# Charm thermodynamics near chiral crossover

Sipaz Sharma

for the HotQCD Collaboration

The 41st Lattice Conference, Lattice 2024

University of Liverpool, United Kingdom

CRC-TR 211
Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

# Questions

- 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]
- In heavy-ion collisions, relevant degrees of freedom change from partonic to hadronic in going from high temperature phase to temperatures below $\mathrm{T_{pc}}$.

# Questions

- 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]
- In heavy-ion collisions, relevant degrees of freedom change from partonic to hadronic in going from high temperature phase to temperatures below $\mathrm{T_{pc}}$.
- Do charmed hadrons start melting at $\mathrm{T_{pc}}$? – compare lattice results with HRG model.

# Onset of the charmed hadrons' melting

- Dimensionless generalized susceptibilities of the conserved charges:

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

# Onset of the charmed hadrons' melting

- Dimensionless generalized susceptibilities of the conserved charges:

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

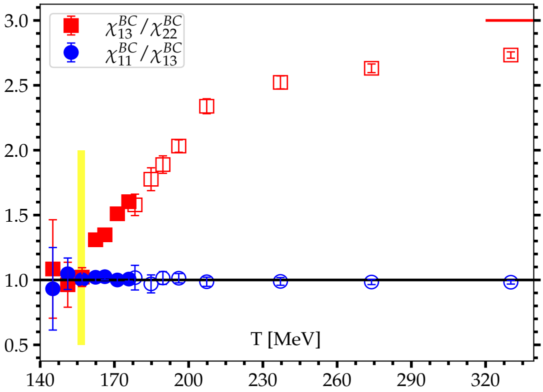
- In the Hadron Resonance gas approximation:

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

- For Baryons the argument of $\cosh$ changes to

$$\mathrm{B_i}\hat{\mu}_{\mathrm{B}}+\mathrm{Q_i}\hat{\mu}_{\mathrm{Q}}+\mathrm{S_i}\hat{\mu}_{\mathrm{S}}+\mathrm{C_i}\hat{\mu}_{\mathrm{C}}$$

# Onset of the charmed hadrons' melting




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

Phys.Lett.B 850 (2024), arXiv:2312.12857

# Questions

- Do charmed hadrons start melting at $\mathrm{T_{pc}}$? – compare lattice results with HRG model.
  Yes, states with fractional $\mathrm{B}$ start appearing near $\mathrm{T_{pc}}$.

# Questions

- Do charmed hadrons start melting at $\mathrm{T_{pc}}$? – compare lattice results with HRG model.
  Yes, states with fractional $\mathrm{B}$ start appearing near $\mathrm{T_{pc}}$.
- What are the relevant charmed dofs after the onset of hadron melting? Can we get a signal for the appearance of quarks at $\mathrm{T_{pc}}$?

# Charm degrees of freedom above $\mathrm{T_{pc}}$

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

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

[S. Mukherjee et al., 2016]

# Charm degrees of freedom above $\mathrm{T_{pc}}$

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

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

[S. Mukherjee et al., 2016]

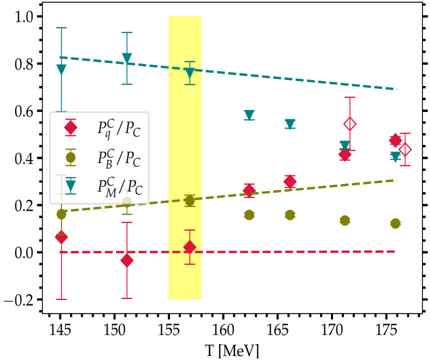
- Use quantum numbers $\mathrm{B}$ and $\mathrm{C}$ to construct partial pressures:

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

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

$\mathrm{c} = \chi_{13}^{\mathrm{BC}} + 3\chi_{31}^{\mathrm{BC}} - 4\chi_{22}^{\mathrm{BC}} = 0$ – our data satisfies this constraint.

# 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 $\mathrm{P_C}$. Phys.Lett.B 850 (2024), arXiv:2312.12857

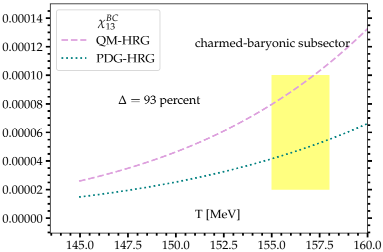
# Questions

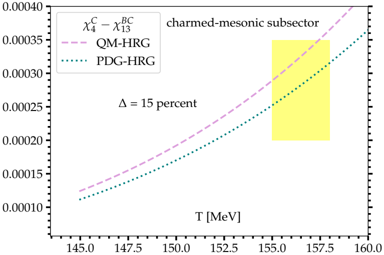
- Do charmed hadrons start melting at $\mathrm{T_{pc}}$?
  Yes, states with fractional $\mathrm{B}$ start appearing near $\mathrm{T_{pc}}$.
- What are the relevant charmed dofs after the onset of hadron melting? Can we get a signal for the appearance of quarks at $\mathrm{T_{pc}}$?
  Evidence of deconfinement in terms of presence of charm quark-like excitations in QGP.
  $\mathrm{P_C}$ receives $50\%$ contribution from charmed hadron-like excitations at $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.

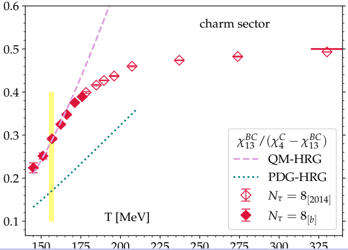
# Questions

- Do charmed hadrons start melting at $\mathrm{T_{pc}}$?
  Yes, states with fractional $\mathrm{B}$ start appearing near $\mathrm{T_{pc}}$.
- What are the relevant charmed dofs after the onset of hadron melting? Can we get a signal for the appearance of quarks 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 $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.
- For $\mathrm{T} < \mathrm{T_{pc}}$, do charm fluctuations calculated on the lattice receive enhanced contributions from not-yet-discovered open charm states?

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




- Missing charmed-baryonic states below $\mathrm{T_{pc}}$.
- $\Delta = (|1-\text{QM-HRG}/\text{PDG-HRG}|)|_{\mathrm{T_{pc}}}$ Preliminary results in the proceedings: [arXiv:2401.01194], [arXiv:2212.11148]; Publication in preparation

# Questions

- Do charmed hadrons start melting at $\mathrm{T_{pc}}$?
  Yes, states with fractional $\mathrm{B}$ start appearing near $\mathrm{T_{pc}}$.
- What are the relevant charmed dofs after the onset of hadron melting? Can we get a signal for the appearance of quarks 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 $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.
- For $\mathrm{T} < \mathrm{T_{pc}}$, do charm fluctuations calculated on the lattice receive enhanced contributions from not-yet-discovered open charm states?
  Incomplete PDG records of the charmed hadrons in each subsector.

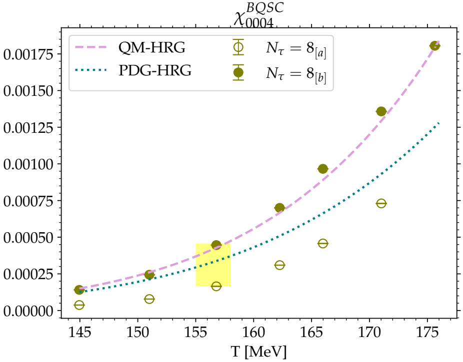
# Questions

- Do charmed hadrons start melting at $\mathrm{T_{pc}}$?
  Yes, states with fractional $\mathrm{B}$ start appearing near $\mathrm{T_{pc}}$.
- What are the relevant charmed dofs after the onset of hadron melting? Can we get a signal for the appearance of quarks 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 $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.
- For $\mathrm{T} < \mathrm{T_{pc}}$, do charm fluctuations calculated on the lattice receive enhanced contributions from not-yet-discovered open charm states?
  Incomplete PDG records of the charmed hadrons in each subsector.
- Wait, what about the simulations details? What about the continuum limit?

# 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. [[HPQCD, UKQCD],2006]
- We have gone upto fourth order in calculating various charm susceptibilties.
- We made use of 500 random vectors to do unbiased stochasic estimation of various traces per configuration.

# Continuum limit: Total charm pressure

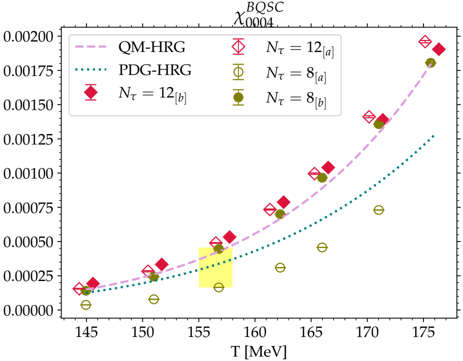



- Two different LCPs:

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

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

# Continuum limit: Total charm pressure

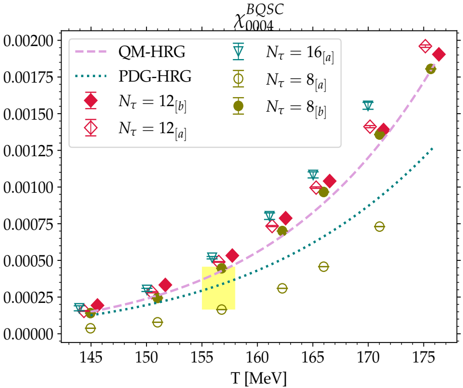



- Two different LCPs:

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

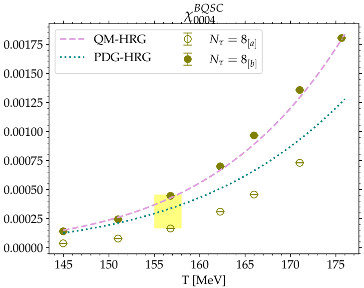
- $\mathrm{a} \approx 0.2$ fm + $\mathrm{a} \approx 0.1$ fm

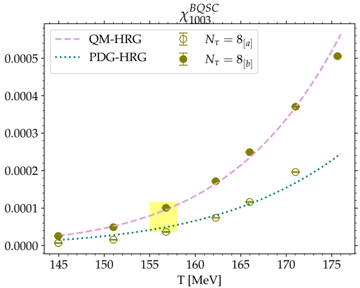
# Continuum limit: Total charm pressure

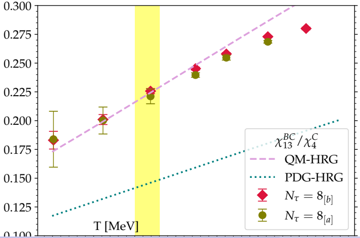



- Absolute predictions in the charm sector are particularly sensitive to the precise tuning of the bare input quark masses.
- Two different LCPs converge in the continuum limit: $\mathrm{a} \approx 0.2$ fm + $\mathrm{a} \approx 0.1$ fm + $\mathrm{a} \approx 0.05$ fm

# Ratios calculated using different LCPs

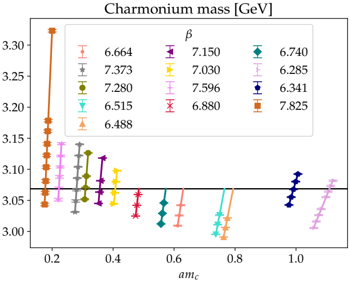


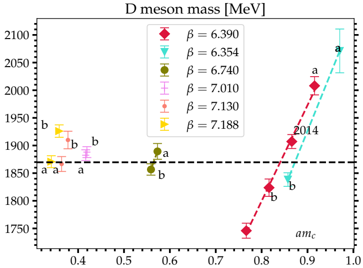




- Sensitivity to the choice of LCP cancels to a large extent in the ratios.
- All previously shown results were based on ratios, and hence valid in the continuum limit.

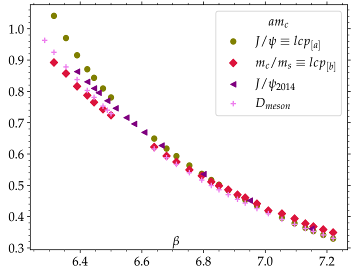
# Major source of the cutoff effects

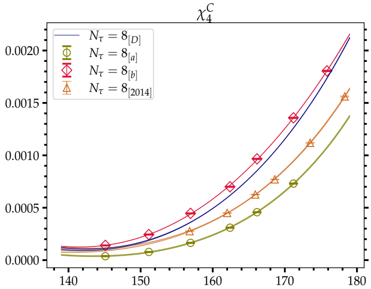



- The ordering of various partial charm pressures based on different LCPs and $N_\tau$ values can be understood from the ordering of the $am_c$ values which determine the mass of the lightest charmed hadron i.e., D-meson.
- $\beta = [6.285 - 6.500]$ is relevant for $N_\tau = 8$; $\beta = [6.712 - 6.910]$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

# Preliminary construction of a new LCP for $N_\tau = 8$




- At a fixed temperature, ln$(\chi_4^C)$ can be approximated as a linear function of $am_c$.
- Construction of a new LCP based on D meson mass is ongoing. This will enable us to take the continuum limit.
- In the right figure, interpolations are based on a rational ansatz. We want to choose an ansatz that incorporates basic features of the low and high temperature limits.

# Summary and Outlook

- 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 $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.
- For $\mathrm{T} < \mathrm{T_{pc}}$, do charm fluctuations calculated on the lattice receive enhanced contributions from not-yet-discovered open charm states?
- Incomplete PDG records of the charmed hadrons in each subsector.

# Summary and Outlook

- 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 $\mathrm{T} \simeq 1.1\ \mathrm{T_{pc}}$.
- For $\mathrm{T} < \mathrm{T_{pc}}$, do charm fluctuations calculated on the lattice receive enhanced contributions from not-yet-discovered open charm states?
- Incomplete PDG records of the charmed hadrons in each subsector.
- 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 $\mathrm{T_{pc}}$.
- Continuum limit will enable unravelling many interesting aspects.