Flavor Correlations and the QCD Phase Structure

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[2] C.S. and K. Redlich, Phys. Rev. D **91**, no. 7, 074021 (2015).
[3] S. Benic, et al., Phys. Rev. D **91**, no. 12, 125034 (2015).
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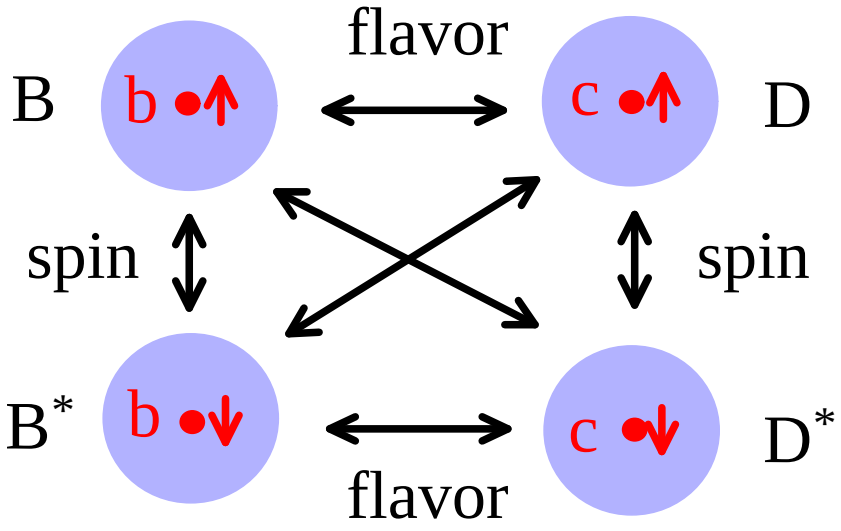
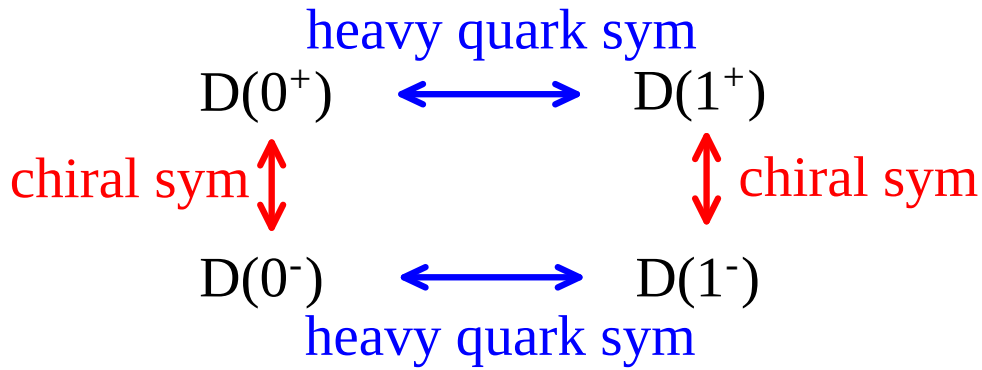
I. Heavy-light flavor correlations

Fine splitting of haevy-light meson masses





[Nowak, Rho, Zahed ('93); Bardeen, Hill ('94)]

- flavor symmetries

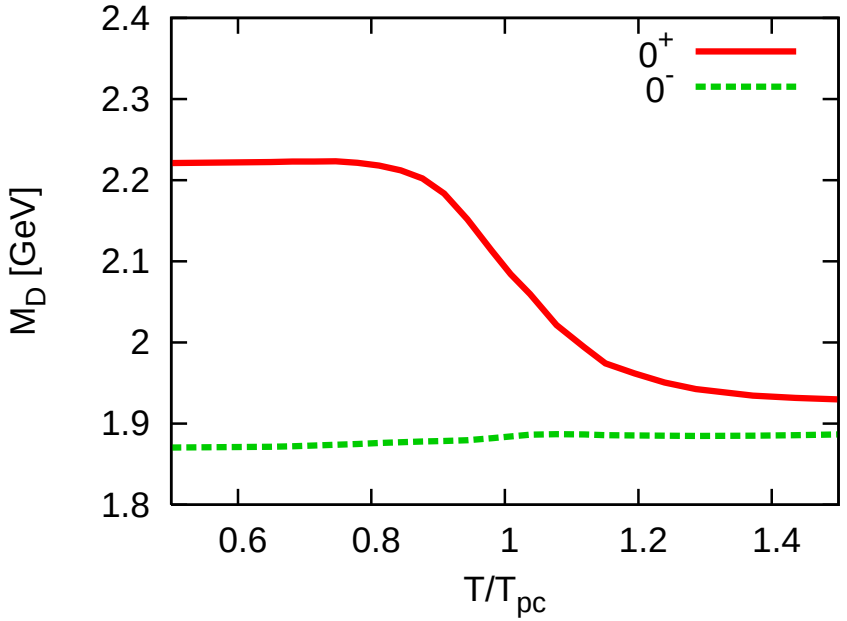
$$\text{chiral symmetry}: \quad m_{u,d}/\Lambda_{\rm QCD} \ll 1\,, \quad m_s/\Lambda_{\rm QCD} < 1\,.$$
$$\text{heavy quark symmetry}: \quad \Lambda_{\rm QCD}/m_{c,b} \ll 1\,.$$

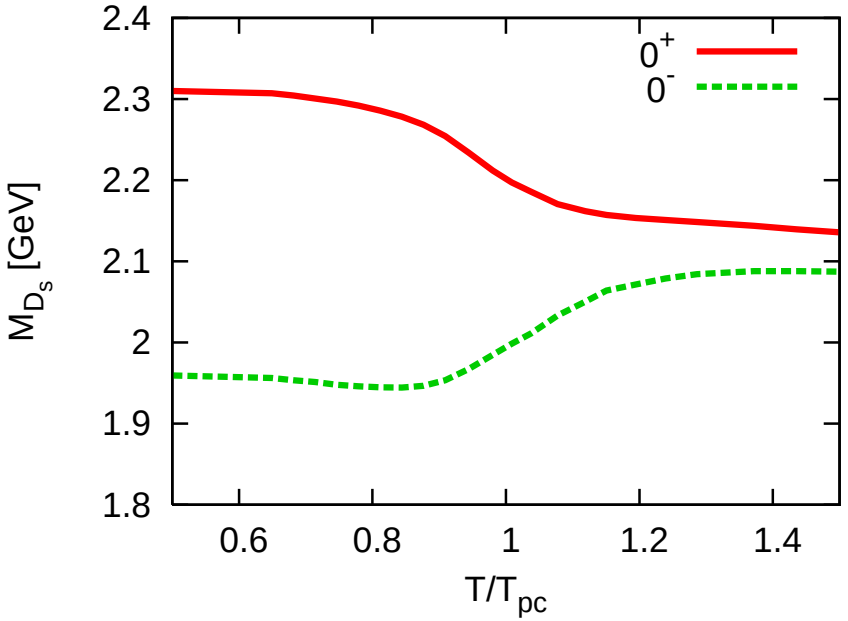
when $m_Q \to \infty$, spin-flavor symmetry emerges. [Shuryak ('81), Isgur-Wise ('89)]

light d.o.f. (q) do not feel the flavor and spin of the heavy quark (Q).

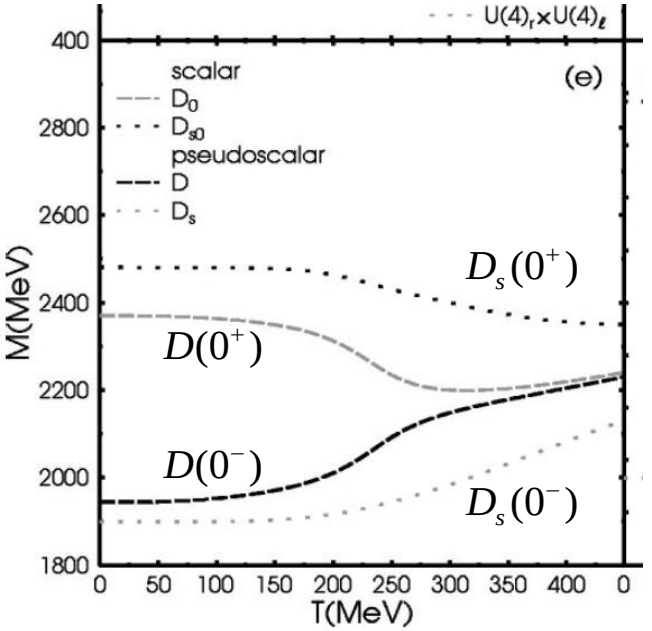
- spontaneous chiral symmetry breaking:
  chiral doublers $D(0^-, 1^-)$ and $D(0^+, 1^+) \Rightarrow \delta m_D \sim 300\text{-}400$ MeV

In-medium charmed-meson masses [CS ('14)]



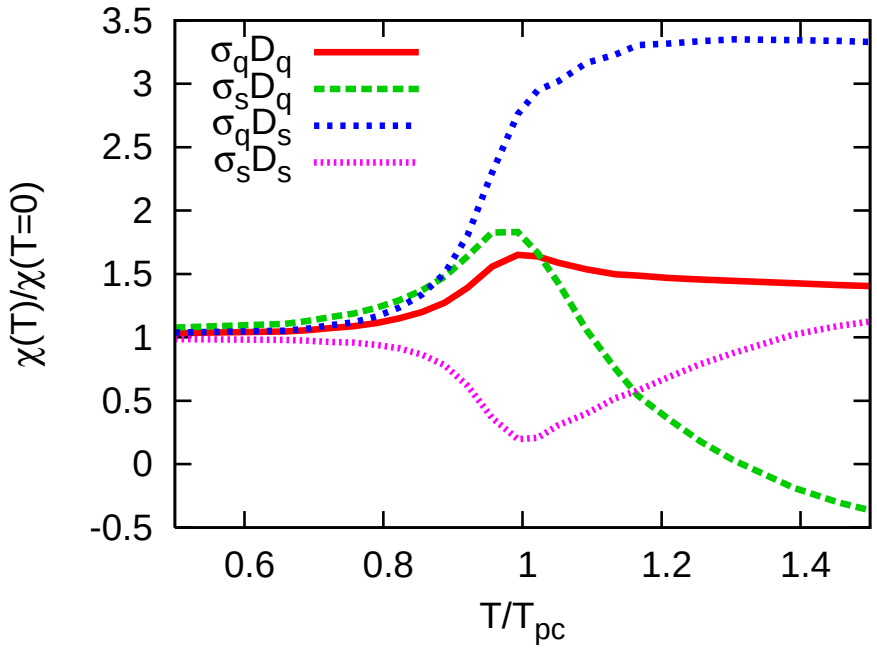


- chiral splitting at $T_{\rm pc}$: $\delta M_D \simeq \delta M_{D_s}$
  $\cdots$ *insensitive to light flavors!*
  $\Rightarrow$ heavy quark symmetry
- light mesons at $T_{\rm pc}$: $\delta M_{\pi\text{-}\sigma} \ll \delta M_{K\text{-}\kappa}$
  $\cdots$ SU(2+1) $\neq$ SU(3)
- cf. chiral SU(4): [Roder-Ruppert-Rischke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

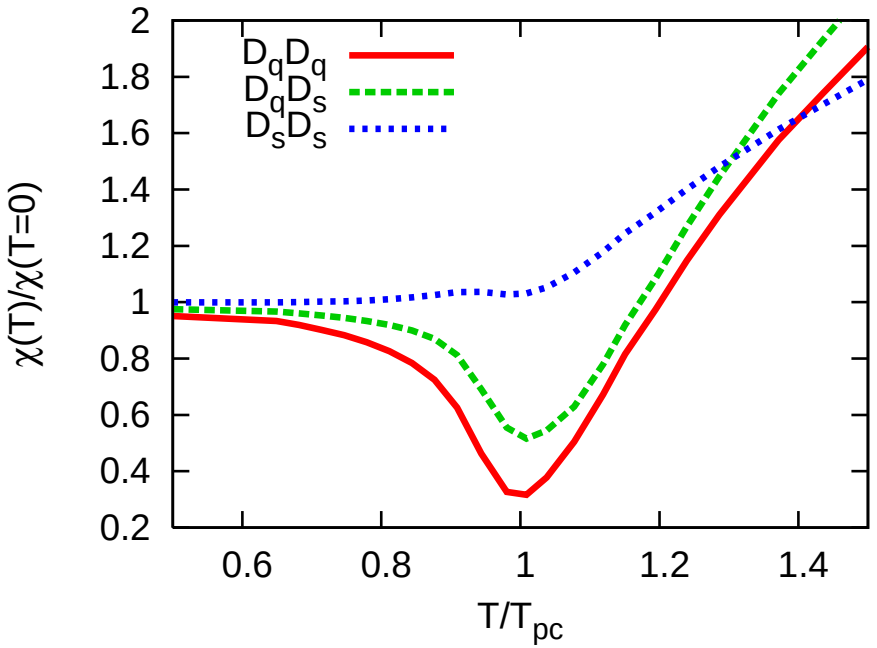


Correlations between light and heavy-light mesons [CS-Redlich ('14)]

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



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



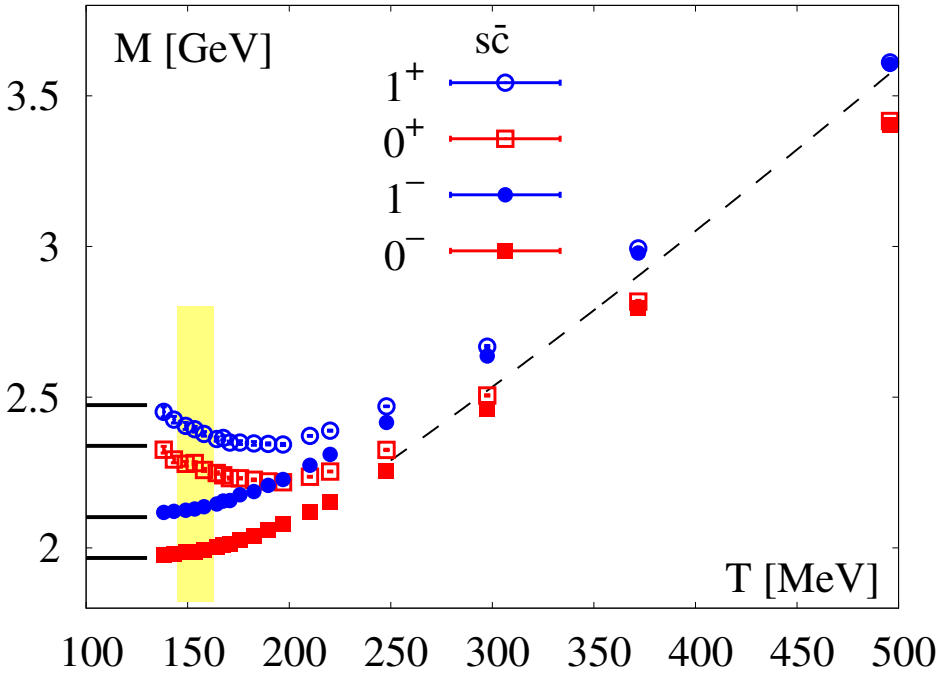
qualitative changes set in at $T \sim T_{\rm pc}$: (NOTE: $\chi_{\rm ch} \sim \partial\sigma_{q,s}/\partial m_{q,s}$)

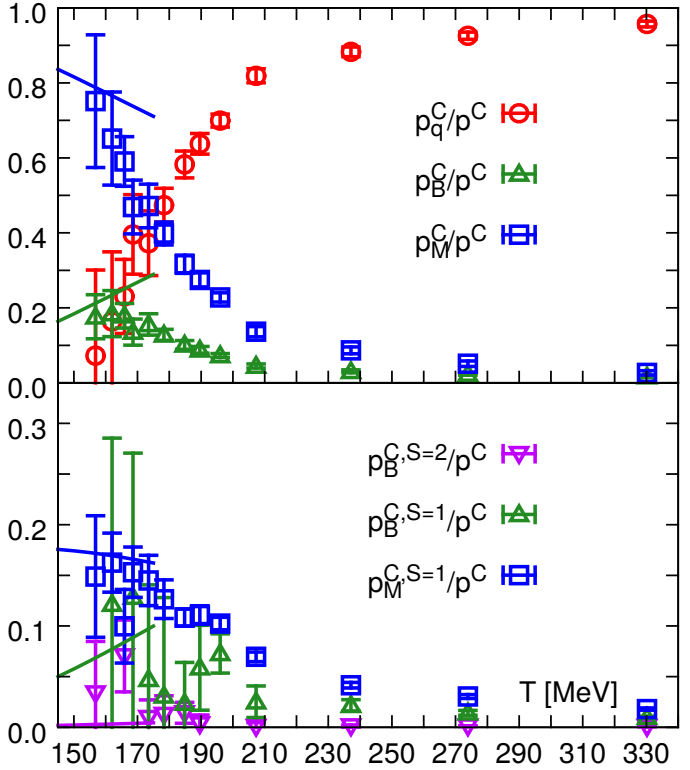
$$\hat{\chi}_{\sigma D} = -\hat{\chi}_{\rm ch}\hat{\mathcal{C}}_{\rm HL}\hat{\chi}_D\,, \quad \hat{\chi}_{D\sigma} = -\hat{\chi}_D\hat{\mathcal{C}}_{\rm HL}\hat{\chi}_{\rm ch}\,,$$
$$\hat{\chi}_{DD} = \hat{\mathcal{C}}_D - \hat{\mathcal{C}}_{\rm HL}\hat{\chi}_{\rm ch}\hat{\mathcal{C}}_{\rm HL} \equiv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

$\frac{m_{q,s}}{m_c}, \frac{T}{m_c} \ll 1 \Rightarrow$ heavy quark symmetry as a reliable guide

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

Lattice observables - consistent with the model





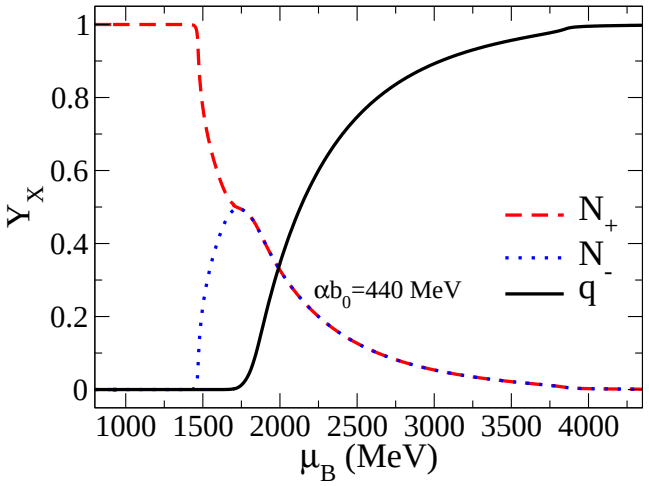
- screening D_s masses [Bazavov et al. ('14)] - the same tend
- 4th-order c-s corr.: survival D_s up to $T = 1.2T_{\rm ch}$ [Mukherjee et al. ('15)]
  D_s changes its property - medium modification sets in at $\sim T_{\rm ch}$.
- fluctuations and correlations of conserved charges X

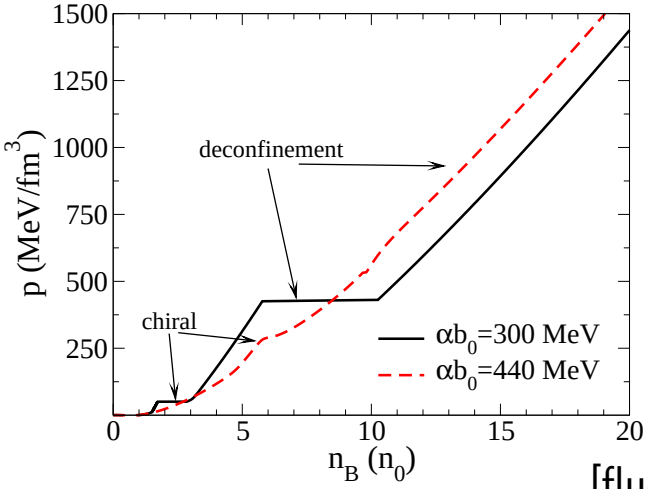
$$\chi_X \sim \begin{pmatrix}\sigma & D\end{pmatrix} \begin{pmatrix}\chi_{\rm ch} & \chi_{\sigma D} \\ \chi_{D\sigma} & \chi_D\end{pmatrix} \begin{pmatrix}\sigma \\ D\end{pmatrix} \sim \underbrace{\chi_{\rm ch}\mathcal{F}(\sigma, D)}_{\text{dominated at } T \sim T_{\rm ch}}$$

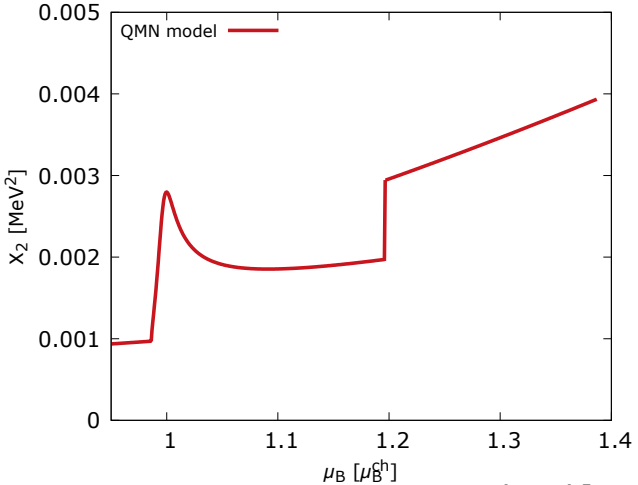
II. Phase structure and in-medium hadrons

Chiral SB vs. confinement at finite density

- SU(2) instantons and dyons: simultaneous transition [Larsen, Shuryak ('14,'15)]
  conf. and DχSB induced by dyon-antidyon interactions (talk by E. Shuryak)
- QH-hybrid model suggests a splitting of the two p.t. [Benic-Mishustin-CS ('15)]
  - IR cutoff b: NJL, SD eq., AdS/QCD [Ebert, Feldmann, Reinhardt ('96); $\cdots$]
    $1/b \sim$ typical size of a hadron $\Rightarrow$ modified FD distribution functions
  - deconfinement criteria $Y_{N_+} + Y_{N_-} = Y_q$; $\quad Y_{N_\pm} = \dfrac{\rho_{N_\pm}}{\rho_B}$, $\quad Y_q = \dfrac{1}{3}\dfrac{\rho_q}{\rho_B}$.
  - parameter-free prediction at $T = 0$: $\rho_{\rm ch}$ separated from $\rho_{\rm dec}$

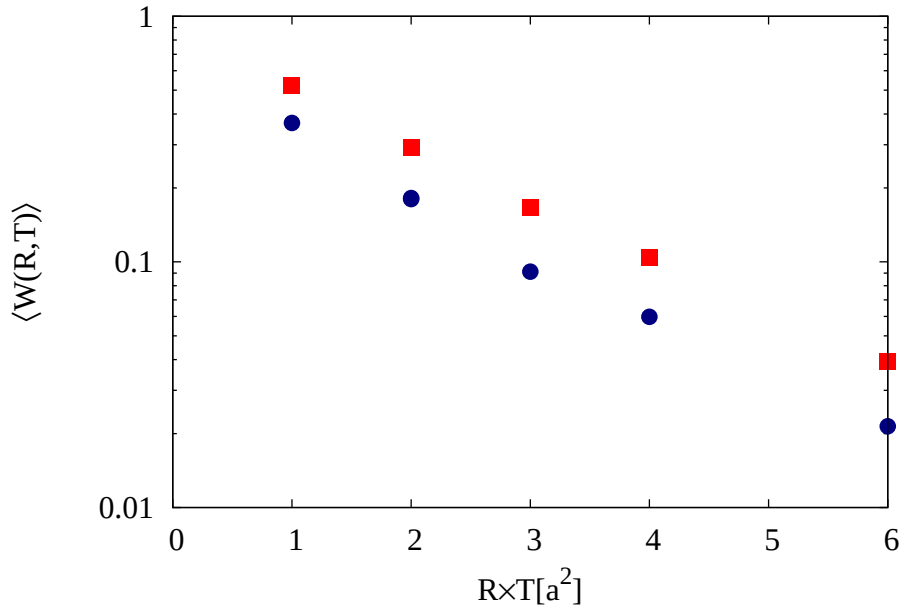


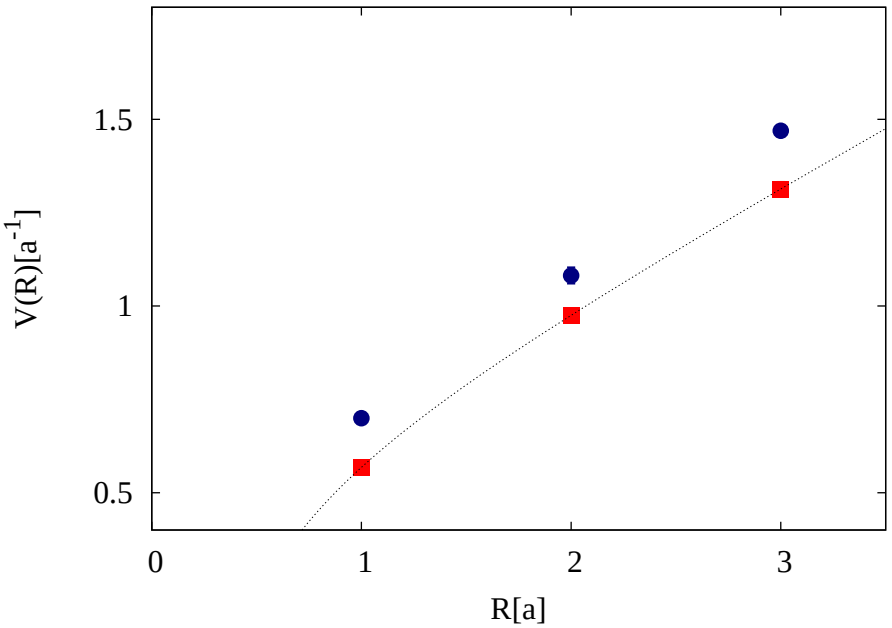




[fluctuations: Marczenko et al. ('16)]

- Dirac-eigenmode expansion on lattice (talk by H. Suganuma)
  NO particular Dirac-modes that crucially affect confinement - $T_{\rm ch} \neq T_{\rm dec}$?





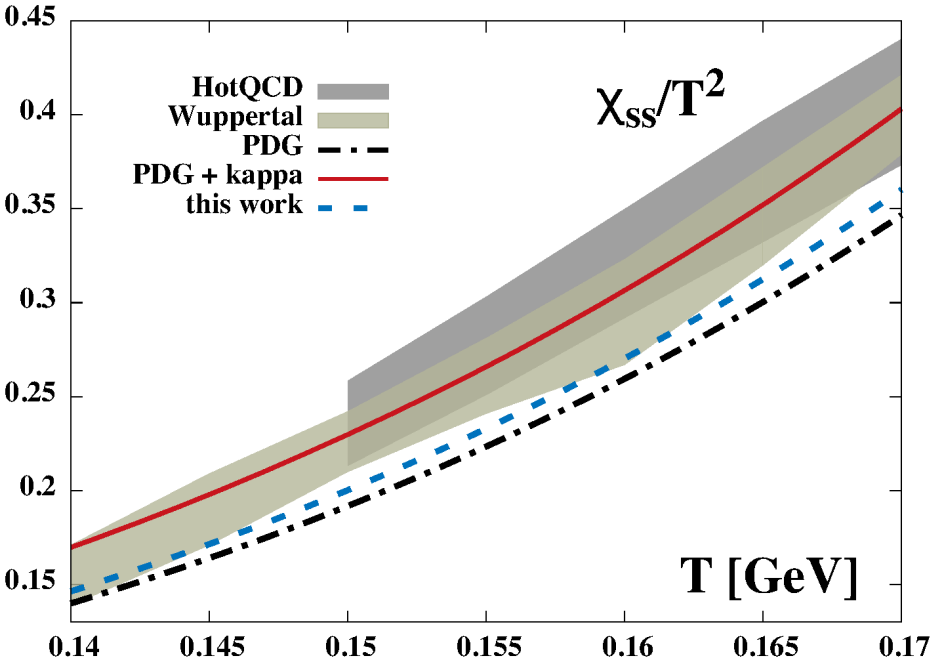
  ■ full vs. ● w/o low-lying modes

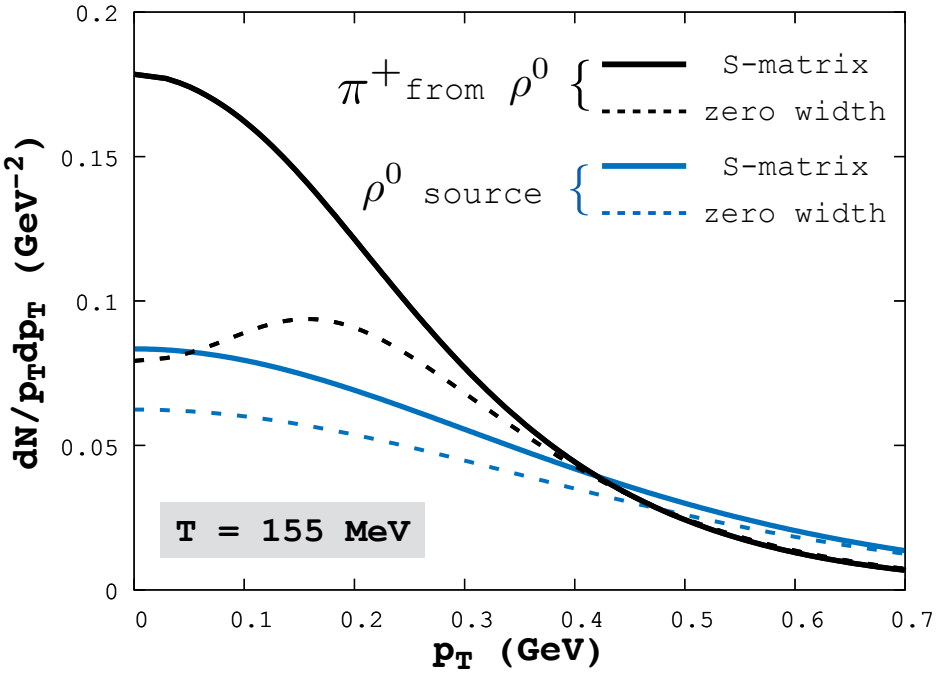
  – Wilson loop, quark potential:
    $\langle W \rangle \propto e^{-\sigma RT}$: string tension *unchanged!* [Gongyo, Iritani, Suganuma ('12)]
  – Polyakov loop susceptibilities unmodified [Doi, Redlich, CS, Suganuma ('15)]

- is it so exotic if the two transitions happened separately?
  NO! cf. adjoint QCD, $T_{\rm ch} \sim 8 T_{\rm dec}$

Modified hadrons in hot matter

[Friman et al. ('15); Huovinen et al. ('16)]

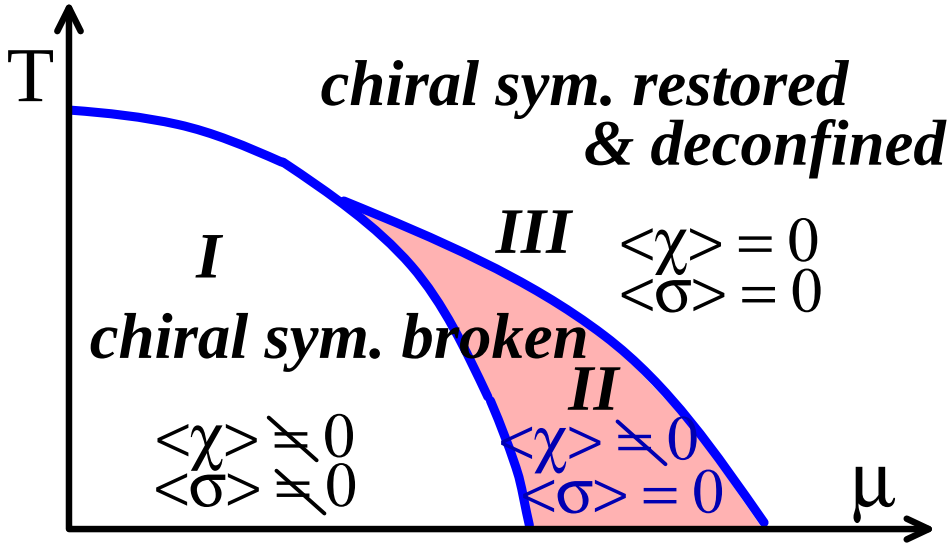


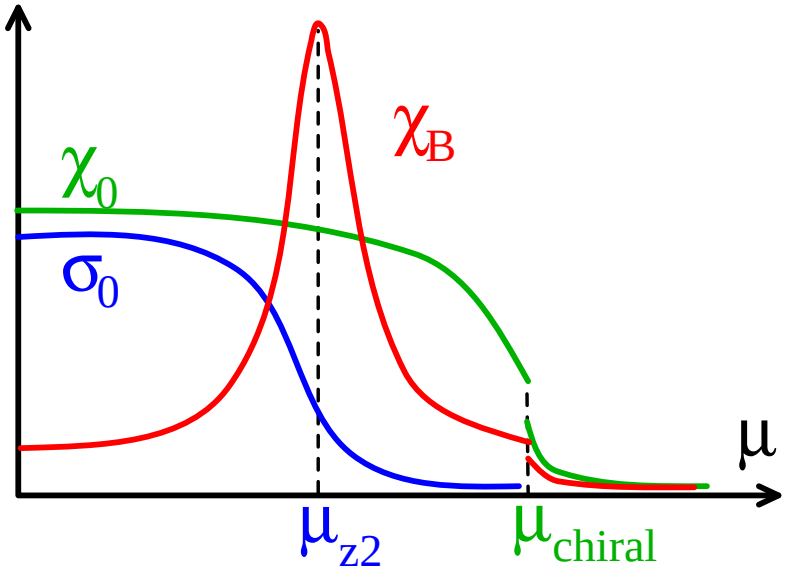


- how to deal with broad resonances? [Dashen et al. ('69); Venugopalan-Prakash ('92)]
  - S matrix approach: empirical $K\pi$ phase shift as $input$
    $\Rightarrow$ consequences of the broad width for thermodynamics
  - fluctuations in LQCD: missing strange state? [Bazavov et al. ('14)]
    putting κ into HRG compatible with LGT!?... CAUTION!
- p_T spectrum of ρ^0 and π^+ from the decay $\rho^0 \longrightarrow \pi^+\pi^-$
  $\Rightarrow$ substantial enhancement in low p_T

Modified hadrons in dense matter

[Harada-CS-Takemoto (09)]





- symmetry breaking: $SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V \times Z_{N_f} \to SU(N_f)_V$
  2-quark state $\sigma \sim \bar{q}q$ and 4-quark state $\chi \sim (\bar{q}q)^2 + \bar{q}\bar{q}$-$qq$
- 3 phases: baryon number flutc. χ_B becomes max. when $\langle\sigma\rangle \to 0$, whereas ch.sym. remains broken by $\langle\chi\rangle \neq 0$
- multiple critical points, the same universality class as the "ordinary" CP
  $\Leftrightarrow$ different universality from anomaly induced CP [Hatsuda et al. (06-07)]
  $\because U(1)_B$ is broken in CFL phase.

- hadron mass spectra

phase I: $\sigma_0 \neq 0\,, \chi_0 \neq 0$	phase II: $\sigma_0 = 0\,, \chi_0 \neq 0$
$SU(2)_V$	$SU(2)_V \times (Z_2)_A$
$m_S \neq 0\,, m_P = 0$ $m_V \neq m_A$	$m_S \neq m_P \neq 0\,, m_{P'} = 0$ $m_V \neq m_A$
$m_{N+} \neq m_{N-}$	$m_{N+} = m_{N-} \neq 0$

phase I: $\sigma_0 \neq 0\,, \chi_0 \neq 0$	phase II: $\sigma_0 = 0\,, \chi_0 \neq 0$
$SU(3)_V$	$SU(3)_V \times (Z_3)_A$
$m_S \neq 0\,, m_P = 0$ $m_V \neq m_A$	$m_S = m_P \neq 0\,, m_{P'} = 0$ $m_V \neq m_A$
$m_{N+} \neq m_{N-}$	$m_{N+} = m_{N-} \neq 0$

- $N_f = 2 + 1$:
  (non-strange) $m_S \neq m_P \quad m_{N+} \simeq m_{N-}$
  (strange) $\quad m_S \simeq m_P \quad m_{N+} \simeq m_{N-}$
  $\Rightarrow$ early onset of χSR for the strange mesons and non-/strange baryons!

Summary

- **Various fluctuations: remnant of underlying symmetry**
- **Dynamical chiral symmetry breaking vs. confinement**
  - why $T_{\rm ch} \simeq T_{\rm dec}$ at $\mu = 0$?: PNJL/QM models, instanton-dyon picture
  - not clear at high density: Dirac eigenmode expansion, model w/ IR cutoff, cf. adjoint QCD: $T_{\rm dec} \neq T_{\rm ch}$
- **Nature of hadrons near QCD phase transition**
  - exotic phases at high density, new CPs, χ_B
  - role of higher-lying hadrons
  - careful treatment of broad resonances required
- **Our goal: from hadrons to quarks and gluons**
  multifaceted studies of gauge dynamics guided by symmetry, topology, ideal limits AND available data from LQCD simulations and HIC