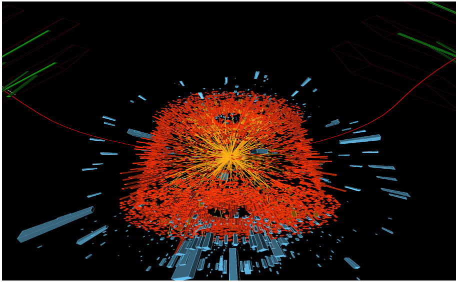
Heavy quark from experiments

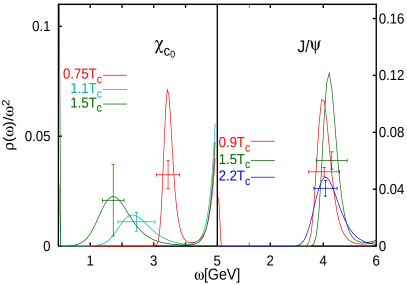


[http://www.cern.ch/news]

- The suppression of 3 Υ states measured → signal of a thermalized QCD medium? [CMS collaboration, QM14]
- Loosely bound excited states melt earlier.
- What happens to heavy-light hadrons?
- R_{AA} and v_2 puzzle for D mesons exist [ALICE collaboration, 15]. Require more input from first principles for heavy quark phenomenology.

What is known about the heavy hadrons: theory

- The $c\bar{c}$ mesons like J/ψ, η_c are also created early.
- 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 [Asakawa & Hatsuda, 03, 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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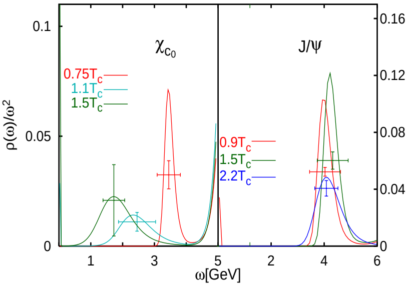
- Bottomonium states show sequential melting above T_c.

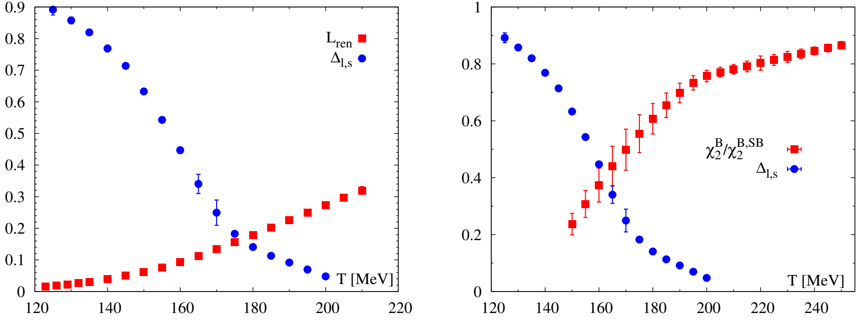
  [H. Ohno, et. al. 13,14, Swansea 14]



(De)Confinement

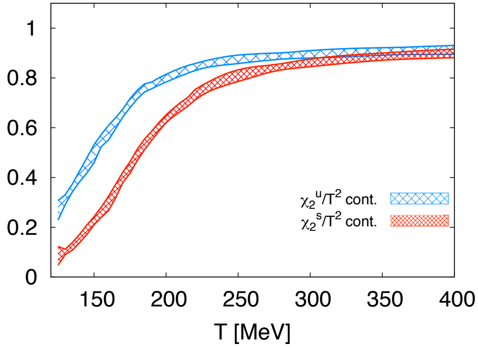
- Deconfinement : Releasing of colored degrees of freedom
- Pure gauge theory: phase transition due to deconfinement
  Polyakov loop L_{ren}
- In QCD with physical masses: no exact order parameter
- χ_{SB} and deconfinement for light quarks occur simultaneously
- When do the heavier strange and charm quarks deconfine?

Bazavov & Petreczky, 13



Deconfinement of strangeness and charm

- Lattice QCD is the most effective non-perturbative tool that can provide answer to such questions
- 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

Motivation for HRG

- At freezeout no more inelastic collisions⇒ the ensemble can be described by a gas of all measured hadrons and possible resonances (HRG) [Dashen, Ma and Bernstein, 69,71]

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

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

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- HRG a good approximation if resonances very near to two particle threshold. [Prakash & Venugopalan, 92]

Is HRG 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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- Related work by Fermi [50] $\Rightarrow$ for strong interaction particle production determined by statistical weights indep. of the details on hadron interactions.
- Expected to work in the charm sector!

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,

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

- 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

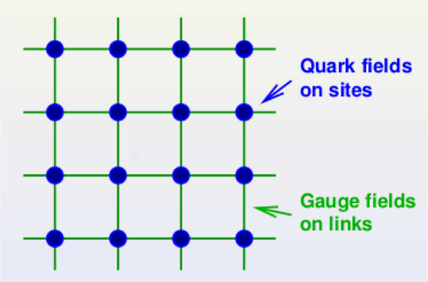
$$\chi_{ij}^{BC} = \frac{\partial^{i+j}}{\partial \hat{\mu}_i^B \partial \hat{\mu}_j^C} P_{tot}/T^4$$

- The partial pressures can be constructed out of 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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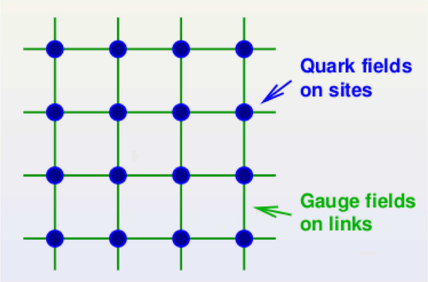

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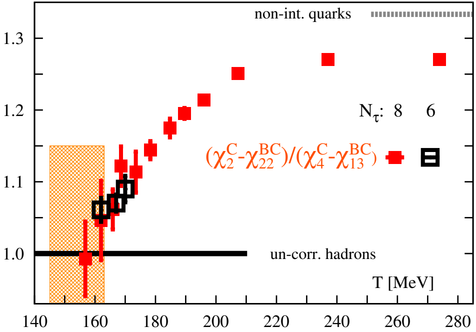
- m_c determined by setting $1/4\left(3m_{J/\psi} + m_{\eta_c}\right)$ to its physical value
- On the lattice measuring susceptibilities is complimentary to the spectral function method.

Our approach for the charm mesons

- 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]

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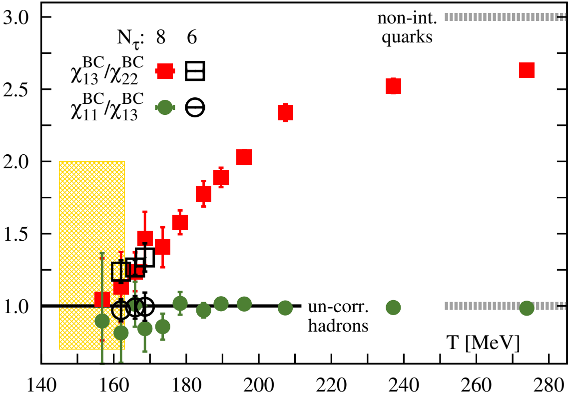

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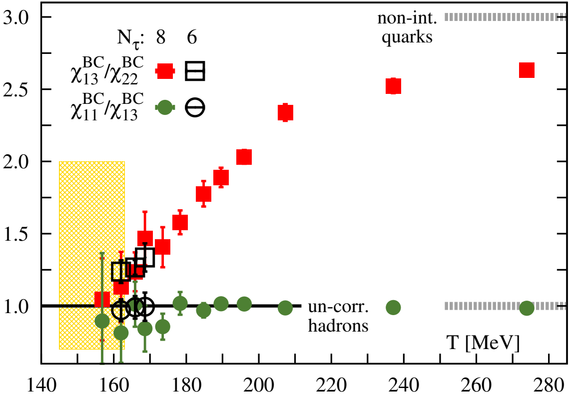

- These melt near T_c too!

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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- 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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- For the first time we could single out the charm baryon contribution to thermodynamics
- What does it imply for the medium properties?

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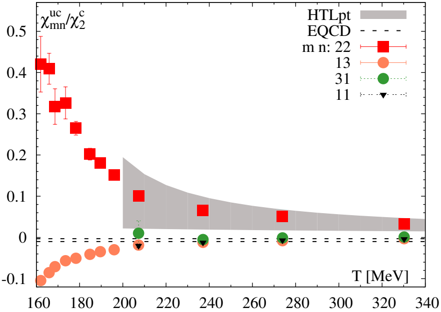

- Deviation from Hard Thermal Loop results between 160 – 200 MeV

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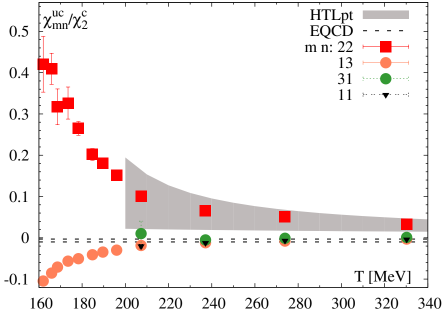

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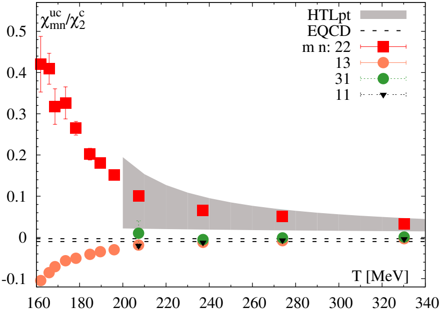

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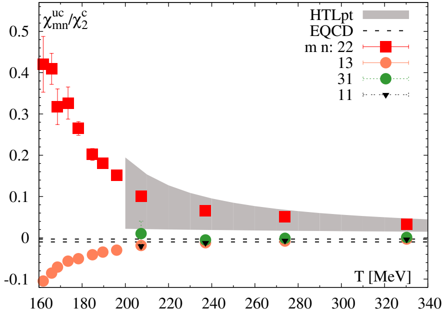

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- Hadrons melt but may survive as broad excitations till $1.2\,T_c$
- Pressure for broad “resonances” considerably lower than sharp width QP [Biro & Jakovac, 14]
- Charm spectral function may have a broad asymmetric peak → not a good quasi-particle below 200 MeV.

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: $c_1 \equiv \chi_{13}^{BC} - 4\chi_{22}^{BC} + 3\chi_{31}^{BC} = 0$.

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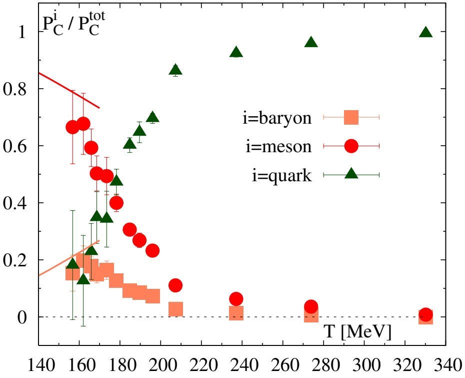


- Meson and baryon like excitations survive upto $1.2\,T_c$.
- Quark-quasiparticles start dominating the pressure beyond $T \gtrsim 200$ MeV $\Rightarrow$ hints of strongly coupled QGP [Mukherjee, Petreczky, SS, 15]

Do diquarks exist beyond T_c?

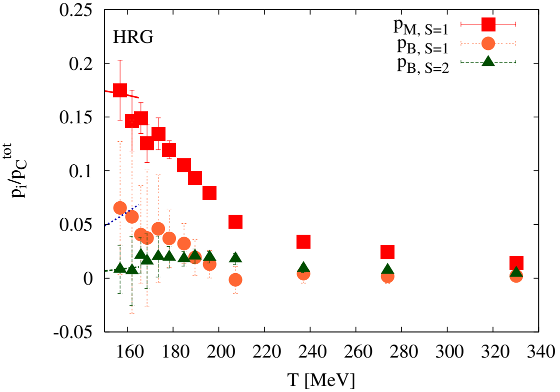
- We look specifically at the sector of strange and charm hadrons.
- Upto 4th order derivatives additionally one has 3 more measurements $\chi^{BSC}_{[112]}$

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

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

Do diquarks exist beyond T_c?

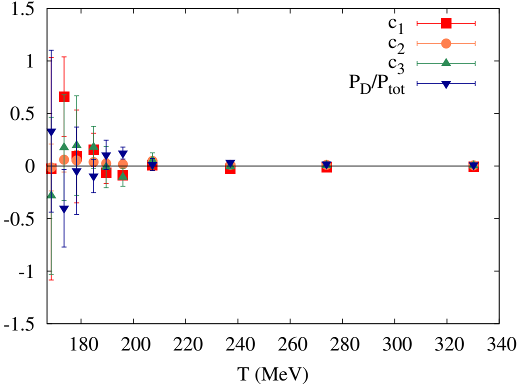
- $p_D = \chi^{BSC}_{[211]} - \chi^{BSC}_{[112]} = 0$ for our data.



- Strange baryon-like excitations suppressed than meson-like excitations.
- These studies consistent with screening mass of sc-mesons [Y. Maezawa et. al., PRD 2015].

Do diquarks exist beyond T_c?

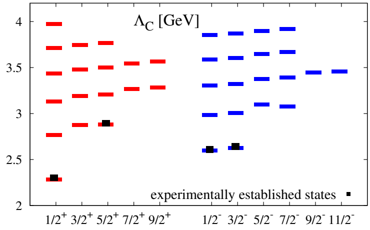
- For these calculations to be valid one should satisfy constraint relations $\rightarrow$ smoothly connect to HRG and free gas at low and high T.

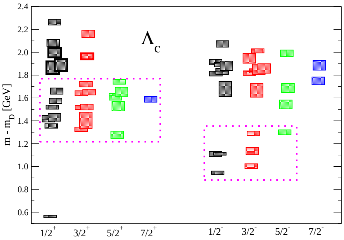


- LQCD data agree with the constraints imposed by our proposed model.

Charm hadron spectrum...story about missing states

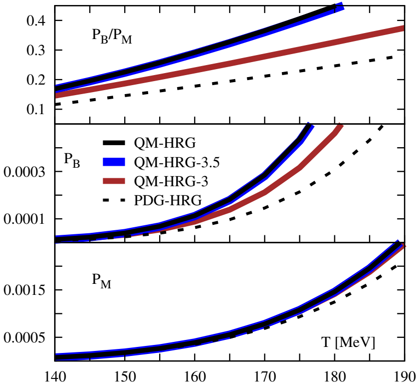
- The charm meson sector is measured experimentally to high precision.
- Many charm baryons states not measured yet predicted from lattice and quark models [Ebert et. al, 10, Padmanath et. al., 13]
- Even spin-parity of ground state Λ_c not measured!





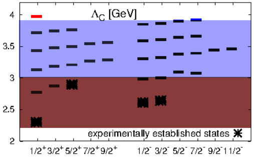
Relevance for QCD thermodynamics at freezeout

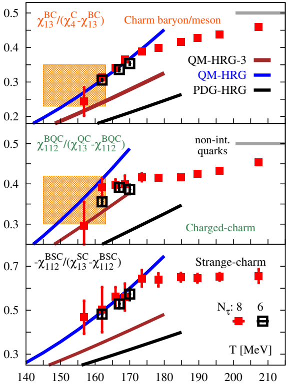
- We construct hadron resonance gas model with experimentally known states: PDG-HRG
- Compare with HRG with experimental+additional states: QM-HRG
- The partial pressure of mesons are similar
- In the baryon sector the difference starts showing up [Bielefeld-BNL collaboration, 14]



Thermodynamic imprints of charm baryons!

- 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 : $\frac{\chi_{112}^{BQC}}{\chi_{13}^{QC} - \chi_{112}^{BQC}}$



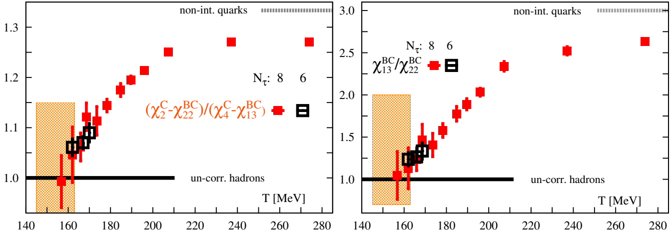


Our data from QCD seems to support the existence of these additional baryon states!

Outline

Conclusions

- We could for the first time distinctly investigate the baryon and the meson sectors for heavy-light systems



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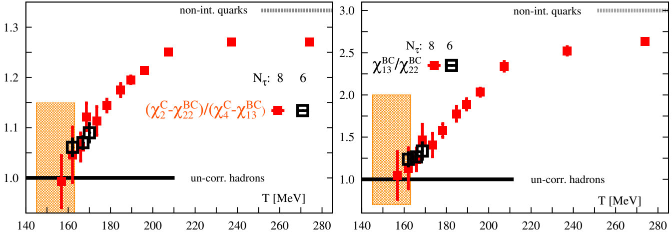

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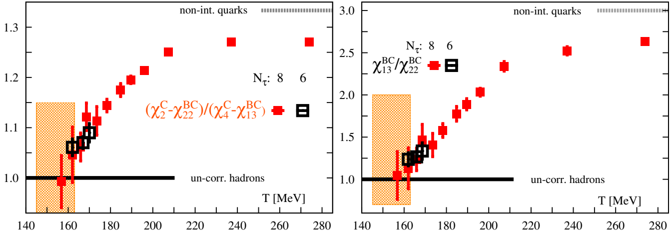
- Interpret experiments to theory it is crucial to account for hadron abundances correctly



Perspectives

- 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?
- Charm baryon and meson-like excitations surviving in the medium till $1.2\ T_c$.
- Our study more in favour for resonant scattering of heavy quarks in the medium [M. He, R. J. Fries, R. Rapp, 12].