Chiral condensate in hadron gas

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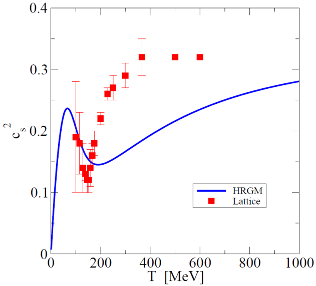
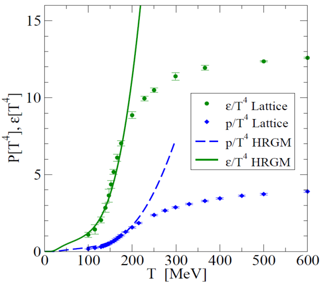
Hadron Resonance Gas

$$\Omega_{\mathrm{HRG}}(T) = \pm \sum_H d_H \int \frac{d^3k}{(2\pi)^3} T \ln\{1 \mp e^{-\beta E_H}\}$$

- Free hadron contribution up to $m_{\mathrm{max}} \sim 2$ GeV
- $T_c \approx 155$ MeV $\approx 10^{12}$K to compare $T_{\mathrm{sun@center}} \approx 10^7$K





Wuppertal-Budapest Collaboration, JHEP **1009**, 073 (2010)

Chiral condensate in Hadron Resonance Gas

- Free hadron contributions,

$$\langle \bar{q}q \rangle = \langle \bar{q}q \rangle_0 - \sum_H \frac{\partial m_H}{\partial m_q} n_H(T) \ ,$$

with scalar densities for mesons and baryons

$$n_H(T) = \frac{d_H}{2\pi^2} \int_0^\infty dk k^2 \frac{m_H}{E_H} \frac{1}{e^{\beta E_H} \pm 1} \ ,$$

where $\beta = 1/T$ and $E_H = \sqrt{m_H^2 + k^2}$.

- Microscopic hadron structure turns out to be crucial for the description of the condensate
- Quantified by hadronic sigma terms

$$\sigma_{qH} = m_q \frac{\partial m_H}{\partial m_q}$$

Baryon sigma terms in ChPT

- N^3LO ChPT sigma terms for $N-$octet and $\Delta-$decuplet

$$m_B = m_0 + m_B^{(2)} + m_B^{(3)} + m_B^{(4)}$$

where m_0- chiral limit mass, $m_B^{(2)} \sim a m_\pi^2 + c m_K^2$

- $\sigma_{\pi N} \sim (42 \pm 14)$ MeV , $\sigma_{\pi \Delta} \sim (28 \pm 9)$ MeV
- $\pi - N$ scattering experiments $\longrightarrow$ $\sigma_{\pi N} \sim 45$ MeV

X. -L. Ren *et al.* arXiv:1307.1896
X. -L. Ren *et al.* Phys. Rev. D **87**, 074001 (2013)

Constituent Quark Picture

- We assume hadron mass is determined by the valence quark masses

$$m_M = (2-N_s)M_q + N_s M_s + \kappa_M \ , \ \ m_B = (3-N_s)M_q + N_s M_s + \kappa_B$$

κ_H are state dependent quantities independent of m_q

- Response of the dynamical quark mass to the current quark mass is estimated by the NJL model

$$\Delta M_q \sim 12.5 \ \mathrm{MeV} \ , \quad \Delta M_s \sim 227.4 \ \mathrm{MeV}$$

- Strangeness content N_s is determined by the hadron flavour structure $N_S = 0, 1, 2, 3$ open strangeness $N_s = 2/3$ or $N_s = 4/3$ for hidden strangeness

JJ, D. Blaschke, M. Spaliński, Phys. Rev. D **87**, 105018 (2013)

Lattice observables

$$\Delta_{l,s}(T) = \frac{\langle \bar{q}q \rangle - \frac{m_q}{m_s}\langle \bar{s}s \rangle}{\langle \bar{q}q \rangle_0 - \frac{m_q}{m_s}\langle \bar{s}s \rangle_0}\ , \tag{1}$$

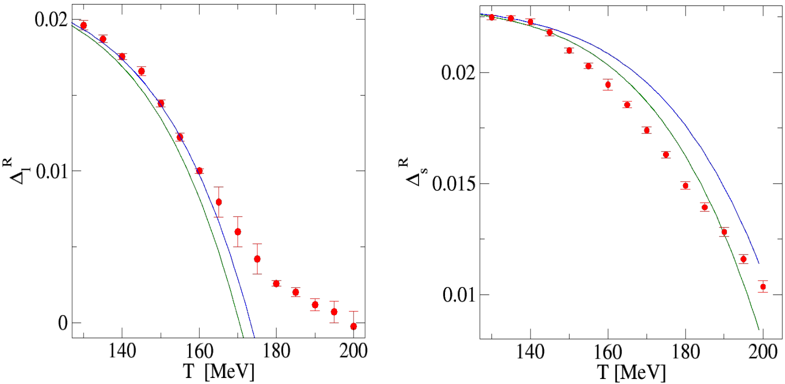
$$\Delta_l^R(T) = d + 2m_s r_1^4(\langle \bar{q}q \rangle - \langle \bar{q}q \rangle_0)\ , \tag{2}$$

$$\Delta_s^R(T) = d + 2m_s r_1^4(\langle \bar{s}s \rangle - \langle \bar{s}s \rangle_0)\ , \tag{3}$$

- Sensitive to χ-symmetry and without renormalization ambiguities both multiplicative and additive
- $d = 0.023$ is related to the value of the chiral condensate in the chiral limit
- $r_1 = 0.174/f_K$, with $f_K = 113$ MeV sets the physical scale

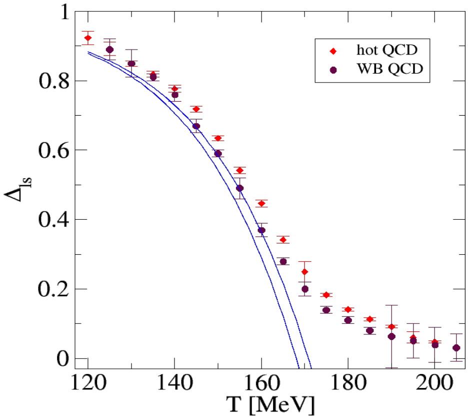
A. Bazavov *et al.*, Phys. Rev. D 85, 054503 (2012)

Results ⟶ hotQCD



A. Bazavov, P. Petreczky, Phys. Rev. D **87**, 094505 (2013)

Results ⟶ hotQCD & Wuppertal-Budapest



A. Bazavov, P. Petreczky, Phys. Rev. D **87**, 094505 (2013)
Wuppertal-Budapest Collaboration, JHEP **1009**, 073 (2010)

Summary

- Most important contribution to the condensates comes from the lightest states
- Possibility to estimate $T_c(\mu_B)$ dependence
- Other chiral observables, like chiral susceptibilities are sensitive to hadron-hadron interactions
  A. Gomez Nicola *et al.* Phys. Rev. D **88**, 076007 (2013)
- Hadron contribution to the melting of the condensate was appreciated in a model for the freeze-out stage of HIC
  D. Blaschke, J. Berdermann, J. Cleymans, K. Redlich,
  Few Body Syst. **53**, 99 (2012)