Charmed Mesons in Matter

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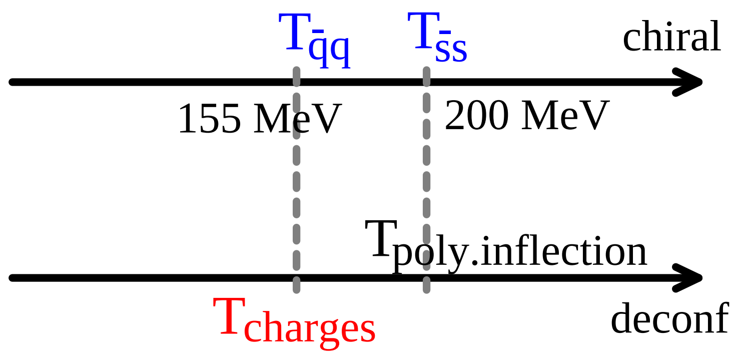
[1] C.S., Phys. Rev. D **90**, no. 11, 114007 (2014).
[2] C.S. and K. Redlich, Phys. Rev. D **91**, no. 7, 074021 (2015).

Introduction: why charm?

- crossover temperatures: *not unique!*



- flavor basis vs. conserved charge basis: strange mesons deconfined at $T_{\rm ch}$!

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

- charm? $\cdots$ lessons from lattice QCD:
  (i) EoS not affected by dynamical c-quark around $T_{\rm ch}$ [Borsanyi et al. ('11)]
  (ii) charm quarks start to appear around $T_{\rm ch}$ [Basavov et al. ('14)]
  (iii) survival charmed hadrons up to $T/T_c = 1.2$ [Mukherjee et al. ('15)]

- correlations between light and heavy-flavor physics, *beyond HRG*
  $\Rightarrow$ how are heavy-light hadrons modified toward chiral crossover?

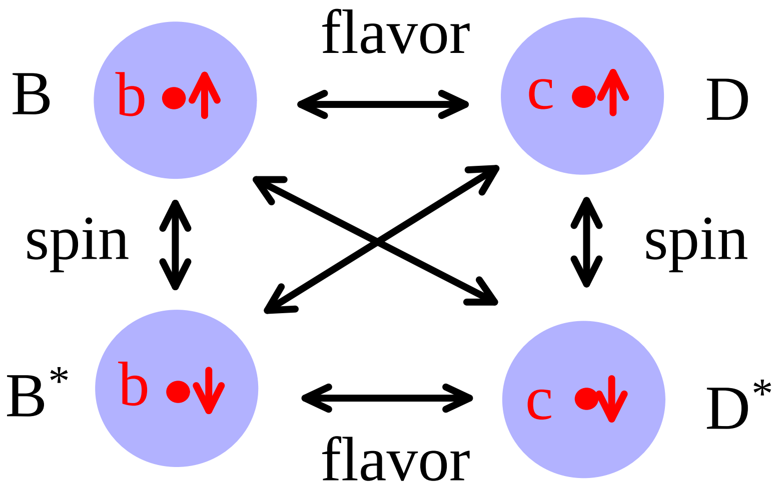
$D_s \sim c\bar{s}$ is like $K \sim q\bar{s}$? $\cdots$ NO!

Symmetries of QCD in the heavy quark mass limit

- flavor symmetries

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

- $SU(2N_{Qf})$ **spin-flavor symmetry** $(m_Q \to \infty)$: [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 $\ll \Lambda_{\rm QCD}$: $1/m_Q$ corr.
$m_{Ds} - m_{Dd} = 100$ MeV , $m_{Bs} - m_{Bd} = 90$ MeV $\ll \Lambda_{\rm QCD}$: m_q corr.

Role of light flavor (chiral) symmetry

- **observation**: 2nd lowest spin doublets

$D_{u,d}(0^+) : 2308\,\text{MeV}$ [Belle (03)] $D_{u,d}(1^+) : 2427\,\text{MeV}$ [Belle (03)]
$D_s(0^+) : 2317\,\text{MeV}$ [Babar (03)] $D_s(1^+) : 2460\,\text{MeV}$ [CLEO (03)]

- mass difference of parity doublets: $\delta m = 300 - 400\,\text{MeV} \sim \Lambda_{\text{QCD}}$
- chiral doubling [Nowak-Rho-Zahed (92); Bardeen-Hill (93)]

$$\begin{tikzcd}
D(0^+) \arrow[r, leftrightarrow, "\text{heavy quark sym}"] \arrow[d, leftrightarrow, "\text{chiral sym}"'] & D(1^+) \arrow[d, leftrightarrow, "\text{chiral sym}"] \\
D(0^-) \arrow[r, leftrightarrow, "\text{heavy quark sym}"'] & D(1^-)
\end{tikzcd}$$

effective theory for heavy-light system based on the two relevant symmetries

Embedding D, D_s in a linear sigma model

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

$$\Sigma \to g_L \Sigma g_R^\dagger\,, \quad \mathcal{H}_{L,R} \to S \mathcal{H}_{L,R} g_{L,R}^\dagger\,.$$

- Lagrangian

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

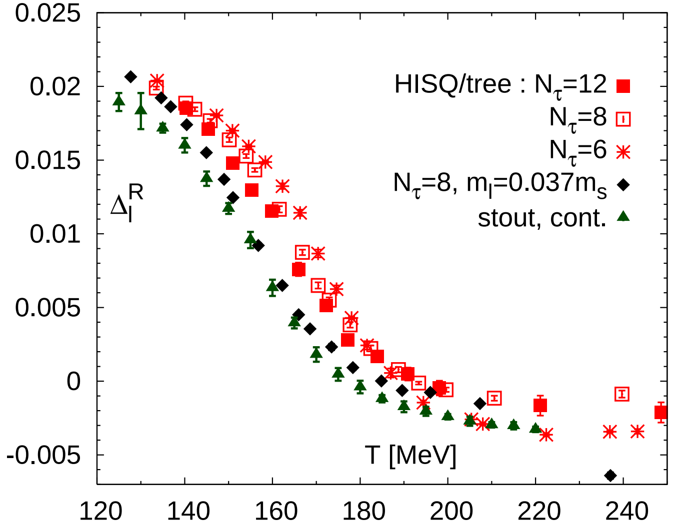
- 6 parameters fixed with $T = 0$ physics

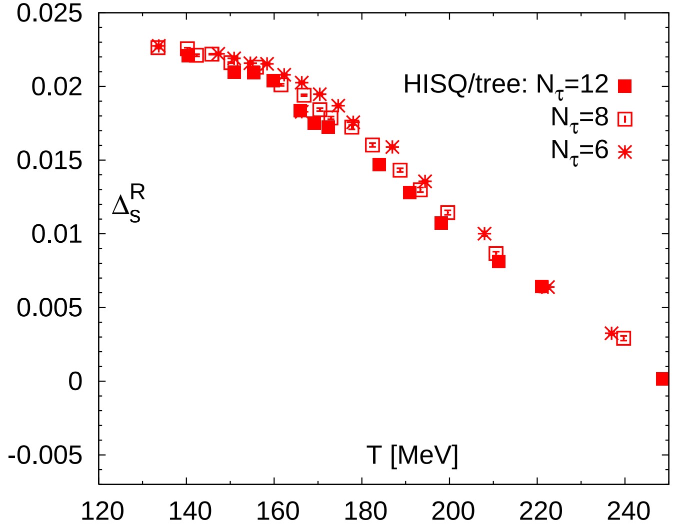
$$V_{\mathrm{HL}}^{(2)} :\ m_0\,, \underbrace{g_\pi^q\,, g_\pi^s}_{\Sigma \leftrightarrow \mathcal{H}^2}\,, \quad V_{\mathrm{HL}}^{(4)} :\ k_0\,, \underbrace{k_q\,, k_s}_{\Sigma \leftrightarrow \mathcal{H}^4}$$

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

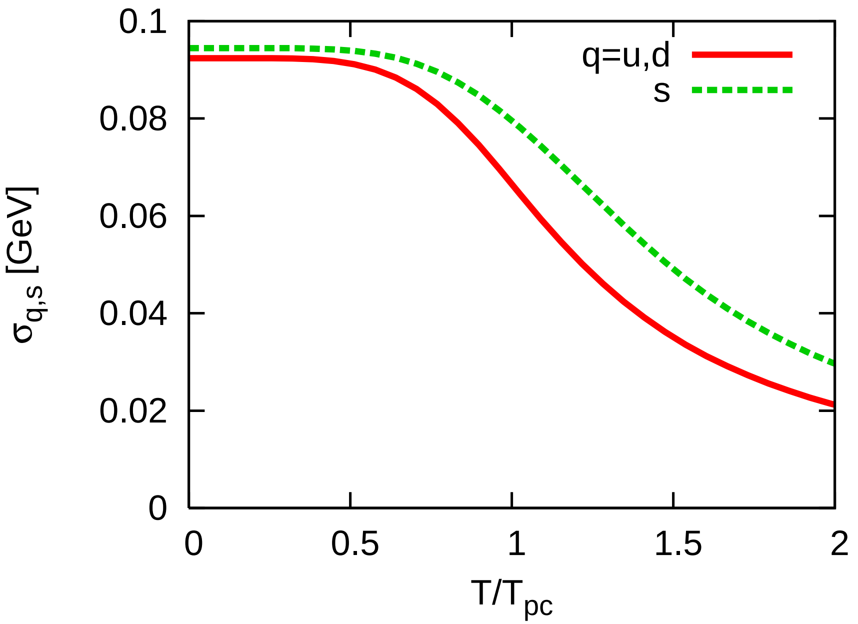
conventional approach ... then?

Chiral condensates: role of charmed-meson MF





[HotQCD Collaboration ('12)]



- 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:

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

$$h_s^* = h_s - \frac{1}{\sqrt{2}} D_s^2 \left(\frac{1}{2} g_\pi^s + 2 k_s D_s^2 \right) .$$

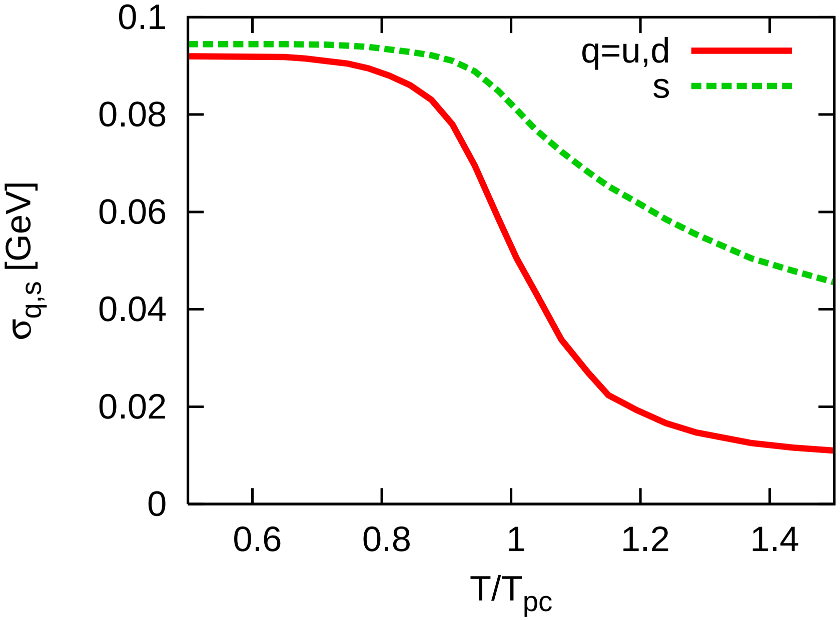
conventional approach:

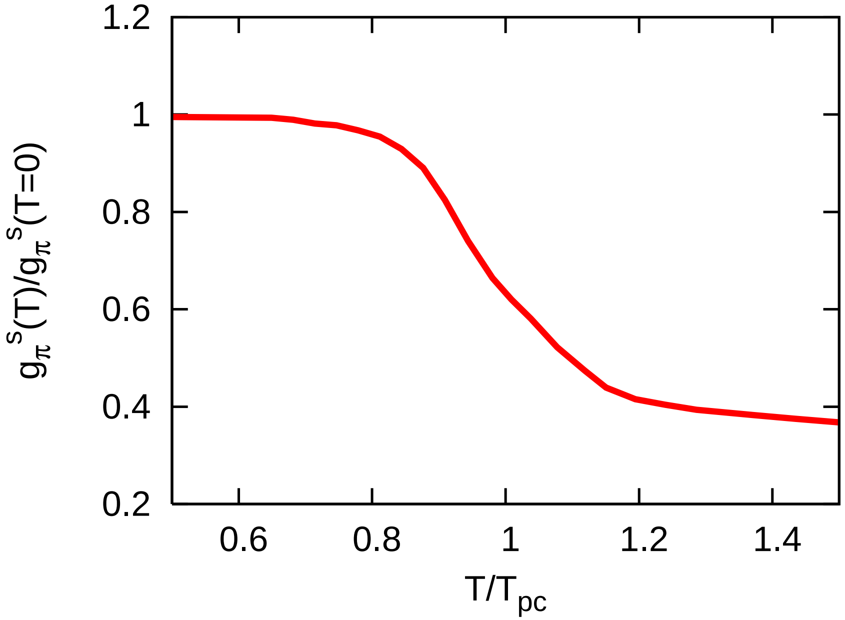
1. set up at $T = 0$, all the parameters are *constant*.
2. 4 gap equations at given T
3. approximate SU(3) $h_q^*/h_s^* \sim 1$ ...!?

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_π, k varying with T
3. $h_q^*/h_s^* \ll 1$ restored

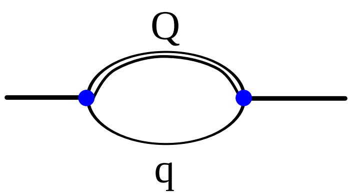
Intrinsic thermal effects

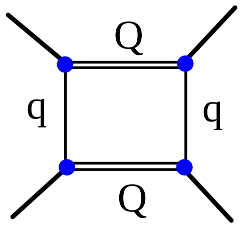




- concept of EFT: generating functional, Green's functions

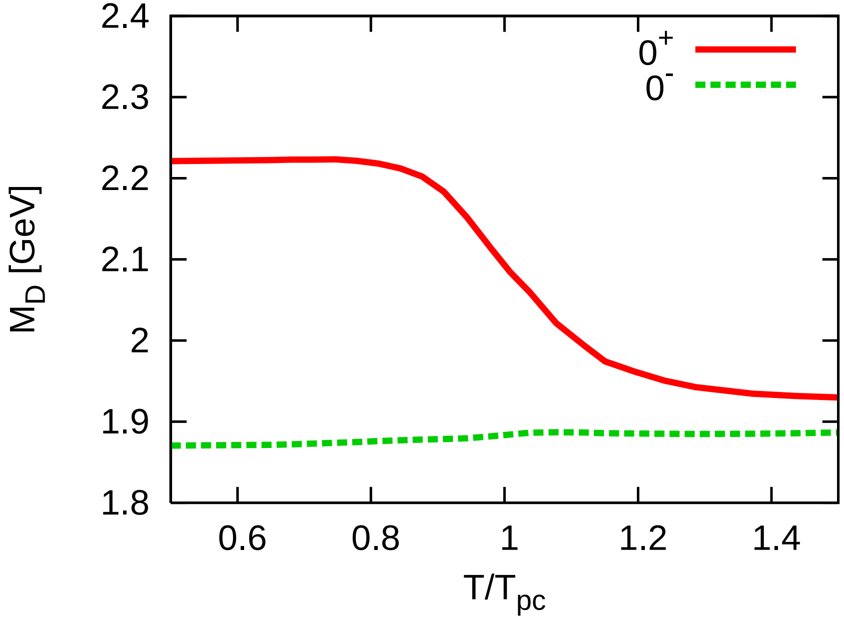
$$Z = \int \mathcal{D}q\mathcal{D}g e^{S_{\mathrm{QCD}}[q,g]} \equiv \int \mathcal{D}U e^{S_{\mathrm{eff}}[U]}$$

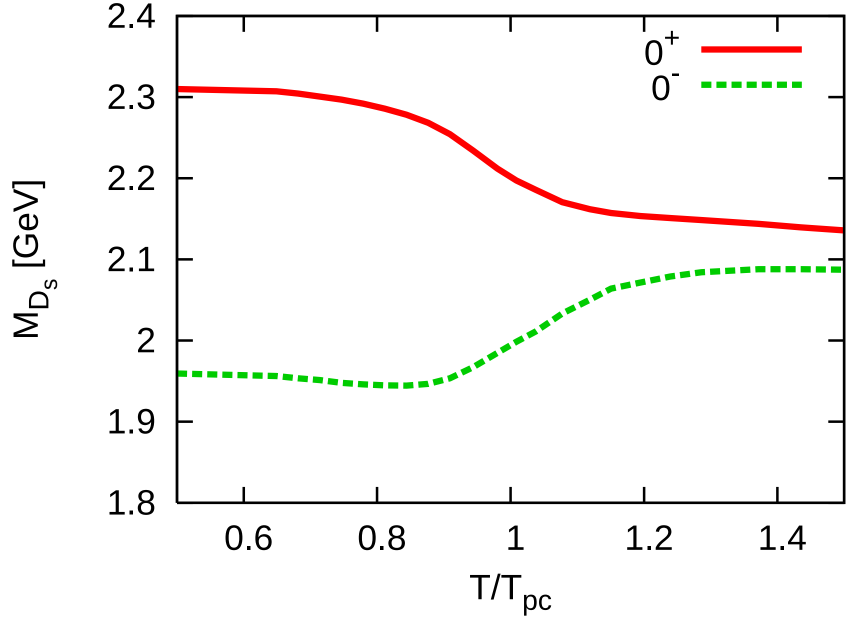




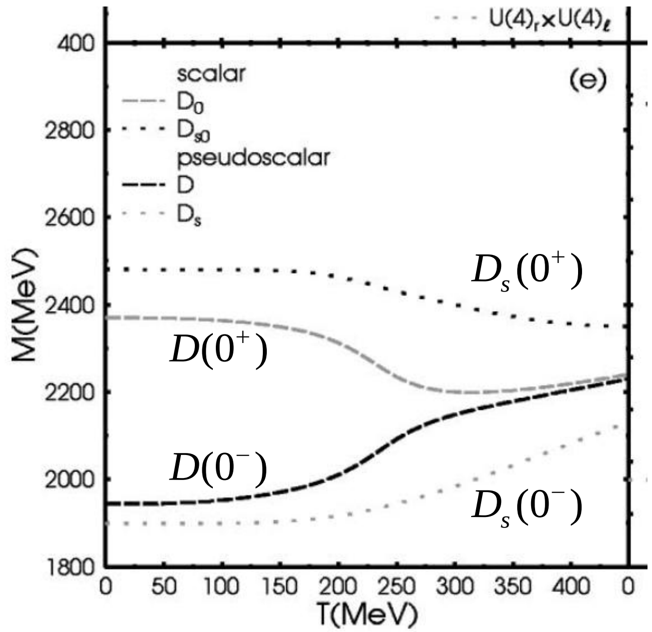
- low-energy constants: high-frequency modes integrated out
  $\Rightarrow$ in a hot/dense medium: effective couplings dep. on T/n
- $\sigma_{q,s}$ profiles from lattice QCD $\Rightarrow$ $g_\pi(T)$ and $k(T)$

In-medium charmed-meson masses





- chiral splitting at $T_{\rm pc}$: $\delta M_D \simeq \delta M_{D_s}$
  $\cdots$ *insensitive to light flavors!*
  $\Rightarrow$ heavy quark symmetry
- light mesons at $T_{\rm pc}$: $\delta M_{\pi\text{-}\sigma} \ll \delta M_{K\text{-}\kappa}$
  $\cdots$ SU(2+1) $\neq$ SU(3)
- cf. chiral SU(4): [Roder-Ruppert-Rischke ('03)]
  $\delta M_D \ll \delta M_{D_s}$



Generalized susceptibilities

- generating functional vs. effective action

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

- fluctuation of ϕ

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

$$\because \;\; 1 = \frac{\delta^2 W}{\delta J \delta J}\frac{\delta^2\Gamma}{\delta\phi_{\rm cl}\delta\phi_{\rm cl}}$$

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

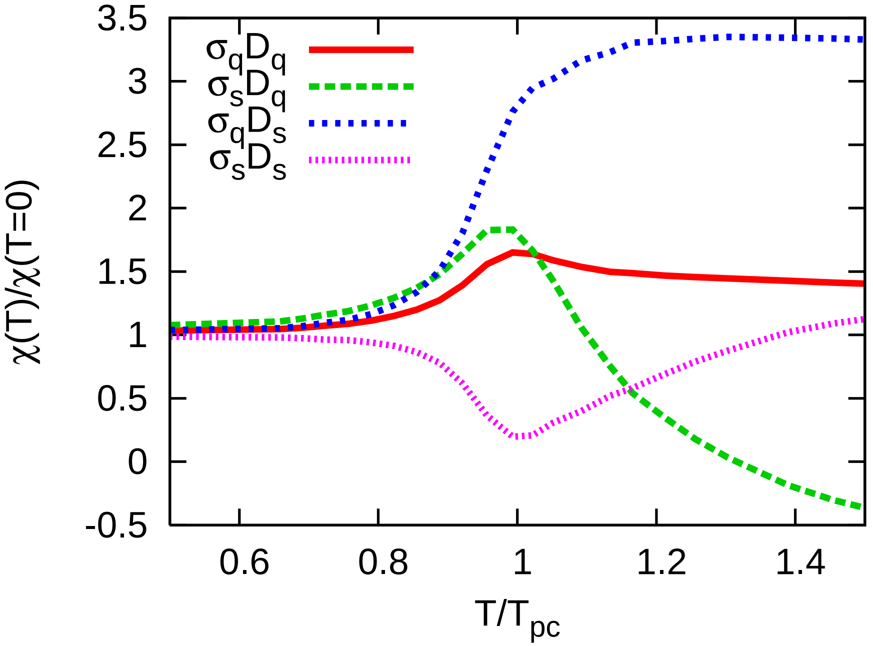
$$\delta_{ij} = \frac{\delta^2 W}{\delta J_i \delta J_k}\frac{\delta^2\Gamma}{\delta\phi_k\delta\phi_j}, \quad \{i,j,k\} = 1, 2, \cdots, n$$

  - 2×2 sus. matrix $\Rightarrow$ $\chi_{qq,qs,ss} \sim \chi_{\rm ch}$: light flavor correlations
  - 4×4 sus. matrix $\Rightarrow$ $\chi_{\sigma D}, \chi_{DD}$: heavy-light flavor correlations

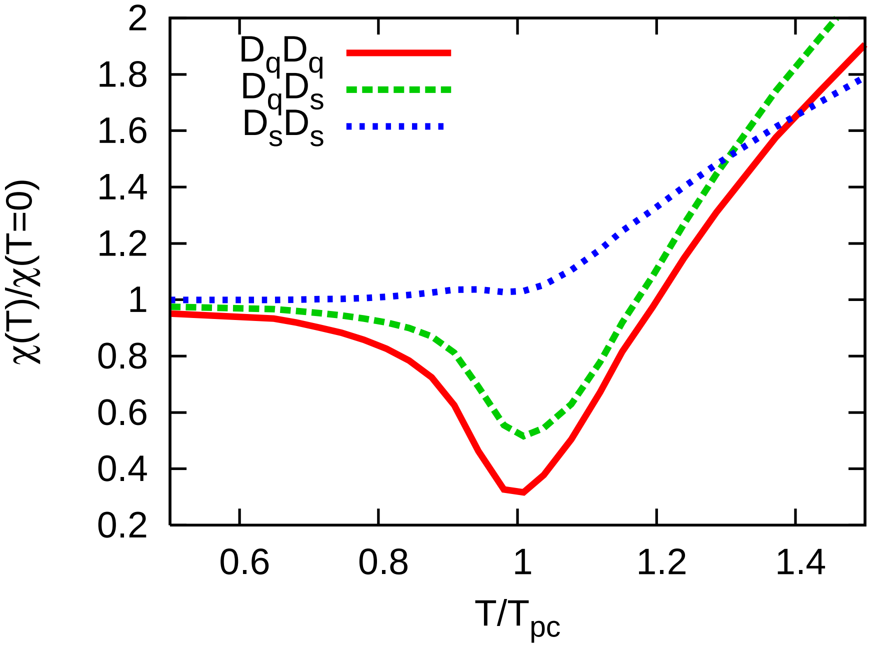
Correlations between light and heavy-light mesons

[CS-Redlich ('14)]

$\sigma_{q,s}$ vs. $D_{q,s}$



$D_{q,s}$ vs. $D_{q,s}$

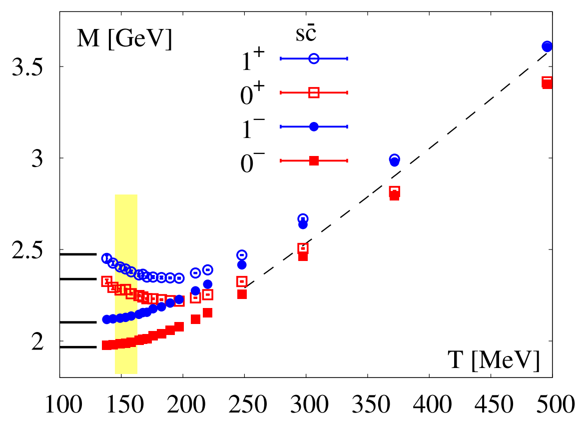


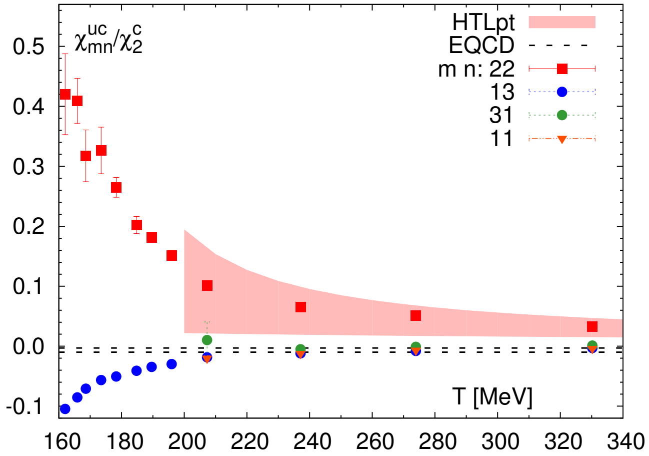
qualitative changes set in at $T \sim T_{\rm pc}$: (NOTE: $\chi_{\rm ch} \sim \partial\sigma_{q,s}/\partial m_{q,s}$)

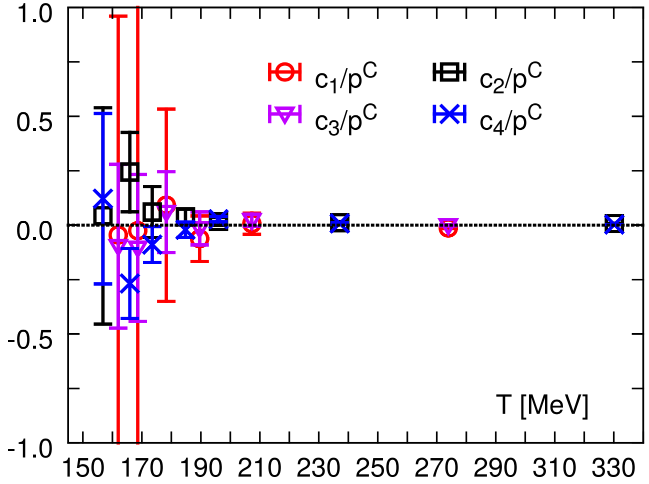
$$\hat{\chi}_{\sigma D} = -\hat{\chi}_{\rm ch}\hat{\mathcal{C}}_{\rm HL}\hat{\chi}_D\,, \quad \hat{\chi}_{D\sigma} = -\hat{\chi}_D\hat{\mathcal{C}}_{\rm HL}\hat{\chi}_{\rm ch}\,,$$
$$\hat{\chi}_{DD} = \hat{\mathcal{C}}_D - \hat{\mathcal{C}}_{\rm HL}\hat{\chi}_{\rm ch}\hat{\mathcal{C}}_{\rm HL} \equiv \hat{\chi}_D\,.$$

in-medium D_s as a probe of O(4)!

Lattice observables - consistent with the model







- screening D_s masses [Bazavov et al. ('14)] - the same tend
- 4th-order c-s corr.: survival D_s up to $T = 1.2T_{\rm ch}$ [Mukherjee et al. ('15)]
  D_s changes its property - medium modification sets in at $\sim T_{\rm ch}$.
- fluctuations and correlations of conserved charges X
  $\chi_X^{\rm (non-reg)} = \mathcal{F}_X(\sigma_{q,s}, D_{q,s}; \chi_{\rm ch})$

Chiral vs. confinement at finite density

- hybrid model suggests a splitting of the 2 phase tr. [Benic-Mishustin-CS ('15)]
- Dirac-eigenmode expansion on lattice (talk by T. Doi)

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 $T_{\rm pc}$: chiral mass splittings of HL mesons insensitive to light flavors.

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

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

  – anomalous suppression of D_s decay widths as a sign of CSR

in-medium D_s as a probe of O(4)!

- **Application to a dense system**

  – strange and charm number conservation

  – intrinsic density dependence - role of higher-lying hadrons

  – chiral restoration vs. deconfinement