

# Chiral Thermodynamics with Charm

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

## 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  $T_{\text{ch}}$  [Borsanyi et al. ('11)]
  - (ii) charmed mesons deconfined together with light mesons [Basavov et al. ('14)]
- correlations between light and heavy-flavor physics  
⇒ thermodynamics of heavy-light mesons near chiral crossover!

**effective theory for light and heavy-light mesons:  
how do chiral partners behave?  $\sigma$ - $\pi$  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

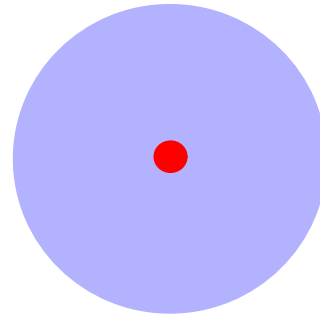
# Symmetries of QCD in the heavy quark mass limit

- flavor symmetries

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:  $Q = c, q = u, d, s$

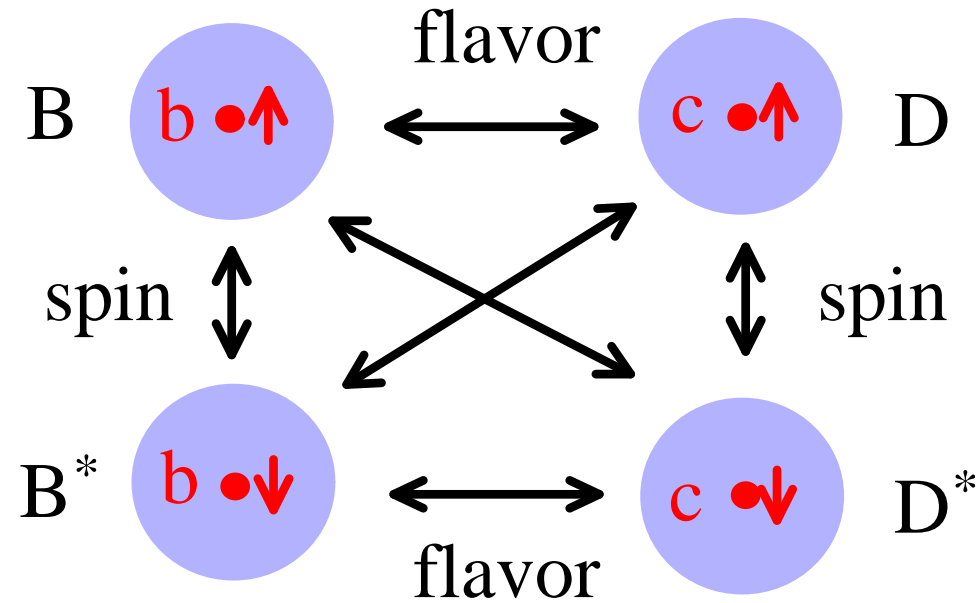


- physical picture ( $m_Q \rightarrow \infty$ )

- **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:**

$$m_{D^*} - m_D = 142 \text{ MeV}, \quad m_{B^*} - m_B = 46 \text{ MeV} \quad \ll \Lambda_{\text{QCD}}$$

...  $1/m_Q$  corrections

$$m_{D_s} - m_{D_d} = 100 \text{ MeV}, \quad m_{B_s} - m_{B_d} = 90 \text{ MeV} \quad \ll \Lambda_{\text{QCD}}$$

...  $m_q$  corrections

## Role of light flavor (chiral) symmetry

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

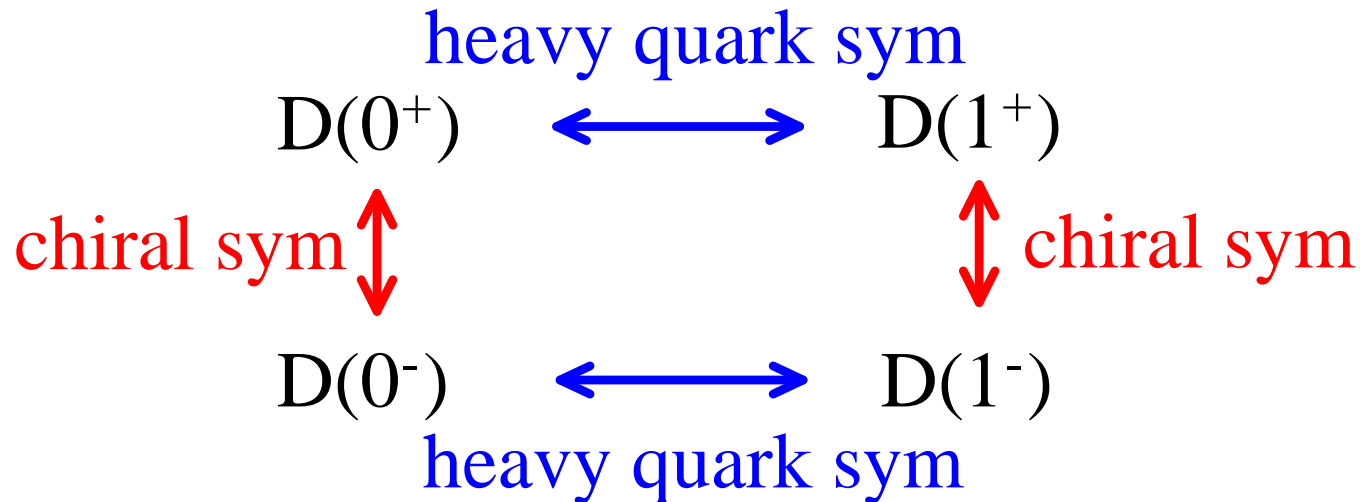
$$D_{u,d}(0^+) : 2308 \text{ MeV} \quad [\text{Belle (03)}] \quad D_{u,d}(1^+) : 2427 \text{ MeV} \quad [\text{Belle (03)}]$$

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

- 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!

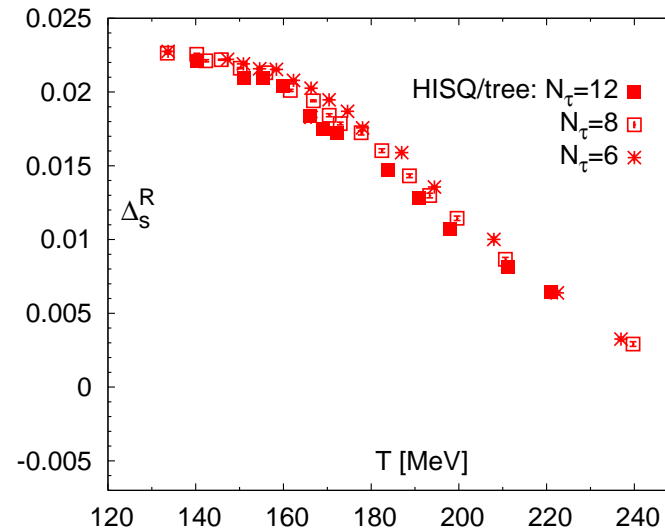
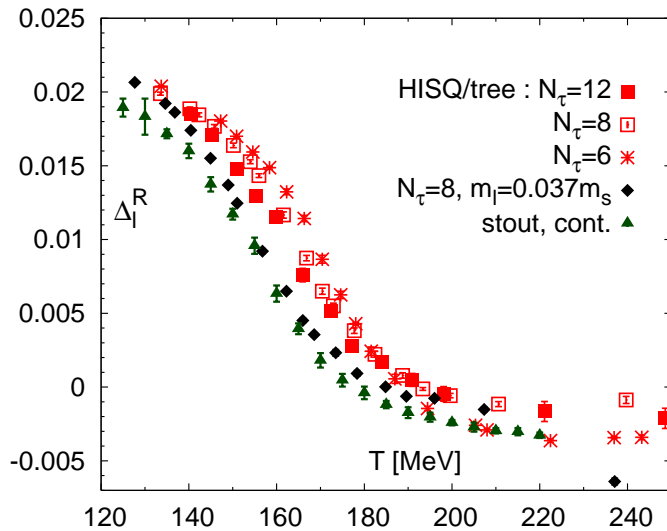
- chiral doubling [Nowak-Rho-Zahed (92); Bardeen-Hill (93)]



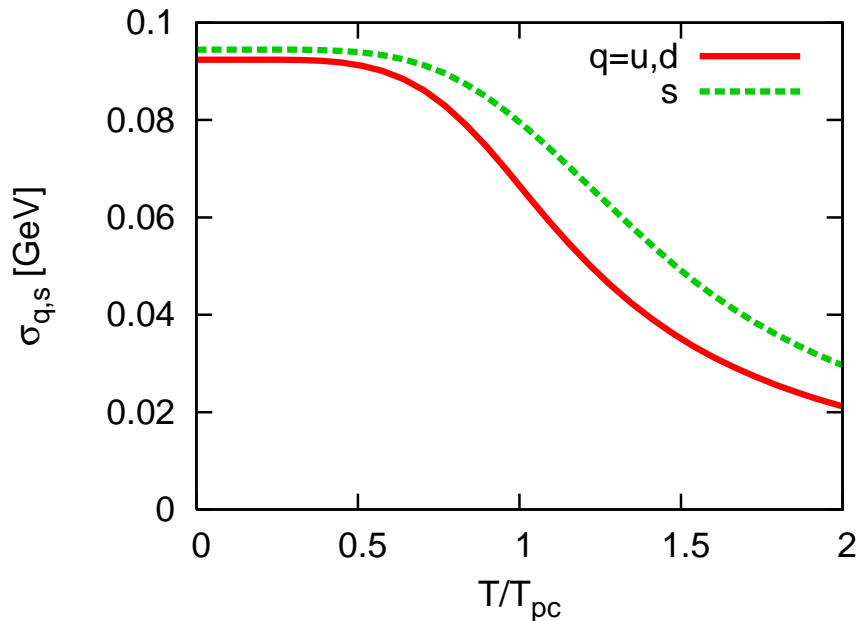
effective theory for heavy-light system based on the two relevant symmetries

## II. Thermodynamics

# Chiral condensates: role of charmed-meson MF



[HotQCD Collaboration ('12)]



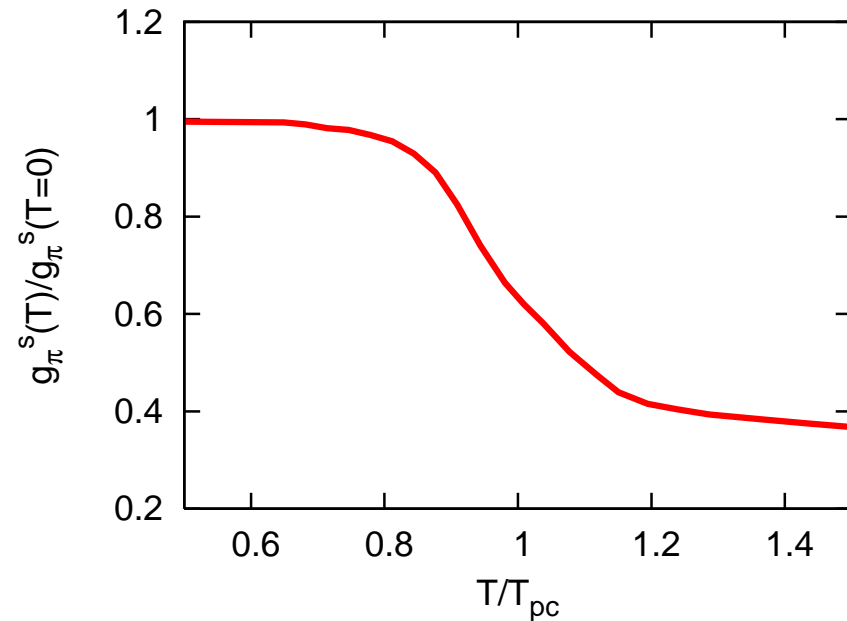
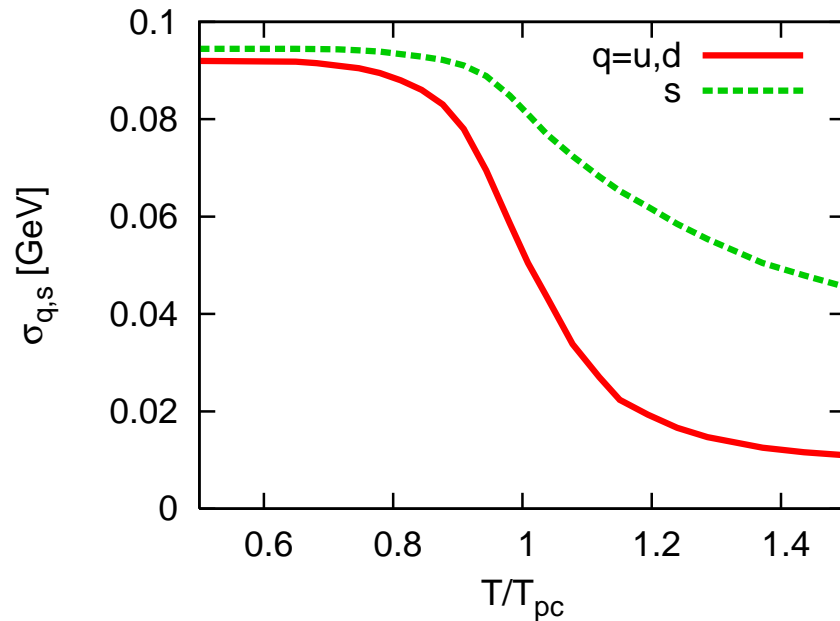
- lattice: qualitative diff. between  $\langle \bar{q}q \rangle$  and  $\langle \bar{s}s \rangle \dots$  **SU(2+1)**:  $T_c^{(u,d)} < T_c^{(s)}$
- chiral model:  $\sigma_{q,s}$  – approx. **SU(3)!**?
- induced chiral sym. breaking:

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

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

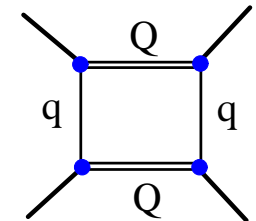
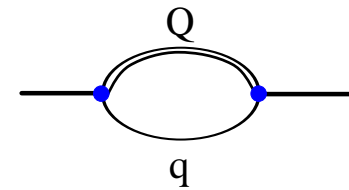


# Intrinsic thermal effects



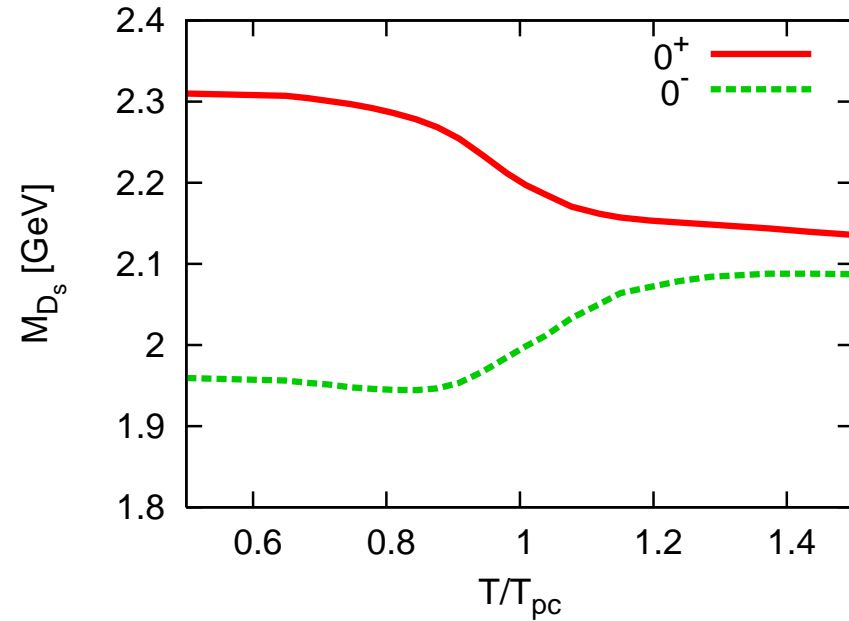
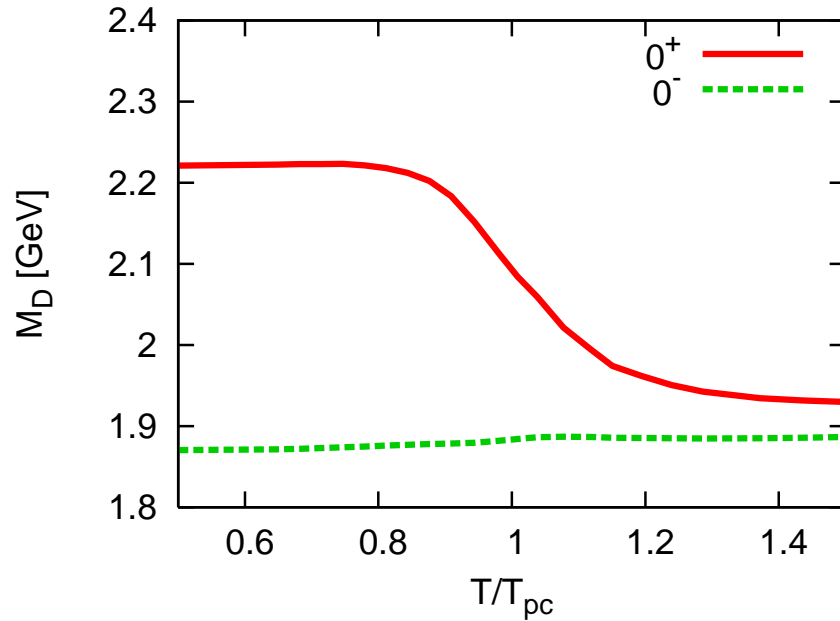
- concept of EFT: generating functional, Green's functions

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

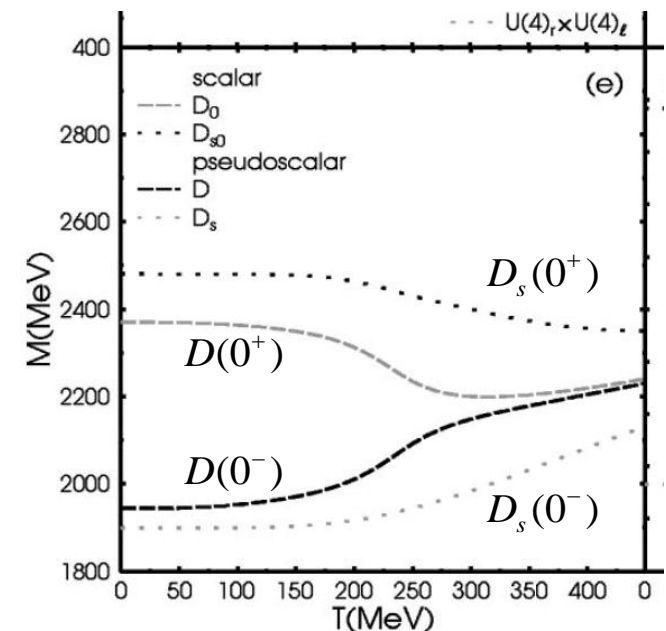


- low-energy constants: high-frequency modes integrated out  
 $\Rightarrow$  in a hot/dense medium: effective couplings dep. on  $T/n$
- L:  $T_{pc}^{\text{lat}} = 154 \text{ MeV} \Rightarrow m_{\sigma} = 400 \text{ MeV}$   
 HL:  $\sigma_{q,s}$  profiles from lattice QCD  $\Rightarrow g_{\pi}^{q,s}(T)$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



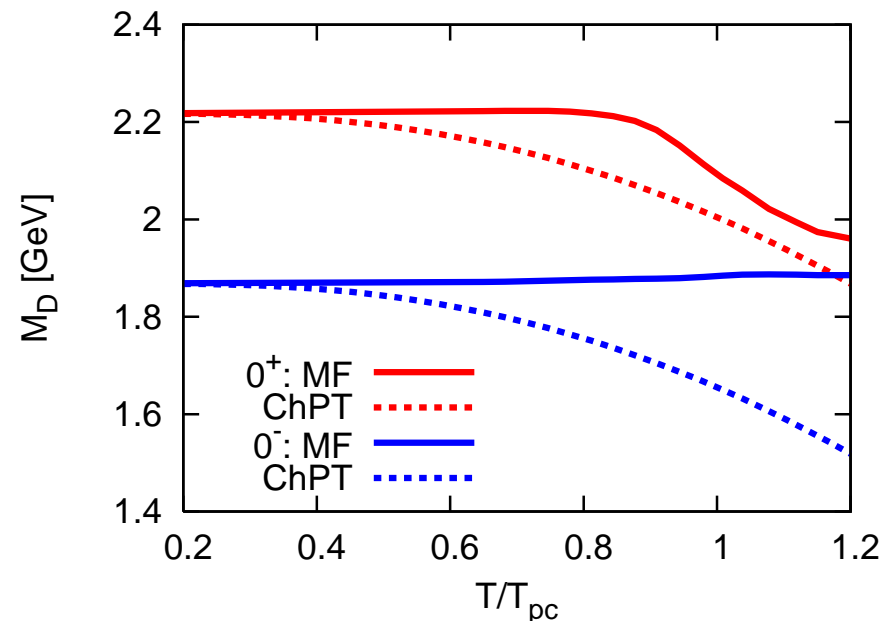
heavy quark symmetry: c & b quarks insensitive to light flavors  
**chiral restoration more manifest in heavy-light  
 than in strange light mesons!**

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

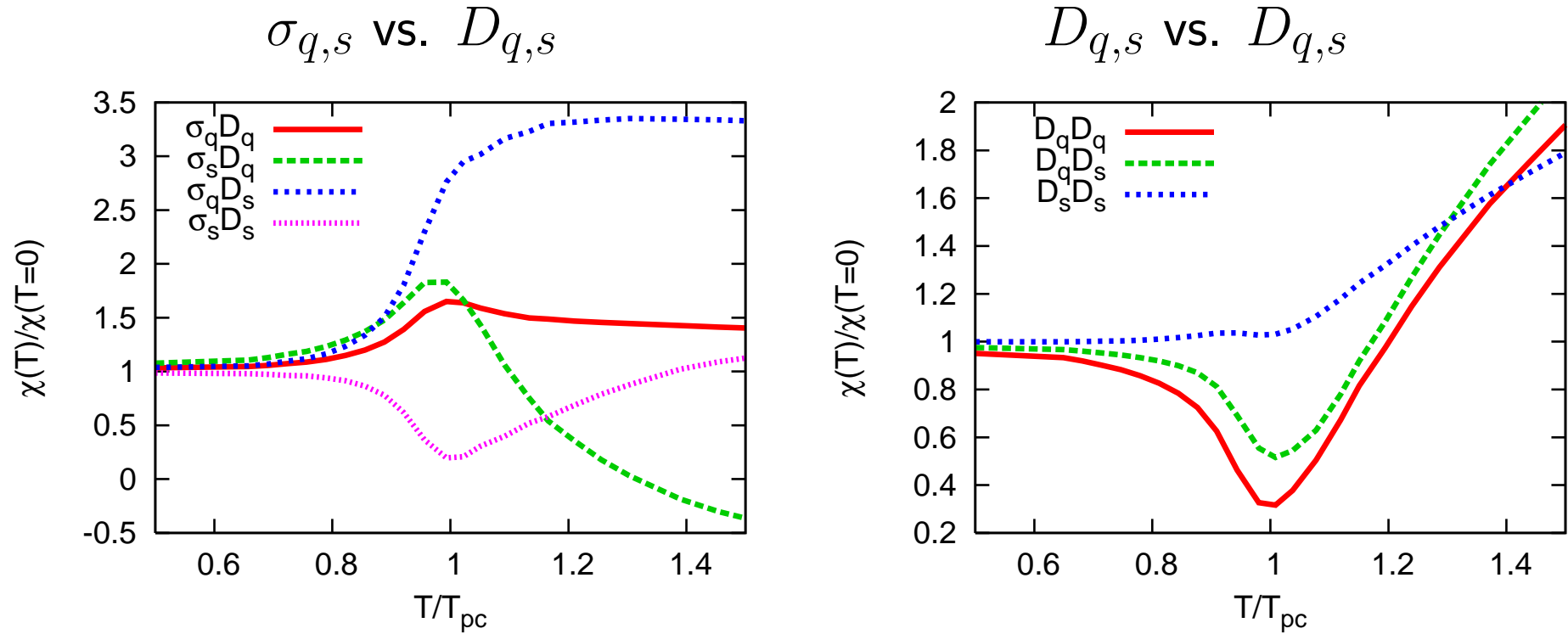
$$\Gamma(0^+/1^+ \rightarrow 0^-/1^- + \pi^0) \propto \underbrace{(g_\pi^s)^2}_{\text{quenched due to CSR}} \cdot \underbrace{\delta_{\pi^0\eta}^2}_{\text{isospin violation}}$$

- **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)]



$$\hat{\chi}_{\sigma D} = -\hat{\chi}_{\text{ch}} \hat{C}_{\text{HL}} \hat{\chi}_D, \quad \hat{\chi}_{D\sigma} = -\hat{\chi}_D \hat{C}_{\text{HL}} \hat{\chi}_{\text{ch}},$$

$$\hat{\chi}_{DD} = \hat{C}_D - \hat{C}_{\text{HL}} \hat{\chi}_{\text{ch}} \hat{C}_{\text{HL}} \equiv \hat{\chi}_D.$$

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

## Summary and Remarks

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

- 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 in decay widths as a sign of CSR

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

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

- **Issues**

- dissociation vs. local field approximation

- $\dots$  chiral restored phase with confinement? — topology, lattice!

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