Charm fluctuations and charm deconfinement from lattice QCD

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CRC-TR 211 Strong-interaction matter under extreme conditions

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Motivation

- Strong interaction matter undergoes a chiral crossover at $\mathrm{T}_{\mathrm{pc}} = 156.5 \pm 1.5$ MeV.
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- When do charmed hadrons stop contributing to the total charm pressure?
- Charm fluctuations (cumulants) calculated in the framework of Lattice QCD can receive enhanced contributions due the existence of not-yet-discovered open-charm states; it is possible to compare this enhancement to the HRG calculations.

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- $$\mathrm{M_C}(\mathrm{T}, \overrightarrow{\mu}) = \frac{1}{2\pi^2} \sum_\mathrm{i} \mathrm{g_i} \left(\frac{\mathrm{m_i}}{\mathrm{T}}\right)^2 \mathrm{K_2}(\mathrm{m_i}/\mathrm{T}) \cosh(\mathrm{Q_i}\hat{\mu}_\mathrm{Q} + \mathrm{S_i}\hat{\mu}_\mathrm{S} + \mathrm{C_i}\hat{\mu}_\mathrm{C})$$

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- $$\mathrm{M_C(T, \overrightarrow{\mu}) = \frac{1}{2\pi^2} \sum_i g_i \left(\frac{m_i}{T}\right)^2 K_2(m_i/T) \cosh(Q_i \hat{\mu}_Q + S_i \hat{\mu}_S + C_i \hat{\mu}_C)}$$

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- $\mathrm{\hat{\mu}_X = \mu/T,\ X \in \{B, Q, S, C\}}$.

Generalized susceptibilities of the conserved charges

$$\mathrm{M_C}(\mathrm{T},\overrightarrow{\mu}) = \frac{1}{2\pi^2}\sum_{\mathrm{i}} \mathrm{g_i}\left(\frac{\mathrm{m_i}}{\mathrm{T}}\right)^2 \mathrm{K_2}(\mathrm{m_i}/\mathrm{T})\cosh(\mathrm{Q_i}\hat{\mu}_\mathrm{Q} + \mathrm{S_i}\hat{\mu}_\mathrm{S} + \mathrm{C_i}\hat{\mu}_\mathrm{C})$$

- $\mathrm{K_2(x)} \sim \sqrt{\pi/2x}\; e^{-x}\;[1+\mathbb{O}(x^{-1})]$. If $\mathrm{m_i} \gg \mathrm{T}$, then contribution to $\mathrm{P_C}$ will be exponentially suppressed.
- Λ_c^+ mass ~ 2286 MeV, Ξ_{cc}^{++} mass ~ 3621 MeV. At $\mathrm{T_{pc}}$, contribution to $\mathrm{B_C}$ from Ξ_{cc}^{++} will be suppressed by a factor of 10^{-4} in relation to Λ_c^+.

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- Dimensionless generalized susceptibilities of conserved charges:

$$\chi_{\mathrm{klmn}}^{\mathrm{BQSC}} = \left. \frac{\partial^{(\mathrm{k+l+m+n})} \;\; [\mathrm{P}\;(\hat{\mu}_\mathrm{B}, \hat{\mu}_\mathrm{Q}, \hat{\mu}_\mathrm{S}, \hat{\mu}_\mathrm{C})\;/\mathrm{T}^4]}{\partial\hat{\mu}_\mathrm{B}^\mathrm{k}\;\; \partial\hat{\mu}_\mathrm{Q}^\mathrm{l}\;\; \partial\hat{\mu}_\mathrm{S}^\mathrm{m}\;\; \partial\hat{\mu}_\mathrm{C}^\mathrm{n}} \right|_{\vec{\mu}=0}$$

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- $\underbrace{\chi^{BC}_{mn}}_{\chi^{\mathrm{BQSC}}_{\mathrm{m00n}}} = B_{C,1} + 2^n B_{C,2} + 3^n B_{C,3} \simeq B_{C,1}$
- At present, we have gone upto fourth order in calculating various cumulants.

Ratios independent of the hadron spectrum

- Irrespective of the details of the baryon mass spectrum, in the validity range of HRG, $\chi^{\mathrm{BC}}_{\mathrm{mn}}/\chi^{\mathrm{BC}}_{\mathrm{kl}} = 1$, $\forall(\mathrm{m}+\mathrm{n}), (\mathrm{k}+\mathrm{l}) \in$ even.

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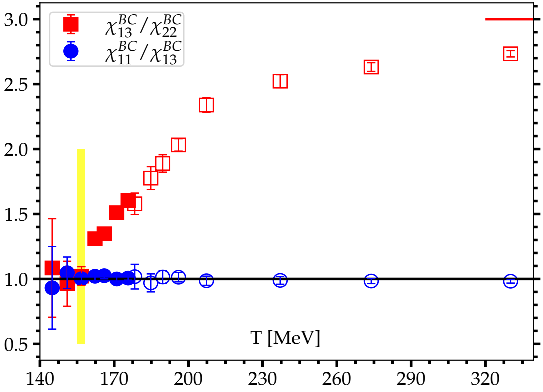
- $\chi^{\mathrm{BC}}_{\mathrm{1n}}/\chi^{\mathrm{BC}}_{\mathrm{1l}} = 1$, $\forall \mathrm{n}, \mathrm{l} \in$ odd, for the entire temperature range.

Change in the charm degrees of freedom

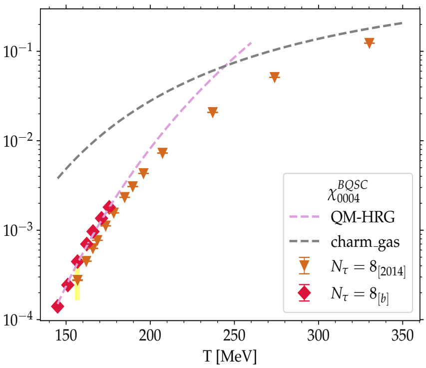


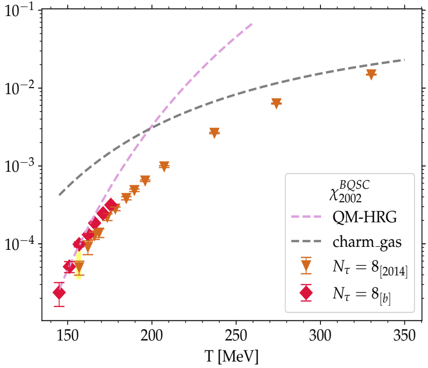
- States with fractional B start appearing near $\mathrm{T_{pc}}$. Is it possible to determine this fractional B?

Approach to free charm-quark gas limit

$$P_c(T, \vec{\mu}) = \frac{3}{\pi^2}\left(\frac{m_c}{T}\right)^2 K_2(m_c/T)\cosh\left(\frac{2}{3}\hat{\mu}_Q + \frac{1}{3}\hat{\mu}_B + \hat{\mu}_C\right)$$

$m_c = 1.27$ GeV.





Charm degrees of freedom in the intermediate T range

Quasi-particle model:

$$P^{C}(T, \hat{\mu}_C, \hat{\mu}_B)/T^4 = P^{C}_{M}(T)\cosh(\hat{\mu}_C) + P^{C}_{B}(T)\cosh(\hat{\mu}_C + \hat{\mu}_B) + P^{C}_{q}(T)\cosh(\hat{\mu}_C + \hat{\mu}_B/3)$$

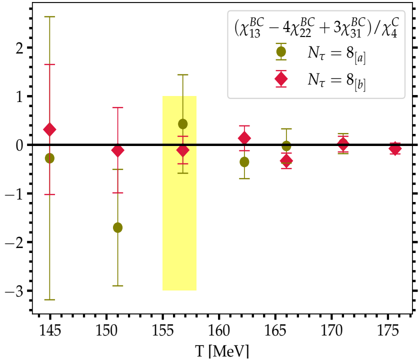
$$P^{C}_{q} = 9(\chi^{BC}_{13} - \chi^{BC}_{22})/2$$
$$P^{C}_{B} = (3\chi^{BC}_{22} - \chi^{BC}_{13})/2$$
$$P^{C}_{M} = \chi^{C}_{4} + 3\chi^{BC}_{22} - 4\chi^{BC}_{13}$$

Constraint on cumulants in a simple quasi-particle model:

$$c = \chi^{BC}_{13} + 3\chi^{BC}_{31} - 4\chi^{BC}_{22} = 0$$

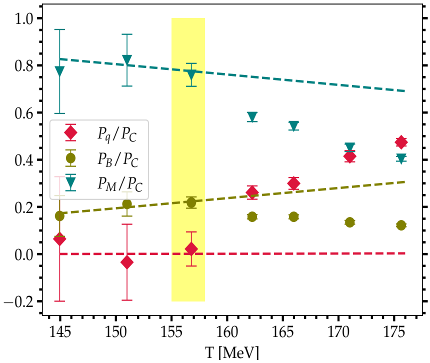
[S. Mukherjee et al., 2016]

Quasi-particle model



The constraint holds true $\implies$ quasi-particle states with $|\mathrm{B}| = 0, 1$ or $1/3$ exist in the intermediate temperature range.

Charm-quark-like excitations in QGP



Right after T_{pc}, P_q starts contributing to P_C, which is compensated by a reduction (and deviation from HRG) in the fractional contribution of the hadron-like states to P_C.

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- We can use four fourth-order QC correlations to determine partial pressures of the four possible electrically-charged-charm subsectors.

$$\mathrm{P}_{\mathrm{C}}^{|\mathrm{Q}|=2/3} = \frac{1}{8}\left[54\chi_{13}^{\mathrm{QC}} - 81\chi_{22}^{\mathrm{QC}} + 27\chi_{31}^{\mathrm{QC}}\right]$$

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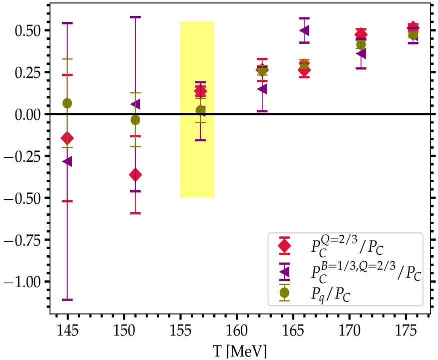
- For the BQC sector there are three possibilities: i)$\{|\mathrm{B}| = 1, |\mathrm{Q}| = 1\}$; ii)$\{|\mathrm{B}| = 1, |\mathrm{Q}| = 2\}$; iii)$\{|\mathrm{B}| = 1/3, |\mathrm{Q}| = 2/3\}$.

$$\mathrm{P}_{\mathrm{C}}^{\mathrm{B}=1/3,\mathrm{Q}=2/3} = \frac{27}{4}\left[\chi_{112}^{\mathrm{BQC}} - \chi_{211}^{\mathrm{BQC}}\right]$$

Charm-quark-like excitations in QGP



Clear agreement between three independent observables which correspond to the partial pressures of
i) $\mathrm{B} = 1/3$, ii) $\mathrm{Q} = 2/3$, and iii) $\mathrm{B} = 1/3$ and $\mathrm{Q} = 2/3$ charm subsectors.

Baryonic and mesonic contributions to $\mathrm{P_C}$

In the low temperature range, where HRG works,

- χ_{13}^{BC} is the partial pressure from the charmed-baryonic subsector.
- $\chi_4^{\mathrm{C}} - \chi_{13}^{\mathrm{BC}}$ can be interpreted as the partial pressure from the charmed-mesonic subsector.

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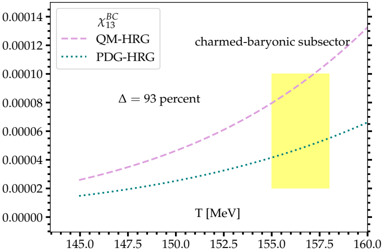
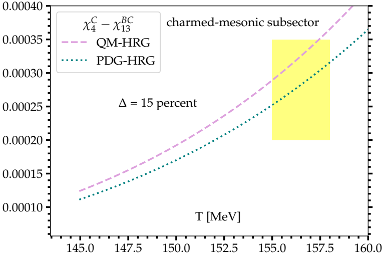
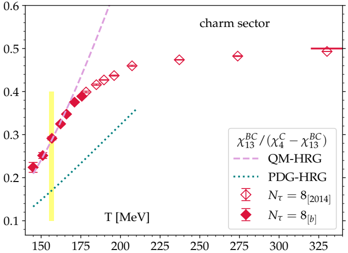
- Unlike the previous quantities shown, ratios such as $\chi_{13}^{\mathrm{BC}}/(\chi_4^{\mathrm{C}} - \chi_{13}^{\mathrm{BC}})$ will partially depend upon the hadron spectrum.

Ratios of baryonic and mesonic contributions to $\mathrm{P_C}$

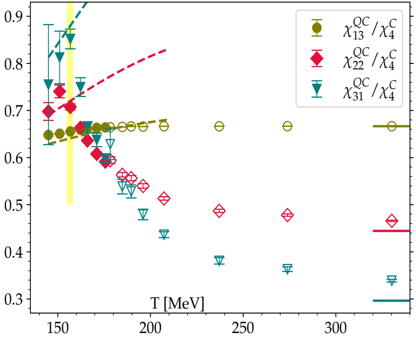


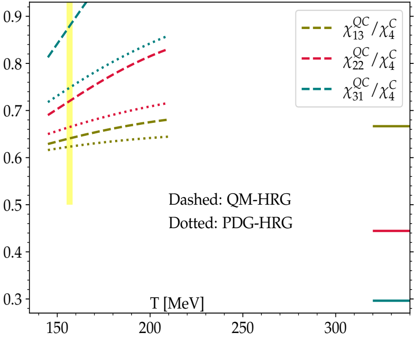




- Missing charmed-baryonic states below $\mathrm{T_{pc}}$.
- $\Delta = (|1-\text{QM-HRG}/\text{PDG-HRG}|)|_{\mathrm{T_{pc}}}$

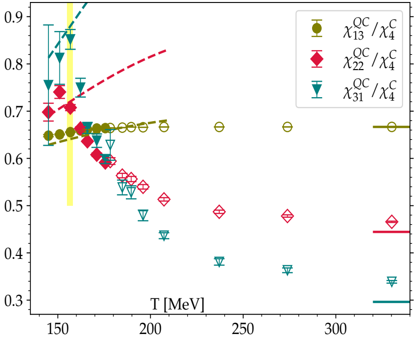
Electrically-charged-charm subsector

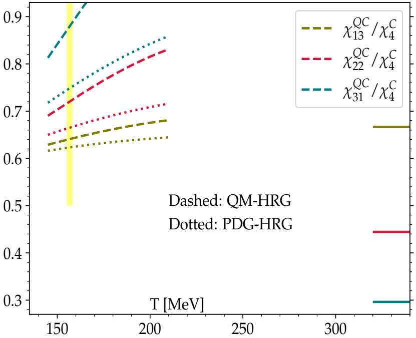




- With now available statistics, possibility of distinguishing $|\mathrm{Q}| = 0, 1, 2$ charm subsectors in the hadronic phase.

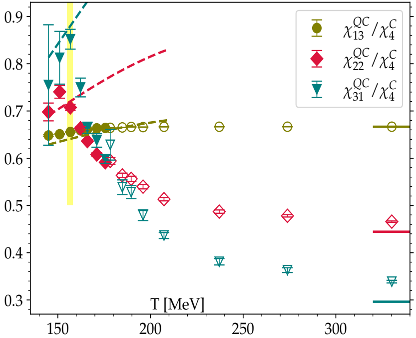
Electrically-charged-charm subsector

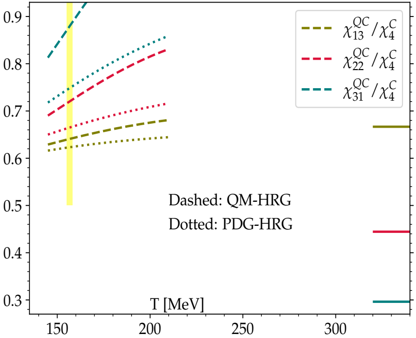




- Ratio of QM-HRG/PDG-HRG increases with increasing Q-moments $\implies$ $|\mathrm{Q}| = 2$ sector more sensitive to 'missing resonances'.
- χ_{22}^{QC} and χ_{31}^{QC} give evidence for 'missing resonances'.

Electrically-charged-charm subsector





- Ratio of QM-HRG/PDG-HRG increases with increasing Q-moments.
- Close to freeze-out, an enhancement over the PDG expectation in the fractional contribution of the $|\mathrm{Q}| = 2$ (Σ_c^{++}) charm subsector to the total charm partial pressure.

Conclusions & Outlook

- Onset of hadron metling at $\mathrm{T_{pc}}$.
- Evidence of deconfinement in terms of presence of charm-quark-like excitations in QGP.
- No evidence for the existence of charmed diquarks above $\mathrm{T_{pc}}$.
- Analysis shows that there are missing states in the PDG record.

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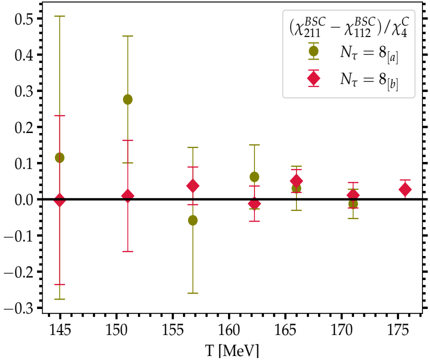
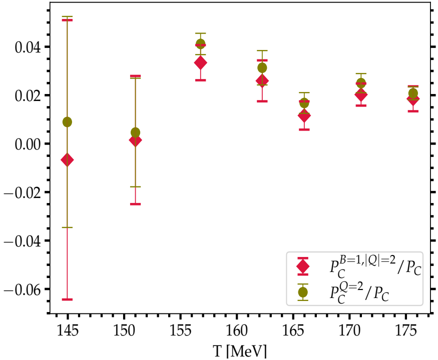
- No evidence for the existence of charmed diquarks above $\mathrm{T_{pc}}$.
- Analysis shows that there are missing states in the PDG record.
- Continuum limit with two different LCPs is in progress; it will enable us to make a statement based on the absolute cumulants.

Backup Slide I



No strange-charm diquarks.

Backup Slide II



Only $|\mathrm{B}| = 1$ sector contributes to partial pressure from $|\mathrm{Q}| = 2$ charmed subsectors.

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