Additional strange resonances from lattice QCD

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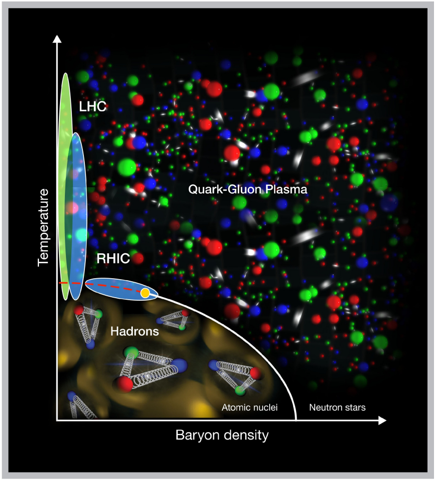
Outline

1. Introduction
   - Hadron Resonance Gas
2. HRG vs LQCD - Missing strange resonances
   - light resonances: $K_0^\star(800)$ meson & S-matrix approach
   - heavy resonances: Hagedorn mass spectrum
3. Conclusions

QCD phase diagram



source: Brookhaven National Laboratory

EFFECTIVE EQUATION OF STATE

↓

relevant degrees of freedom

+

interactions

hadrons and their resonances

+

point-like and independent species

↓

HADRON RESONANCE GAS MODEL

Idea of Hadron Resonance Gas

- Resonance production dominates the interactions
- Information about the interactions $\longrightarrow$ medium composition

$$\ln Z \approx \sum_{i \in mes} \ln Z_i^M + \sum_{i \in bar} \ln Z_i^B, \quad \rho(m) = \sum_{i \in had} d_i \delta(m - m_i)$$

Pressure (Boltzmann approximation)

$$\hat{P} \equiv \frac{P}{T^4} = \frac{1}{2\pi^2} \sum_{i \in had} d_i \frac{m_i^2}{T^2} K_2 \left(\frac{m_i}{T} \right) e^{\hat{\mu}_i} \Big|_{\hat{\mu}_B = \hat{\mu}_S = \hat{\mu}_Q = 0}$$

$$\hat{\mu}_i = B_i \hat{\mu}_B + S_i \hat{\mu}_S + Q_i \hat{\mu}_Q, \quad \hat{\mu} = \mu / T$$

Fluctuations in Hadron Resonance Gas

2^{nd} order correlations $\longrightarrow$ generalized susceptibilities

Generalized susceptibilities

$$\hat{\chi}_{xy} = \frac{\partial^2 \hat{P}}{\partial \hat{\mu}_x \partial \hat{\mu}_y}, \qquad x, y = B, S, Q$$

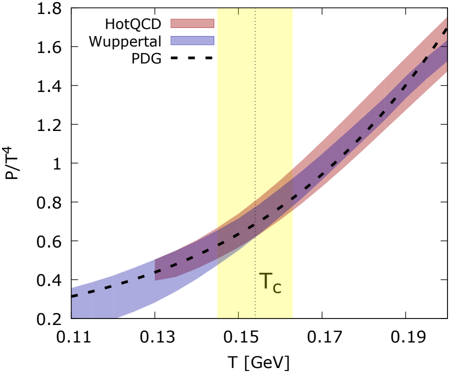
$$\hat{\chi}_{\mathrm{BB}} = \sum_i \frac{d_i}{\pi^2} \frac{m_i^2}{T^2} K_2\left(\frac{m_i}{T}\right) {B_i}^2 \qquad \text{baryons}$$

$$\hat{\chi}_{\mathrm{BS}} = \sum_i \frac{d_i}{\pi^2} \frac{m_i^2}{T^2} K_2\left(\frac{m_i}{T}\right) S_i B_i \qquad \text{strange baryons}$$

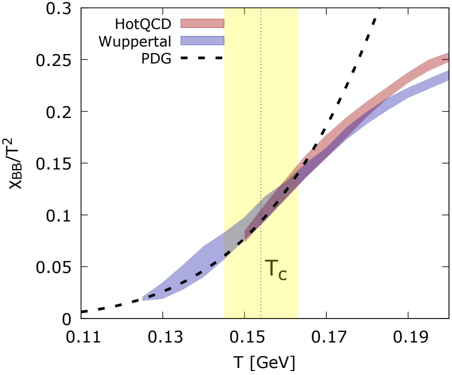
$$\hat{\chi}_{\mathrm{SS}} = \sum_i \frac{d_i}{\pi^2} \frac{m_i^2}{T^2} K_2\left(\frac{m_i}{T}\right) {S_i}^2 \qquad \text{strange hadrons}$$

HRG vs Lattice QCD

total thermodynamic pressure



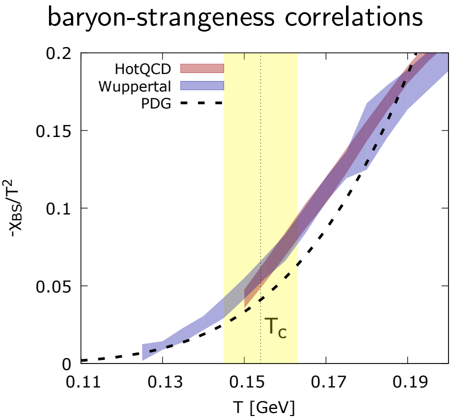
net-baryon number fluctuations

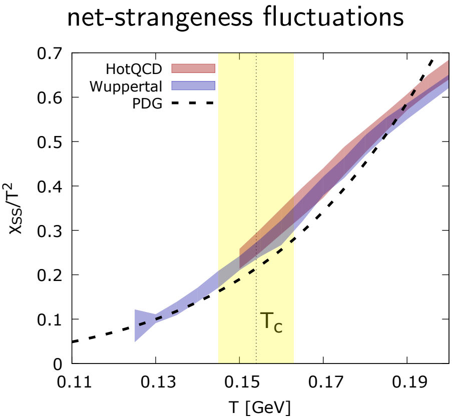


S. Borsányi *et al* (Budapest-Wuppertal coll.), JHEP **1201**, 138 (2012); Phys. Lett. **B**, 730 (2014)

A. Bazavov *et al* (HotQCD coll.), Phys. Rev. D **86**, 0534509 (2012); Phys. Rev. D **90**, 094503 (2014)

HRG vs Lattice QCD





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Missing strangeness

- $\hat{P}$, $\hat{\chi}_{\rm BB} \longrightarrow$ match LQCD results
- $\hat{\chi}_{\rm BS} \longrightarrow$ missing resonances in the strange-baryonic sector
- $\hat{\chi}_{\rm SS} \longrightarrow$ missing resonances in the strange sector

$\downarrow$

Known states are not sufficient

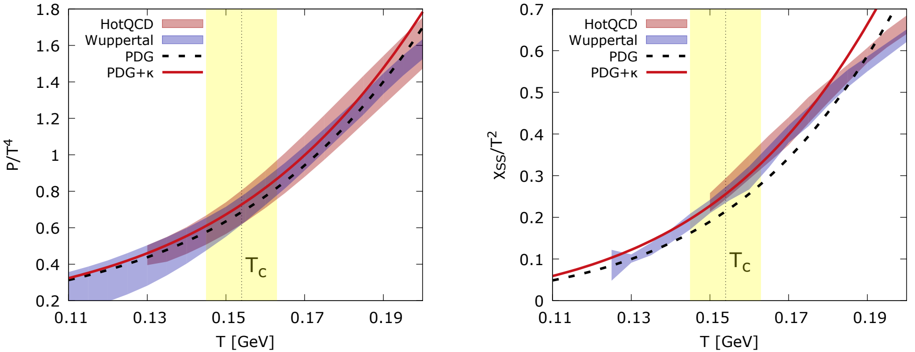
A. Bazavov *et al*, Phys. Rev. Lett. **113**, 072001 (2014)

$\downarrow$

Goal:

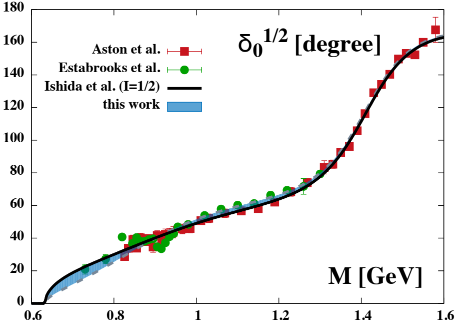
Identify the possible origins of the discrepancies in the strange-hadronic sector of the HRG model

Low-mass resonances → $K_0^\star(800)$ a.k.a. κ meson



- κ is a broad resonance with m $\sim$ 682 MeV, $\Gamma \sim$ 550 MeV
- zero-width approximation IS NOT an accurate description
- one needs a consistent treatment of all interaction effects

Relevant phase shift → $K\pi$ S-wave, $I = \frac{1}{2}$ channel



B. Friman *et al*, Phys. Rev. D **92**, 074003 (2015)

- Near threshold
  $\delta_0^{1/2}(\sqrt{s} \simeq m_{\rm th}) \approx a_0^{1/2} P_{\rm CM}(s)$
  $a_0^{1/2} \approx (0.18 - 0.39) m_\pi^{-1}$

- The total phase shift

$$\delta_0^{1/2} = \delta_\kappa + \delta_{K_0^\star} + \delta_{\rm BG}$$

- resonances → Breit-Wigner

$$\delta(s) = \text{arc tg}\left(\frac{-\sqrt{s}\Gamma(s)}{s - M_0{}^2}\right)$$

$$\Gamma(s) = \frac{\alpha}{2}\theta\left(s - m_{\rm th}^2\right)\frac{P_{\rm CM}(s)}{s}$$

- hardcore backround term

$$\delta_{\rm BG}(s) = -r_c P_{\rm CM}(s)$$

S-matrix approach

R. Dashen *et al*, Phys. Rev. **187**, 345 (1969)

E. Beth and G. Uhlenbeck, Physica **4**, 915 (1937).

Thermodynamic potential and pressure

$$\Omega = \Omega_\pi + \Omega_K + \Omega_{\mathrm{int}}, \quad P = -\frac{\Omega}{V}$$

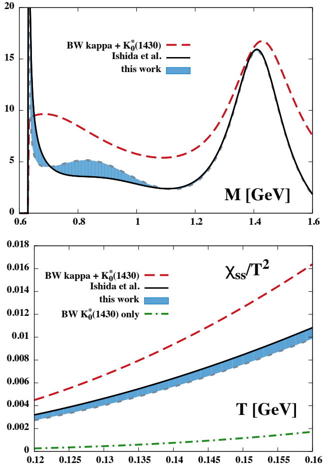
$$\Omega_{\mathrm{int}} \approx 2TV \int_{m_{\mathrm{th}}}^{\infty} \frac{\mathrm{d}M}{2\pi} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \mathcal{B}(M) \sum_{\gamma=\pm1} \ln\left[1 - e^{-\left(\hat{E}+\gamma\hat{\mu}_s\right)}\right]$$

Relation to the phase shift

W. Weinhold *et al*, Phys. Lett. B **433**, 236 (1998)

$$\mathcal{B}(M) = 2\frac{\mathrm{d}}{\mathrm{d}M}\delta(M)$$

Result → enhancement of $\hat{\chi}_{SS}$

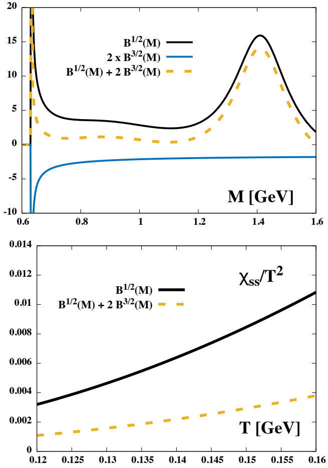


B. Friman *et al*, Phys. Rev. D **92**, 074003 (2015)

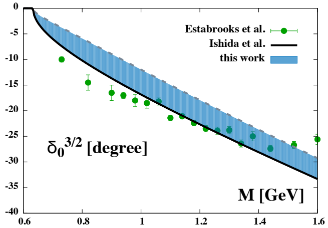
- $\mathcal{B}(M)$ diverges at the threshold unlike standard Breit-Wigner
- overestimate from standard Breit-Wigner

- finally, the enhancement of $\hat{\chi}_{SS}$ due to κ is reduced by $\sim 80\%$

The effect of $I = \frac{3}{2}$ $K\pi$ scattering



B. Friman *et al*, Phys. Rev. D **92**, 074003 (2015)



- κ-contribution almost fully cancels!
- κ alone is only a part of missing contribution!
- similar result for the σ meson

W. Broniowski *et al*, Phys. Rev. C **92**, 034905 (2015)

Contribution from heavy (unobserved?) resonances

Hagedorn mass spectrum

R. Hagedorn, Nuovo Cim. Suppl. **3**, 147 (1965)

$$\rho^H(m) = \frac{A\ e^{m/T_H}}{\left(m^2 + m_0^2\right)^{5/4}}$$

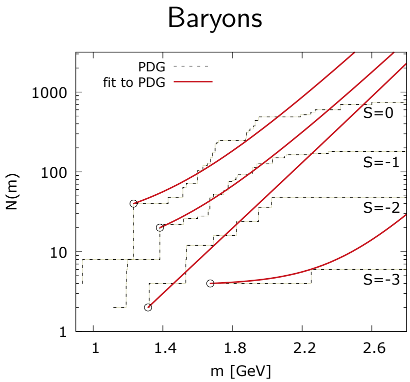
Our key assumptions:

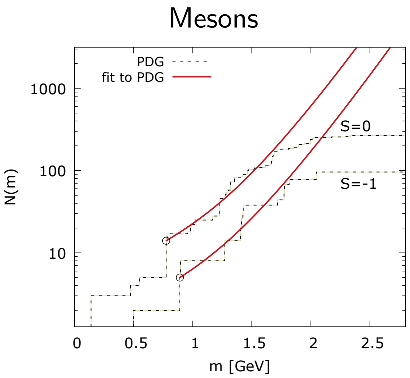
- $T_H > T_c$ for the observables to be consistent with LQCD;
- the same $T_H \sim 180$ MeV in all sectors;

Two possible sources:

- Heavy resonances beyond current experimental reach;
- resonances excluded from PDG;

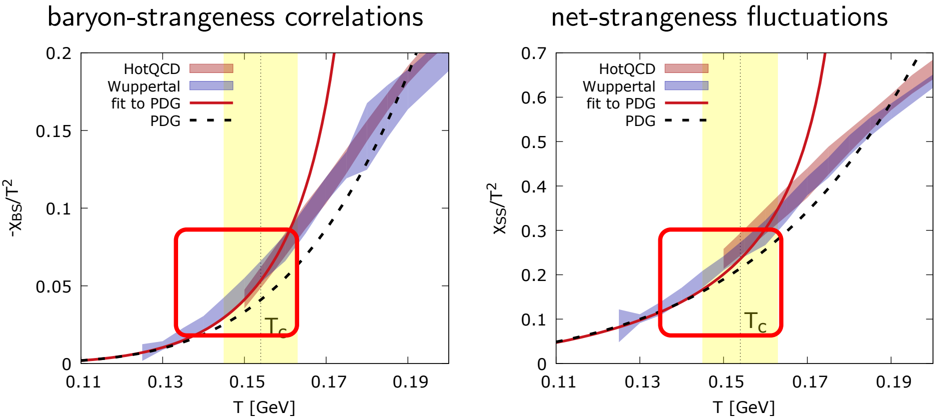
Fit to PDG cumulants





$$N(m) = \int_0^m \mathrm{d}m' \rho(m') \quad \text{such that} \quad \rho = \partial N / \partial m$$

Heavy resonanes capture the difference only for high T



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A. Bazavov *et al* (HotQCD coll.), Phys. Rev. D **86**, 0534509 (2012); Phys. Rev. D **90**, 094503 (2014)

Implication of observables on medium composition

Only $\hat{\chi}_{\mathrm{BS}}$ and $\hat{\chi}_{\mathrm{SS}}$ to constrain four spectra

$$\rho_{\mathrm{B}}^{|\mathrm{S}|=1}, \rho_{\mathrm{B}}^{|\mathrm{S}|=2}, \rho_{\mathrm{B}}^{|\mathrm{S}|=3}, \rho_{\mathrm{M}}^{|\mathrm{S}|=1}$$

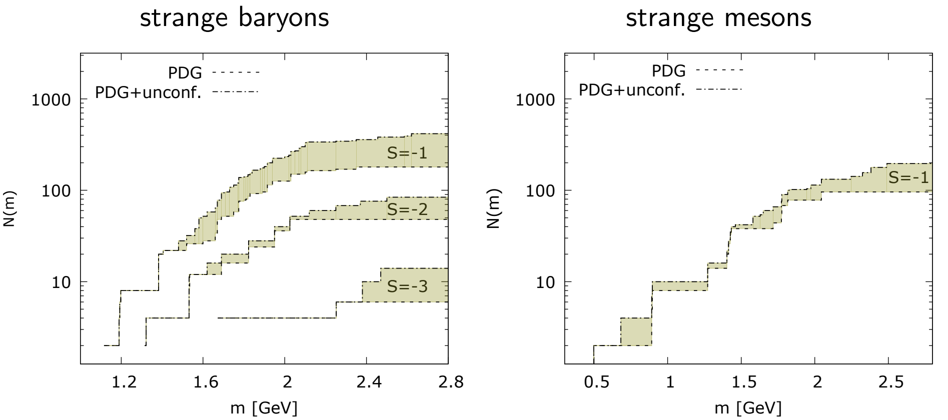
- we can only constrains their linear combination!
- more data needed to constrain individual sectors, e.g. kurtosis;

- $\hat{\chi}_{\mathrm{BS}}$ is dominated by $|S| = 1$ sector (Boltzmann suppresion);
- $\hat{\chi}_{\mathrm{SS}}$ is dominated by mesons (Boltzmann suppresion);

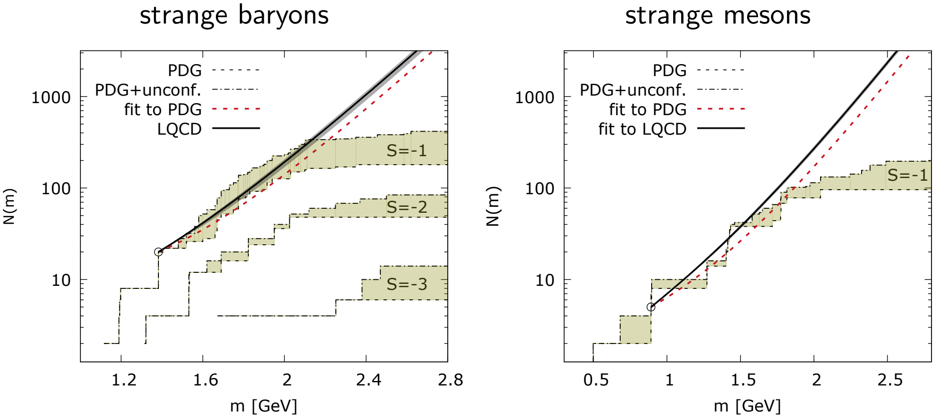
Assumption:

- missing strength comes solely from $|S| = 1$ sector;
- $|S| = 2, 3$ sectors $\to$ fit to PDG;

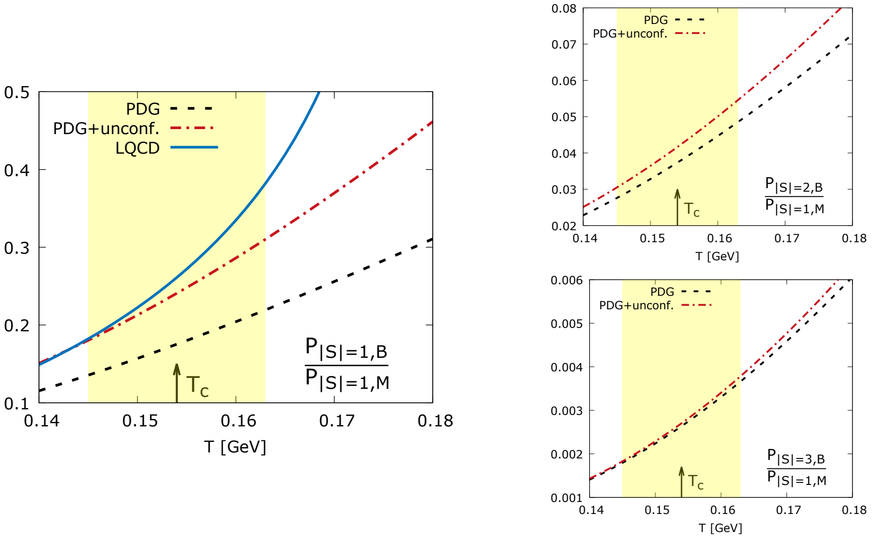
Results → mass spectrum



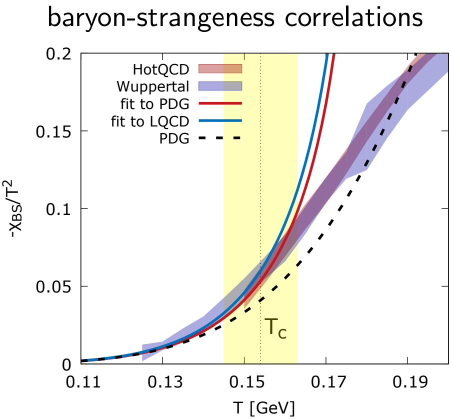
Results → mass spectrum

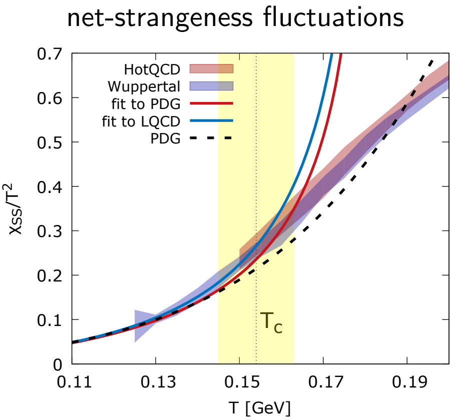


Magnitude of the interaction strength in the strange sector



Results → observables





Conclusions

We addressed the problem of missing strange resonances utilizing the HRG model

- HRG is not a good approximation for broad resonances
  - S-matrix approach shows consistently importance of the width and non-resonant background;
  - κ meson alone is insufficient to fix the discrepancy in $\hat{\chi}_{\mathrm{SS}}$.
- Substantial contribution from intermediate states to the fluctuations near T_c
  - Spectra for strange baryons are consistent with unconfirmed states in the PDG;
  - Spectrum for mesons exceeds that of the PDG $\longrightarrow$ new extra states?

The End

Hagedorn mass spectrum

Continuous mass spectrum

R. Hagedorn, Nuovo Cim. Suppl. **3**, 147 (1965)

$$\rho^H(m) = \frac{A\, e^{m/T_H}}{(m^2 + m_0^2)^{5/4}}$$

Previous fits $\longrightarrow$ different T_H for mesons and baryons:

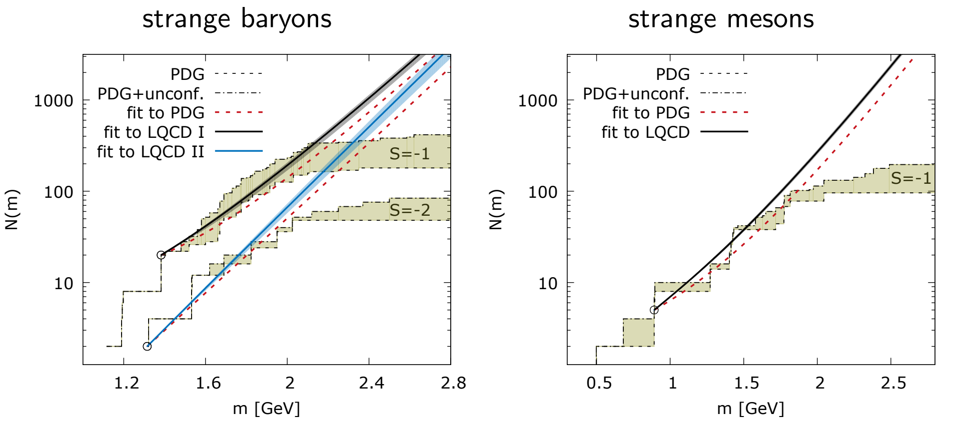
- $T_H^M = 197$ MeV
- $T_H^B = 141$ MeV $< T_c \sim 155$ MeV $\Rightarrow$ disfavored by LQCD

W. Broniowski *et al*, Phys. Lett. B **490**, 223 (2000), Phys. Rev. D **70**, 117503 (2004)

Our key assumptions:

- $T_H > T_c$ for the observables to be consistent with LQCD;
- the same $T_H \sim 180$ MeV in all sectors;

Results → mass spectrum



P. M. Lo *et al*, Phys. Rev. C **92**, 055206 (2015)

Different functional form → similar conclusions

Functional form

- $\rho^H(m) = Ae^{m/B}$