Chiral Thermodynamics with Charm

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Introduction: why heavy flavors?

- heavy-ion exp.: transport coefficients, diffusion of D mesons, R_{AA}
- 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
  $\Rightarrow$ thermodynamics of heavy-light mesons near chiral crossover!

effective theory for light and heavy-light mesons:
how do chiral partners behave? σ-π **vs.** D_0^*-D

chiral mass splitting $M_{D_0^*} - M_D \sim 350$ MeV at $T = \mu_B = 0$
cf. "fine structure": $M_{D^-} - M_{D^+} \sim 50$ MeV at finite density

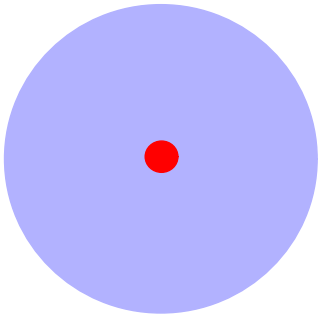
I. Chiral Structure of Heavy-light Mesons

Symmetries of QCD in the heavy quark mass limit

- flavor symmetries

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

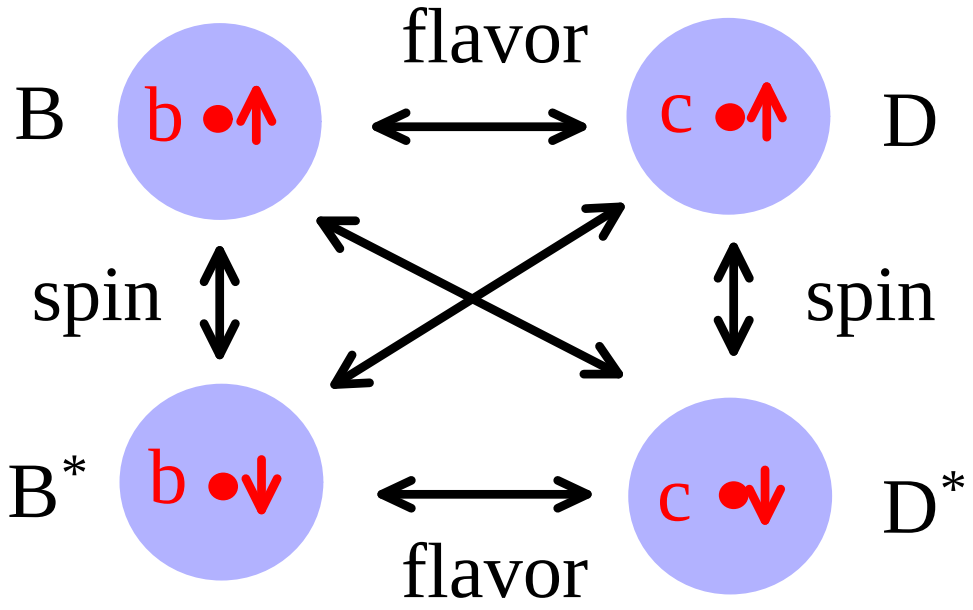
- heavy-light $(Q\bar{q})$ mesons $\quad Q$: heavy quark and q : light quark
  e.g. D mesons: $Q = c$, $q = u, d, s$



- 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

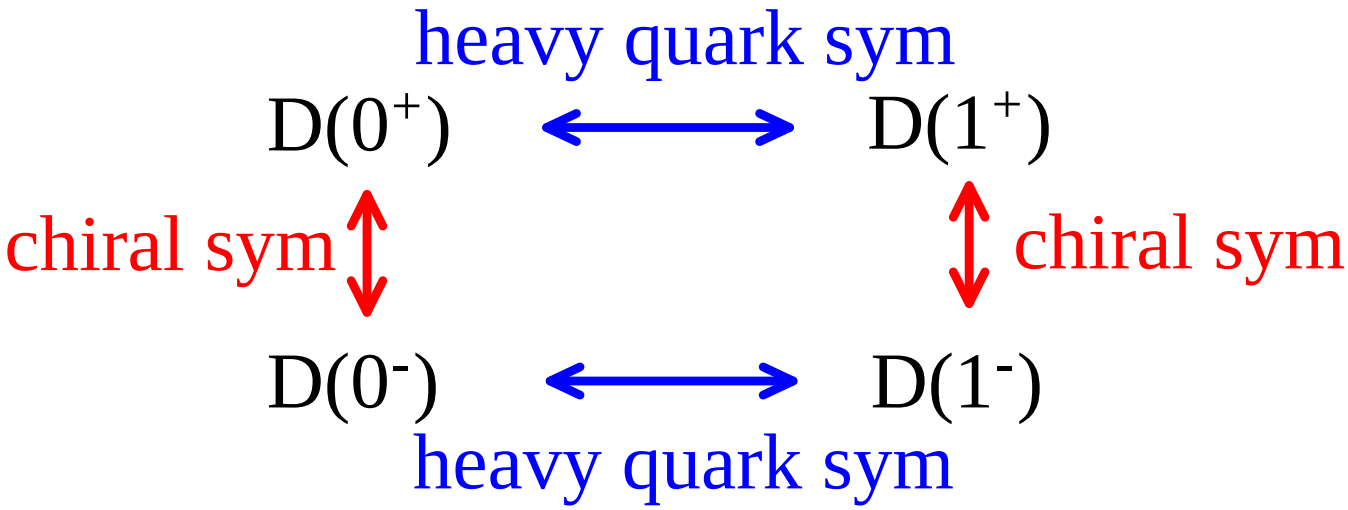
  $D_{u,d}(0^+) : 2308\,\text{MeV}$ [Belle (03)] $D_{u,d}(1^+) : 2427\,\text{MeV}$ [Belle (03)]

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

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

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

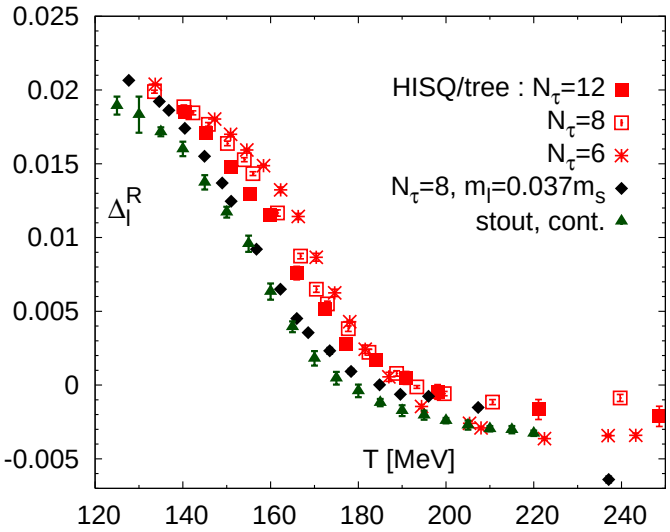
- chiral doubling [Nowak-Rho-Zahed (92); Bardeen-Hill (93)]

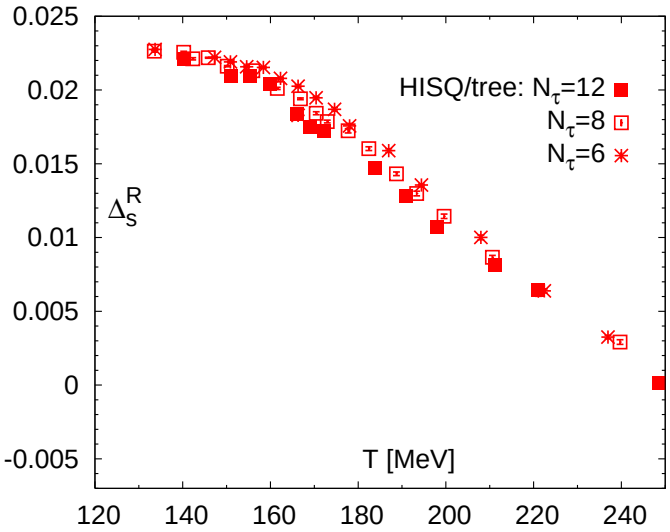


effective theory for heavy-light system based on the two relevant symmetries

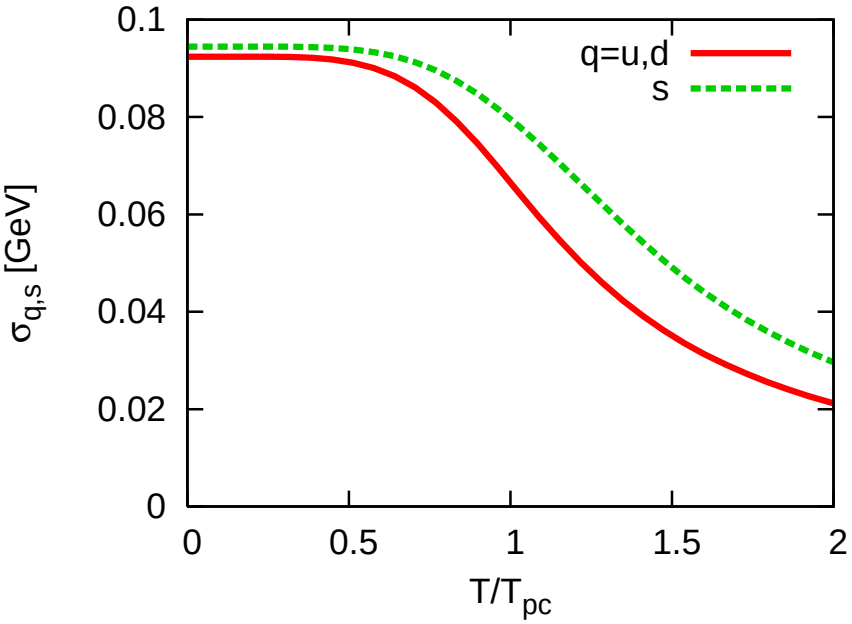
II. Thermodynamics

Chiral condensates: role of charmed-meson MF





[HotQCD Collaboration ('12)]

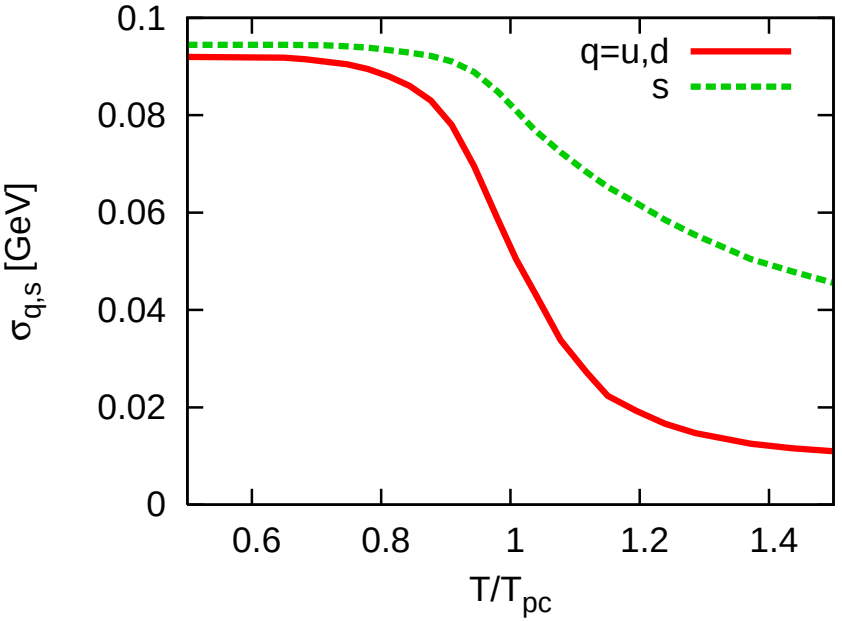


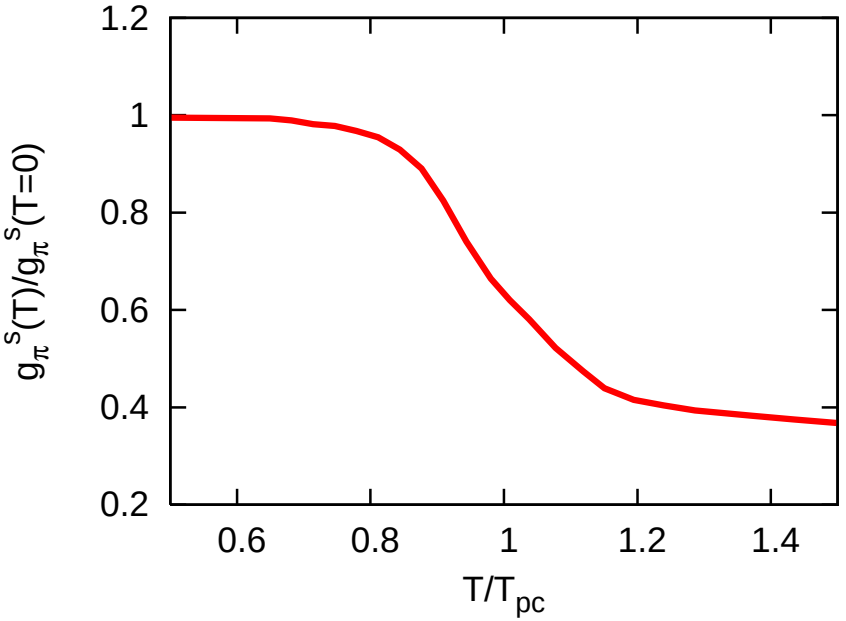
- lattice: qualitative diff. between $\langle \bar{q}q \rangle$ and $\langle \bar{s}s \rangle$ $\cdots$ SU(2+1): $T_c^{(u,d)} < T_c^{(s)}$
- chiral model: $\sigma_{q,s}$ – approx. SU(3)!?
- induced chiral sym. breaking:

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

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

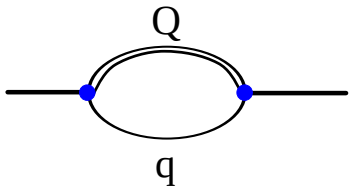
Intrinsic thermal effects

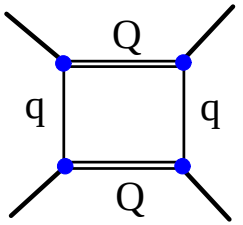




- concept of EFT: generating functional, Green's functions

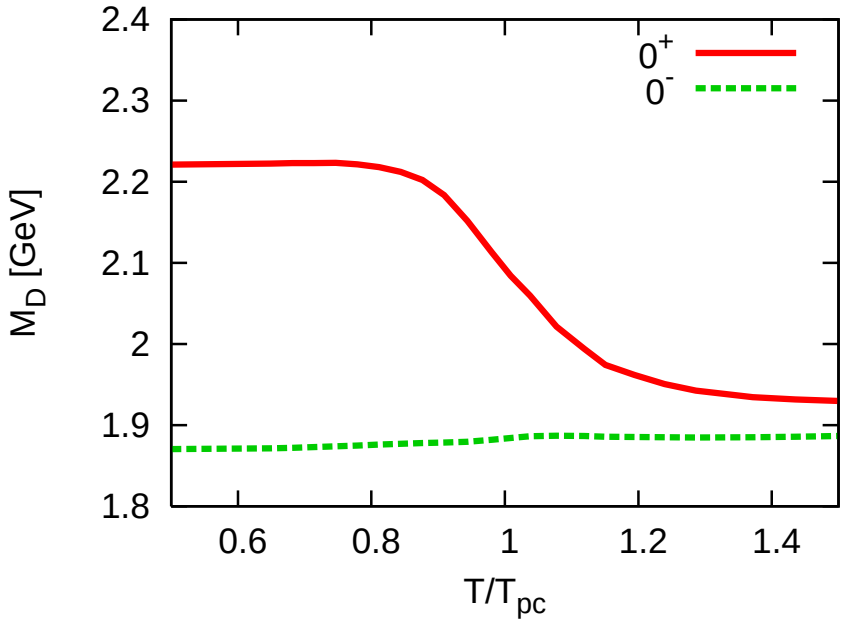
$$Z = \int \mathcal{D}q\mathcal{D}g e^{S_{\rm QCD}[q,g]} \equiv \int \mathcal{D}U e^{S_{\rm eff}[U]}$$

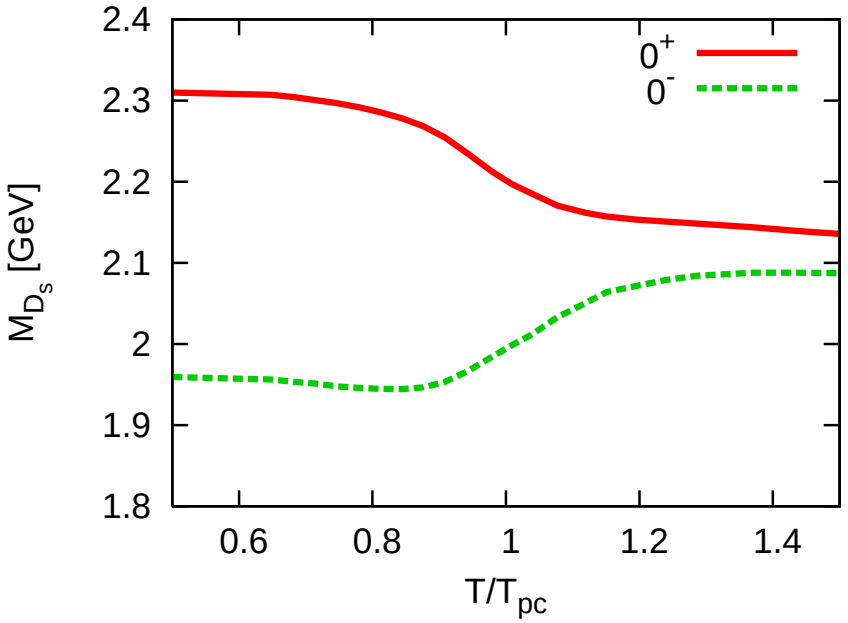




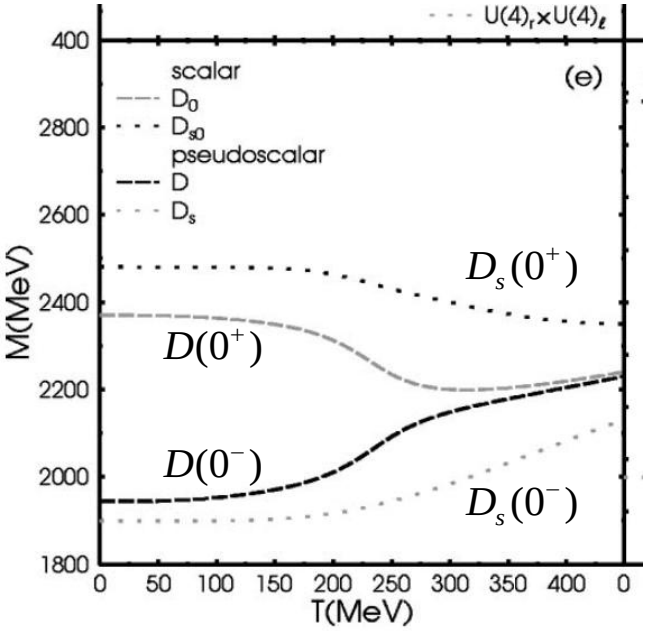
- low-energy constants: high-frequency modes integrated out
  $\Rightarrow$ in a hot/dense medium: effective couplings dep. on T/n
- L: $T_{\rm pc}^{\rm lat} = 154$ MeV $\Rightarrow$ $m_\sigma = 400$ MeV
  HL: $\sigma_{q,s}$ profiles from lattice QCD $\Rightarrow$ $g_\pi^{q,s}(T)$ etc.

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)]
  $\delta M_D \ll \delta M_{D_s}$

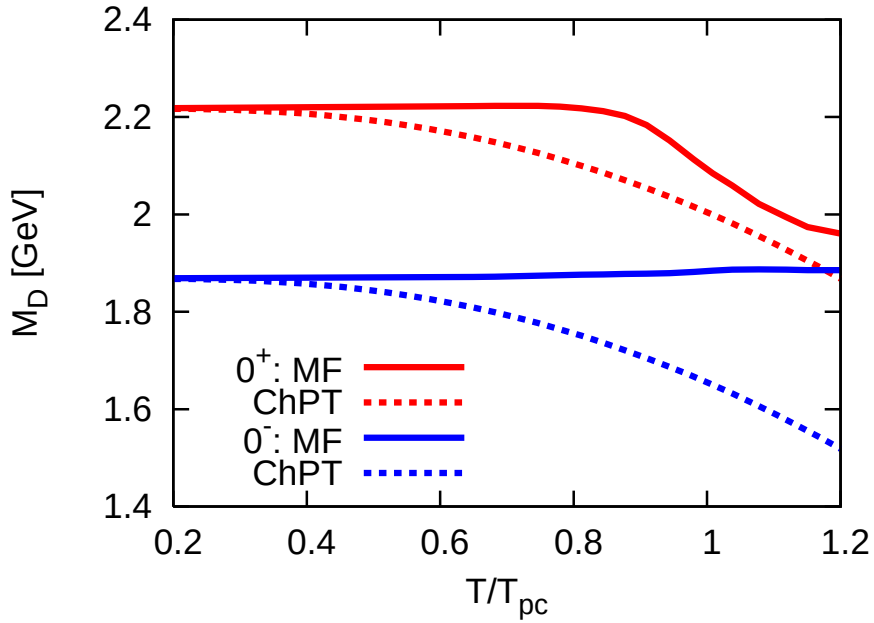


heavy quark symmetry: c & b quarks insensitive to light flavors
chiral restoration more manifest in heavy-light
than in strange light mesons!

- **Quenched HL coupling and D_s decays:** anomalous suppression

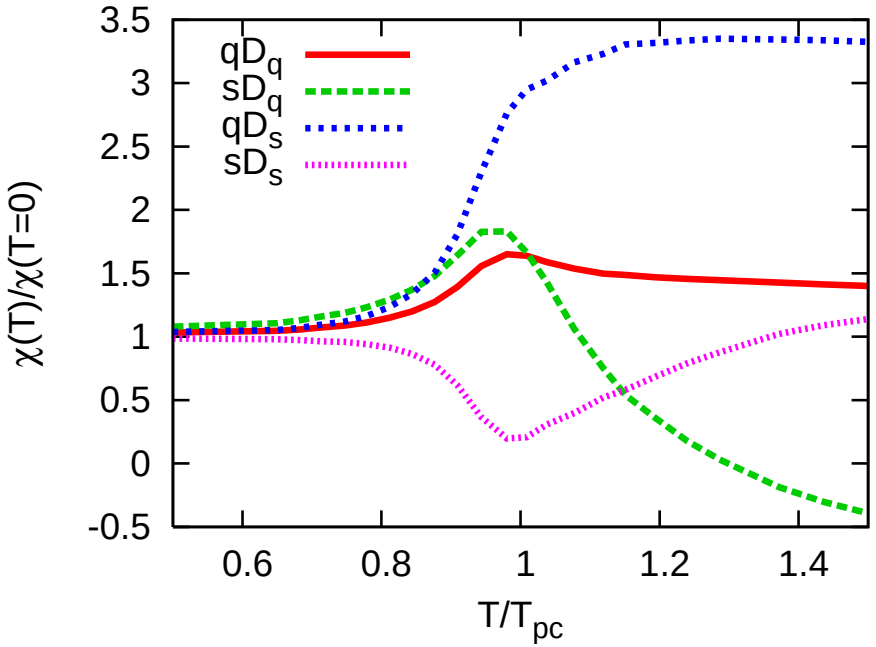
$$\Gamma(0^+/1^+ \to 0^-/1^- + \pi^0) \propto \underbrace{(g_\pi^s)^2}_{\text{quenched due to CSR}} \cdot \underbrace{\delta^2_{\pi^0\eta}}_{\text{isospin violation}}$$

- **MF model vs. 1-loop chiral perturbation theory:**
  a deviation sets in at $T \sim f_\pi$.

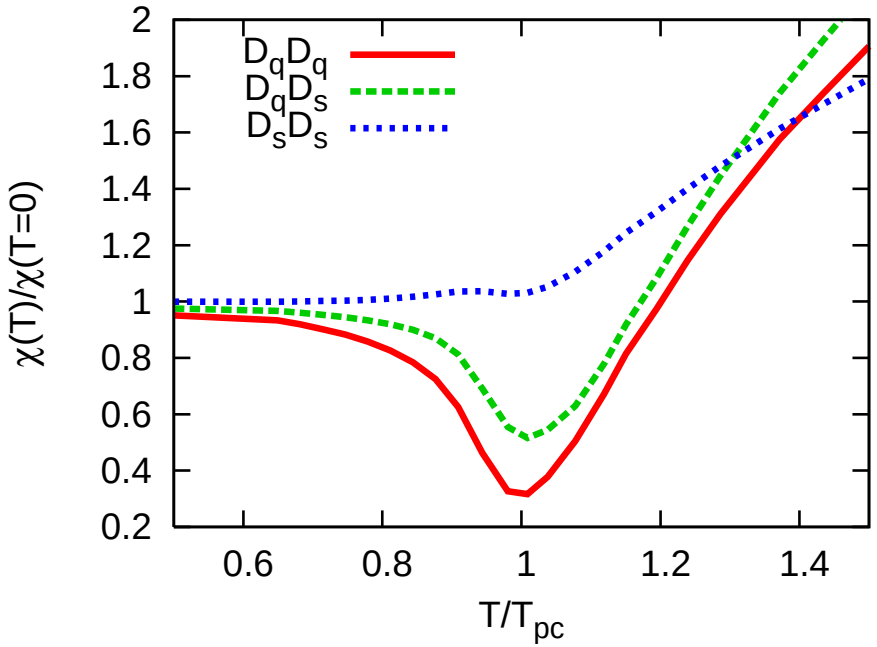


- **correlations between light and heavy-light mesons** [CS-Redlich ('14-15)]

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



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



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

$\mu_B = 0$: qualitative changes set in at $T \sim T_{\rm pc}$!

Summary and Remarks

- **Synthesis of light and heavy quark dynamics**
  - at $T_{\rm pc}$: chiral mass splittings of HL mesons insensitive to light flavors.

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

  - anomalous suppression in decay widths as a sign of CSR

$$\left(\frac{\Gamma_{D_s}}{\Gamma_D}\right)_{T\sim 0} \gg \left(\frac{\Gamma_{D_s}}{\Gamma_D}\right)_{T\sim T_{\rm pc}}$$

- **Issues**
  - dissociation vs. local field approximation
    $\cdots$ chiral restored phase with confinement?
  - fluctuations and correlations, transport properties etc.
  - application to a dense system
    * strange and charm number conservation
    * μ_B dep. of effective interactions? $\cdots$ more microscopic approach