Testing the hadronic spectrum in the strange sector

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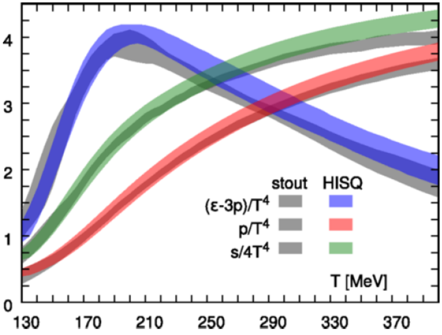
FAIRness 2017, Sitges, Spain, May 31st, 2017

- **First-principle tool** to extract thermodynamics of strong interactions in non-perturbative regime
- Unprecedented accuracy and agreement between different groups



[Wuppertal-Budapest] Phys.Lett. B730 (2014) 99104
[HotQCD] Phys.Rev. D90 (2014) 094503

Introduction

Hadron Resonance Gas model

- Interacting hadrons in the ground state well approximated by non-interacting resonance gas
- Pressure given by the sum of partial contributions:

$$\frac{P}{T^4} = \frac{1}{VT^3} \sum_i \ln Z_i(T, V, \vec{\mu})$$

with:

$$\ln Z_i^{M/B} = \mp \frac{V d_i}{(2\pi)^3} \int d^3k \, \ln\left(1 \mp \exp\left[-\left(\epsilon_i - \mu_a X_a^i\right)/T\right]\right)$$

where:

- energy $\epsilon_i = \sqrt{k^2 + m_i^2}$
- conserved charges $\vec{X}_i = (B_i, S_i, Q_i)$
- degeneracy d_i, mass m_i, volume V

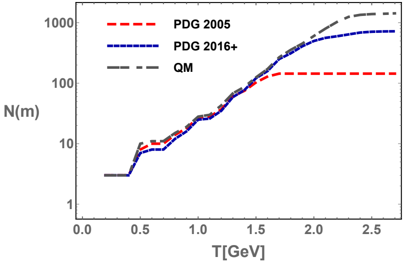
NOTE: model fed with **hadronic spectrum**. Particle spectrum becomes a "variable"!

The hadronic spectrum
Hagedorn idea

Exponentially increasing mass spectrum when counting states with degeneracies:

$$N^{HRG}(m) = \sum_i d_i \Theta\left(m - m_i\right) = A\,\frac{1}{(m^2 + m_0^2)^B}\,e^{\frac{m}{T_H}}$$

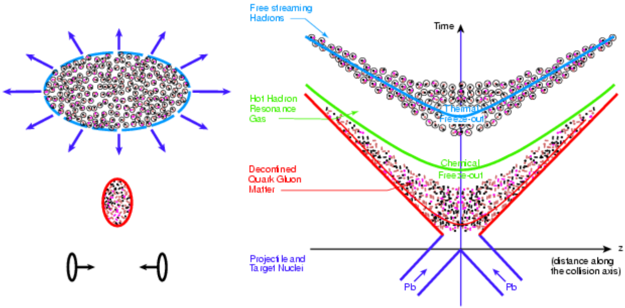
- **Particle Data Group** provides up to date listings of particles
  K. A. Olive et al. [Particle Data Group Collaboration], Chin. Phys. C 38, 090001 (2014)
- **Relativistic Quark Models** predict the existence of further states
  S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985),S. Capstick and N. Isgur, Phys. Rev. D 34, 2809 (1986)



Freeze-out

Chemical freeze-out: inelastic collisions cease, chemical composition (abundances, fluctuations) are fixed

Kinetic freeze-out: elastic collisions disappear too, spectra and correlations freeze (free streaming)



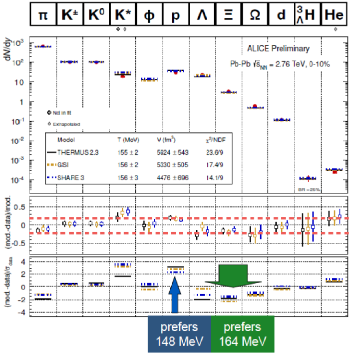
Observables related to system composition can **track back to chemical freeze-out**

Thermal fits

From HRG it is possible to compute hadron abundances:

$$N_i\left(T,\mu\right) = -T\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i V}{2\pi^2}\int_0^\infty dp\, p^2 \frac{1}{\exp\left[\left(E_i-\mu\right)/T\right]\pm 1}$$

- Relative abundances are volume independent and comparison with experiment allows to extract T and μ_B at freeze-out
- Recent results show that **strange and light matter might not freeze-out at the same temperature**

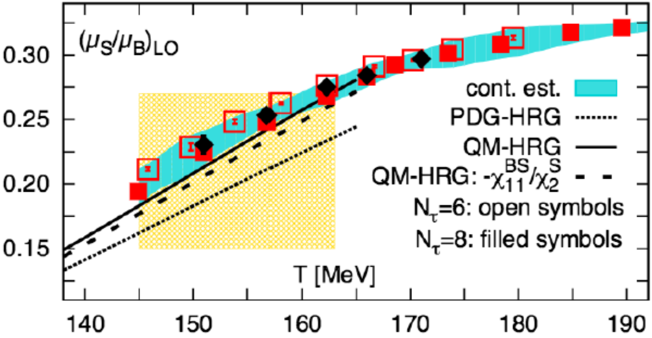


M. Floris: QM 2014

The extraction of such parameters is affected by the hadronic spectrum

Strange vs Light freeze-out: Are we missing states?

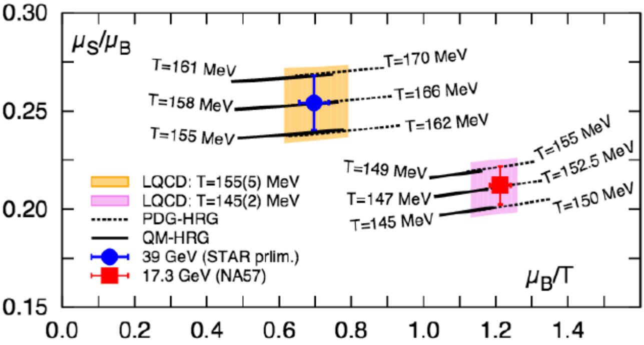
The agreement of HRG prediction with Lattice data is not always satisfying for strangeness-related observables:



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

Strange vs Light freeze-out: Are we missing states?

- Adding more resonances could eliminate this difference in temperature

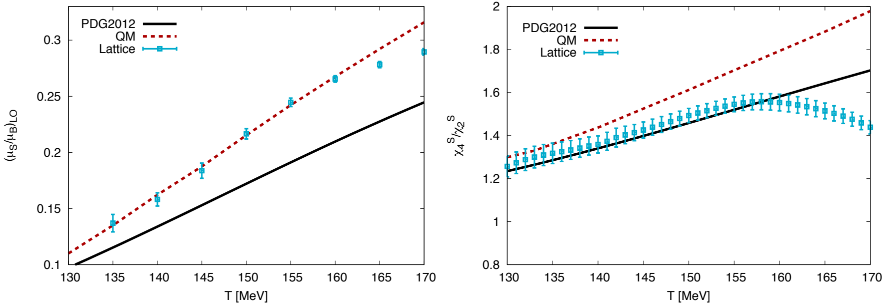


A. Bazavov et al., Phys. Rev. Lett. 113, 072001 (2014)

NOTE: **Effect of decays not taken into account**

Are we missing strange states?

Strangeness-related observables show conflicting results when further states are added to the spectrum:



P. Alba, PP et al. arXiv: 1702.01113 [hep-lat]

$$\left(\frac{\mu_S}{\mu_B}\right)_{LO} = -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B}$$

$$\chi_4^S/\chi_2^S \sim \left\langle S^2 \right\rangle$$

Need a systematic analysis of the hadronic content

Constrain the hadronic spectrum

A look at different lists

- **Particle Data Group** (PDG) lists particles according to experimental evidence
  1. **PDG 2016** (**, *** and **** states): 608 states
  2. **PDG 2016+** (*, **, *** and **** states): 738 states

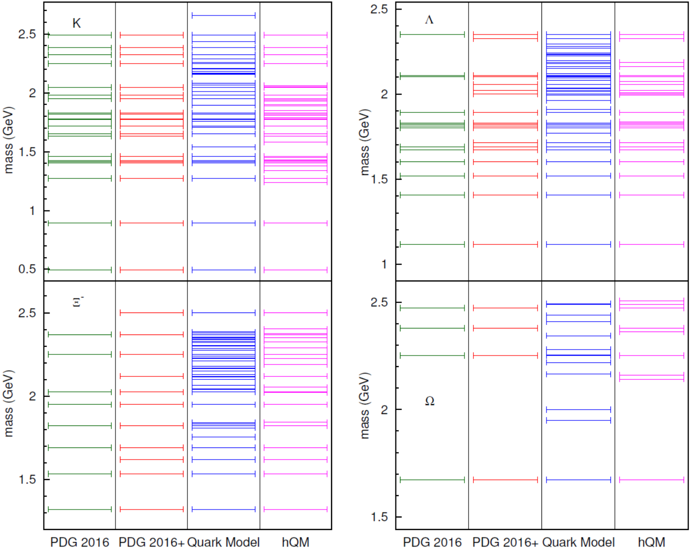
- **Quark models** predict many additional states (especially in the strange sector)
  3. **"Original" Quark Model**: 1446 states
  4. **Hypercentral QM (hQM)**: 1237 states

NOTE: JLab KLF Project for possible "missing" resonances

C. Patrignani et al. (Particle Data Group), Chin. Phys. C40, 100001, S. Capstick and N. Isgur, Phys.Rev. D34, 2809 (1986), M. Ferraris et al., Phys. Lett. B364, 231 (1995)

Constrain the hadronic spectrum

A look at different lists



Constrain the hadronic spectrum

Partial pressures

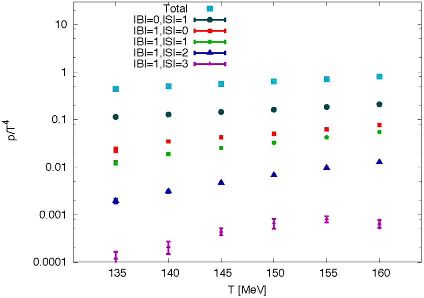
Separate contribution to the pressure from different quantum numbers (in Boltzmann approximation):

$$\frac{P}{T^4} = \sum_i (-1)^{B_i+1} \frac{d_i}{2\pi^2 T^3} \int dk\, k^2 \ln\Big(1 + (-1)^{B_i+1} \exp\left[-\left(\epsilon_i - \mu_i\right)/T\right]\Big) \simeq$$

$$\simeq \sum_i \frac{d_i}{2\pi^2 T^3} \int dk\, k^2 e^{-(\epsilon_i - \mu_i)/T} \simeq \sum_i e^{\mu_i/T} \frac{d_i}{2\pi^2 T^3} \int dk\, k^2 e^{-\epsilon_i/T}$$

The pressure then becomes:

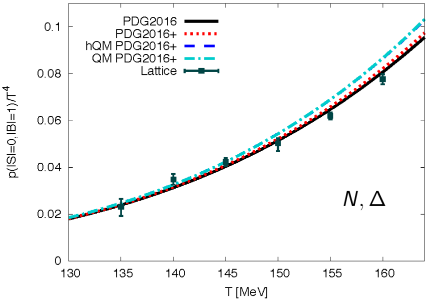
$$P(T, \frac{\mu_B}{T}, \frac{\mu_S}{T}) = P_{00}^{BS} + P_{10}^{BS} \cosh(\frac{\mu_B}{T}) +$$
$$+ P_{01}^{BS} \cosh(\frac{\mu_S}{T}) +$$
$$+ P_{11}^{BS} \cosh(\frac{\mu_B}{T} - \frac{\mu_S}{T}) +$$
$$+ P_{12}^{BS} \cosh(\frac{\mu_B}{T} - 2\frac{\mu_S}{T}) +$$
$$+ P_{13}^{BS} \cosh(\frac{\mu_B}{T} - 3\frac{\mu_S}{T})$$

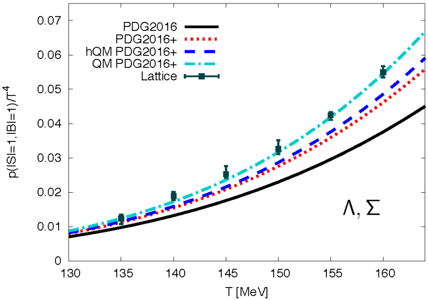


P. Alba, PP et al. arXiv: 1702.01113 [hep-lat]

Partial pressures: $|S| = 0, 1$ baryons

Comparison between Lattice QCD and HRG for different lists:



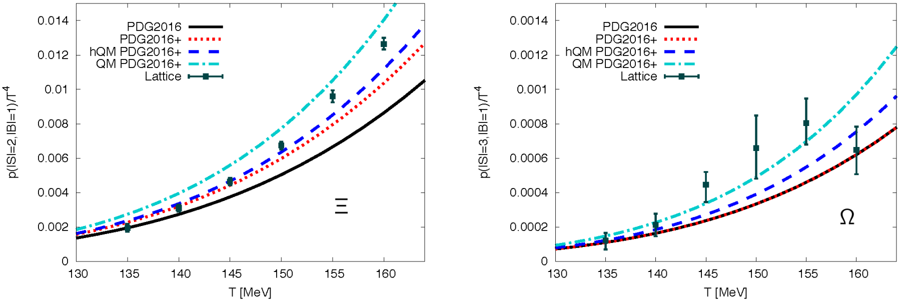


- $|S| = 0$: All lists give very good agreement
- $|S| = 1$: Need for QM states

P. Alba, PP et al. arXiv: 1702.01113 [hep-lat]

Partial pressures: $|S| = 2, 3$ baryons

Comparison between Lattice QCD and HRG for different lists:

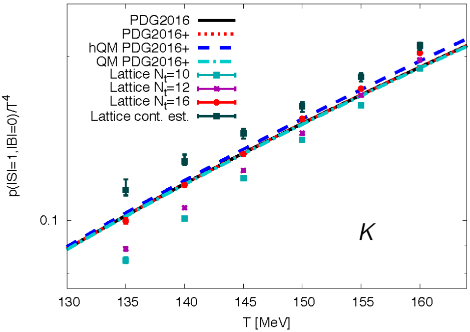


- $|S| = 2$: PDG 2016+ yields the best agreement
- $|S| = 3$: Large error bars, but probably need for QM states

P. Alba, PP et al. arXiv: 1702.01113 [hep-lat]

Partial pressures: Strange Mesons

Comparison between Lattice QCD and HRG for different lists:



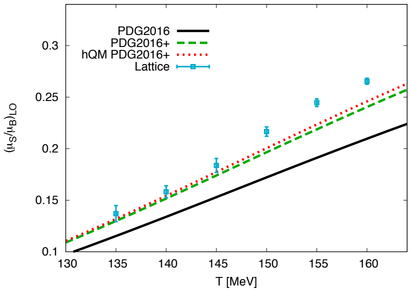
P. Alba, PP et al. arXiv: 1702.01113 [hep-lat]

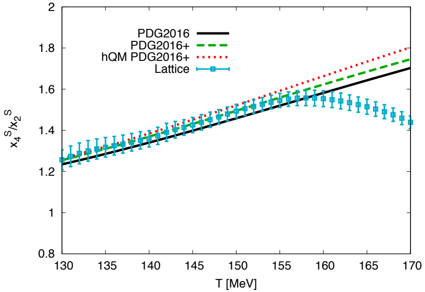
- All lists underestimate Lattice data for strange mesons

  → Still missing Kaons, or ideal HRG too simple?

Hadronic spectrum: a look back

The hQM and PDG2016+ lists certainly give a better compromise in reproducing strangeness observables



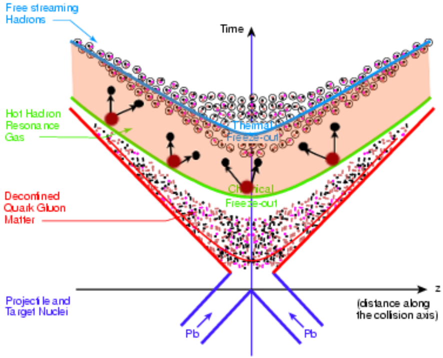


P. Alba, PP et al. arXiv: 1702.01113 [hep-lat]

Agreement up to $T \simeq 145 - 150\,$MeV is satisfactory

Freeze-out parameters extraction

A note on resonance decays



Partial chemical equilibrium

- Most hadronic states **decay into the few stable ones**
- Final spectra of stable particles are largely affected by feed down

Hadronic decays

- Information on the **decay properties (BR)** of hadrons is necessary
- States from QM have no info (even PDG ones have very little in some cases)
  - **Ongoing work:** extrapolate BR from known PDG states

Fluctuations of conserved charges

The fluctuations are thermodynamic quantities (**susceptibilities**):

$$\chi_{ijk}^{BSQ} = \left.\frac{\partial^{i+j+k}\left(P/T^4\right)}{\partial\left(\mu_B/T\right)^i \, \partial\left(\mu_S/T\right)^j \, \partial\left(\mu_Q/T\right)^k}\right|_{\vec{\mu}=0}$$

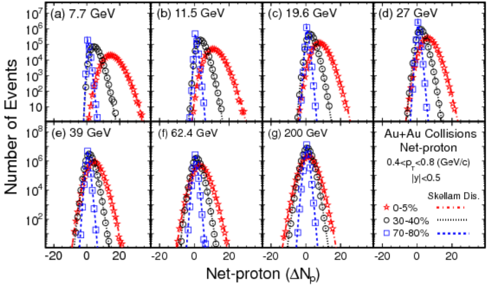
with chemical potentials defined as:

$$\mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q$$
$$\mu_d = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q$$
$$\mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S$$

Fluctuations of conserved charges

- Susceptibilities are related to moments of distribution measured in experiments

$$mean : M = \chi_1 \qquad variance : \sigma^2 = \chi_2$$
$$skewness : S = \chi_3/\chi_2^{3/2} \qquad kurtosis : \kappa = \chi_4/\chi_2^2$$



STAR Collaboration: Phys.Rev.Lett. 112 (2014) 032302

- They can be calculated on the lattice
  F. Karsch, Central Eur.J.Phys. 10 (2012) 1234-1237

Freeze-out

- Ratios of susceptibilities can be compared to experiment to extract freeze-out parameters
- This has been done both from HRG (resonance decays + acceptance cuts taken into account) and directly from the lattice

  P. Alba et al., Physics Letters B 738 (2014) 305310 (2014)
- Extraction of freeze-out parameters from lattice using fluctuations of B and Q yields a temperature $T_{\mathrm{fo}} \simeq 148\,\mathrm{MeV}$

  S. Borsanyi et al., Phys. Rev. Lett. 113, 052301 (2014) , A. Bazavov et al., Phys. Rev. D 93, 014512 (2016)
- **Will the same analysis for strangeness yield the same temperature?**

Freeze-out of charged Kaons

A first principle determination

Data for Kaons are becoming available for the Beam Energy Scan

$\Rightarrow$ **Can we isolate this contribution on the lattice?**

It is possible to further refine the decomposition for the first time:

$$P_S(\hat{\mu}_B, \hat{\mu}_S) = \dots + P_{011} \cosh(\hat{\mu}_S + \hat{\mu}_Q) + \dots$$

Partial pressure of $K^{+/-}$:

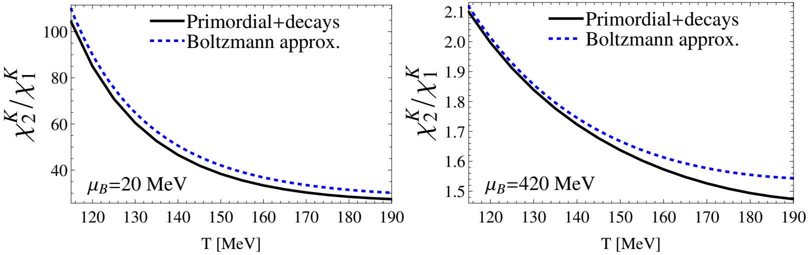
$$\boxed{P_{K^{+/-}} = P_{011} \cosh(\hat{\mu}_S + \hat{\mu}_Q)}$$

And fluctuations ratios are:

$$\frac{\chi_o^K}{\chi_e^K} = \frac{\cosh(\hat{\mu}_S + \hat{\mu}_Q)}{\sinh(\hat{\mu}_S + \hat{\mu}_Q)} \qquad \frac{\chi_e^K}{\chi_e^K} = 1 = \frac{\chi_o^K}{\chi_o^K}$$

Freeze-out of charged Kaons

A first principle determination



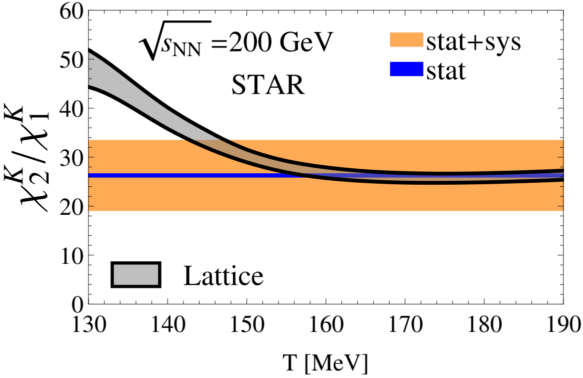
J. Noronha-Hostler, P.P. et al. [arXiv:1607.02527]

- Boltzmann approximation for lower order ratios provides results very similar to full contribution (primordial kaons + resonance decays)

$\Rightarrow$ **It is safe to extract such ratios from the lattice**

Freeze-out of charged Kaons

A first principle determination



J. Noronha-Hostler, P.P. et al. [arXiv:1607.02527]
STAR data: Ji Xu at SQM 2016

- Experimental error is too large to allow us to draw conclusions

Conclusions

Constraining the hadronic spectrum

- Lattice results for partial pressures allow one to determine whether additional states are missing, and in which family
  - QM states necessary for $|S| = 1, 3$
  - Still missing Kaons
- Need to test how additional states (with decays) impact on freeze-out parameters extraction

Freeze-out of charged Kaons

- Lattice could give a final response to inquiries on kaons freeze-out, provided that experimental errors are under control