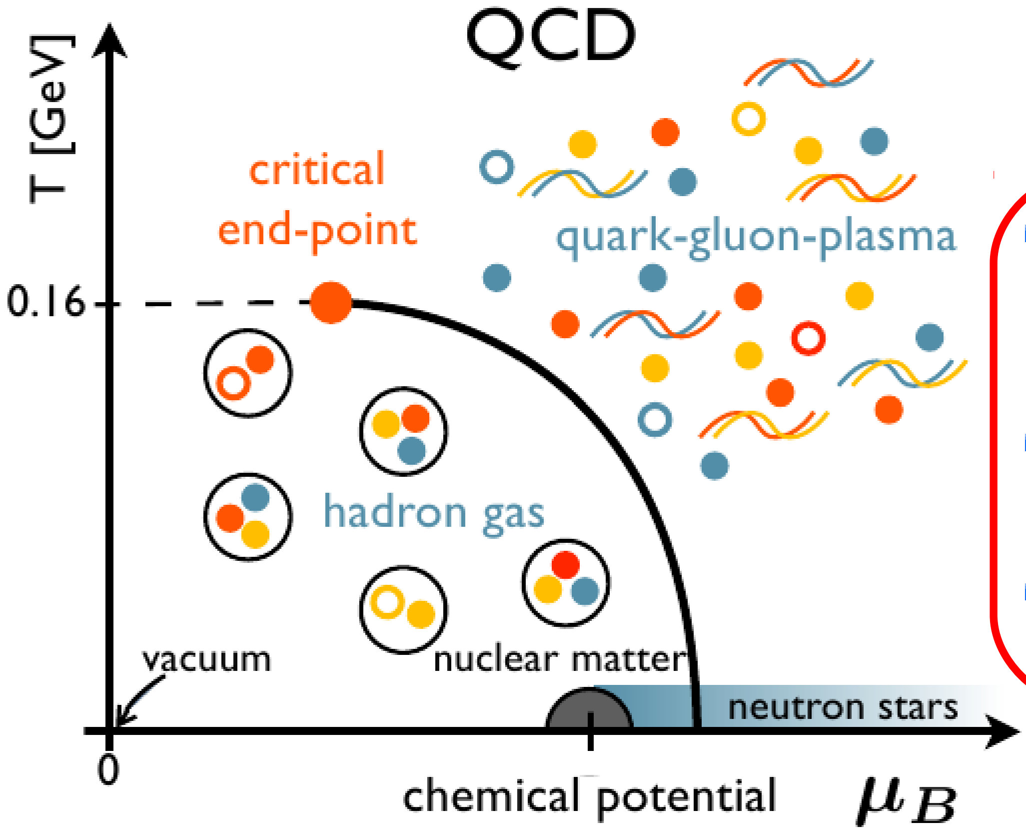
# Strangeness and charm content of strongly interacting matter

Frithjof Karsch, BNL/Bielefeld

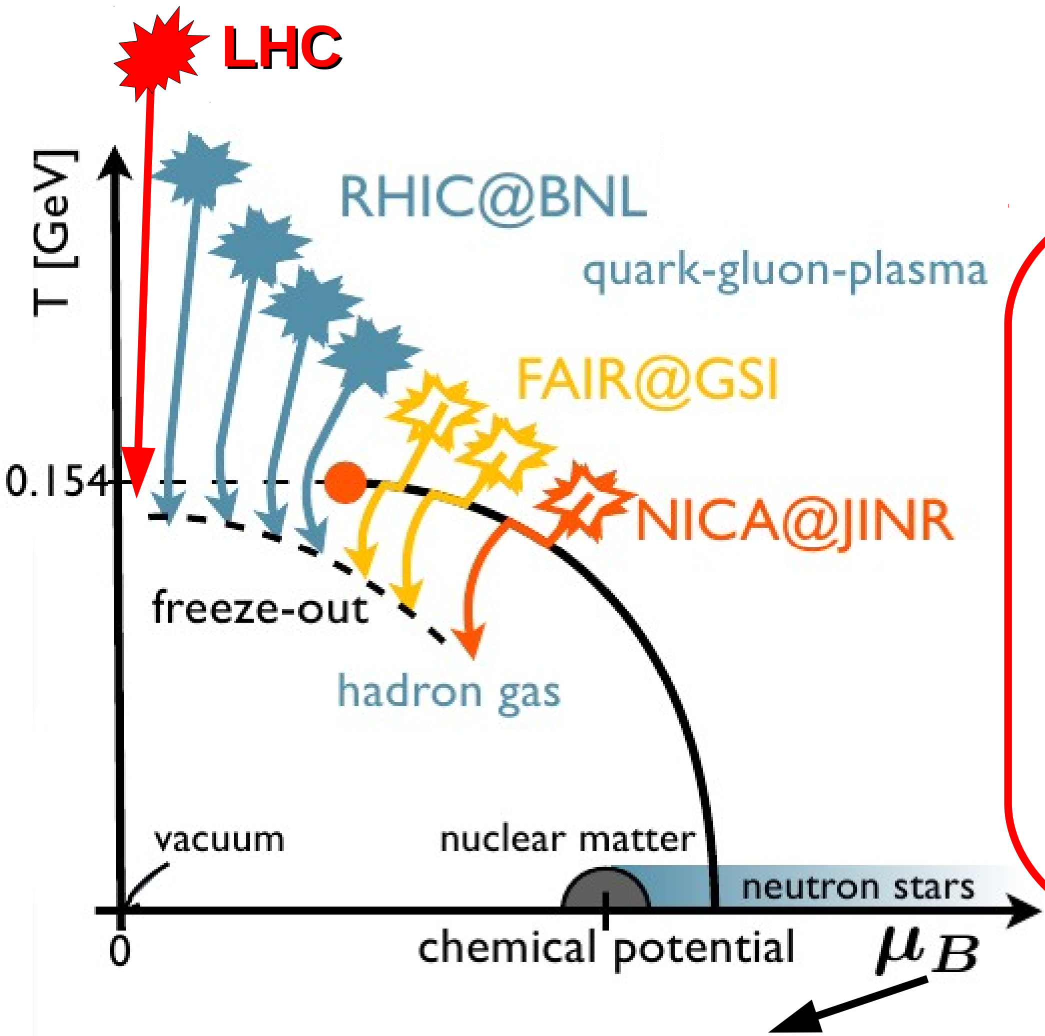



## Key Questions

- What are the phases of strongly interacting matter, and what role do they play in the cosmos?
- What does QCD predict for the **properties of strong interacting matter**?
- What governs the transition of quarks and gluons into pions and nucleons?

– the physics/thermodynamics of strong interaction matter is described by the theory of strong interactions – Quantum Chromo Dynamics (QCD)
– understanding highly non-perturbative/collective effects like phase transitions requires the application of numerical techniques – lattice QCD

# QCD thermodynamics & heavy ion collisions

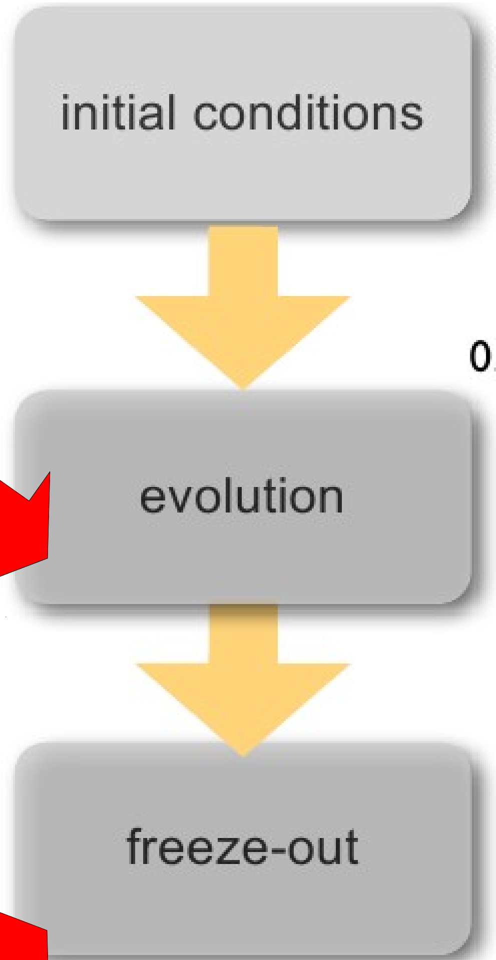


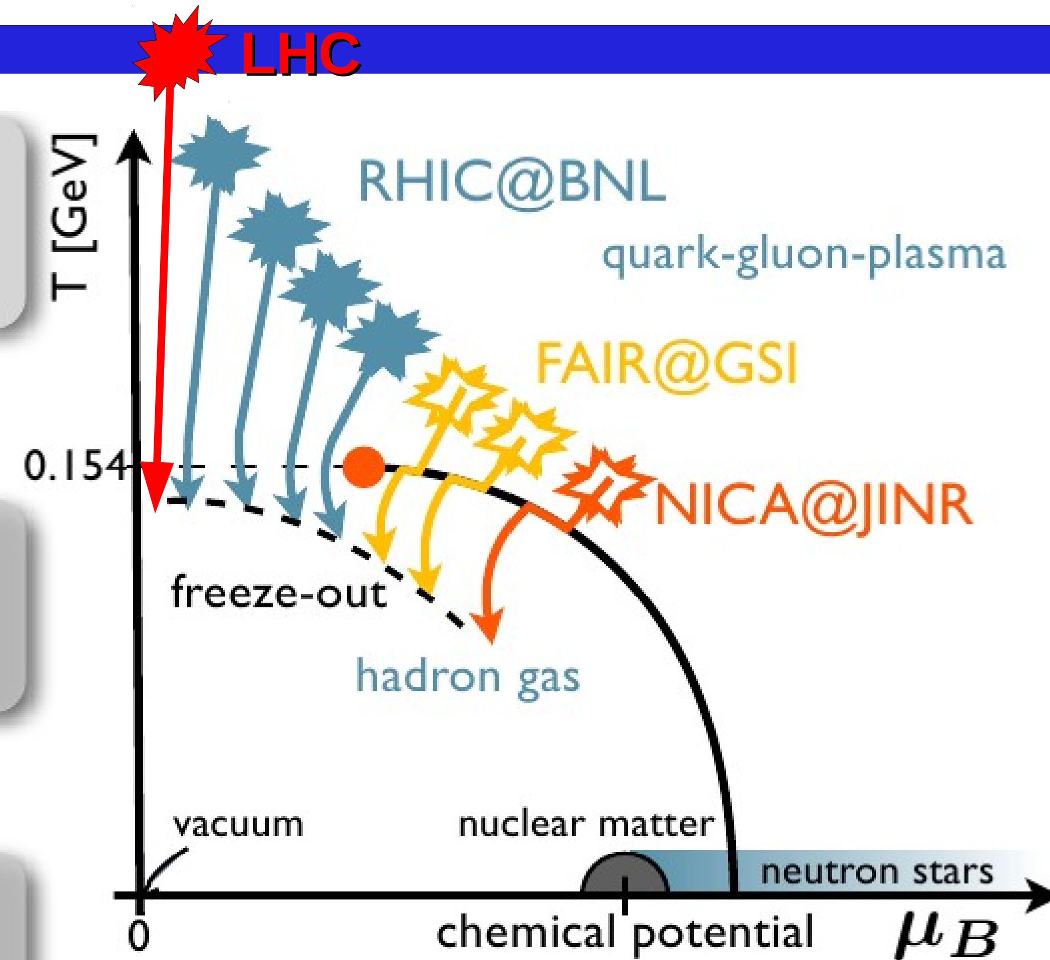

**Key Experiments**

- heavy ion experiments with varying incident beam energies (RHIC beam energy scan) probe the structure of the QCD phase diagram
  - – lower beam energy
    → more efficient stopping of nuclei
    → higher net baryon density
- search for a 2nd order critical point followed by a line of 1st order phase transitions

chemical potentials for baryon number, electric charge, strangeness control net density of these conserved charges

# Exploring the QCD phase diagram




controlled by the **QCD equation of state,** $T_c$

**expectation:**
**freeze-out** close to QCD transition line

**observable consequences:**
freeze-out/hadronization pattern of mesons and baryons, controlled by $T_f, \mu_B, \mu_S$

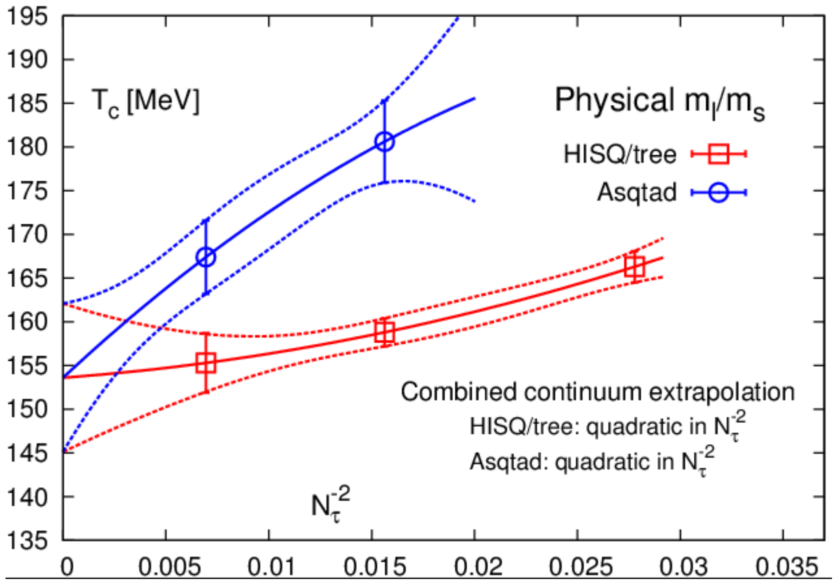
– LHC: establish contact with the QCD PHASE transition

– RHIC: locate/provide evidence for the QCD critical point

# Outline

- **Equation of state and transition temperature**
  - continuum extrapolated transition temperature and equation of state
- **Charge fluctuations and freeze-out parameter;**
  the RHIC search for the critical point
  - evidence for many new strange and charmed baryons
  - using electric charge fluctuations to search for the critical point

# Equation of state and transition temperature




$$T_c = (154 \pm 9)\ \mathrm{MeV}$$

– well defined pseudo-critical temperature
– quark mass dependence of susceptibilities consistent with O(4) scaling

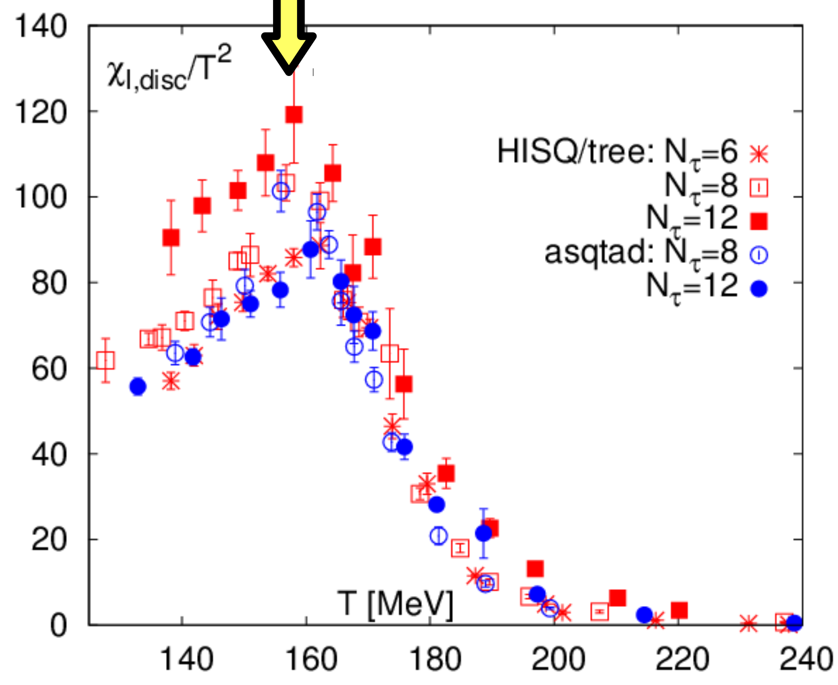
A. Bazavov et al. (hotQCD),
Phys. Rev. D85, 054503 (2012), arXiv:1111.1710

lattice: $N_\sigma^3 \cdot N_\tau$
temperature: $T = 1/N_\tau a$

Critical temperature from location
Of peak in the fluctuation of the
chiral condensate (order parameter):

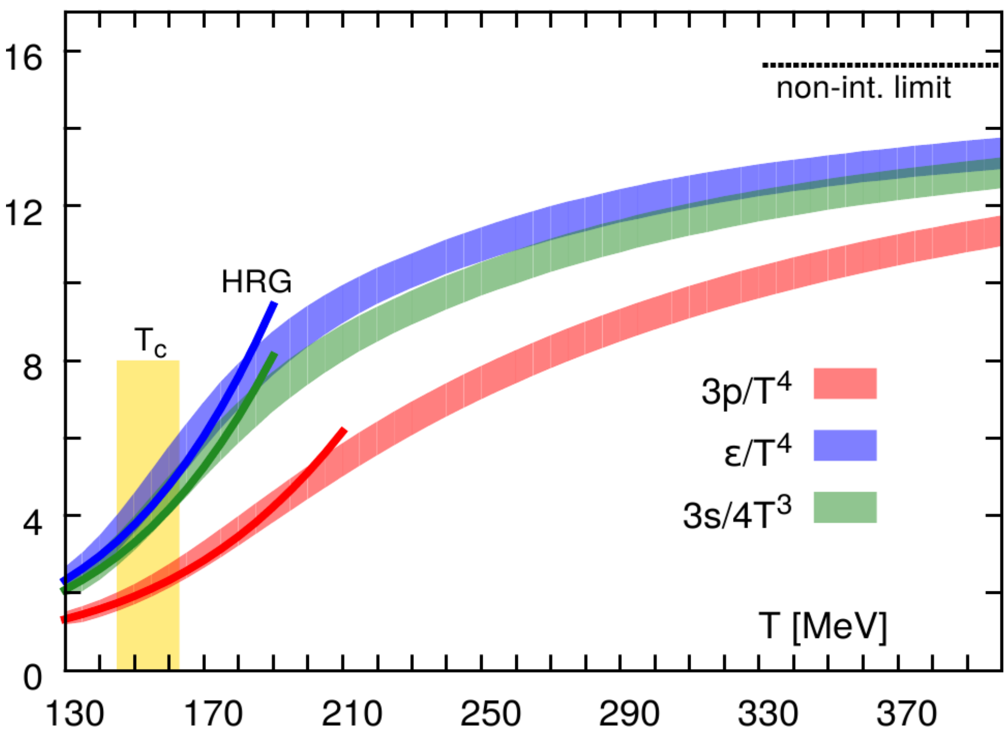
**Chiral susceptibility**

$$\chi_l = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m_l^2} = \chi_{l,disc} + \chi_{l,con}$$

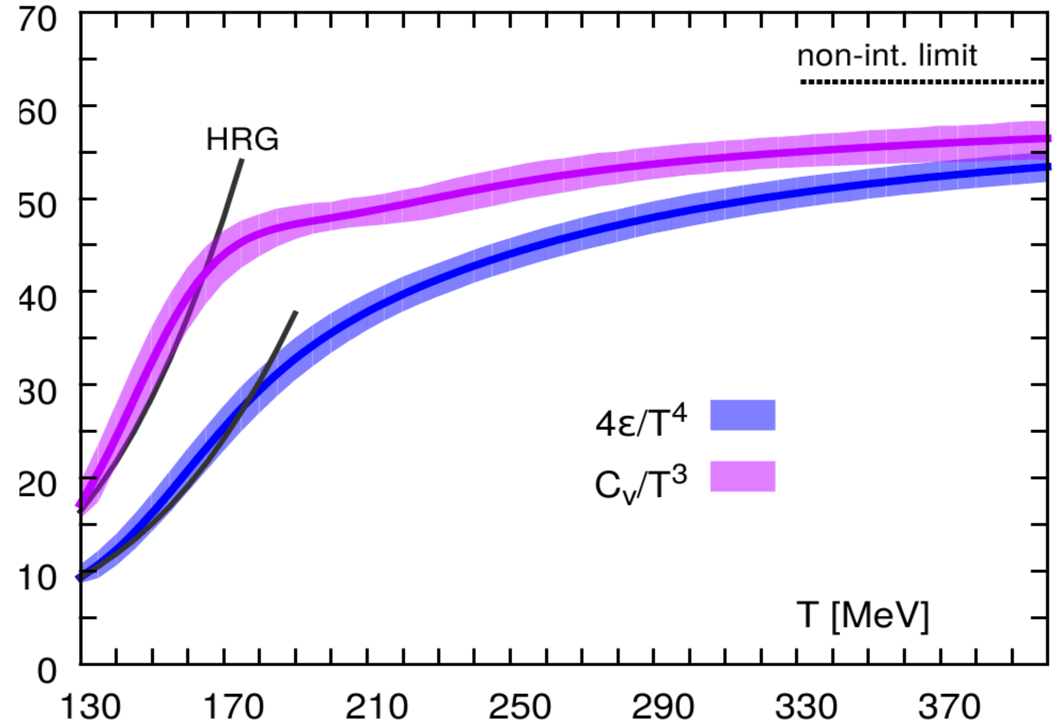


# Equation of state of (2+1)-flavor QCD

**pressure**, **entropy** & **energy** density




**specific heat** & **energy density**




hotQCD , arXiv:1407.6387

– improves over earlier hotQCD calculations:
A. Bazavov et al., Phys. Rev. D80, 014504 (2009)

– consistent with:S. Borsanyi et al., PL B730, 99 (2014)

– up to the crossover region the QCD EoS agrees well with hadron resonance gas (HRG) model calculations; **However**, QCD results are systematically above HRG

– **there is 'room for additional resonances' not accounted for by the HRG model**

# QCD-EoS and the Hadron Resonance Gas (HRG)

HRG thermodynamics

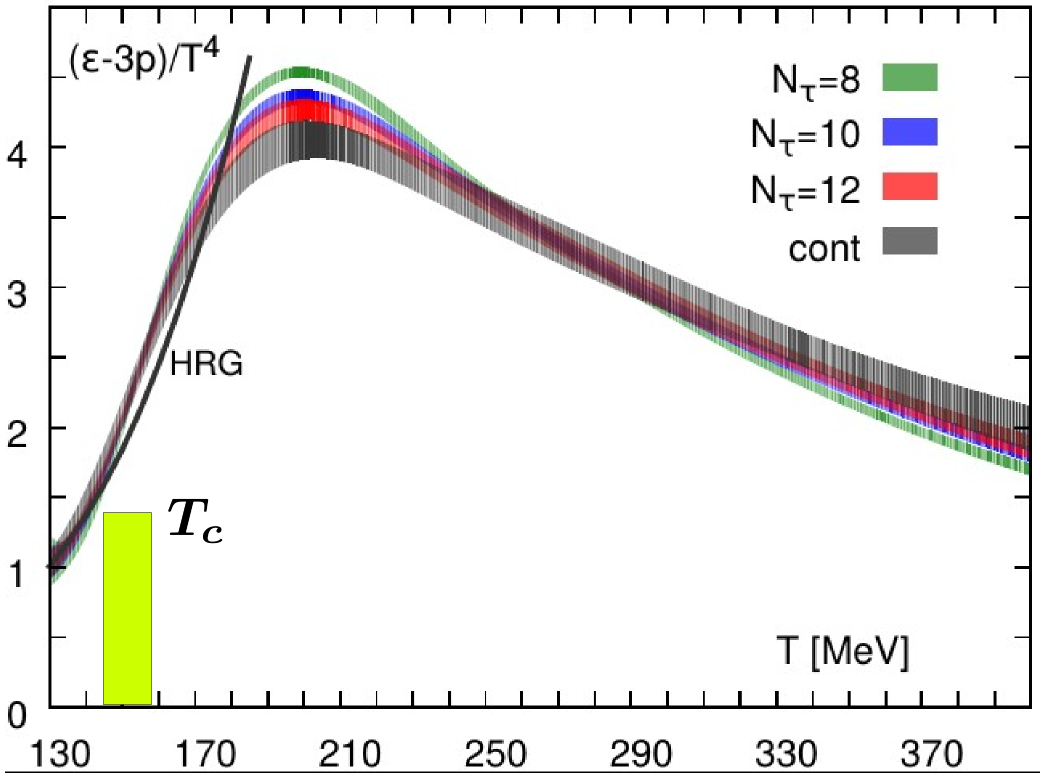
Pressure
$$\frac{P}{T^4} = \sum_{m\in mesons} \ln Z_m^b(T,V,\mu) + \sum_{m\in baryons} \ln Z_m^f(T,V,\mu)$$

Trace anomaly
$$\frac{\epsilon - 3P}{T^4} = T\frac{\mathrm{d}P/T^4}{\mathrm{d}T}$$

$$\left(\frac{\epsilon - 3P}{T^4}\right)_{QCD} > \left(\frac{\epsilon - 3P}{T^4}\right)_{HRG}$$

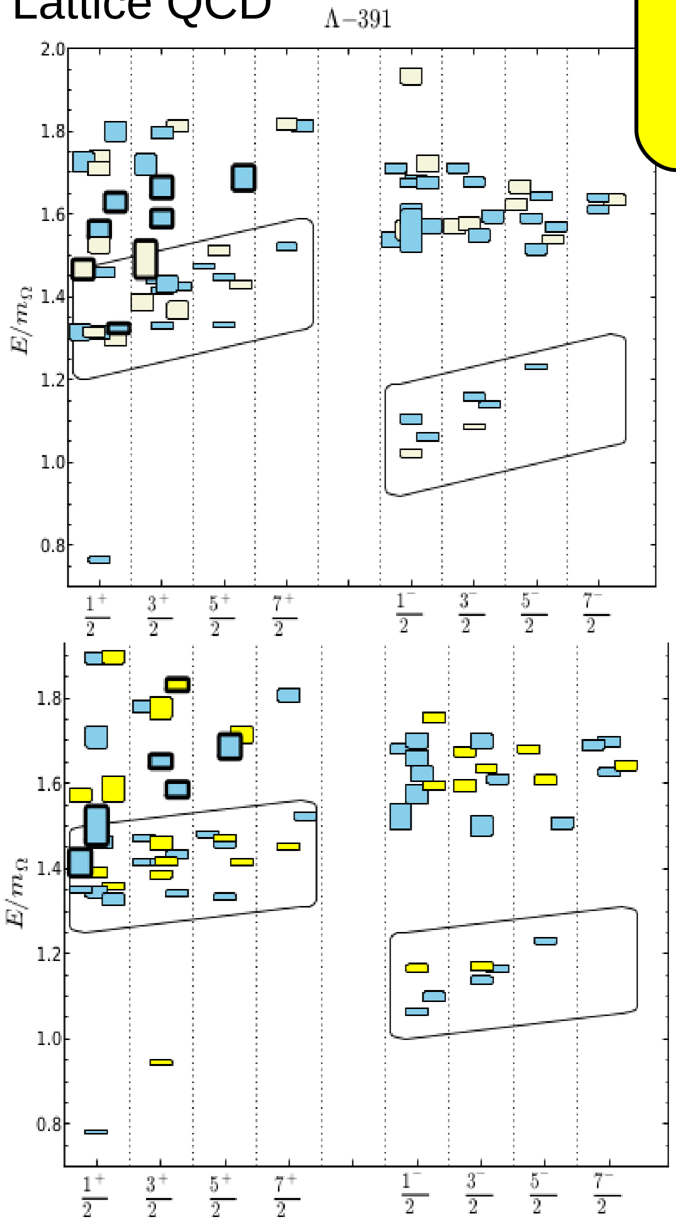
larger pressure, larger trace anomaly

**more resonances??**



# Probing the hadron spectrum using QCD thermodynamics

Lattice QCD




$$P_{tot} = \sum P_h$$

h=all hadrons

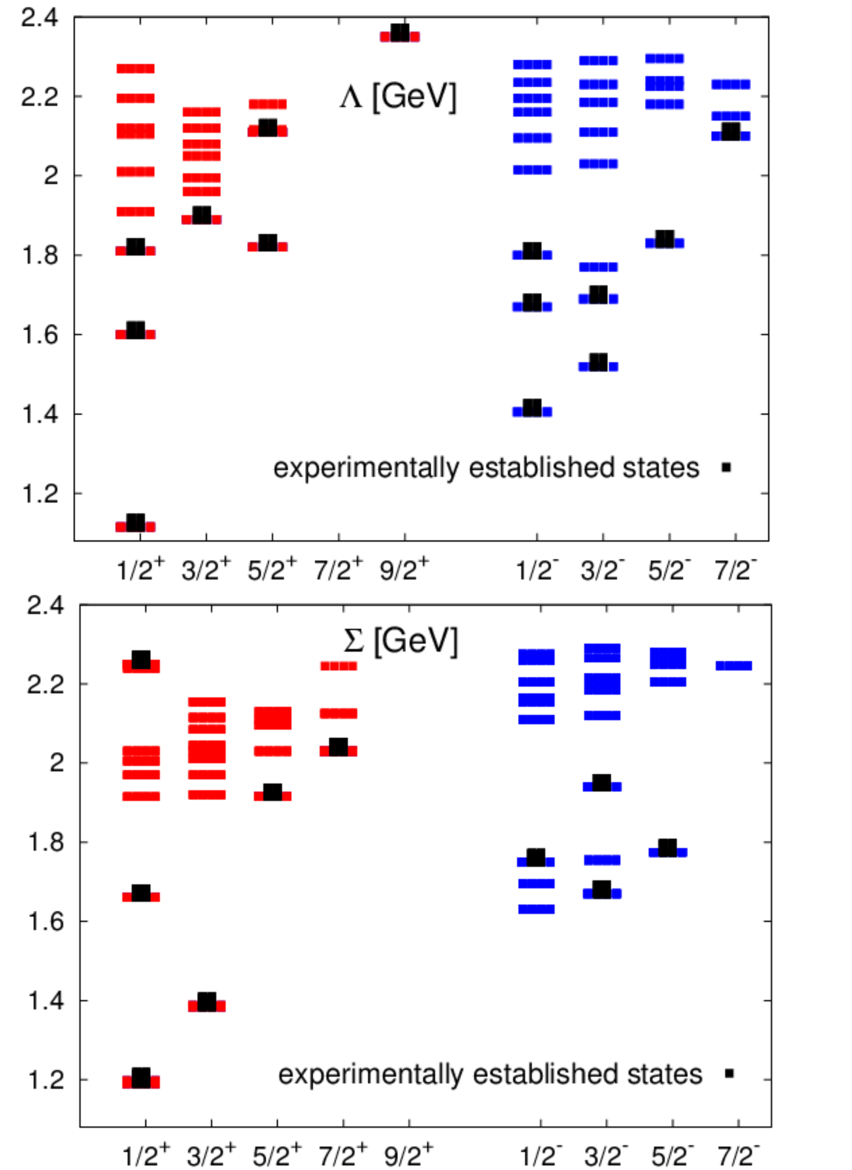
**strange baryons**

more strangeness

=

larger fluct.

Quark Model



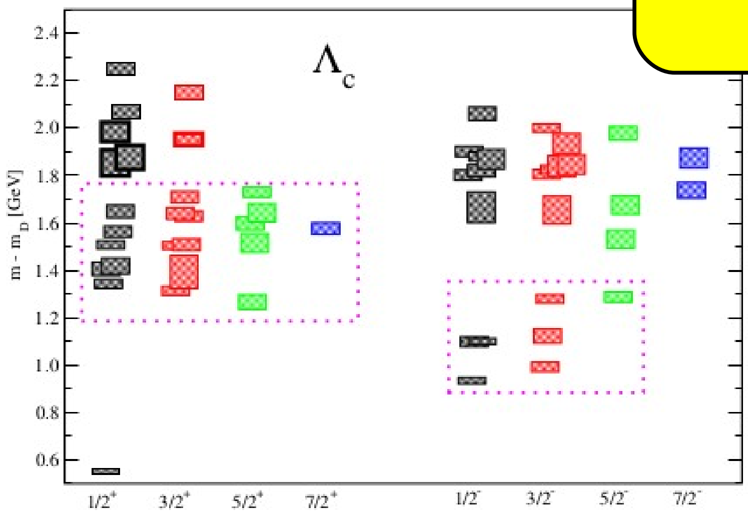

R. Edwards et.al., Phys. Rev D87, 054506 (2013)

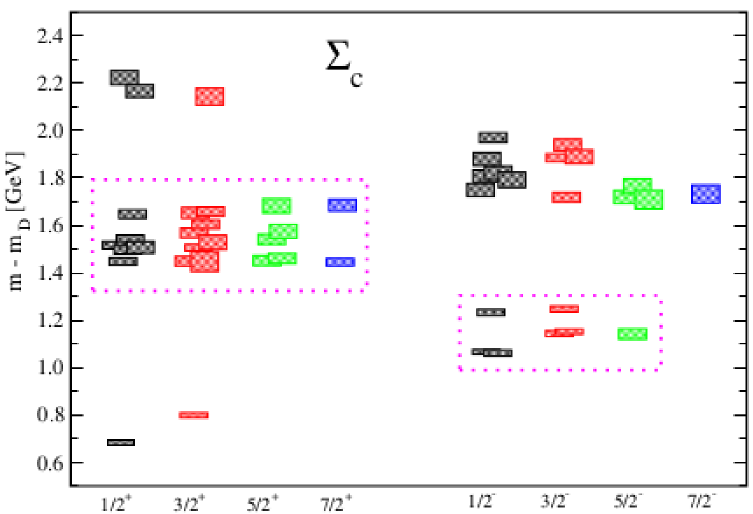
S. Capstick, N. Isgur, Phys. Rev. D34, 2809 (1986)

# Probing the hadron spectrum using QCD thermodynamics

$$P_{tot} = \sum_{\text{h=all hadrons}} P_h$$

Lattice QCD




*M. Padmanath et.al., arXiv:1311.4806*

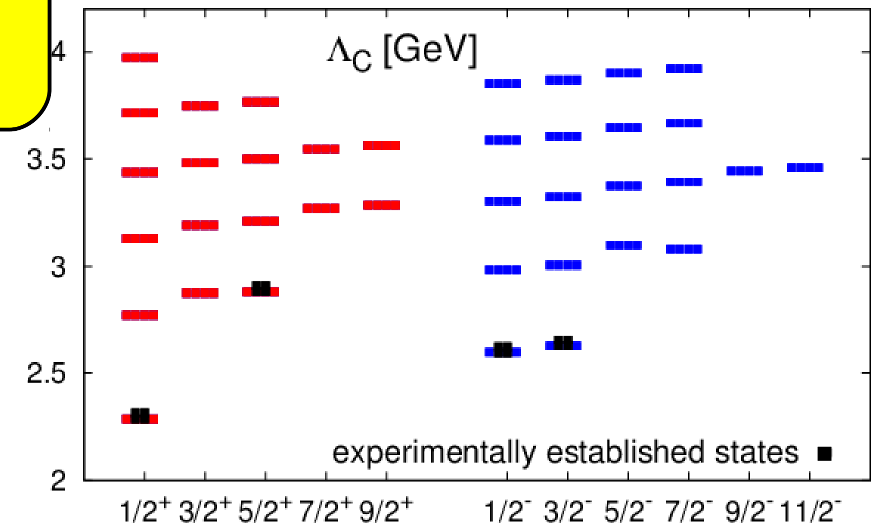
**charmed baryons**

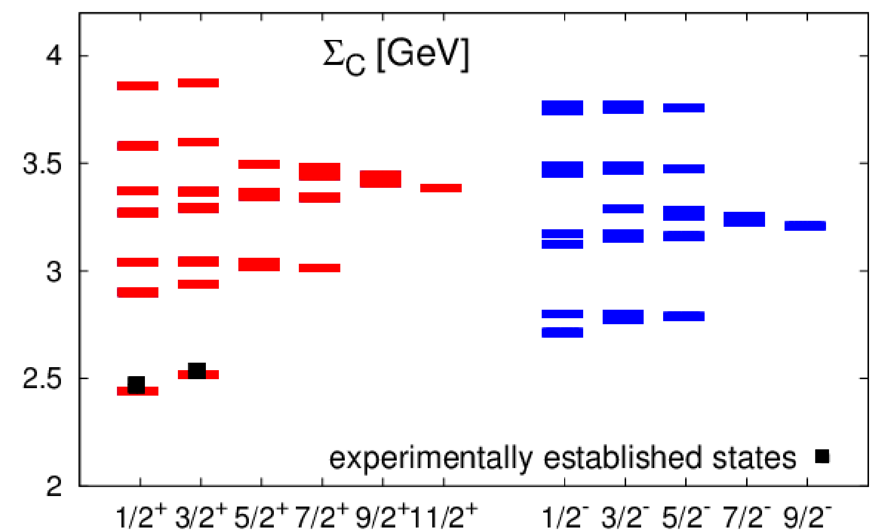
more charm

=

larger fluct.

Quark Model




*D. Ebert et. al., Eur. Phys. J. C66, 197 (2010); Phys. Rev. D84, 014025 (2011)*

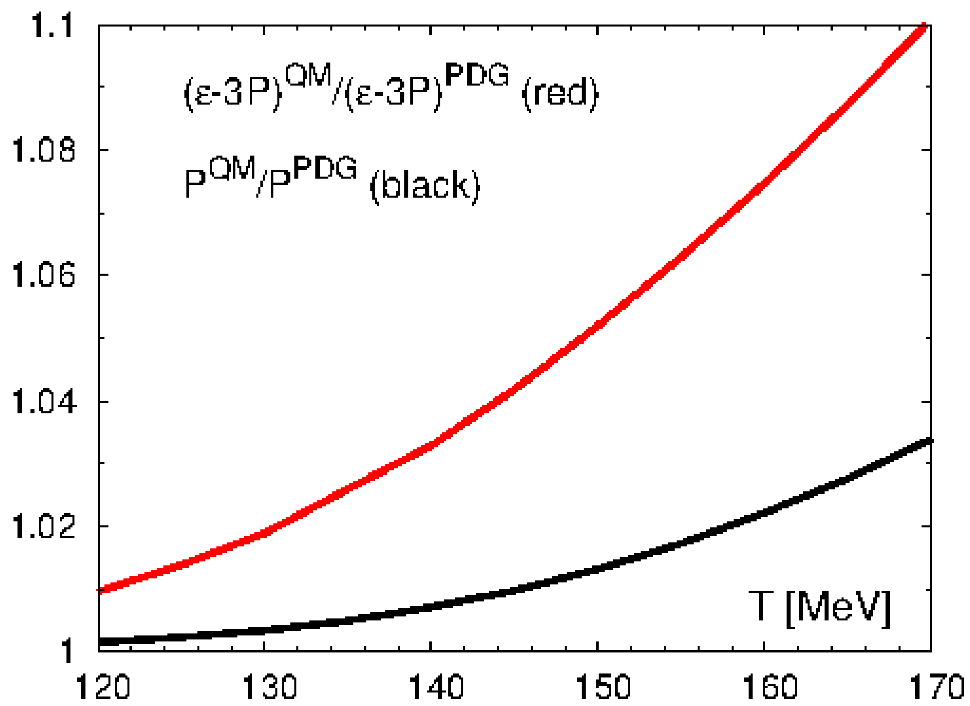
# Probing the hadron spectrum using QCD thermodynamics

– additional resonance in the hadron spectrum increase the pressure, energy density as well as trace anomaly

– charmed baryons are too heavy to have any impact on bulk thermodynamics

– additional strange baryons may increase the pressure by about 3% at T=160 MeV

– need to be more selective to see effects of additional strange and charmed hadronic resonances



# Fluctuations and Correlations: Susceptibilities

– probing the response of a thermal medium to an external field, i.e. variation of one of its external control parameters: $T$, $\mu$, $m_q$

(generalized) response functions == (generalized) susceptibilities

pressure: $$\frac{p}{T^4} \equiv \frac{1}{VT^3} \ln Z(V, T, \mu_{B,Q,S}, m_{u,d,s})$$

net number density: $$\chi_1^q = \frac{1}{VT^3} \frac{\partial \ln Z}{\partial \mu_q/T}$$

(quark) number susceptibility: $$\chi_2^q = \frac{1}{VT^3} \frac{\partial^2 \ln Z}{\partial (\mu_q/T)^2}$$

4th order cumulant: $$\chi_4^q = \frac{1}{VT^3} \frac{\partial^4 \ln Z}{\partial (\mu_q/T)^4}$$

mean    variance    kurtosis

generalized quark number susceptibilities:

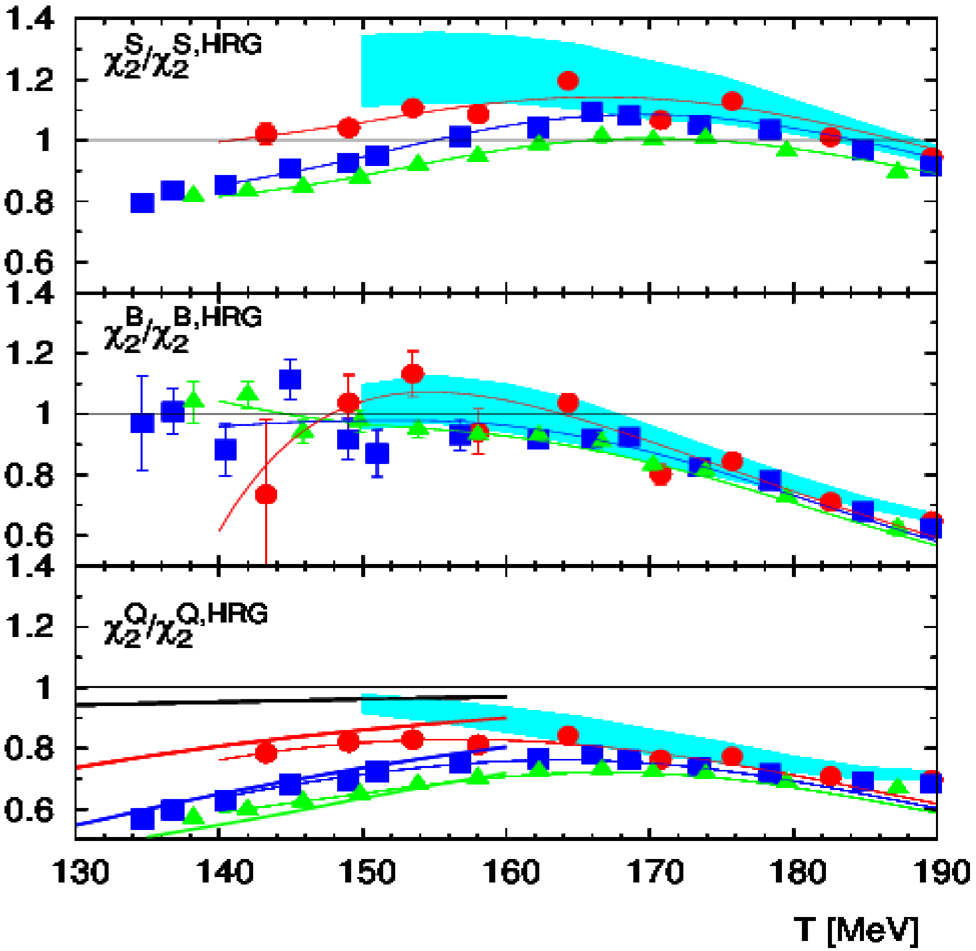
$$\frac{\partial^{i+j+k} p/T^4}{\partial \hat{\mu}_B^i \partial \hat{\mu}_Q^j \partial \hat{\mu}_S^k}$$

**evaluated at**

$$\hat{\mu}_{\mathbf{X}} \equiv \mu_{\mathbf{X}}/\mathbf{T} = 0$$

# Fluctuations: Hadron Resonance Gas vs. LQCD

Fluctuations and Correlations of net baryon number, electric charge, and strangeness:
A comparison of lattice QCD results with the hadron resonance gas model




A. Bazavov et al. [HotQCD Collaboration], Phys. Rev. D 86, 034509 (2012)

**O(20%) deviations from "ordinary" HRG model expectations**

– continuum extrapolated results (band) for quadratic fluctuations of conserved charges

– comparison with HRG model calculations

– quantify validity range of the HRG model

– **evidence for "additional" resonances ?**

– **HRG model depends on input hadron spectrum**

# Correlations and Fluctuations: HRG vs. LQCD

– construct QCD observables that would project onto specific quantum numbers, if QCD = HRG

E.g.: HRG pressure:

$$\frac{P}{T^4} = \sum_{m \in mesons} \ln Z^b_m(T,V,\mu) + \sum_{m \in baryons} \ln Z^f_m(T,V,\mu)$$

HRG baryon susceptibilities:

$$\chi^{BQSC}_{nmkl} = \sum_{m \in baryons} \left. \frac{\partial^{(n+m+k+l)} \ln Z^f_m(T,V,\mu)}{\partial \mu_B^n \partial \mu_Q^m \partial \mu_S^k \partial \mu_C^l} \right|_{\mu=0}$$

**sum "knows" about spectrum**

# Correlations and Fluctuations: HRG vs. LQCD

– in a HRG charge fluctuations obey some simple relations because B, Q, S quantum numbers are integer; –- or even restricted to |B|=0, 1

– baryonic part of the pressure:

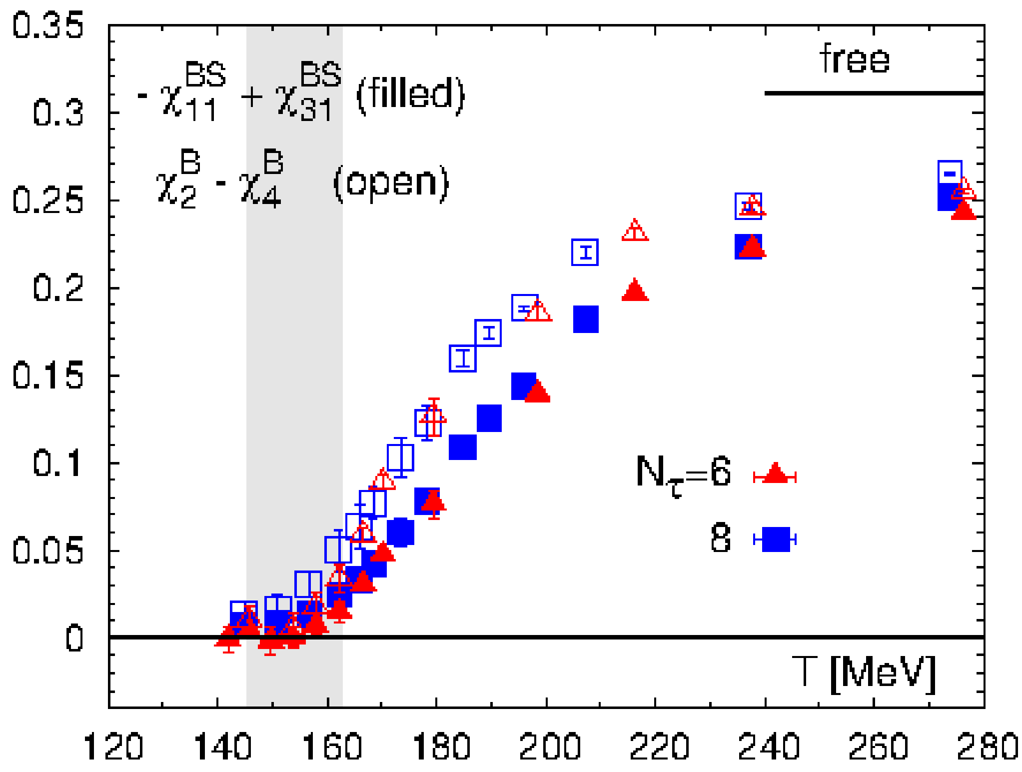
$$\frac{P^{baryon}}{T^4} = \sum_{m\in baryons} f(T,m)\cosh(B\mu_B + S\mu_S + Q\mu_Q)$$

$$\chi_{nmkl}^{BQSC} = \sum_{m\in baryons} \left.\frac{\partial^{(n+m+k+l)} \ln Z_m^f(T,V,\mu)}{\partial\mu_B^n \partial\mu_Q^m \partial\mu_S^k \partial\mu_C^l}\right|_{\mu=0}$$

$$\chi_{amkl}^{BQSC} = \chi_{bmkl}^{BQSC} \;,\; a>0,\; b>0, a+b \text{ even}$$

e.g. $\chi_{11}^{BS} = \chi_{31}^{BS}$ , $\chi_2^B = \chi_4^B$ .... valid in any HRG (irresp. of the spectrum)

# Correlations and Fluctuations: HRG vs. LQCD




- HRG model description of fluctuations and correlations breaks down above T=160 MeV
- this also is the case for the strange baryon sector

A. Bazavov et al. (BNL-Bielefeld-CCNU), Phys. Rev. Lett. 111, 082301 (2013)

# Correlations and Fluctuations: HRG vs. LQCD

– suitable combinations of susceptibilities allow to construct observables that would project onto the pressure in a specific hadron sectors,
iff a HRG model description is still valid

– e.g. $$M_S = \chi_2^S - \chi_{22}^{BS}$$ pressure of open strange mesons

$$B_{|S|=1} = \frac{1}{2}\left(\chi_4^S - \chi_2^S + 5\chi_{13}^{BS} + 7\chi_{22}^{BS}\right)$$

pressure of open strange baryons with |S|=1

etc.....

these observables are not unique, e.g.

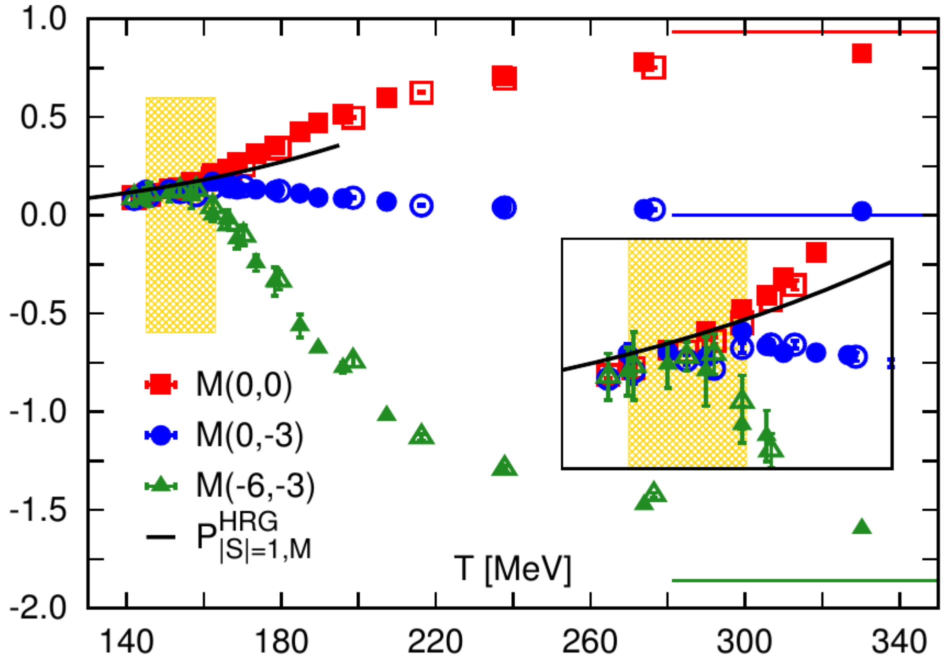
$$M_S(c_1,c_2) = \chi_2^S - \chi_{22}^{BS} + c_1 v_1 + c_2 v_2$$

$$v_1 = \chi_{31}^{BS} - \chi_{11}^{BS}$$

$$v_2 = \frac{1}{3}(\chi_2^S - \chi_4^S) - 2\chi_{13}^{BS} - 4\chi_{22}^{BS} - 2\chi_{31}^{BS}$$

# Correlations and Fluctuations: HRG vs. LQCD

– all observables for "partial strange meson pressure" should give a unique result in a HRG

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# Evidence for many charmed baryons in thermodynamics

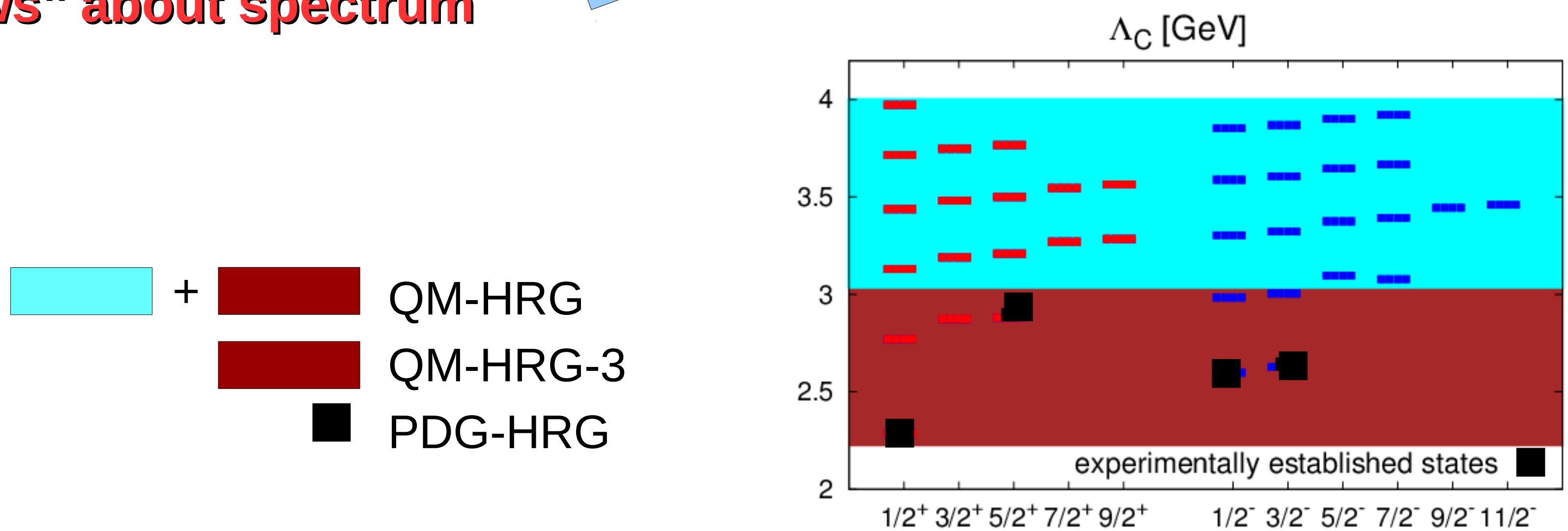
– use charge fluctuations and correlations to probe the hadron spectrum

– HRG pressure of open charmed mesons and baryons particularly simple, because multiple charmed baryons are too havy to be of thermodynamic relevance; e.g.

$$\chi_{11}^{BC} \simeq \chi_{22}^{BC} \simeq \chi_{13}^{BC}$$

open charm baryon to meson pressure ratio: $$\frac{B_C}{M_C} = \frac{\chi_{13}^{BC}}{\chi_4^C - \chi_{13}^{BC}}$$

**sum "knows" about spectrum**



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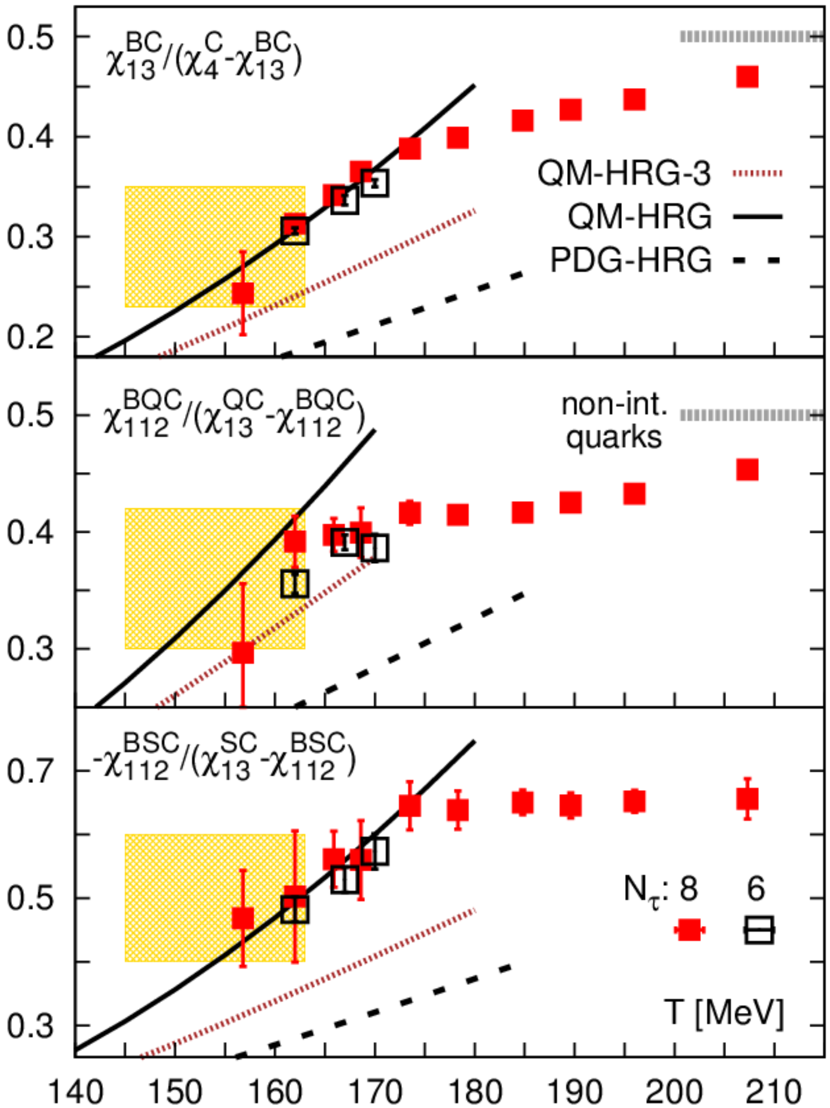



A. Bazavov et al., arXiv:1404.4043

close to Tc charmed baryon fluctuations are about 50% larger than expected in a HRG based on known charmed baryon resonances (PDG-HRG)

charmed pressure ratios

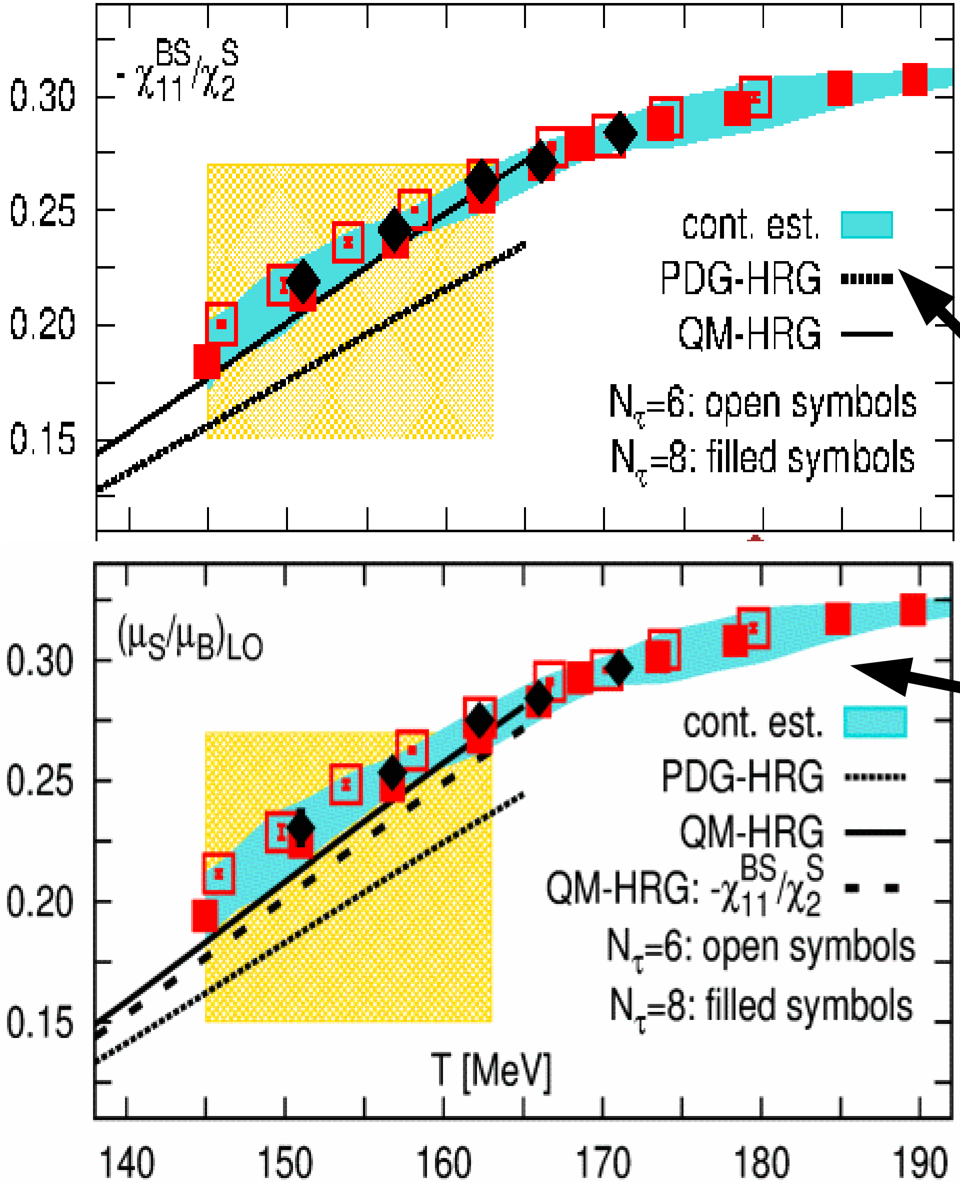
all charmed baryons/mesons

charged charmed baryons/mesons

strange charmed baryons/mesons

including resonance predicted in quark model calculations and observed in lattice QCD calculations allows for a HRG model (QM-HRG) description of lattice QCD results on conserved charge fluctuations and correlations

# Evidence for more strange baryons in thermodynamics




close to Tc strange baryon fluctuations are about (10-20)% larger than expected in a HRG based on known strange baryon resonances (PDG-HRG)

QM-HRG model agrees well with lattice QCD

**enhanced**
strangeness-baryon correlation over strangeness fluctuations

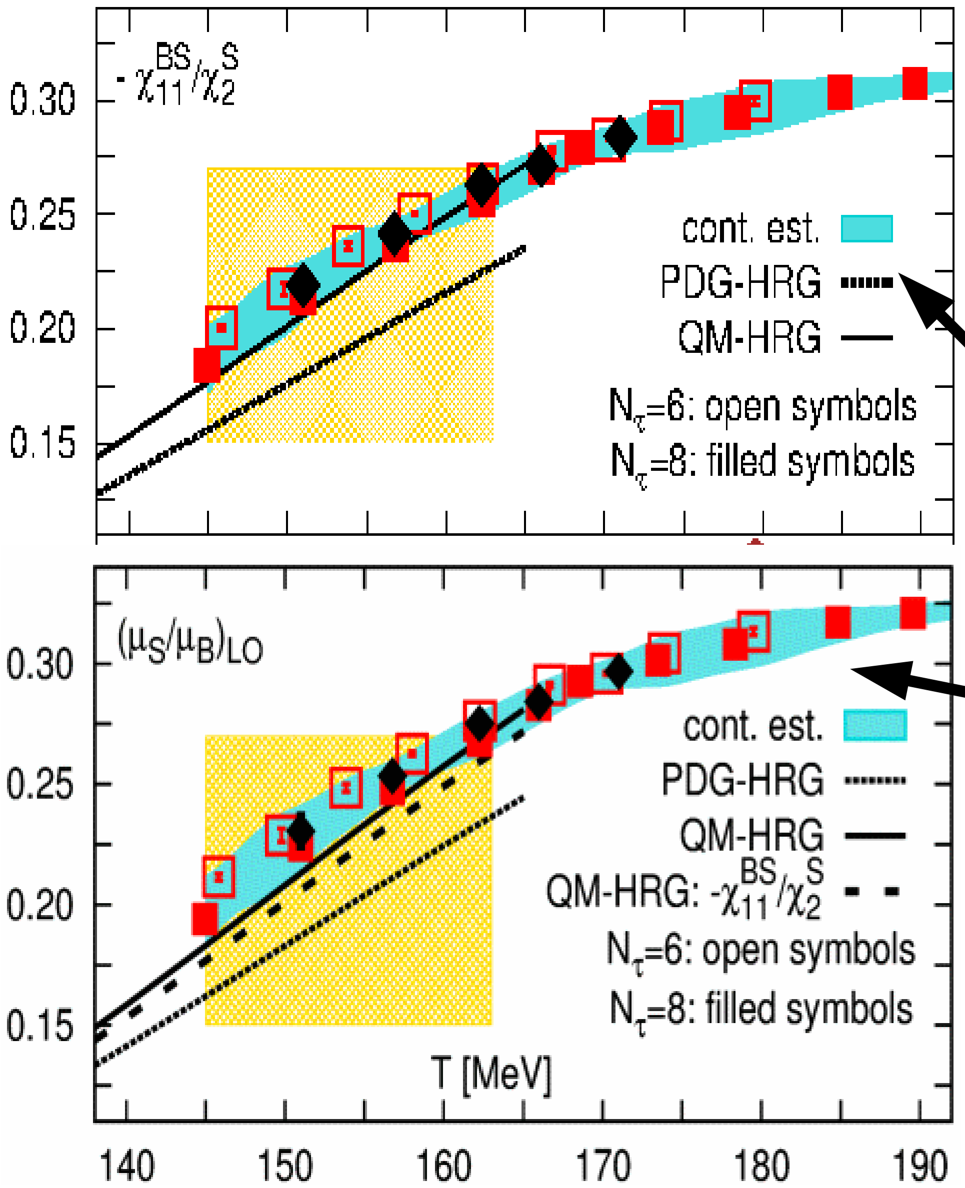
**strangeness neutrality**
enforces relation between chemical potentials

$$\langle n_S \rangle = 0$$
$$= \chi_2^S \hat{\mu}_S^2 + \chi_{11}^{BS} \hat{\mu}_S \hat{\mu}_B + \mathcal{O}(\mu^4)$$

$$\frac{\mu_S}{\mu_B} = -\frac{\chi_{11}^{BS}}{\chi_2^S} + \mathcal{O}(\mu^2)$$

A. Bazavov et al.,
Phys. Rev. Lett. 113, 072001 (2014), arXiv:1404.6511

# Evidence for more strange baryons in thermodynamics




A. Bazavov et al.,
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QM-HRG model agrees well with lattice QCD

**enhanced**
strangeness-baryon correlation over strangeness fluctuations

↓

**enhanced**
strangeness over baryon chemical potential ratio

↓

leads to the prediction of a
**smaller freeze-out temperature**

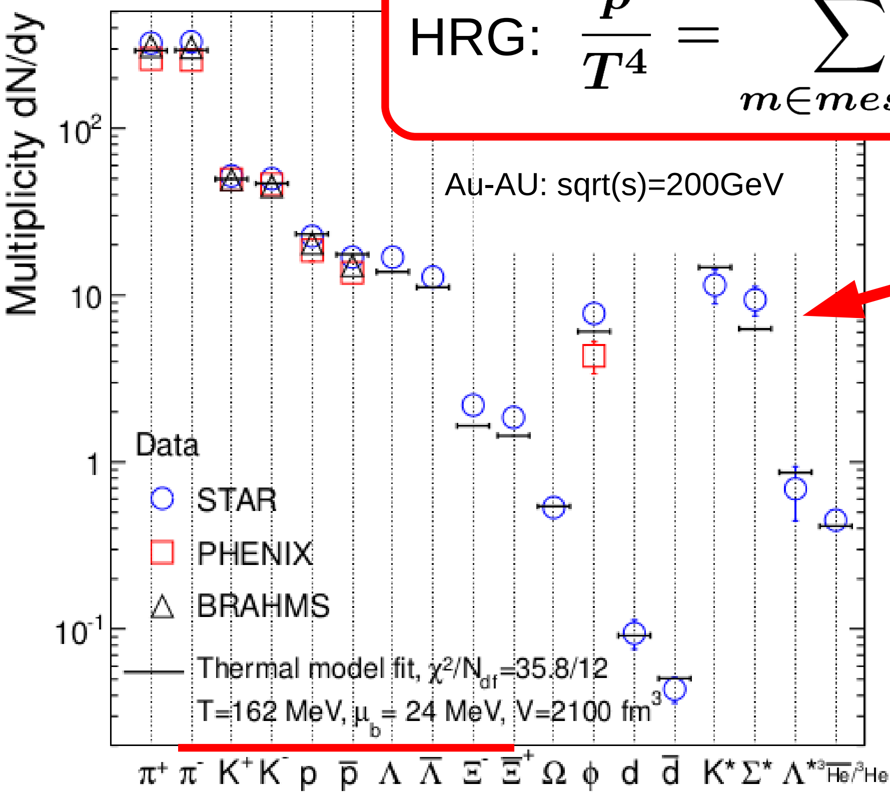
# HRG model, lattice QCD and critical behavior

- **for a wide range of baryon chemical potentials freeze-out happens in or close to the QCD transition region:** predicted ➡ P. Braun-Munzinger et al., Phys. Lett. B596, 61 (2004)

caveat: freeze-out parameter extracted from experimental data by comparing to the Hadron Resonance Gas (HRG) model, i.e. not QCD

$$\text{HRG:}\quad \frac{p}{T^4} = \sum_{m\in meson} \ln Z_m^b(T,V,\mu) + \sum_{m\in baryon} \ln Z_m^f(T,V,\mu)$$

$$\sim e^{-m_H/T} e^{(B\mu_B + S\mu_S + Q\mu_Q)/T}$$




*Andornic et.al.: Nucl. Phys. A904, 535c (2013)*

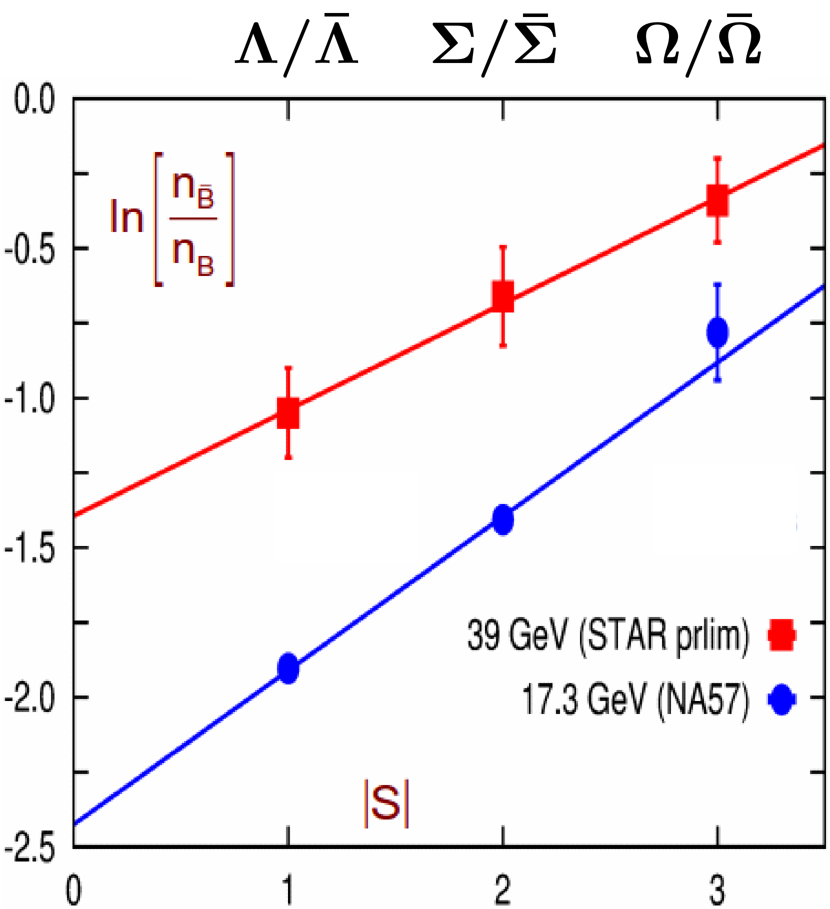
goal: describe freeze-out in terms of QCD thermodynamics

➡ freeze-out parameter from comparison of measured moments of charge fluct. with QCD calculation

BNL-Bielefeld, PRL 109, 12302 (2012)

# Strange hadron yields in HIC

$$\frac{n_{\bar\Lambda}}{n_\Lambda},\ \frac{n_{\bar\Sigma}}{n_\Sigma},\ = \frac{n_{\bar\Omega}}{n_\Omega} = \exp\left[-\frac{2\mu_B^f}{T^f} - \frac{2\mu_S^f}{T^f}|S|\right] = \exp\left[-\frac{2\mu_B^f}{T^f}\left(1 - \frac{\mu_S^f}{\mu_B^f}|S|\right)\right]$$



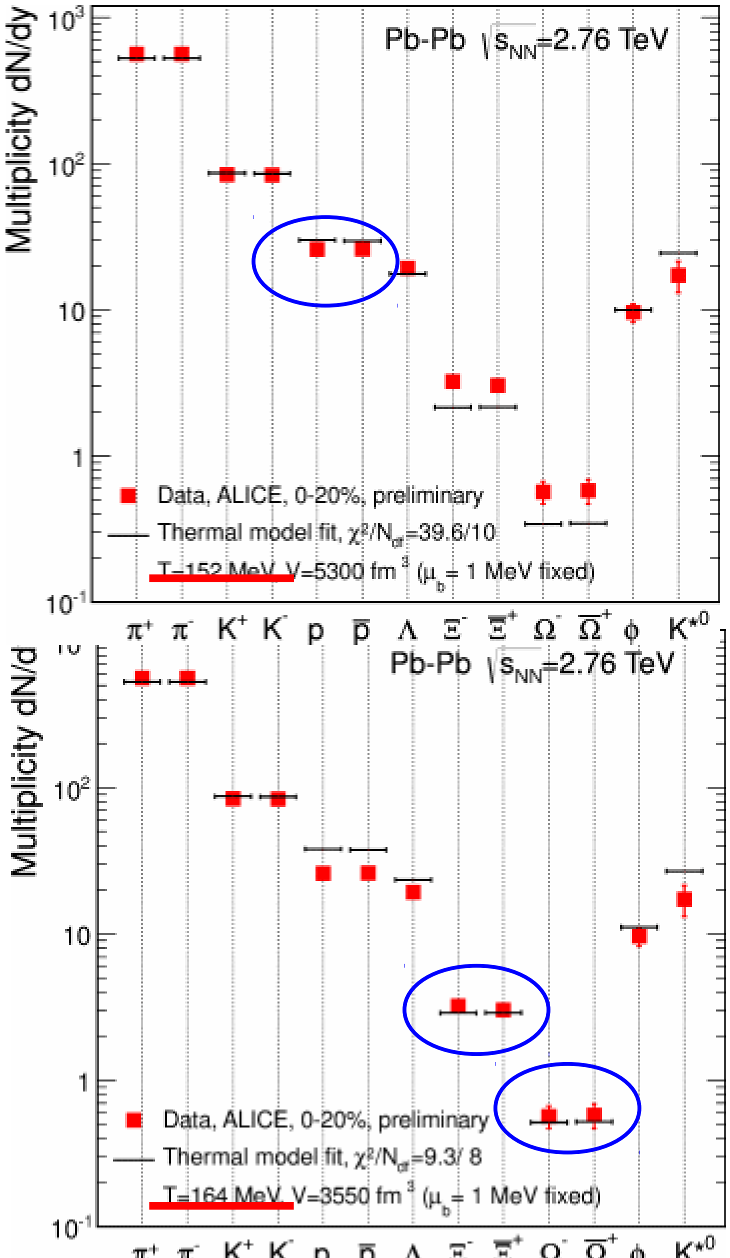

presence of unobserved higher resonances get imprinted in the yields of ground state hadrons

extract chemical potentials from particle/anti-particle ratios of multiple strange baryon yields (eliminates mass dependence)

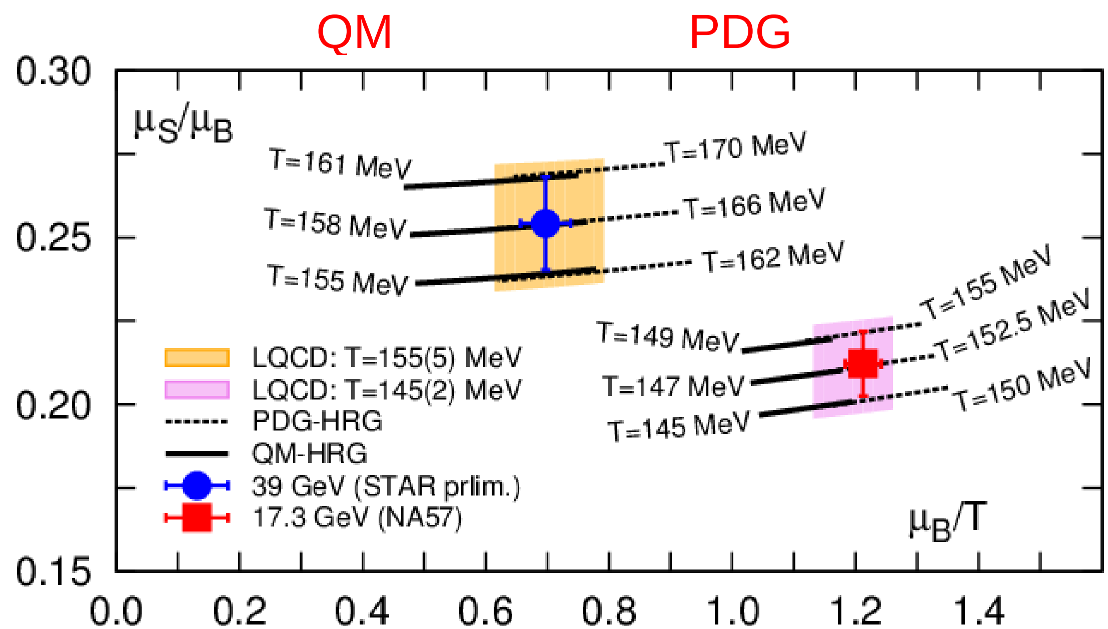
data:

STAR: F. Zhao, PoS CPOD2013 (2013) 036
NA57: F. Antinori et al, PLB 595 (2004) 68

# Impact on determination of freeze-out parameter




*A. Andronic et.al.: Nucl. Phys. A904, 535c (2013)*




A. Bazavov et al., Phys. Rev. Lett. 113, 072001 (2014), arXiv:1404.6511

including more strange baryons will change determination of freeze-out parameters

⬇

better agreement of strange and non-strange particle yields at lower freeze-out temperature

# Conclusions

- During recent years LGT calculations have achieved two important goals:
  - determination of transition temperature Tc
  - calculation of the equation of state

  with physical quark masses in the continuum limit

- Gross features of bulk thermodynamics at low temperatures are compatible with hadron resonance gas thermodynamics;

- deviations from PDG-HRG provide

**evidence for a richer strange and charmed baryon spectrum than so-far known experimentally**