Strange partial pressures from Lattice QCD

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Strangeness in Quark Matter 2016
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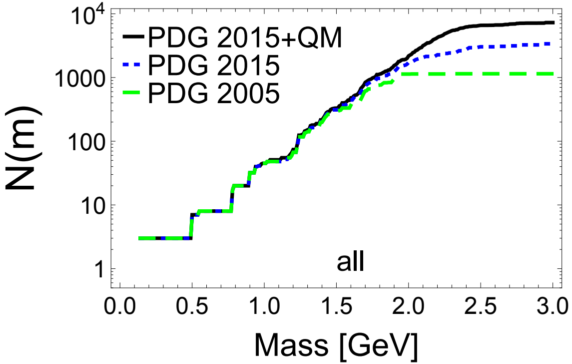
Outline

Hagedorn: Exponentially increasing mass spectrum

Counting up hadronic resonances and their degeneracies..

$$N^{HRG}(m) = \sum_i d_i \Theta(m - m_i)$$

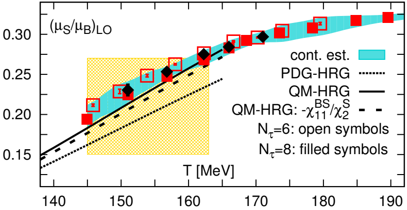


See also Broniowski,Florkowski,Glozman,PRD70,117503(2004); Lo et al. Phys.Rev. C92 (2015) no.5, 055206

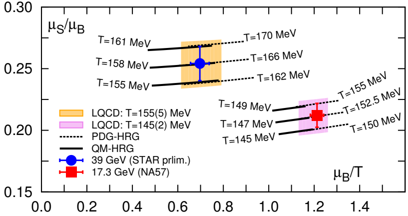
Determining the Number of Hadronic States

Quark Model states*..

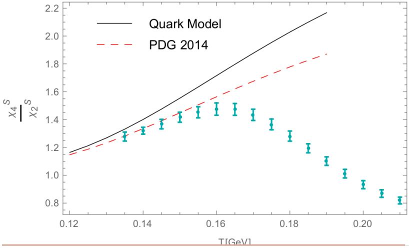
Converge μ_S/μ_B with Hadron Resonance Gas



Change the freeze-out line**



However, issues exist with χ_4^S/χ_2^S from [WB] collaboration (preliminary) calculations



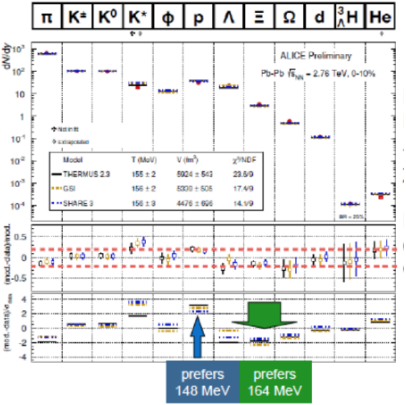
Strange vs. light chemical freezeout

- Can separate switching temperatures for light and strange hadrons be the solution?

  [WB] Collaboration Phys.Rev.Lett. 111 (2013) 202302

- Or adding in more resonances?

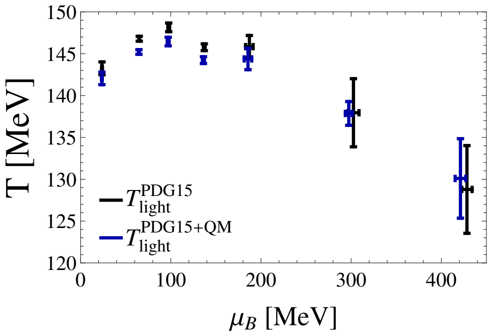
  From the QM states: Phys.Rev.Lett. 113 (2014) no.7, 072001
  or Hagedorn States: JNH and Greiner, Nucl.Phys. A931 (2014) 1108-1113, arXiv:1405.7298



Michele Floris Quark Matter 2014

Quark Models+decays effect on freeze-out

Freeze-out line from susceptibilities (net-p and net-Q)



- Thermal fits coming soon
- Still two separate temperatures for strange and light?
- First, we need to know the number of strange particles

Pressure by Baryon Number, Strangeness, Charge

Pressure comes from: $p^{HRG}/T^4 = \frac{1}{VT^3}\sum_i \ln Z_i(T,\mu)$
such that

$$\ln Z_i^{M/B} \simeq \frac{d_i}{2\pi^2}\left(\frac{m_i}{T}\right)^2 \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k^2} K_2\left(\frac{km_i}{T}\right) \cosh\left[k\left(B_i\mu_B + S_i\mu_S + Q_i\mu_Q\right)/T\right]$$

E.g. for strange hadrons (can separate by any BSQ, though)

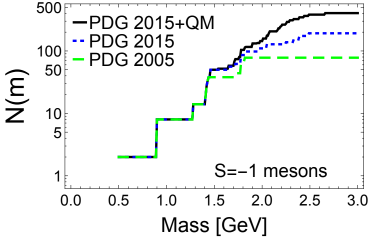
$$\begin{aligned} P_S(\hat\mu_B,\hat\mu_S) &= P_{0|1|}\cosh(\hat\mu_S) \\ &+ P_{1|1|}\cosh(\hat\mu_B-\hat\mu_S) \\ &+ P_{1|2|}\cosh(\hat\mu_B-2\hat\mu_S) \\ &+ P_{1|3|}\cosh(\hat\mu_B-3\hat\mu_S) \end{aligned}$$

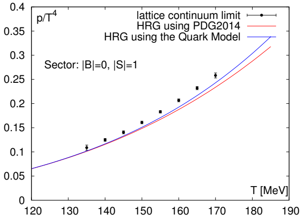
$$\begin{aligned} P_{0|1|} &= \chi_2^S - \chi_{22}^{BS} \\ P_{1|1|} &= \frac{1}{2}\left(\chi_4^S - \chi_2^S + 5\chi_{13}^{BS} + 7\chi_{22}^{BS}\right) \\ P_{1|2|} &= -\frac{1}{4}\left(\chi_4^S - \chi_2^S + 4\chi_{13}^{BS} + 4\chi_{22}^{BS}\right) \\ P_{1|3|} &= \frac{1}{18}\left(\chi_4^S - \chi_2^S + 3\chi_{13}^{BS} + 3\chi_{22}^{BS}\right) \end{aligned}$$

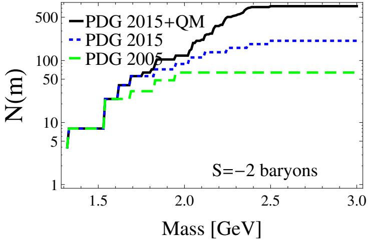
Note all $P_{B|S|}$ taken at the limit of $\mu_B = 0$

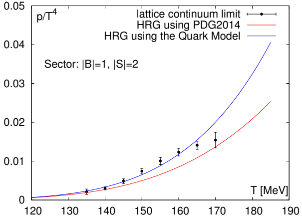
Light Mesons vs. $|S| = 3$ Baryons

Missing strange, mesons explain differences between *PDG*15 + *QM* and lattice for χ_4^S/χ_2^S!









Fluctuations of Conserved Charges

Susceptibilities

$$\chi_{lmn}^{BSQ} = \frac{\delta^{l+m+n} p/T^4}{\delta\left(\mu_B/T\right)^l \delta\left(\mu_S/T\right)^m \delta\left(\mu_Q/T\right)^n}$$

where the chemical potentials are related via:

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

Connecting the Beam Energy Scan to Lattice QCD

RHIC measures [STAR] Phys.Rev.Lett. 112 (2014) 032302

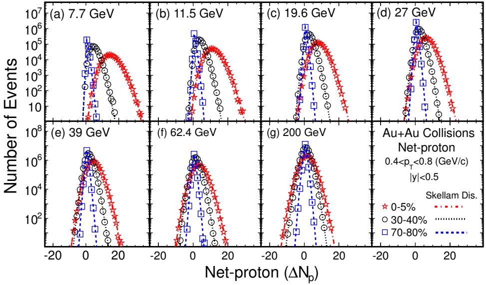
$$\textit{mean} : M = \chi_1 \qquad \textit{variance} : \sigma^2 = \chi_2$$

$$\textit{skewness} : S = \chi_3/\chi_2^{3/2} \qquad \textit{kurtosis} : \kappa = \chi_4/\chi_2^2$$

Lattice QCD calculates Karsch Central Eur.J.Phys. 10 (2012) 1234-1237

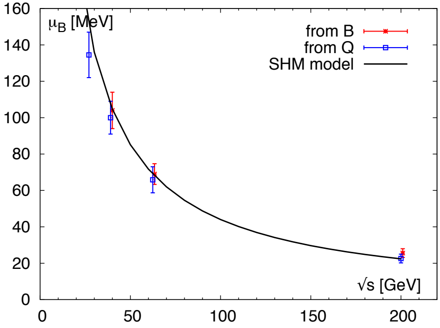
$$S\sigma = \chi_3/\chi_2 \qquad \kappa\sigma^2 = \chi_4/\chi_2$$

$$\sigma^2/M = \chi_2/\chi_1 \qquad S\sigma^3/M = \chi_3/\chi_1$$



Freeze-out baryon chemical potential from Lattice

Ratios of baryon susceptibilities can be compared to experimental data



[WB] Phys.Rev.Lett. 113 (2014) 052301

Effects from acceptance cuts, decays, finite size effects etc (see end of talk)

Partial pressure of charged kaons

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

$$P_{K^{+/-}} = P_{0|1||1|} \cosh(\hat{\mu}_S + \hat{\mu}_Q) \text{ where } P_{0|1||1|} = \chi_2^S - \chi_{22}^{BS}$$

Taking derivatives:

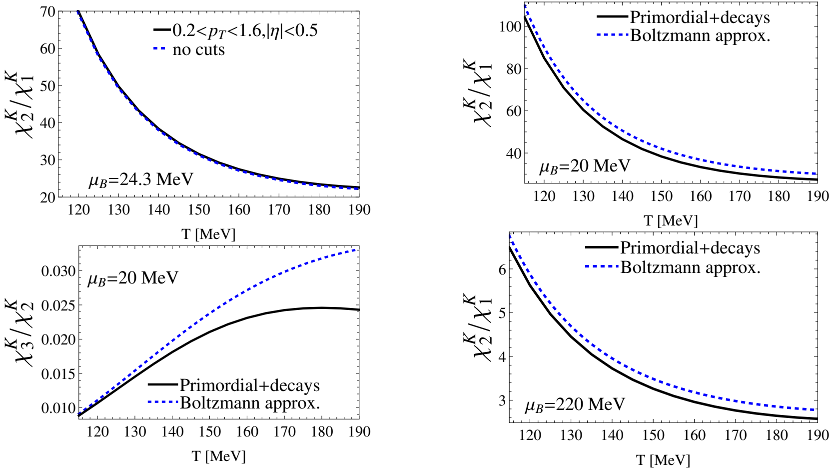
$$\frac{\chi_2^K}{\chi_1^K} = \frac{\cosh(\hat{\mu}_S + \hat{\mu}_Q)}{\sinh(\hat{\mu}_S + \hat{\mu}_Q)}$$

$$\frac{\chi_3^K}{\chi_2^K} = \frac{\sinh(\hat{\mu}_S + \hat{\mu}_Q)}{\cosh(\hat{\mu}_S + \hat{\mu}_Q)}$$

$$\frac{\chi_4^K}{\chi_2^K} = \frac{\chi_e^K}{\chi_e^K} = 1$$

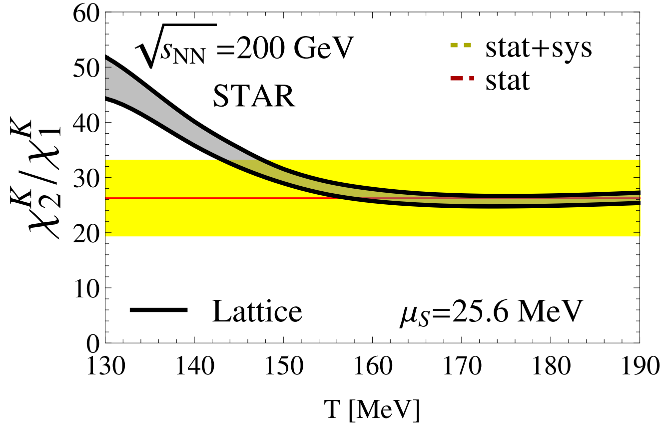
Effects of decays, full statistics, acceptance cuts

Acceptance/decays small effect for χ_2/χ_2 but higher order cumulants necessitate decays!



Waiting on Smaller Experimental Error Bars

Only can see a minimum $T_{strange}^{min} > 148$ MeV.



[WB] collaboration preliminary
STAR data from Ji Xu on Tuesday

Significance of extra (massive) resonances

Extra (massive) resonances...

- $\Downarrow \eta/s$ and $\Uparrow \zeta/s$ at the transition region
  JNH, Noronha, Greiner PRL103(2009)172302; PRC86(2012)024913; Kadam, Mishra NPA934(2014)133-147; Pal PLB684(2010)211-215
- allows dynamical chemical equilibrium after phase transition
  JNH, Greiner, Shovkovy PRL100(2008)252301; JNH et al PRC81(2010)054909, Beitel, Greiner, Stoecker arXiv:1601.02474
- improve thermal fits JNH, Ahmad, Noronha, Greiner Phys.Rev. C82 (2010) 024913
- affect the flow harmonics at high switching temperatures
  JNH, et al Phys.Rev. C89 (2014) no.5, 054904 ;Paquet et al,Phys.Rev. C93 (2016) no.4, 044906
- affect the order parameters of the phase transition
  Europhys. Lett. 76,402(2006); JPG36 (2009) 095005; NPA781,150(2007); PRC78,034916(2008); PRC79,034905(2009); PRC79,054913(2009); PRE86,061107(2012)
- affect HRG matching to the Lattice EOS
  JNH, Noronha, Greiner PRL103(2009)172302; Majumder, Muller PRL105(2010)252002 ; Bluhm et al, NPA929(2014)157-168

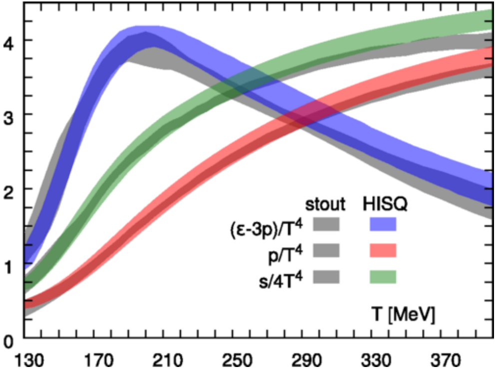
Conclusions

- Partial pressures indicate missing strange mesons beyond the Quark Model states
- Quark Models states lower the light freeze-out temperature (from susceptibilities)
- Charged Kaon fluctuations data can be extracted from Lattice QCD
- Will the light and strange freeze-out temperatures converge on the lattice?

  Bellwied et al, Phys.Rev.Lett. 111 (2013) 202302
- Looking forward to smaller experimental error bars

The Success of Lattice QCD

Equation of State agrees for stout (WB) and HISQ (HotQCD) actions



[WB] Phys.Lett. B730 (2014) 99-104
[HotQCD] Phys.Rev. D90 (2014) 094503