New Insights into Charm Thermodynamics from the Lattice Continuum Limit

Sipaz Sharma, F. Karsch, P. Petreczky, et al.

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Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

Motivation I

- Strong interaction matter undergoes a chiral crossover at $\mathrm{T_{pc}} = 156.5 \pm 1.5$ MeV.
  [HotQCD Collaboration, 2019; Borsanyi et al., 2020; Kotov et al., 2021]
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- If yes, what are the relevant charmed dofs after the onset of hadron melting? Can we get a signal for the appearance of quarks at T_{pc}?
- 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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- $\hat{\mu}_{\mathrm{X}} = \mu/\mathrm{T}$, $\mathrm{X} \in \{\mathrm{B}, \mathrm{Q}, \mathrm{S}, \mathrm{C}\}$.

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 the conserved charges:

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

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

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

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- $\chi^C_m = P_C, \forall m \in$ even
- At present, we have gone upto fourth order in calculating various cumulants.

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 $\mathrm{m_s}/\mathrm{m_l} = 27$ 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.

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- Derivatives of the pressure consist of expectation values of various traces comprised of inversions and derivatives of the fermion matrices.
- First derivative w.r.t μ will be $\left\langle \text{Tr}\left(\mathrm{D}^{-1}\frac{\partial \mathrm{D}}{\partial \mu}\right)\right\rangle$.

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- First derivative w.r.t μ will be $\left\langle \text{Tr} \left(\mathrm{D}^{-1} \frac{\partial \mathrm{D}}{\partial \mu} \right) \right\rangle$.
- We used 500 random vectors to do unbiased stochastic estimation:

$$\langle \eta_{\mathrm{i}} \rangle = \lim_{\mathrm{N_s} \to \infty} \frac{1}{\mathrm{N_S}} \sum_{\mathrm{k}=1}^{\mathrm{N_S}} \eta_{\mathrm{ki}} = 0 \ , \tag{1}$$

$$\langle \eta_{\mathrm{i}} \eta_{\mathrm{j}} \rangle = \lim_{\mathrm{N_s} \to \infty} \frac{1}{\mathrm{N_S}} \sum_{\mathrm{k}=1}^{\mathrm{N_S}} \eta^*_{\mathrm{ki}} \eta_{\mathrm{kj}} = \delta_{\mathrm{ij}} \tag{2}$$

$$\text{Tr} \left(\mathrm{D}^{-1} \right) = \frac{1}{\mathrm{N}} \sum_{\mathrm{k}=1}^{\mathrm{N}} \eta^\dagger_{\mathrm{k}} \underbrace{\mathrm{D}^{-1} \eta_{\mathrm{k}}}_{\mathrm{x}} \ . \tag{3}$$

Ratios independent of the hadron spectrum

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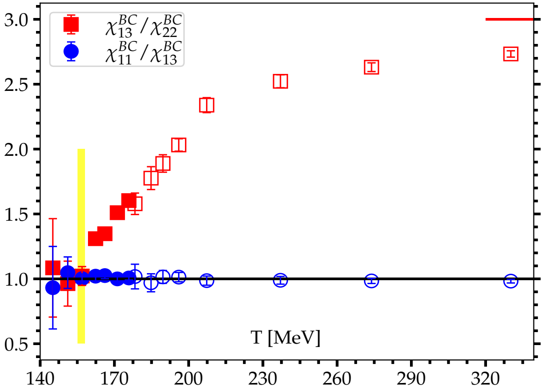
- $\chi^{\rm BC}_{\rm 1n}/\chi^{\rm BC}_{\rm 1l} = 1$, $\forall {\rm n}, {\rm l} \in$ odd, for the entire temperature range.

Onset of the charmed hadron melting

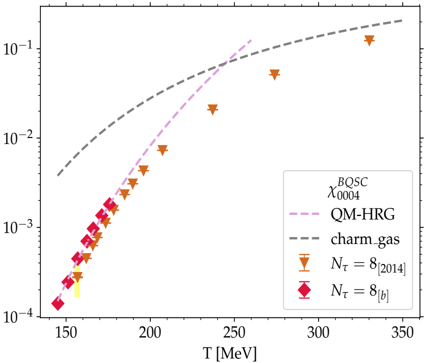


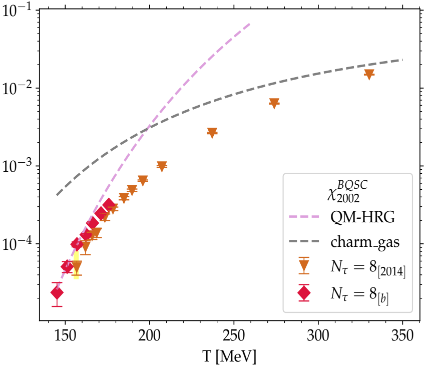
- States with fractional B start appearing near $\mathrm{T_{pc}}$. Is it possible to determine this fractional B?

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:

$$\mathrm{P_C}(\mathrm{T}, \hat{\mu}_\mathrm{C}, \hat{\mu}_\mathrm{B})/\mathrm{T}^4 = \mathrm{P_M^C}(\mathrm{T})\cosh(\hat{\mu}_\mathrm{C} + ...) + \mathrm{P_B^C}(\mathrm{T})\cosh(\hat{\mu}_\mathrm{C} + \hat{\mu}_\mathrm{B} + ...) + \mathrm{P_q^C}(\mathrm{T})\cosh(\frac{2}{3}\hat{\mu}_\mathrm{Q} + \frac{1}{3}\hat{\mu}_\mathrm{B} + \hat{\mu}_\mathrm{C})$$

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$$\mathrm{+P^C_q(T)\cosh(\frac{2}{3}\hat{\mu}_Q + \frac{1}{3}\hat{\mu}_B + \hat{\mu}_C)}$$

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- Use quantum numbers B and C to construct partial pressures:

$$\mathrm{P^C_q} = 9(\chi^{BC}_{13} - \chi^{BC}_{22})/2$$
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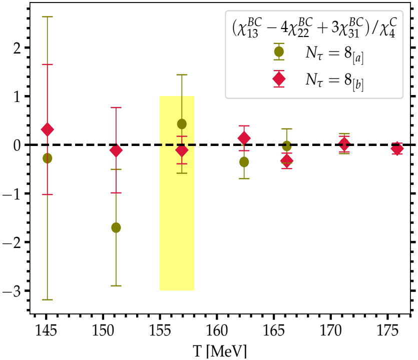
$$\mathrm{P_M^C} = \chi_4^{\mathrm{C}}+3\chi_{22}^{\mathrm{BC}}-4\chi_{13}^{\mathrm{BC}}$$

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

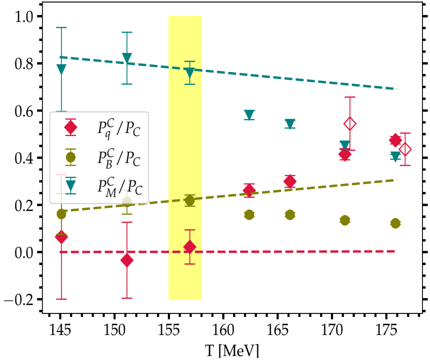
$$\mathrm{c} = \chi_{13}^{\mathrm{BC}}+3\chi_{31}^{\mathrm{BC}}-4\chi_{22}^{\mathrm{BC}}=0$$

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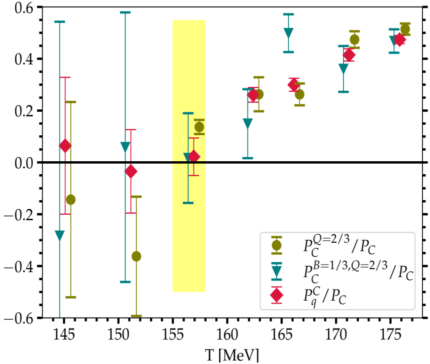
- For the BQC sector there are three possibilities: i)$\{|\mathrm{B}| = 1, |\mathrm{Q}| = 1\}$; ii)$\{|\mathrm{B}| = 1, |\mathrm{Q}| = 2\}$; iii)$\{|\mathrm{B}| = 1/3, |\mathrm{Q}| = 2/3\}$.

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

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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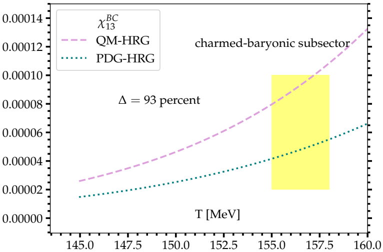
- $\mathrm{P_C}$ receives 50% contribution from charmed hadron-like excitations at $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.
- We performed most calculations at $\mathrm{N_\tau} = 8$. Since cutoff effects largely cancel in the ratios of different generalized susceptibilities, we expect our conclusions 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 $\mathrm{T_{pc}}$.

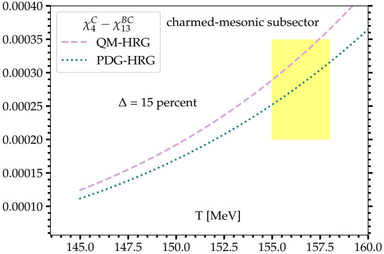
Baryonic and mesonic contributions to $\mathrm{P_C}$

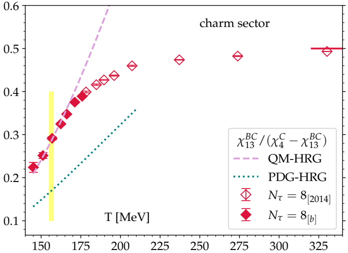
In the low temperature range, where HRG works,

- 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 $\mathrm{P_C}$

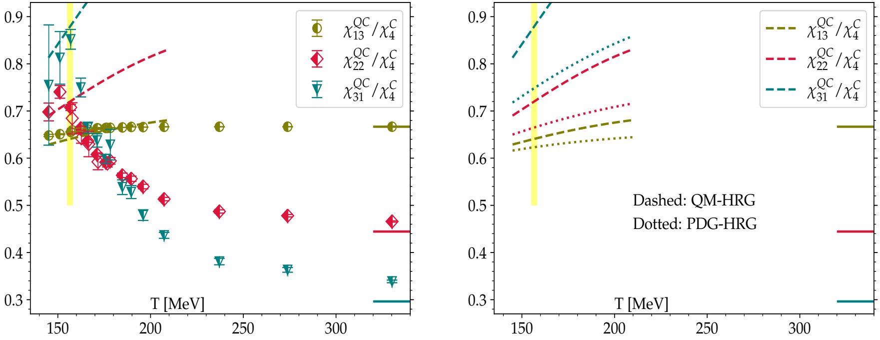






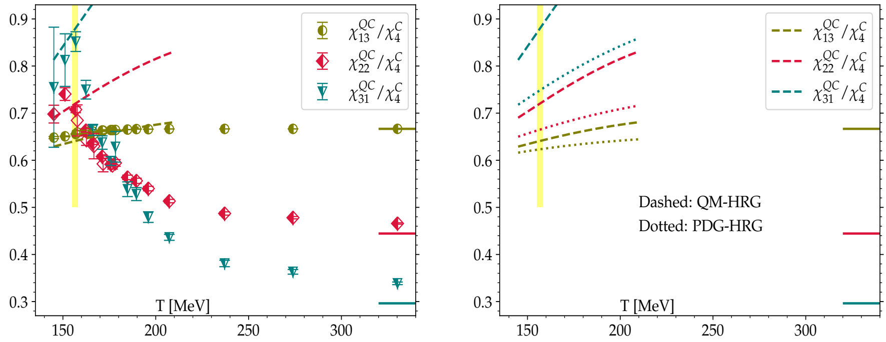
- Missing charmed-baryonic states below $\mathrm{T_{pc}}$.
- $\Delta = (|1-\text{QM-HRG}/\text{PDG-HRG}|)|_{\mathrm{T_{pc}}}$

Electrically-charged-charm subsector



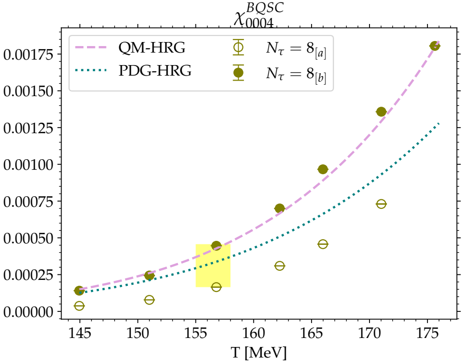
- Ratio of QM-HRG/PDG-HRG increases with increasing Q-moments
  $\implies |\mathrm{Q}| = 2$ sector more sensitive to 'missing resonances'.
- χ_{22}^{QC} and χ_{31}^{QC} give evidence for 'missing resonances'.

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

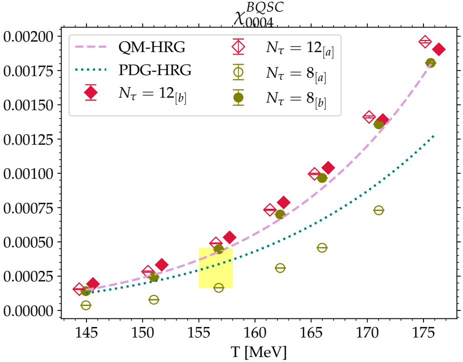


- Two different LCPs:

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

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

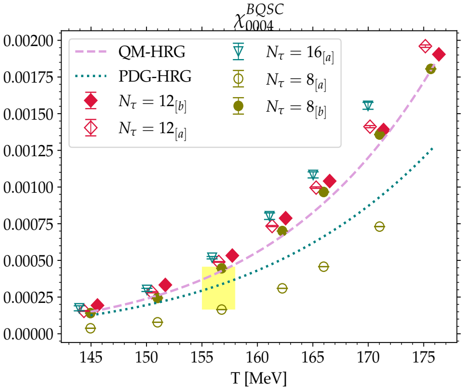
Continuum limit: Total charm pressure



- Two different LCPs:

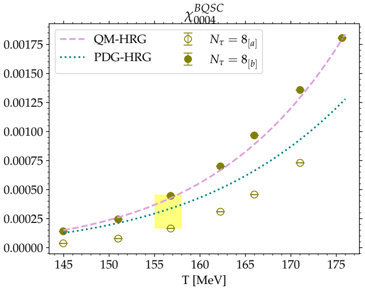
  a) charmonium mass, b) $\mathrm{m_c/m_s}$
- $\mathrm{a} \approx 0.2$ fm + $\mathrm{a} \approx 0.1$ fm

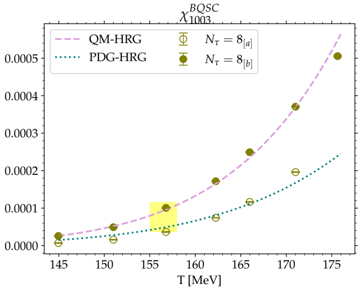
Continuum limit: Total charm pressure

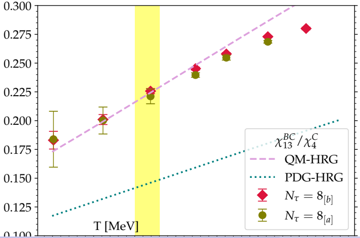


- Absolute predictions in the charm sector are particularly sensitive to the precise tuning of the bare input quark masses.
- Two different LCPs converge in the continuum limit: $\mathrm{a} \approx 0.2$ fm + $\mathrm{a} \approx 0.1$ fm + $\mathrm{a} \approx 0.05$ fm

Ratios calculated using different LCPs

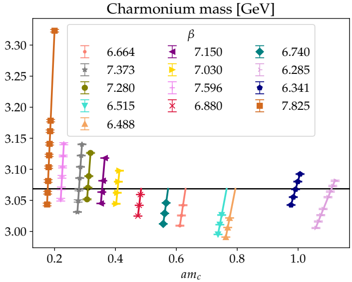


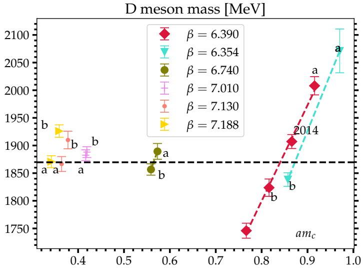




- Sensitivity to the choice of LCP cancels to a large extent in the ratios.
- All previously shown results were based on ratios, and hence valid in the continuum limit.

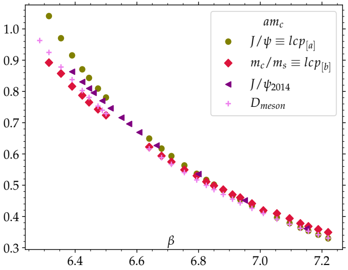
Major source of the cutoff effects

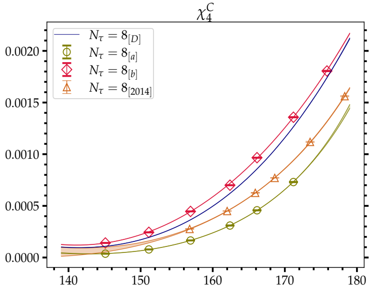




- The ordering of various partial charm pressures based on different LCPs and N_τ values can be understood from the ordering of the am_c values which determine the mass of the lightest charmed hadron i.e., D-meson.
- $\beta = [6.285 - 6.500]$ is relevant for $N_\tau = 8$; $\beta = [6.712 - 6.910]$ is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

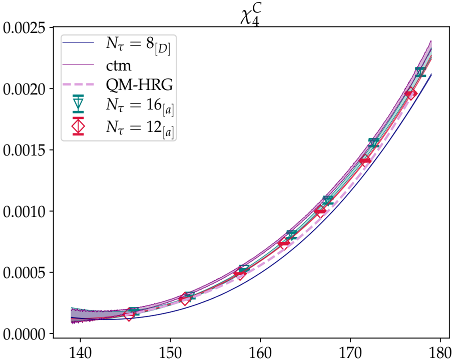
Constructing a new LCP for $\mathrm{N}_\tau = 8$





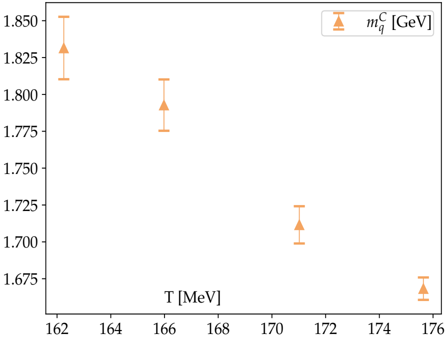
- At a fixed temperature, $\ln(\chi_4^{\mathrm{C}})$ can be approximated as a linear function of $\mathrm{am_c}$.
- Construction of a new LCP based on physical D meson mass.

Preliminary Continuum Limit

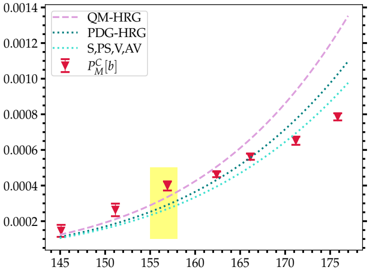


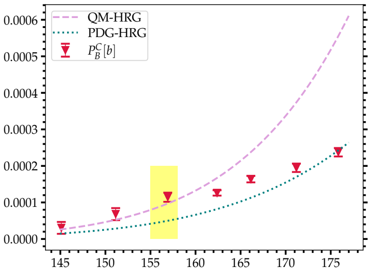
Preliminary thermal mass of charm quark-like excitation

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



Preliminary hadronic pressure

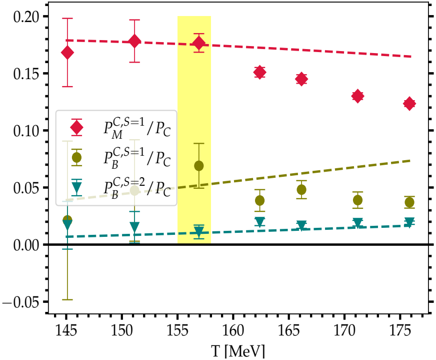




Conclusions and Outlook II

- 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.

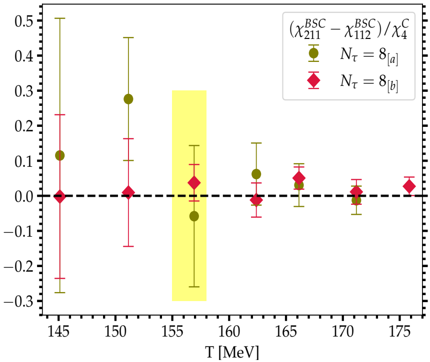
Backup slide I



Why not consider only charm-quark-like excitations?

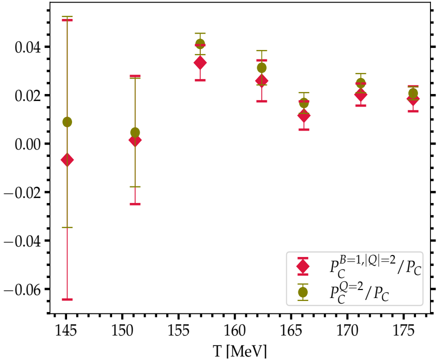
$\implies$ Contribution from SC sector above $\mathrm{T_{pc}}$ – these states can not be quark-like.

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.