Heavy-light Flavor Correlations on the QCD Phase Boundary

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• crossover temperatures: not unique!

\[ T_{\bar{q}q} \quad T_{\bar{s}s} \quad \text{chiral} \]
\[ 155 \text{ MeV} \quad 200 \text{ MeV} \]

\[ T_{\text{poly.inflection}} \quad T_{\text{charges}} \quad \text{deconf} \]

• flavor basis vs. conserved charge basis: strange mesons deconfined at \( T_{ch} \)!

\[ \mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q, \quad \mu_d = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q, \quad \mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S. \]

• charm? · · · lessons from lattice QCD:
  (i) EoS not affected by dynamical c quark around \( T_{ch} \) [Borsanyi et al. ('11)]
  (ii) charmed mesons deconfined together with light mesons [Basavov et al. ('14)]

• correlations between light and heavy-flavor physics
  \[ \Rightarrow \text{how are heavy-light hadrons modified toward chiral crossover?} \]

\[ D_s \sim c\bar{s} \text{ is like } K \sim q\bar{s}? \cdot \cdot \cdot \text{ NO!} \]
I. Chiral Structure of Heavy-light Mesons
Symmetries of QCD in the heavy quark mass limit

- flavor symmetries

  chiral symmetry: \( m_{u,d}/\Lambda_{\text{QCD}} \ll 1, \quad m_s/\Lambda_{\text{QCD}} < 1 \).  
  heavy quark symmetry: \( \Lambda_{\text{QCD}}/m_{c,b} \ll 1 \).

- heavy-light (\( Q\bar{q} \)) mesons  
  \( Q \): heavy quark and \( q \): light quark  
  e.g. D mesons: \( Q = c, \quad q = u, d, s \)

- physical picture (\( m_Q \to \infty \))
  - flavor symmetry (\( c \leftrightarrow b \)): cloud does not feel the flavor of \( Q \).
  - spin symmetry: cloud does not feel the spin of \( Q \).

Spin and flavor symmetries of heavy quarks are entangled!
• $SU(2N_{Q_f})$ spin-flavor symmetry: [Shuryak ('81), Isgur-Wise ('89)]
  light d.o.f. (q) do not feel the flavor and spin of the heavy quark (Q).

• spin partners: $D(0^-)$ and $D(1^-)$, $B(0^-)$ and $B(1^-)$

• real world:
  $m_{D^*} - m_D = 142$ MeV, $m_{B^*} - m_B = 46$ MeV $\ll \Lambda_{QCD}$
  $\cdots \ 1/m_Q$ corrections
  $m_{D_s} - m_{D_d} = 100$ MeV, $m_{B_s} - m_{B_d} = 90$ MeV $\ll \Lambda_{QCD}$
  $\cdots m_q$ corrections
Role of light flavor (chiral) symmetry

- **Observation**: 2nd lowest spin doublets
  
  \[ D_{u,d}(0^+) : 2308 \text{ MeV} \quad \text{[Belle (03)]} \quad D_{u,d}(1^+) : 2427 \text{ MeV} \quad \text{[Belle (03)]} \]
  
  \[ D_s(0^+) : 2317 \text{ MeV} \quad \text{[Babar (03)]} \quad D_s(1^+) : 2460 \text{ MeV} \quad \text{[CLEO (03)]} \]

- Mass difference of parity doublets: \( \delta m = 300 - 400 \text{ MeV} \sim \Lambda_{\text{QCD}} \)

  **NOTE**: potential model for D mesons (cf. hydrogen atom) does not work!

- **Chiral doubling**
  
  [Nowak-Rho-Zahed (92); Bardeen-Hill (93)]

\[
\begin{align*}
\text{heavy quark sym} & \\
D(0^+) & \leftrightarrow D(1^+) & \text{chiral sym} & \uparrow \\
D(0^-) & \leftrightarrow D(1^-) & \text{chiral sym} & \uparrow \\
\text{heavy quark sym} & 
\end{align*}
\]

**Effective theory for heavy-light system based on the two relevant symmetries**
II. Thermodynamics
Embedding $D, D_s$ in a linear sigma model

- chiral fields $\Sigma = \sigma + i\pi$, heavy-light meson fields $H(0^-, 1^-), G(0^+, 1^+)$

\[ \Sigma \rightarrow g_L \Sigma g_R^\dagger, \quad H_{L,R} \rightarrow S H_{L,R} g_L^\dagger. \]

- Lagrangian

\[ \mathcal{L} = \mathcal{L}_L(\Sigma) + \mathcal{L}_{HL}(\mathcal{H}, \Sigma), \quad V_{HL} = V_{HL}(\mathcal{H}^2, \mathcal{H}^4; \Sigma) + V_{HL}^{(exp)}. \]

- 6 parameters fixed with $T = 0$ physics

\[ V_{HL}^{(2)} : m_0, g^q_{\pi}, g^s_{\pi}, \quad V_{HL}^{(4)} : k_0, k^q, k_s \]

- isospin sym & mean field approximation: $\langle \sigma_q \rangle, \langle \sigma_s \rangle, \langle D_q \rangle, \langle D_s \rangle$

conventional approach ... then?
Chiral condensates: role of charmed-meson MF

- lattice: qualitative diff. between $\langle \bar{q}q \rangle$ and $\langle \bar{s}s \rangle \cdots$ SU(2+1): $T_c^{(u,d)} < T_c^{(s)}$

- chiral model: $\sigma_{q,s}$ — approx. SU(3)!

- induced chiral sym. breaking:

  $h_q^* = h_q - D_q^2 \left( \frac{1}{2} g_{q\pi}^2 + 2k_q D_q^2 \right)$,

  $h_s^* = h_s - \frac{1}{\sqrt{2}} D_s^2 \left( \frac{1}{2} g_{s\pi}^2 + 2k_s D_s^2 \right)$.
conventional approach:
1. set up at $T = 0$, all the parameters are *constant*.
2. 4 gap equations at given $T$
3. approximate SU(3) $h_q^*/h_s^* \sim 1$ ...!? 

resolution:
1. $\langle \sigma_q \rangle$ and $\langle \sigma_s \rangle$ as input e.g. lattice chiral consansates
2. $\langle D_q \rangle$, $\langle D_s \rangle$ and 2 HL-couplings as output $\Rightarrow g_\pi, k$ varying with $T$
3. $h_q^*/h_s^* \ll 1$ restored
Intrinsic thermal effects

- concept of EFT: generating functional, Green’s functions

\[ Z = \int \mathcal{D}q \mathcal{D}g e^{S_{QCD}[q,g]} \equiv \int \mathcal{D}U e^{S_{\text{eff}}[U]} \]

- low-energy constants: high-frequency modes integrated out
  \[ \Rightarrow \text{in a hot/dense medium: effective couplings dep. on } T/n \]

- L: \( T_{\text{pc}}^{\text{lat}} = 154 \text{ MeV} \Rightarrow \text{quartic coupling such that } m_\sigma = 400 \text{ MeV} \)

- HL: \( \sigma_{q,s} \) profiles from lattice QCD \( \Rightarrow g_{\pi}^{q,s}(T) \) etc.
In-medium charmed-meson masses

- chiral splitting at $T_{pc}$: $\delta M_D \simeq \delta M_{D_s}$
  - insensitive to light flavors!
  - $\Rightarrow$ heavy quark symmetry

- light mesons at $T_{pc}$: $\delta M_{\pi-\sigma} \ll \delta M_{K-\kappa}$
  - $SU(2+1) \neq SU(3)$

- cf. chiral SU(4): [Roder-Ruppert-Rischke (’03)]
  $\delta M_D \ll \delta M_{D_s}$
• $D_s$ screening mass from lattice QCD

[ Bazavov-Karsch-Maezawa-Mukherjee-Petreczky ('14) ]

• Quenched HL coupling and $D_s$ decays: anomalous suppression

$$\Gamma(0^+/1^+ \rightarrow 0^-/1^- + \pi^0) \propto \left(\frac{g_s}{\pi}\right)^2 \cdot \delta^{2}_{\pi^0\eta}$$

quenched due to CSR

isospin violation
Generalized susceptibilities

• generating functional vs. effective action

\[ \Gamma[\phi_{\text{cl}}] = -W[J] - \int d^4x J(x) \phi_{\text{cl}}(x) \]

• fluctuation of \( \phi \)

\[ \langle \phi(x)\phi(y) \rangle - \langle \phi(x) \rangle \langle \phi(y) \rangle = \frac{\delta^2 W[J]}{\delta J(x)\delta J(y)} = \left( \frac{\delta^2 \Gamma[\phi]}{\delta \phi_{\text{cl}}(x)\delta \phi_{\text{cl}}(y)} \right)^{-1} \]

\[ \therefore 1 = \frac{\delta^2 W}{\delta J_i \delta J_k} \frac{\delta^2 \Gamma}{\delta \phi_{\text{cl}}(x) \delta \phi_{\text{cl}}(y)} \]

• multiple fields \( \vec{\phi} = (\phi_1, \phi_2, \cdots, \phi_n) \)

\[ \delta_{ij} = \frac{\delta^2 W}{\delta J_i \delta J_k} \frac{\delta^2 \Gamma}{\delta \phi_{\text{cl}}(x) \delta \phi_{\text{cl}}(y)} , \quad \{i, j, k\} = 1, 2, \cdots, n \]

\(-2 \times 2 \text{ sus. matrix} \Rightarrow \chi_{qq,qs,ss} \sim \chi_{\text{ch}}: \text{light flavor correlations} \)

\(-4 \times 4 \text{ sus. matrix} \Rightarrow \chi_{\sigma D}, \chi_{DD}: \text{heavy-light flavor correlations} \)
Correlations between light and heavy-light mesons

\[ \sigma_{q,s} \text{ vs. } D_{q,s} \]

\[ D_{q,s} \text{ vs. } D_{q,s} \]

Qualitative changes set in at \( T \sim T_{pc} \): (NOTE: \( \chi_{ch} \sim \partial \sigma_{q,s}/\partial m_{q,s} \))

\[
\hat{\chi}_{\sigma D} = -\hat{\chi}_{ch} \hat{C}_{HL} \hat{\chi}_D, \quad \hat{\chi}_{D \sigma} = -\hat{\chi}_D \hat{C}_{HL} \hat{\chi}_{ch}, \\
\hat{\chi}_{DD} = \hat{C}_D - \hat{C}_{HL} \hat{\chi}_{ch} \hat{C}_{HL} \equiv \hat{\chi}_D.
\]

in-medium \( D_s \) as a probe of O(4)!
Toward high-density QCD

• effective Lagrangian parameters vary with $T$!
  ⇒ other hadrons: more and more states activated toward QCD p.t.
  – role of higher KK modes in open moose model [Son, Stephanov ('03)]
    correct high-energy behavior for current correlator
  – nuclear matter saturation in Walecka model
density-dep. parameters: many-body effects integrated out

How to handle them?

• holographic QCD models: $1/N_c$ corrections?
• 4d effective theories: higher resonances, careful treatment of broad resonances ⇒ talk by Pok Man Lo
• microscopic approach: lattice QCD, DS/FRG
Summary

• Synthesis of light and heavy quark dynamics

\[ \frac{m_q}{m_c}, \frac{m_s}{m_c}, \frac{T}{m_c} \ll 1 \quad \text{heavy quark symmetry as a reliable guide} \]

– at \( T_{pc} \): chiral mass splittings of HL mesons insensitive to light flavors.

\[ \delta M_{D,B} \simeq \delta M_{D_s,B_s} \quad \text{vs.} \quad \delta M_{\pi-\sigma} \ll \delta M_{K-\kappa} \]

– remnant of O(4) in HL mixed fluctuations.

– anomalous suppression of \( D_s \) decay widths as a sign of CSR

\textbf{in-medium} \( D_s \) \textbf{as a probe of O(4)!}

• Application to a dense system

– strange and charm number conservation

– role of higher-lying hadrons

– chiral restoration vs. deconfinement \( \cdots \) \text{lat. Dirac-eigenmode expansion}

– fluc. of conserved charges \( \chi_{X}^{(\text{non-reg})} = \mathcal{F}_{X}(\sigma_{q,s}, D_{q,s}; \chi_{\text{ch}}) \)