Chiral Thermodynamics with Charm

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ref. arXiv:1409.3420 [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 $T_{\rm ch}$ [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

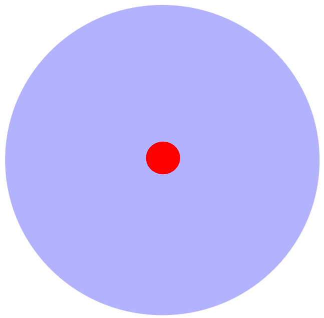
I. Chiral Structure of Heavy-light Mesons

Symmetries of QCD in the heavy quark mass limit

- flavor symmetries

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

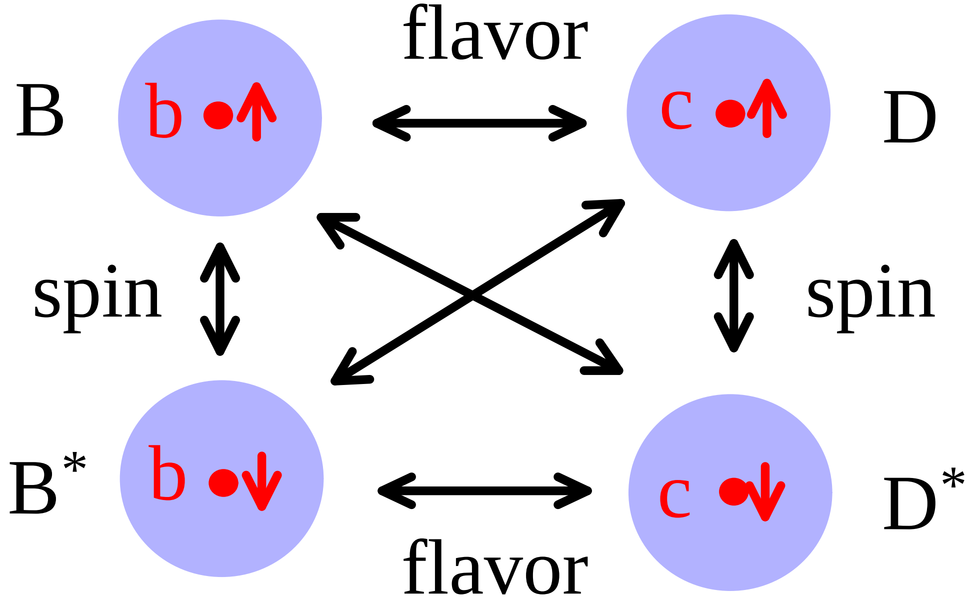
- heavy-light ($Q\bar{q}$) mesons Q : heavy quark and q : light quark
  e.g. D mesons: $Q = c$, $q = u, d, s$



- 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**: [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**:

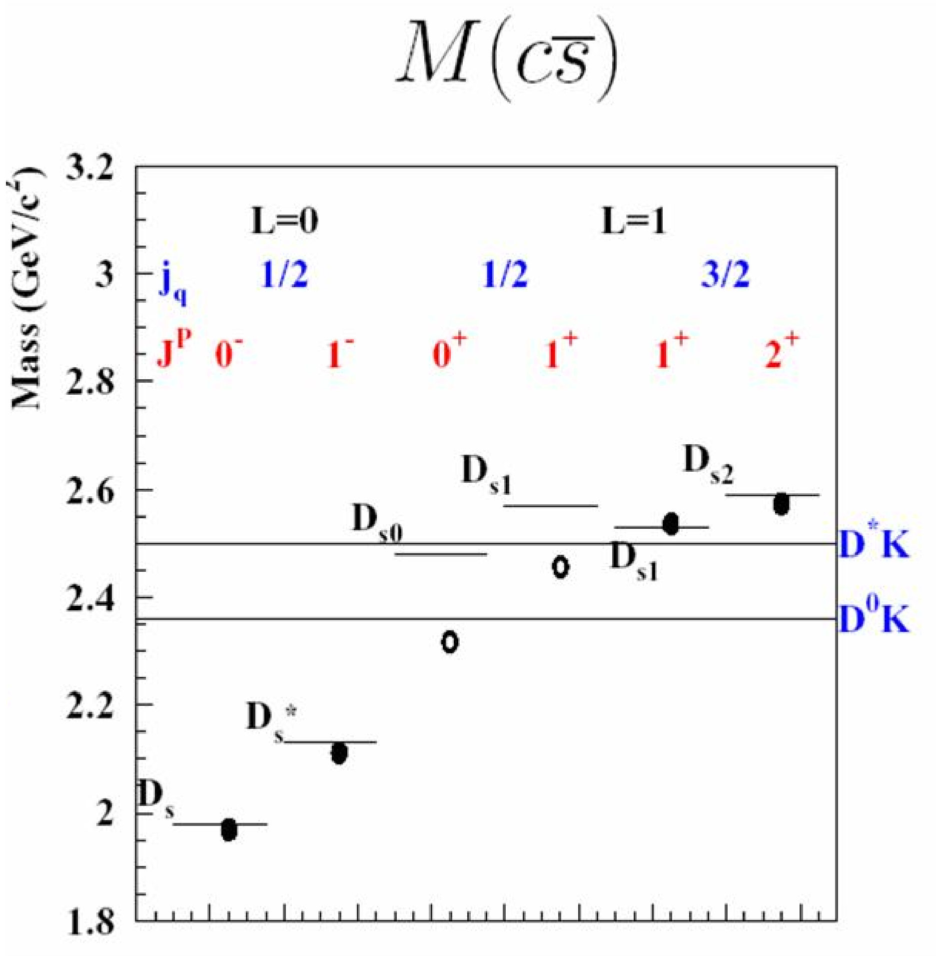
$$D_{u,d}(0^+) : 2308\,\text{MeV} \quad \text{[Belle (03)]}$$
$$D_{u,d}(1^+) : 2427\,\text{MeV} \quad \text{[Belle (03)]}$$
$$D_s(0^+) : 2317\,\text{MeV} \quad \text{[Babar (03)]}$$
$$D_s(1^+) : 2460\,\text{MeV} \quad \text{[CLEO (03)]}$$

- spin doublets: $D(0^+)$-$D(1^+)$
- mass difference:

$$m(0^+, 1^+) - m(0^-, 1^-) = 300 - 400\,\text{MeV} \sim \Lambda_{\text{QCD}}\,.$$

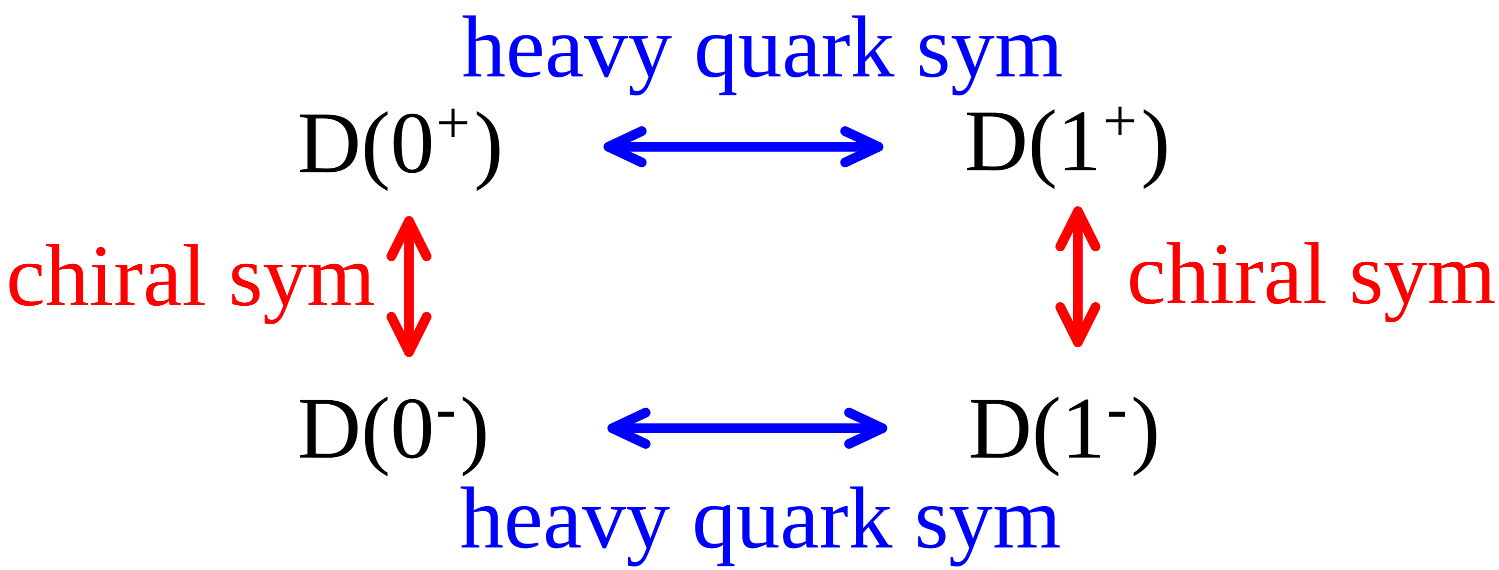
Why is Δm so small?

• potential model for D mesons   cf. hydrogen atom



what is missing? — chiral symmetry!!

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



chiral partners:

$$m(0^+) - m(0^-)\,, \quad m(1^+) - m(1^-) \;\propto \langle \bar{q}q \rangle \sim m_{\rm const}$$

- 4-fermi (qqQQ) theory: heavy modes integrated out
  $\Rightarrow$ an effective Lagrangian for HL mesons

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

- confirmed by the measurements in 2003!

II. Chiral Lagrangian with Heavy Quark Symmetry

Constructing effective Lagrangian

- heavy fermion reduction

$$p_Q^\mu = m_Q v^\mu + k^\mu \,, \quad k^\mu \sim \mathcal{O}(\Lambda_{\mathrm{QCD}}) \,.$$

4-velocity in the rest frame of Q: $v^\mu = (1, \vec{0})$

- heavy-light meson fields $H : (0^-, 1^-)$, $G : (0^+, 1^+)$

$$H = \frac{1+\not{v}}{2}\left[P_\mu \gamma^\mu + iP\gamma_5\right] \,, \quad G = \frac{1+\not{v}}{2}\left[-iQ_\mu \gamma^\mu \gamma_5 + Q\right] \,.$$

$\Leftrightarrow$ chiral eigenstates

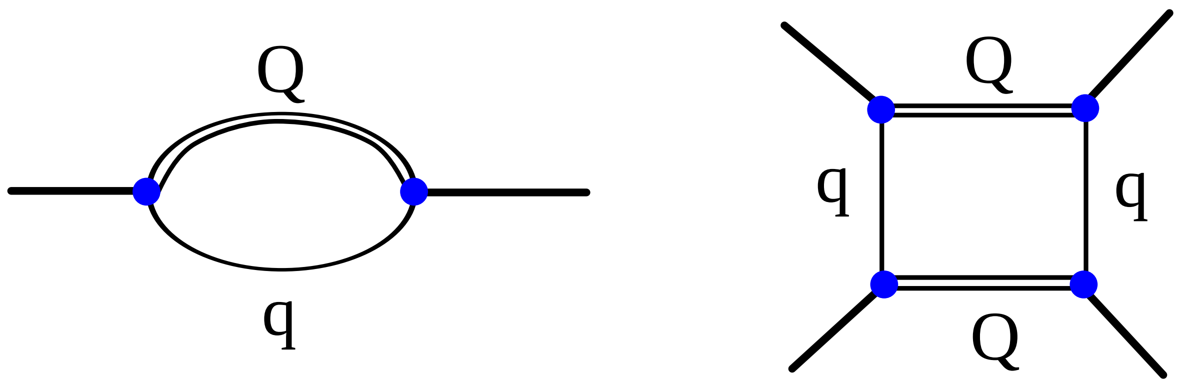
$$\mathcal{H}_{L,R} = \frac{1}{\sqrt{2}}(G \pm iH\gamma_5) \to S\mathcal{H}_{L,R} g_{L,R}^\dagger \,,$$

with

$$g_{L,R} \in SU(3)_{L,R} \,, \quad S \in SU(2)_{Q=c} \,.$$

- HL Lagrangian w/ chiral SU(3) symmetry

$$\mathcal{L}_{\mathrm{HL}} = \frac{1}{2}\mathrm{Tr}\left[-\bar{H}iv\cdot\partial H + \bar{G}iv\cdot\partial G\right] - V_{\mathrm{HL}}\,,$$
$$V_{\mathrm{HL}} = V_{\mathrm{HL}}^{(2)}\left(\mathcal{H}^2,\Sigma\right) + V_{\mathrm{HL}}^{(4)}\left(\mathcal{H}^4,\Sigma\right) + V_{\mathrm{HL}}^{\mathrm{exp}}\,.$$
$$\Rightarrow\ \mathcal{L} = \mathcal{L}_{\mathrm{L}} + \mathcal{L}_{\mathrm{HL}}\,.$$



- mean field approximation *plus* isospin-inv.

$$\Sigma^a \to \sigma^0,\sigma^8 \to \sigma_q,\sigma_s\,,\quad H\to 0\,,\quad G \to \frac{1+\not{v}}{2}D\,,$$
$$D = (D_u, D_d, D_s) = (D_q, D_q, D_s)\,.$$

- 6 parameters $\Leftarrow m_c\,,M_D(0^-)\,,M_{D_s}(0^-)\,,M_{D_s}(0^+)\,,f_\pi\,,f_K$ on PDG

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

- thermodynamic potential and EoM

$$\Omega=\Omega_{f=u,d,s}+V_{\rm L}+V_{\rm HL}\,,\qquad \frac{\partial\Omega}{\partial\sigma_q}=\frac{\partial\Omega}{\partial\sigma_s}=\frac{\partial\Omega}{\partial D_q}=\frac{\partial\Omega}{\partial D_s}=0\,.$$

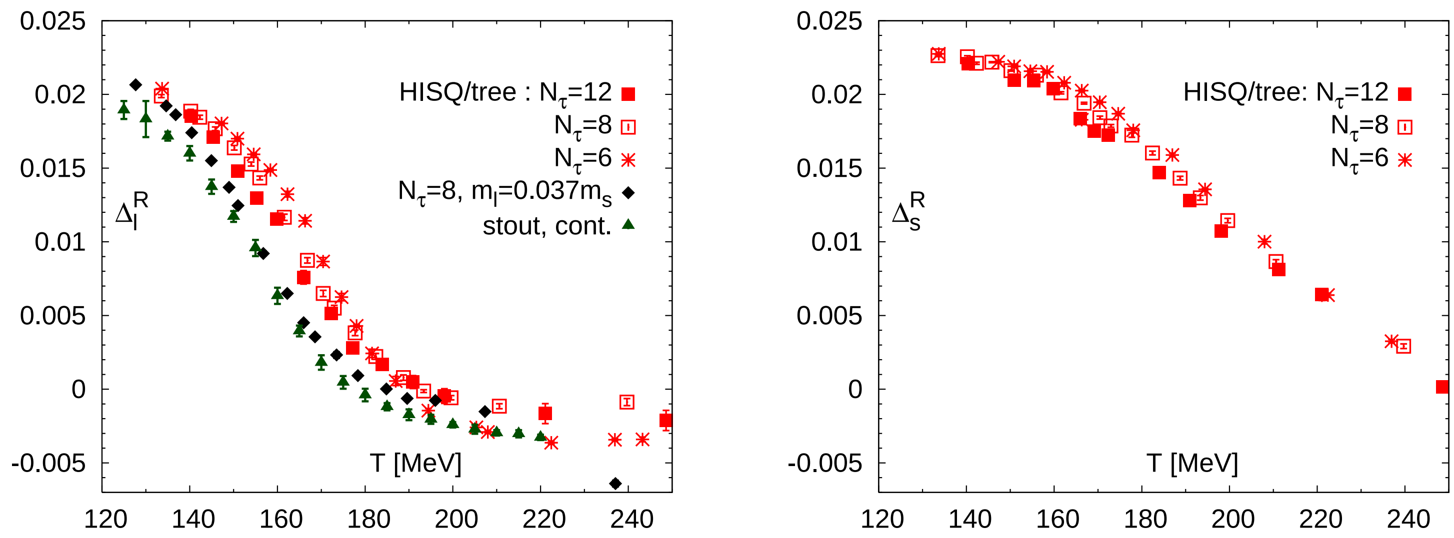
- **chiral SU(3) breaking at $T=0$**
  - light: $m_K-m_\pi=358$ MeV
  - HL (0^-): $m_{D_s}-m_D=100$ MeV from PDG
    HL (0^+): $m_{D_s}-m_D=25$ MeV [QCDSR: Narison (05)]
  - PDG: $m_{D_s}=2317.8\pm0.6$ MeV, $m_D=2318\pm29$ MeV

much smaller SU(3) breaking in HL sector!

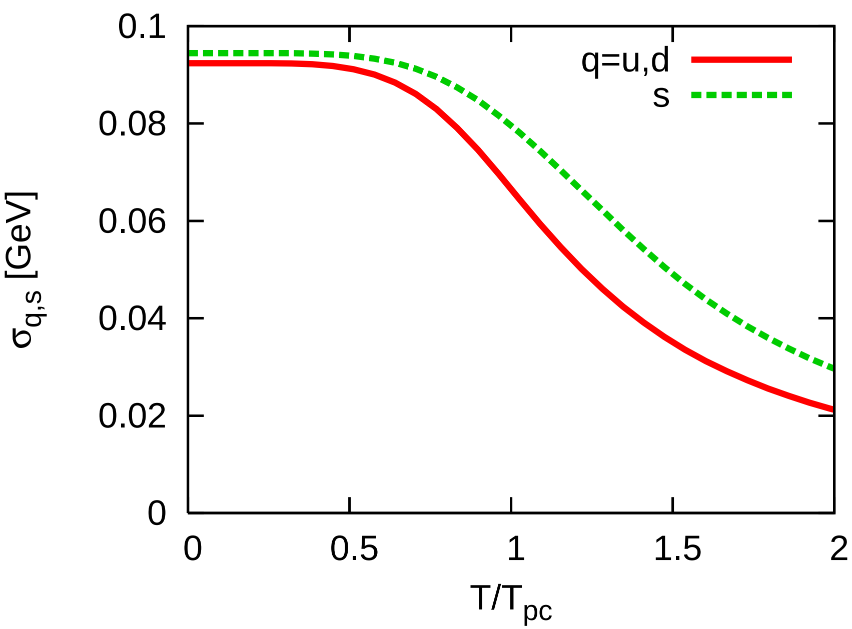
$\Rightarrow$ non-trivial modification of $\langle\sigma_{q,s}\rangle$ at finite temperature

III. Thermodynamics

Chiral condensates: role of charmed-meson MF



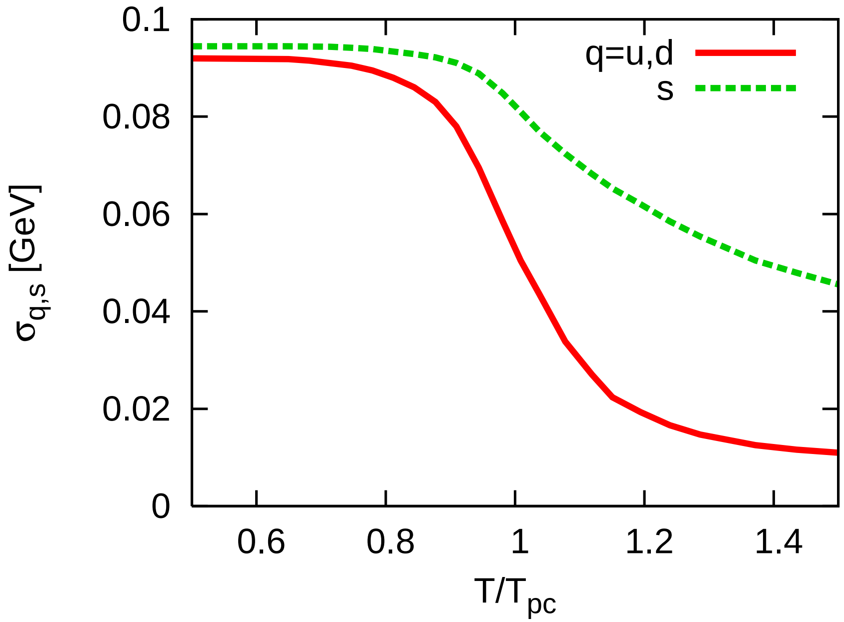
[HotQCD Collaboration ('12)]

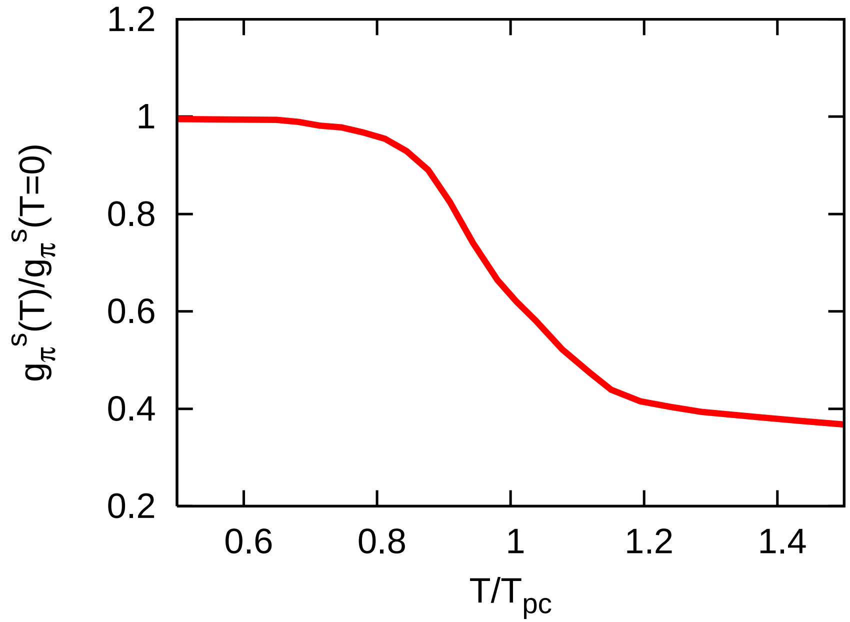


- lattice: qualitative diff. between $\langle \bar{q}q \rangle$ and $\langle \bar{s}s \rangle$ $\cdots$ SU(2+1): $T_c^{(u,d)} < T_c^{(s)}$
- chiral model: $\sigma_{q,s}$ $\cdots$ approx. SU(3)
- induced chiral sym. breaking:

$$
\begin{aligned}
h_q^* &= h_q - D_q^2 \left(\frac{1}{2} g_\pi^q + 2 k_q D_q^2 \right) , \\
h_s^* &= h_s - \frac{1}{\sqrt{2}} D_s^2 \left(\frac{1}{2} g_\pi^s + 2 k_s D_s^2 \right) .
\end{aligned}
$$

Intrinsic thermal effects



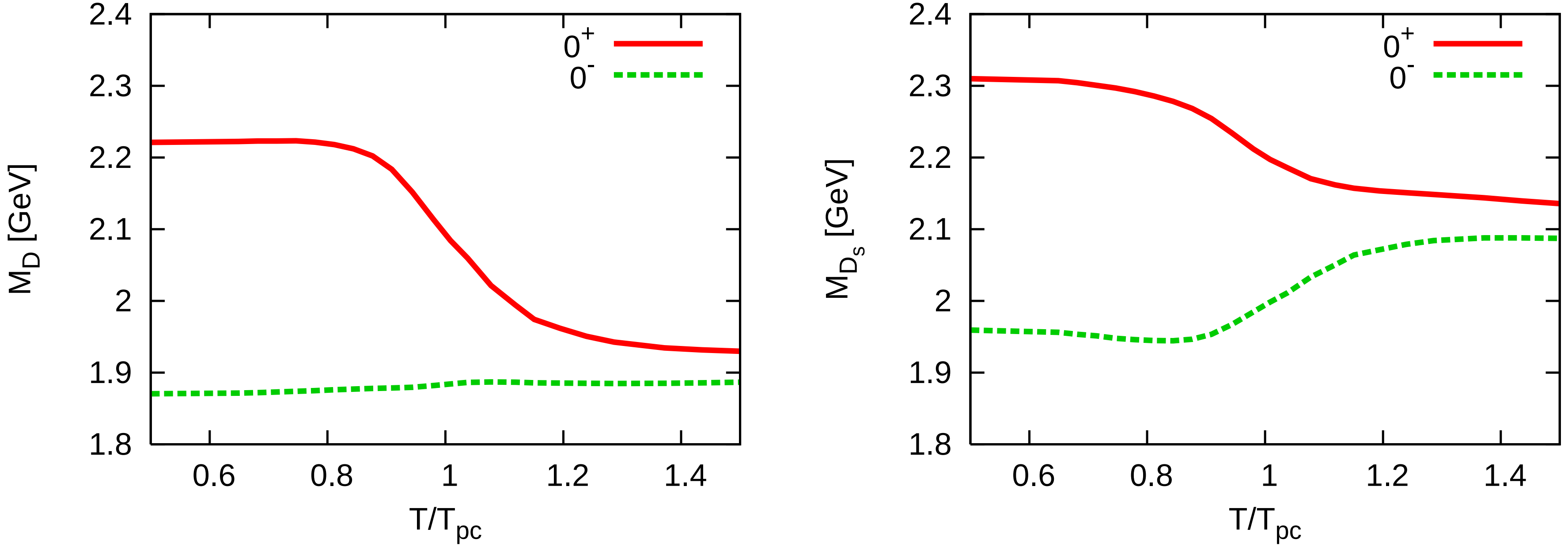


- concept of EFT: generating functional, Green's functions

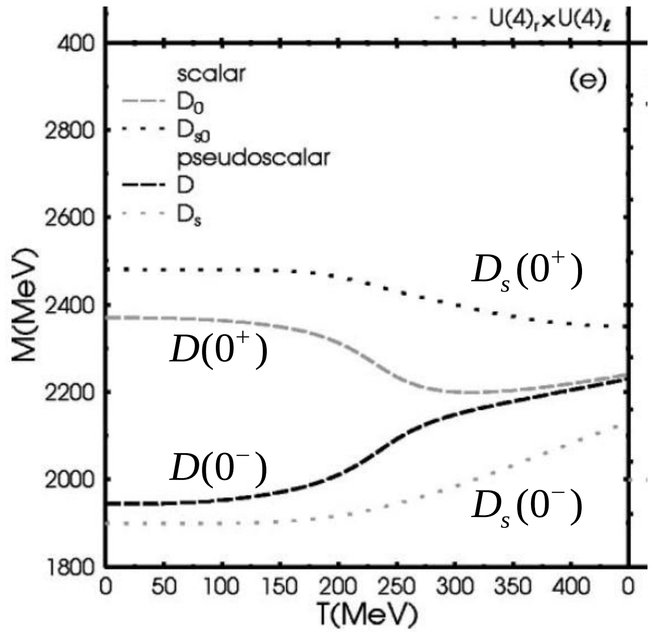
$$Z = \int \mathcal{D}q\mathcal{D}g e^{S_{\mathrm{QCD}}[q,g]} \equiv \int \mathcal{D}U e^{S_{\mathrm{eff}}[U]}$$

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

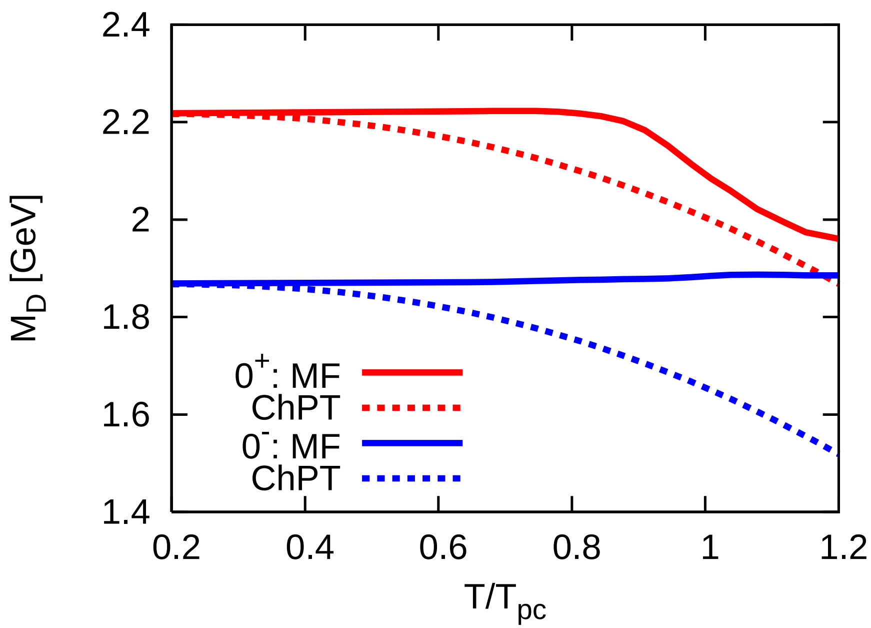


heavy quark symmetry: c & b quarks blind to light flavors
chiral restoration more manifest in heavy-light
than in strange light mesons!

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

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

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



Summary and Remarks

- **Synthesis of light and heavy quark dynamics**
  - formulated at $\mu_B = 0$, consistent with lattice QCD around $T_{\rm pc}$
  - in-medium couplings between HL and L mesons introduced: $g_\pi(T)$
  - at $T_{\rm pc}$: chiral mass splittings of HL mesons insensitive to light flavors.

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

- **Issues**
  - fluctuations and correlations, transport properties etc.
  - application to a dense system
    - strange and charm number conservation
    - μ_B dependence of effective interactions? $\cdots$ more microscopic model