Charm degrees of freedom in the vicinity of $\mathrm{T_{pc}}$ from lattice QCD

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Motivation I

- Strong interaction matter undergoes a chiral crossover at $\mathrm{T_{pc}} = 156.5 \pm 1.5$ MeV.
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- When do charmed hadrons stop contributing to the total charm pressure?

Motivation II

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

Generalized susceptibilities of the conserved charges

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

- $K_2(x) \sim \sqrt{\pi/2x}\, e^{-x}\, [1 + \mathbb{O}(x^{-1})]$. If $m_i \gg T$, then contribution to P_C will be exponentially suppressed.
- Λ_c^+ mass ~ 2286 MeV, Ξ_{cc}^{++} mass ~ 3621 MeV. At T_{pc}, contribution to 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 the conserved charges:

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

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- Dimensionless generalized susceptibilities of the conserved charges using $\mathrm{P_C}$:

$$\chi^{\mathrm{BQSC}}_{\mathrm{klmn}} = \frac{1}{2\pi^2} \sum_{\mathrm{i} \in \text{C-H}} \mathrm{g_i} \left(\frac{\mathrm{m_i}}{\mathrm{T}}\right)^2 \mathrm{K_2}(\mathrm{m_i}/\mathrm{T})\ \mathrm{B^k Q^l S^m C^n}$$

- $\underbrace{\chi^{BC}_{mn}}_{\chi^{\mathrm{BQSC}}_{\mathrm{m00n}}} = \mathrm{B_{C,1}} + 2^{\mathrm{n}}\mathrm{B_{C,2}} + 3^{\mathrm{n}}\mathrm{B_{C,3}} \simeq \mathrm{B_{C,1}} = \mathrm{B_C}, \forall (\mathrm{m}+\mathrm{n}) \in$ even

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- $\chi^{\mathrm{C}}_{\mathrm{m}} = \mathrm{P_C}, \forall \mathrm{m} \in$ even
- 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, $\chi_{\mathrm{mn}}^{\mathrm{BC}}/\chi_{\mathrm{kl}}^{\mathrm{BC}} = 1$, $\forall (\mathrm{m}+\mathrm{n}), (\mathrm{k}+\mathrm{l}) \in$ even.

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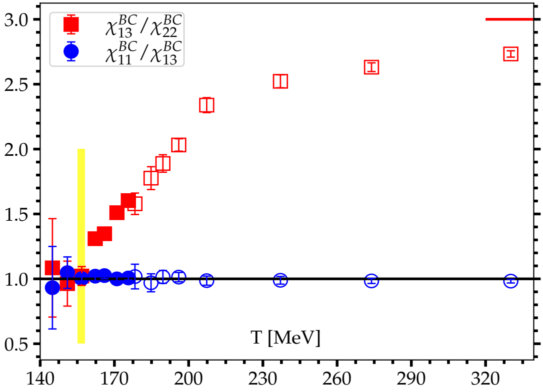
- $\chi^{\mathrm{BC}}_{1\mathrm{n}}/\chi^{\mathrm{BC}}_{1\mathrm{l}} = 1$, $\forall \mathrm{n}, \mathrm{l} \in$ odd, for the entire temperature range.

Onset of the charmed hadron melting

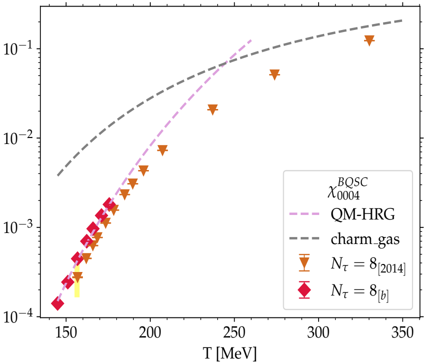


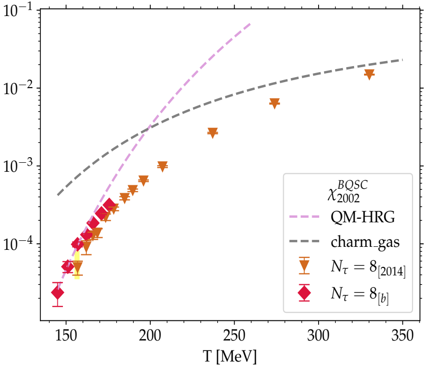
- States with fractional B start appearing near $\mathrm{T_{pc}}$. Is it possible to determine this fractional B?

Approach to free charm-quark gas limit

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

$m_c = 1.27$ GeV.





Charm degrees of freedom in the intermediate T range

- Based on carrriers of C in low and high-T phase, pose a quasi-particle model consisting of non-interacting meson, baryon and quark-like states:

$$\mathrm{P_C}(\mathrm{T}, \hat{\mu}_\mathrm{C}, \hat{\mu}_\mathrm{B})/\mathrm{T}^4 = \mathrm{P^C_M}(\mathrm{T})\cosh(\hat{\mu}_\mathrm{C} + ...) + \mathrm{P^C_B}(\mathrm{T})\cosh(\hat{\mu}_\mathrm{C} + \hat{\mu}_\mathrm{B} + ...)$$
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- Use quantum numbers B and C to construct partial pressures:

$$\mathrm{P_q^C} = 9(\chi_{13}^{\mathrm{BC}} - \chi_{22}^{\mathrm{BC}})/2$$
$$\mathrm{P_B^C} = (3\chi_{22}^{\mathrm{BC}} - \chi_{13}^{\mathrm{BC}})/2$$
$$\mathrm{P_M^C} = \chi_4^{\mathrm{C}} + 3\chi_{22}^{\mathrm{BC}} - 4\chi_{13}^{\mathrm{BC}}$$

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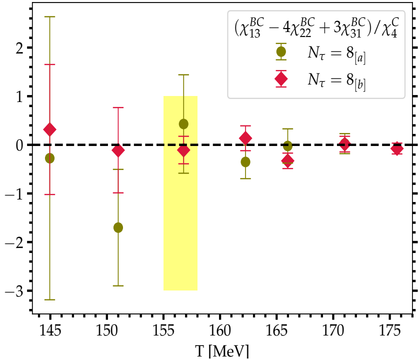
$$\mathrm{P^C_M} = \chi^{\mathrm{C}}_4 + 3\chi^{\mathrm{BC}}_{22} - 4\chi^{\mathrm{BC}}_{13}$$

  - Constraint on cumulants in a simple quasi-particle model:

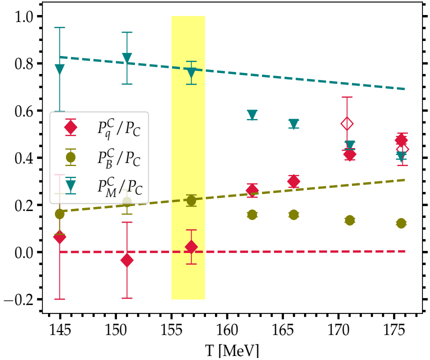
$$\mathrm{c} = \chi^{\mathrm{BC}}_{13} + 3\chi^{\mathrm{BC}}_{31} - 4\chi^{\mathrm{BC}}_{22} = 0$$

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

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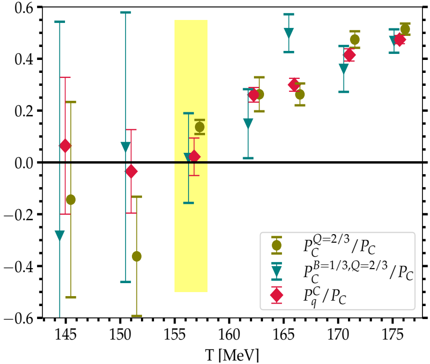
- For the BQC sector there are three possibilities: i)$\{|\mathrm{B}| = 1, |\mathrm{Q}| = 1\}$; ii)$\{|\mathrm{B}| = 1, |\mathrm{Q}| = 2\}$; iii)$\{|\mathrm{B}| = 1/3, |\mathrm{Q}| = 2/3\}$.

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

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.

Conclusions and Outlook I

- Charmed hadrons start dissociating at $\mathrm{T_{pc}}$.
- Evidence of deconfinement in terms of presence of charm quark-like excitations in QGP.
- $\mathrm{P_C}$ receives 50% contribution from charmed hadron-like excitations at $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.

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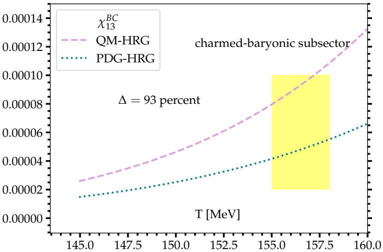
- $\mathrm{P_C}$ receives 50% contribution from charmed hadron-like excitations at $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.
- We performed most calculations at $\mathrm{N}_\tau = 8$. Since cutoff effects largely cancel in the ratios of different generalized susceptibilities, we expect our conclusions based on these ratios to hold in the continuum limit.
- It would be good to look into spectral functions for charmed hadron correlators in order to further give support to the quasi-particle nature of the hadronic excitations above $\mathrm{T_{pc}}$.

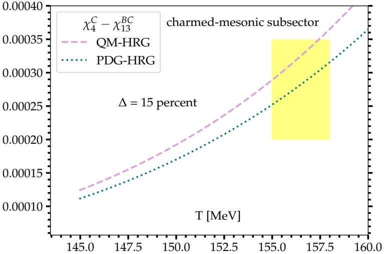
Baryonic and mesonic contributions to $\mathrm{P_C}$

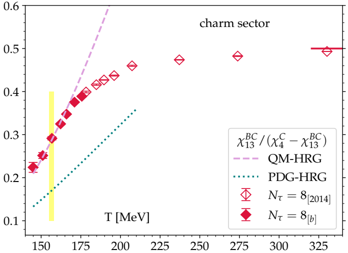
In the low temperature range, where HRG works,

- 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.

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

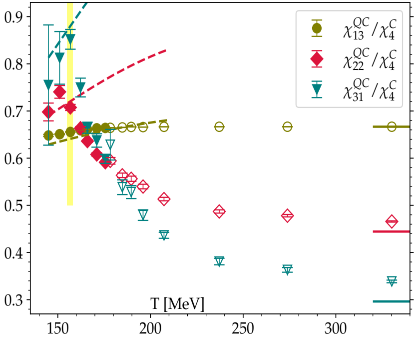


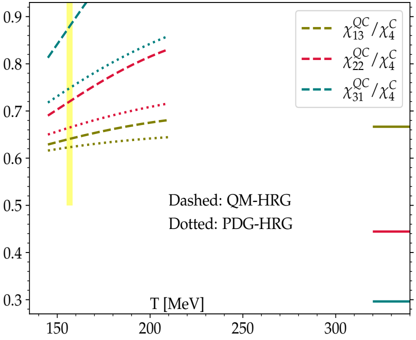




- Missing charmed-baryonic states below $\mathrm{T_{pc}}$.
- $\Delta = (|1 - \text{QM-HRG}/\text{PDG-HRG}|)|_{\mathrm{T_{pc}}}$

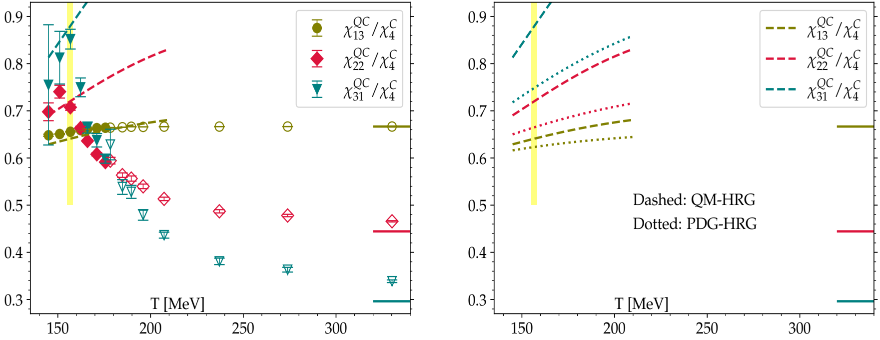
Electrically-charged-charm subsector





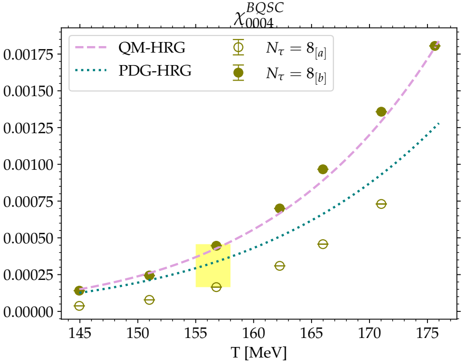
- Ratio of QM-HRG/PDG-HRG increases with increasing Q-moments
  $\implies$ $|\mathrm{Q}| = 2$ sector more sensitive to 'missing resonances'.
- χ_{22}^{QC} and χ_{31}^{QC} give evidence for 'missing resonances'.

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.

Continuum limit: Total charm pressure



- Two different LCPs:

  a) charmonium mass, b) $\mathrm{m_c/m_s}$

- $\mathrm{a} \approx 0.2$ fm

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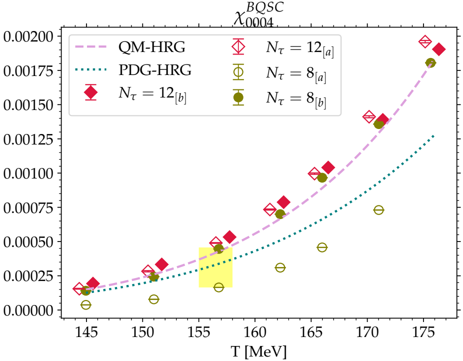

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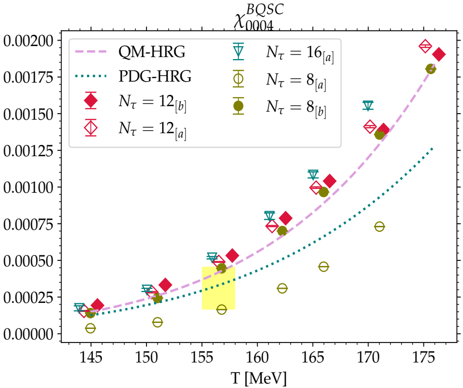
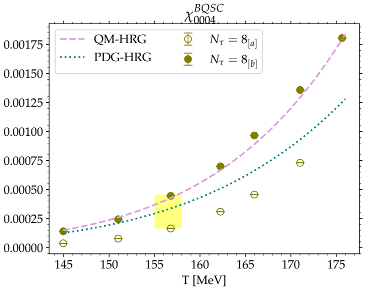
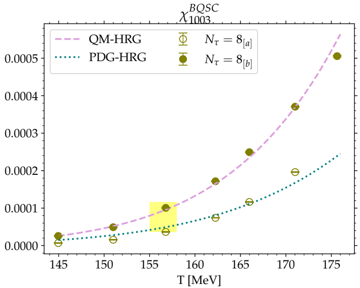
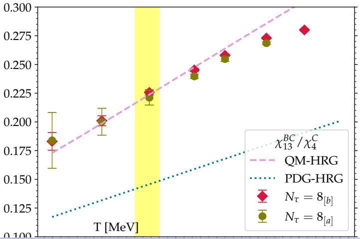


- Absolute predictions in the charm sector are particularly sensitive to the precise tuning of the bare input quark masses.
- Two different LCPs converge in the continuum limit:
  $\mathrm{a} \approx 0.2$ fm $+ \mathrm{a} \approx 0.1$ fm $+ \mathrm{a} \approx 0.05$ fm

Ratios calculated using different LCPs

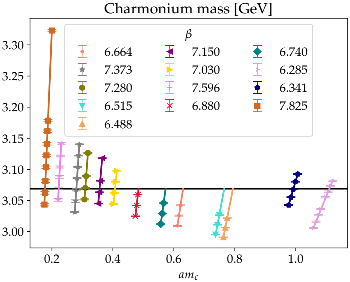


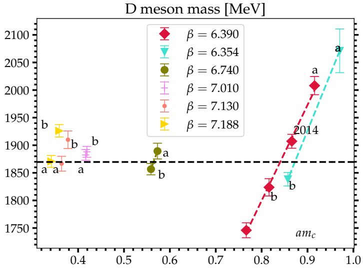




- Sensitivity to the choice of LCP cancels to a large extent in the ratios.
- All previously shown results were based on ratios, and hence valid in the continuum limit.

Major source of the cutoff effects





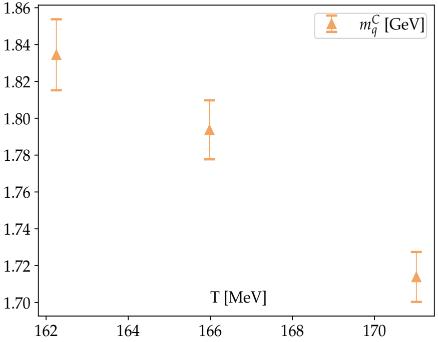
- The ordering of various partial charm pressures based on different LCPs and N_τ values can be understood from the ordering of the am_c values which determine the mass of the lightest charmed hadron i.e., D-meson.
- $\beta = [6.285 - 6.500]$ is relevant for $N_\tau = 8$; $\beta = [6.712 - 6.910]$ is relevant for $N_\tau = 12$; $\beta = [7.054 - 7.095]$ is relevant for $N_\tau = 16$.

Conclusions and Outlook II

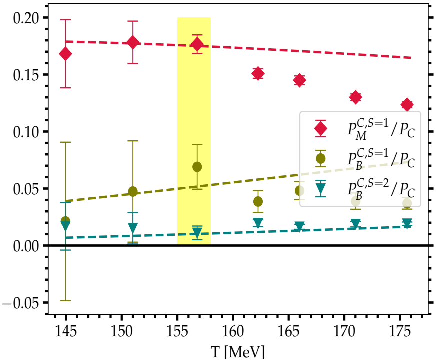
- For $\mathrm{N}_\tau > 8$, results from two different LCPs converge and lie within 20% of the QM-HRG prediction for $\mathrm{T} < \mathrm{T}_{\mathrm{pc}}$. the QM-HRG model calculations.
- Incomplete PDG records of the charmed hadrons in each subsector.
- Soon will be publishing our low-T $(\mathrm{T} < \mathrm{T}_{\mathrm{pc}})$ analysis on the high-statistics datasets of HotQCD collaboration. Preliminary results in the proceedings: [arXiv:2401.01194], [arXiv:2212.11148].
- Continuum limit with three different LCPs is in progress.

Preliminary thermal mass of charm quark-like excitation

$$\mathrm{P_q^C(T,\overrightarrow{\mu}) = \frac{3}{\pi^2}\left(\frac{m_q^C}{T}\right)^2 K_2(m_q^C/T)\cosh\left(\frac{2}{3}\hat{\mu}_Q + \frac{1}{3}\hat{\mu}_B + \hat{\mu}_C\right)}$$



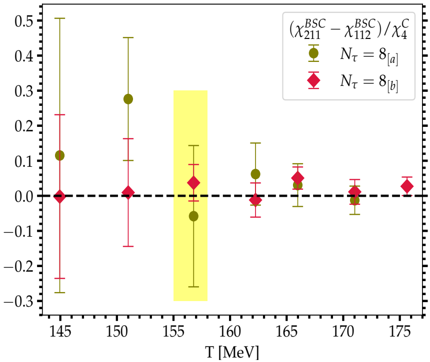
Backup slide I



Why not consider only charm-quark-like excitations?

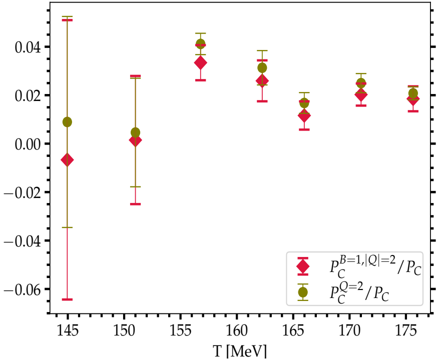
$\implies$ Contribution from SC sector above $\mathrm{T_{pc}}$ – these states can not be quark-like.

Backup slide II: Fate of diquarks



If strange-quark diquarks exist in QGP, their contribution to P_C has to be less than 20%.

Backup slide III



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

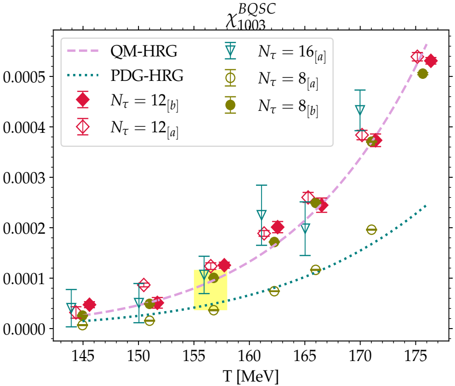
Backup slide IV: Simulation Details

- Partition function of QCD with 2 light, 1 strange and 1 charm quark flavors is :

$$\mathcal{Z} = \int \mathcal{D}[\mathrm{U}]\{\text{det } \mathrm{D}(\mathrm{m_l})\}^{2/4}\{\text{det } \mathrm{D}(\mathrm{m_s})\}^{1/4}\{\text{det } \mathrm{D}(\mathrm{m_c})\}^{1/4}\mathrm{e}^{-\mathrm{S_g}}.$$

  This can be used to calculate susceptibilities in the BQSC basis.
- We used (2+1)-flavor HISQ configurations generated by HotQCD collaboration for $\mathrm{m_s/m_l} = 27$ and $\mathrm{N}_\tau = 8, 12$ and 16.
- $T = (aN_\tau)^{-1} \implies$ three lattice spacings at a fixed temperature.
- We treated charm-quark sector in the quenched approximation.
- $O(am_c^4)$ tree level lattice artifacts are removed by adding so-called epsilon-term, which leads to sub-percent errors in observables linked to charm at $am_c \approx 0.5$ or $a \approx 0.1$ fm.

Continuum limit: BC correlations



- For $N_\tau = 12$, an enhancement of charmed baryon pressure by a factor $2.3 - 2.6$ at T_{pc}.