Chiral Thermodynamics with Charm

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[1] C.S., Phys. Rev. D **90**, no. 11, 114007 (2014).
[2] C.S. and K. Redlich, arXiv:1412.7365 [hep-ph].

Introduction: quark flavors vs. conserved charges

- chiral: melting quark condensates, $T_{\rm u,d} \sim 155$ MeV $< T_{\rm s} \sim 200$ MeV
- deconfinement: conserved charges
  - B: baryon number, S: strangeness, Q: electric charge

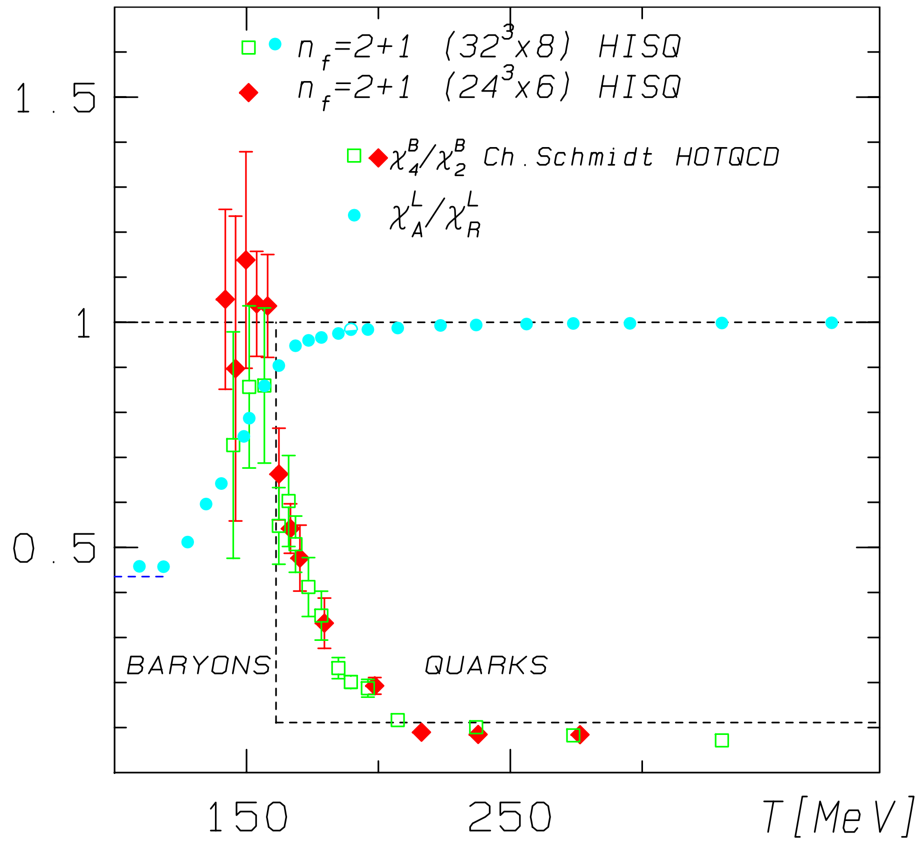
$$\mu = B\mu_B + S\mu_S + Q\mu_Q$$

  - kurtosis of baryon number fluctuations

$$\kappa = \chi_4^B/\chi_2^B\,,$$
$$\chi_n^B = \partial^n(P/T^4)/\partial(\mu_B/T)^n$$

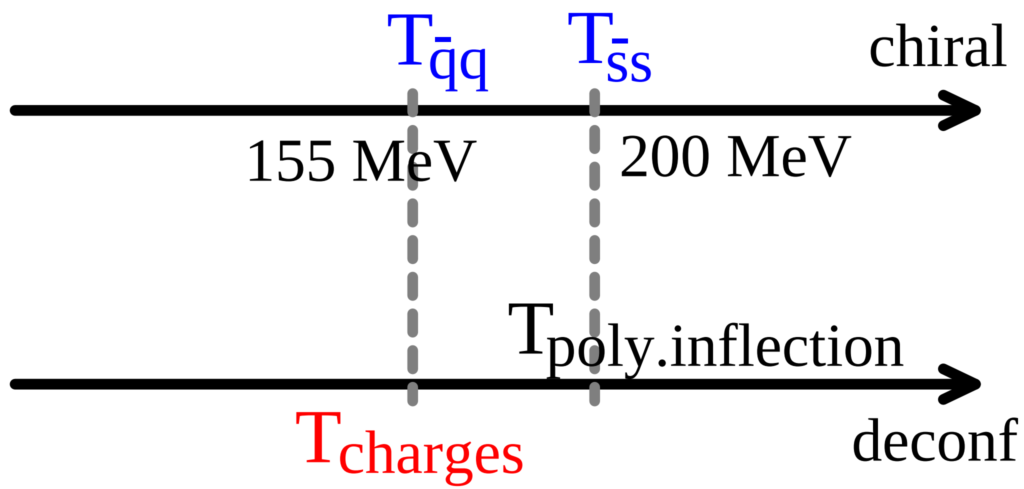
asymptotic values:

$$\kappa = B^2 = \begin{cases} 1\,, & T \ll T_c \\ 1/9\,, & T \gg T_c \end{cases}$$



- coincidence: $T_{\rm ch} \simeq T_{\rm dec}$

- 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) charmed mesons deconfined together with light mesons [Basavov et al. ('14)]

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

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

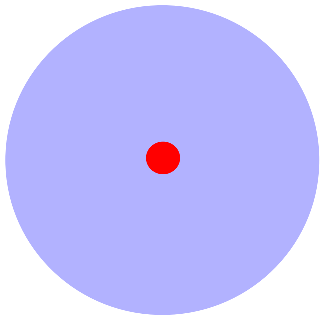
I. Chiral Structure of Heavy-light Mesons

Symmetries of QCD in the heavy quark mass limit

- flavor symmetries

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

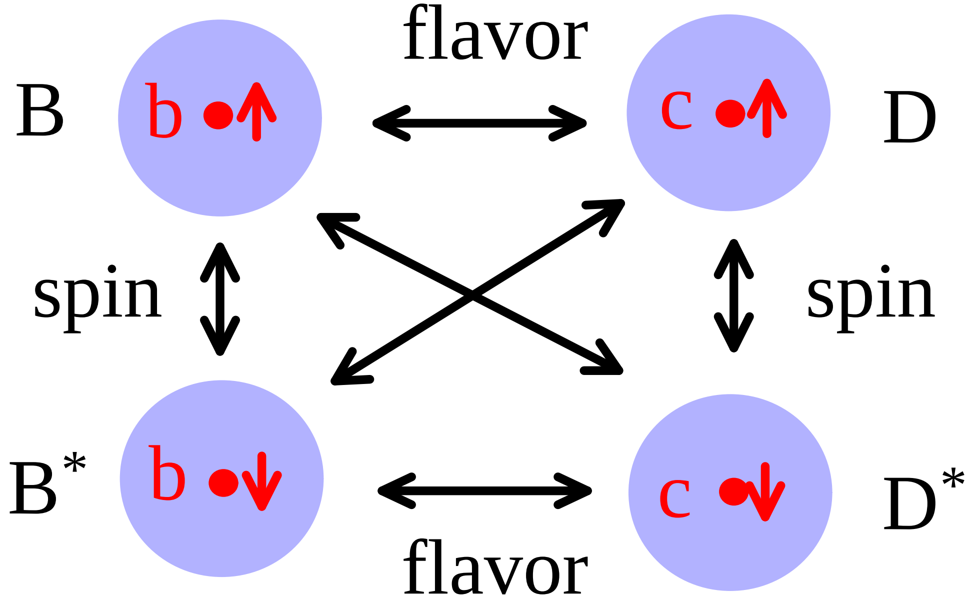
- heavy-light ($Q\bar{q}$) mesons Q : heavy quark and q : light quark
  e.g. D mesons: $Q = c$, $q = u, d, s$



- 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!

- $SU(2N_{Qf})$ **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 $\ll \Lambda_{\rm QCD}$
$\cdots$ $1/m_Q$ corrections
$m_{Ds} - m_{Dd} = 100$ MeV , $m_{Bs} - m_{Bd} = 90$ MeV $\ll \Lambda_{\rm QCD}$
$\cdots$ m_q corrections

Role of light flavor (chiral) symmetry

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

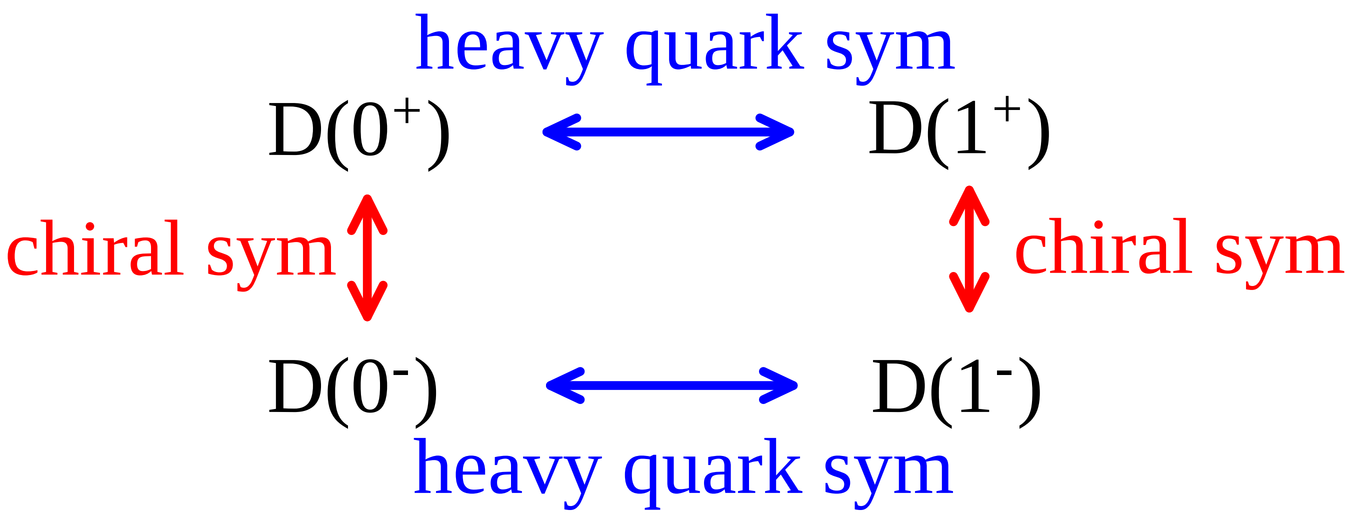
  $D_{u,d}(0^+) : 2308\,$MeV [Belle (03)] $D_{u,d}(1^+) : 2427\,$MeV [Belle (03)]

  $D_s(0^+) : 2317\,$MeV [Babar (03)] $D_s(1^+) : 2460\,$MeV [CLEO (03)]

- mass difference of parity doublets: $\delta m = 300 - 400\,$MeV $\sim \Lambda_{\mathrm{QCD}}$

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

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



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 $H(0^-, 1^-), G(0^+, 1^+)$

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

- Lagrangian

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

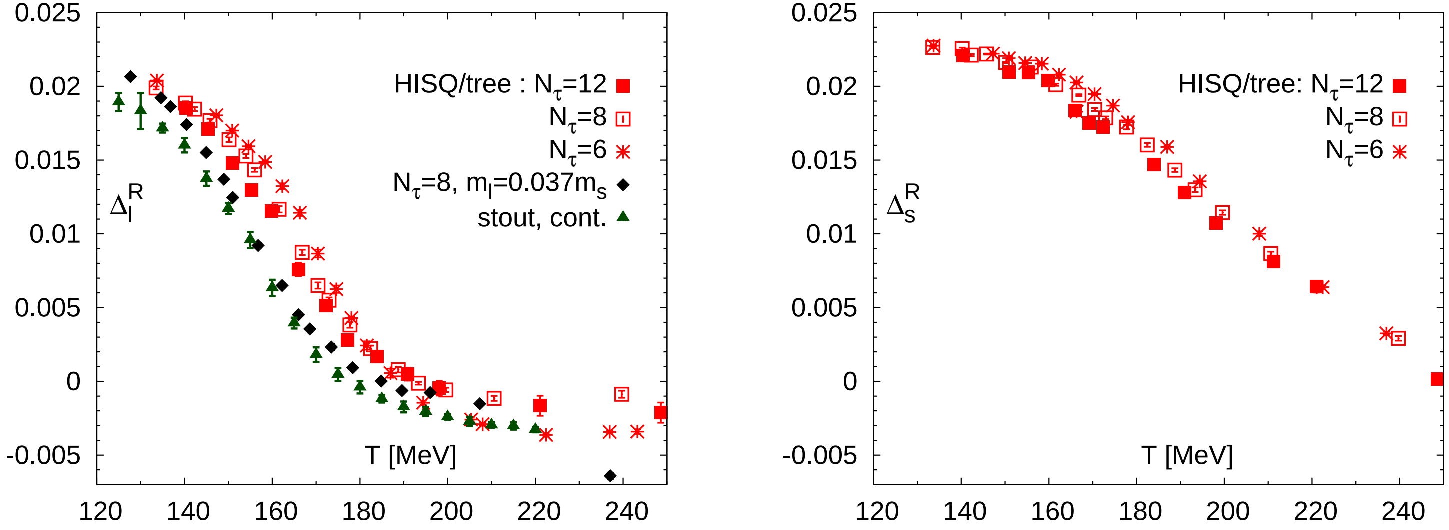
- 6 parameters fixed with $T = 0$ physics

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

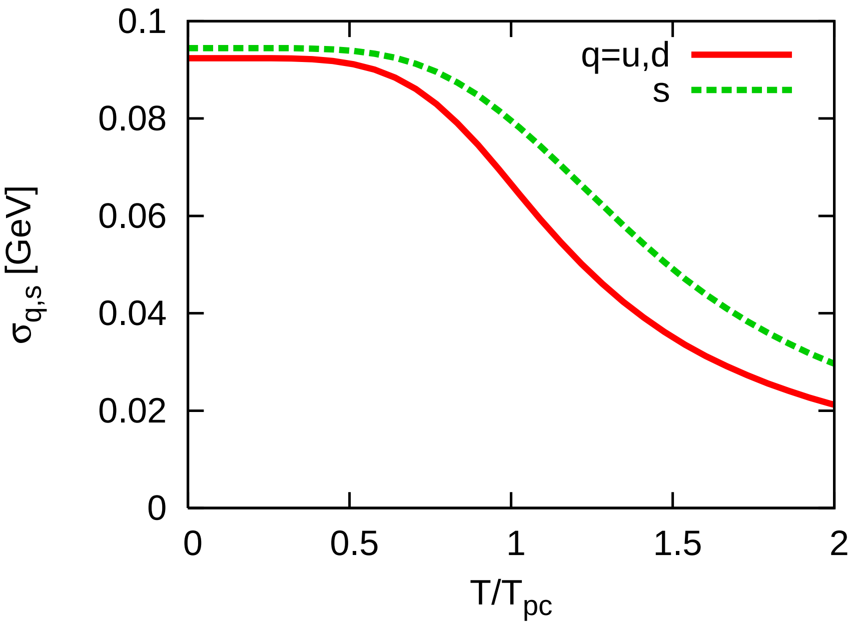
- isospin sym & mean field approximation: $\langle \sigma_q \rangle \,, \langle \sigma_s \rangle \,, \langle D_q \rangle \,, \langle D_s \rangle$

conventional approach ... then?

Chiral condensates: role of charmed-meson MF



[HotQCD Collaboration ('12)]

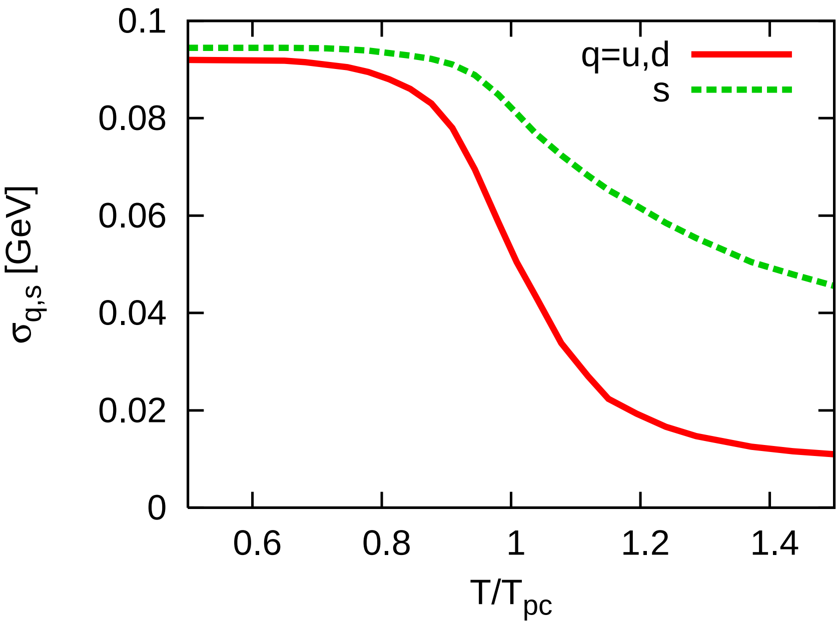


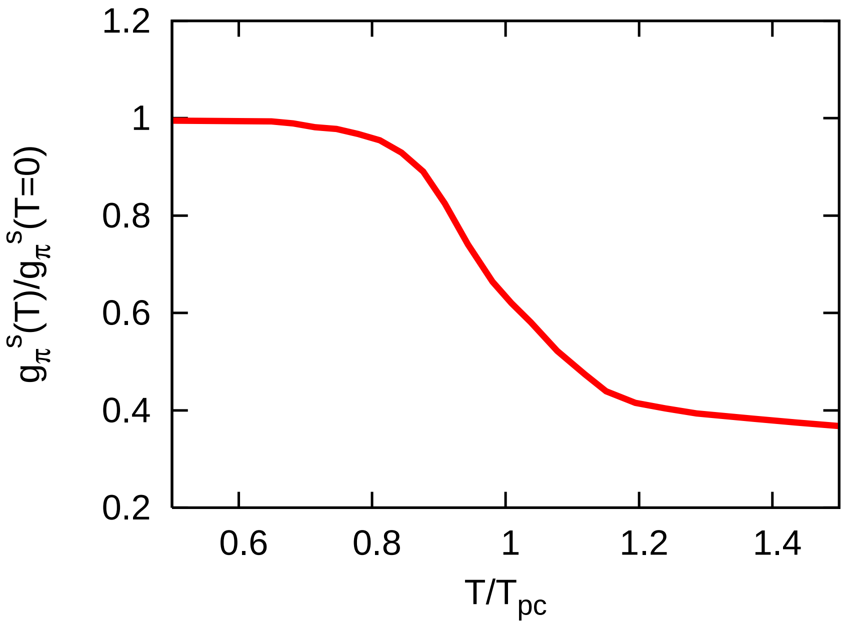
- lattice: qualitative diff. between $\langle \bar{q}q \rangle$ and $\langle \bar{s}s \rangle$ $\cdots$ SU(2+1): $T_c^{(u,d)} < T_c^{(s)}$
- chiral model: $\sigma_{q,s}$ — approx. SU(3)!?
- induced chiral sym. breaking:

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

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

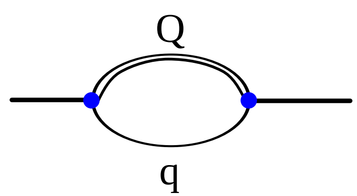
Intrinsic thermal effects

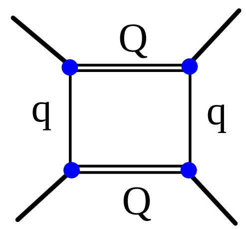




- concept of EFT: generating functional, Green's functions

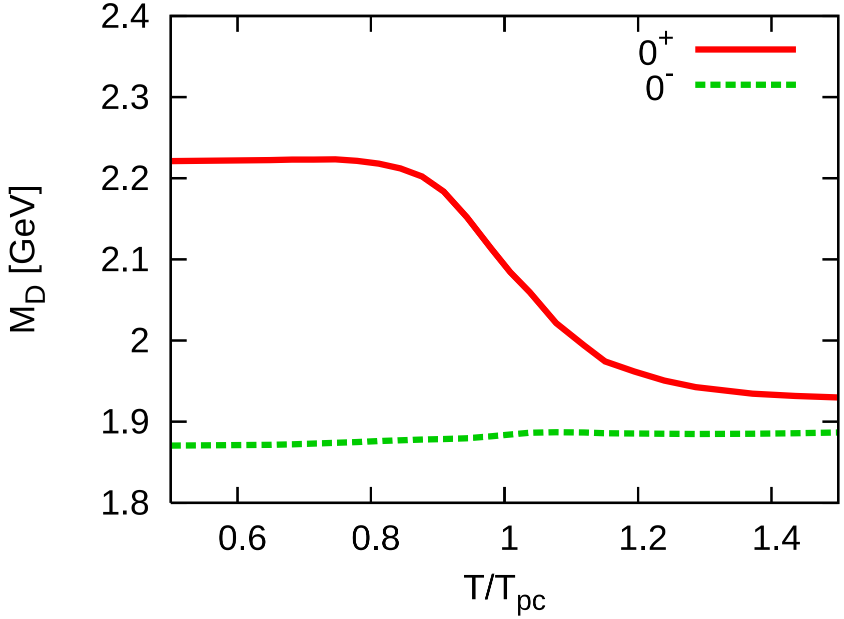
$$Z = \int \mathcal{D}q\mathcal{D}g e^{S_{\mathrm{QCD}}[q,g]} \equiv \int \mathcal{D}U e^{S_{\mathrm{eff}}[U]}$$

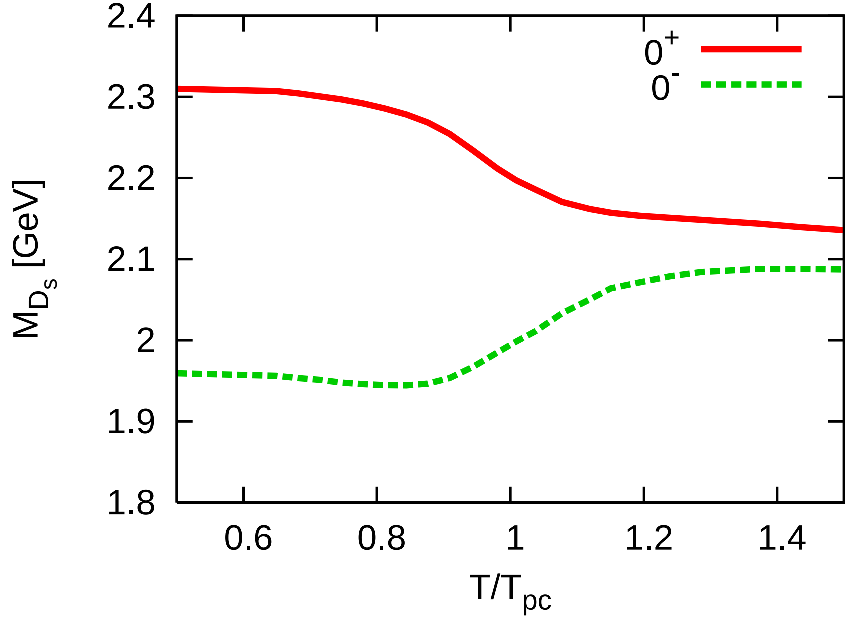




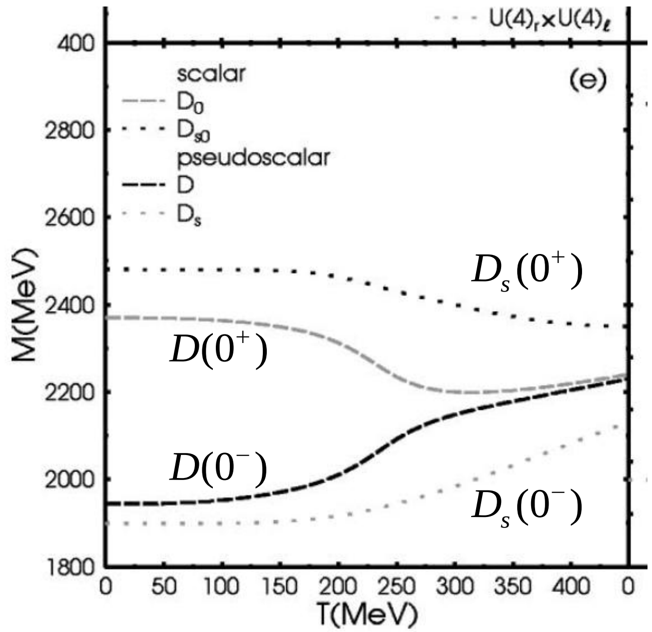
- low-energy constants: high-frequency modes integrated out
  $\Rightarrow$ in a hot/dense medium: effective couplings dep. on T/n
- L: $T_{\mathrm{pc}}^{\mathrm{lat}} = 154$ MeV $\Rightarrow$ $m_\sigma = 400$ MeV
  HL: $\sigma_{q,s}$ profiles from lattice QCD $\Rightarrow$ $g_\pi^{q,s}(T)$ etc.

In-medium charmed-meson masses



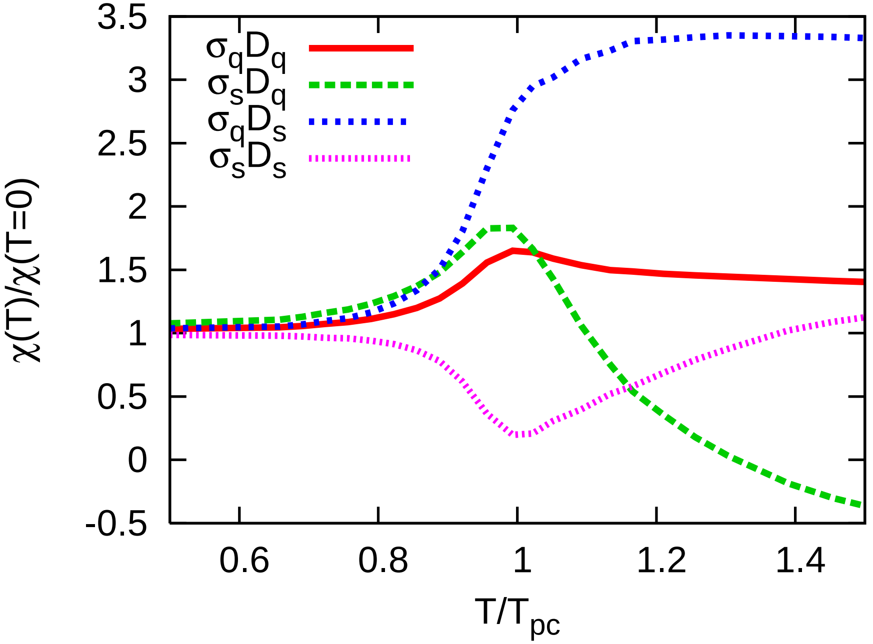


- chiral splitting at $T_{\rm pc}$: $\delta M_D \simeq \delta M_{D_s}$
  $\cdots$ *insensitive to light flavors!*
  $\Rightarrow$ heavy quark symmetry
- light mesons at $T_{\rm pc}$: $\delta M_{\pi\text{-}\sigma} \ll \delta M_{K\text{-}\kappa}$
  $\cdots$ SU(2+1) $\neq$ SU(3)
- cf. chiral SU(4): [Roder-Ruppert-Rischke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

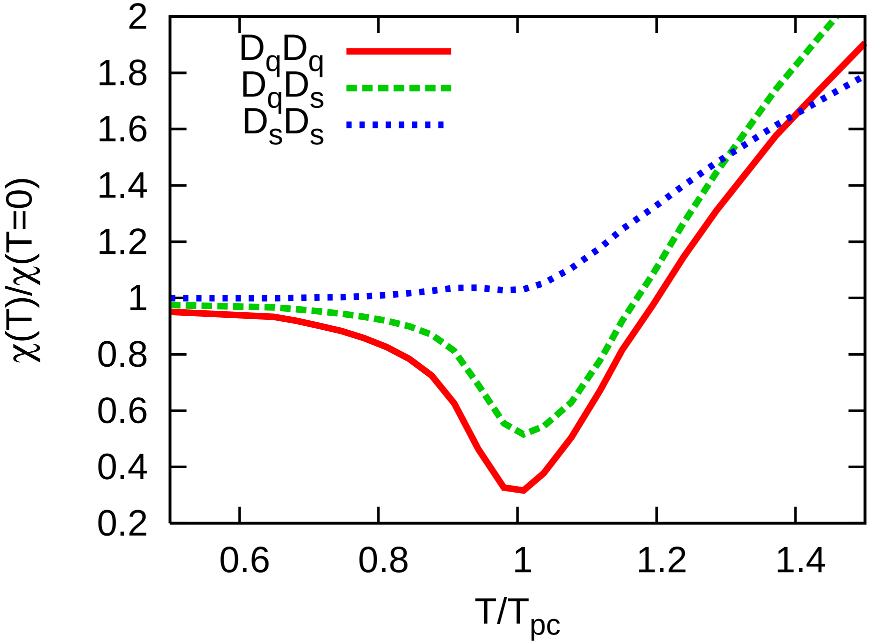


Correlations between light and heavy-light mesons [CS-Redlich ('14)]

$\sigma_{q,s}$ 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)!

Chiral restoration vs. deconfinement in QCD

- small μ: only *crossover*, $T_{\rm ch} \sim T_{\rm dec}$ from lattice studies

To which extent is the hadronic picture reliable?

- **lesson 1**: [Rapp, van Hees]
  in-medium ρ meson vs. SPS dilepton data
- **lesson 2**: [Kitazawa, Kunihiro, Nemoto]
  $N_f = 2$ NJL, mesonic collective modes above chiral crossover
  $\Rightarrow$ talk by T. Kunihiro (Thu)
- **lesson 3**: [Gattringer; Bruckmann, Gattringer, Hagen; Synatschke, Wipf, Langfeld; Gongyo, Doi, Iritani, Suganuma; Glozman, Lang, Schrock]
  LL Dirac eigenmodes, confined phase with unbroken chiral symmetry
  $\Rightarrow$ talk by T. Doi (Thu)

- large μ: ???
  quark-meson-nucleon hybrid model at $T = 0$ and large μ_B
  $\Rightarrow$ $\rho_{\rm ch}$ separated from $\rho_{\rm dec}$ [Benic- Mishustin-CS, ('15)]

Summary and Remarks

- **Synthesis of light and heavy quark dynamics**

$$\frac{m_q}{m_c} \sim \mathcal{O}(10^{-3}) \,,\ \frac{m_s}{m_c} \sim \mathcal{O}(10^{-2}) \ \ll 1$$

  – 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)!

- **Issues**

  – dissociation vs. local field approximation
  $\cdots$ chiral restored phase with confinement? — topology, lattice!

  – application to a dense system *under* strange and charm number conservation