More strange hadrons from QCD thermodynamics and strangeness freeze-out in HIC

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Content

arXiv:1404.6511

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cumulants and correlations of conserved charge fluctuations, (lattice) QCD vs HRG

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arXiv:1404.4043

- **Evidence for experimentally not yet observed open charm hadrons**
- **Melting of open charm hadrons**

$\Longrightarrow$ see Poster by S. Sharma

Definitions

Expansion of the pressure:

$$\frac{p}{T^4} = \sum_{i,j,k=0}^{\infty} \frac{1}{i!j!k!} \chi_{ijk,0}^{BQS} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

$X = B, Q, S$: conserved charges

Lattice

$$\chi_n^X = \left.\frac{\partial^n [p/T^4]}{\partial(\mu_X/T)^n}\right|_{\mu_X=0}$$

generalized susceptibilities

$\Rightarrow$ only at $\mu_X = 0$!

Experiment

$$\begin{aligned} VT^3 \chi_2^X &= \langle(\delta N_X)^2\rangle \\ VT^3 \chi_4^X &= \langle(\delta N_X)^4\rangle - 3\langle(\delta N_X)^2\rangle^2 \\ VT^3 \chi_6^X &= \langle(\delta N_X)^4\rangle \\ &\quad -15\langle(\delta N_X)^4\rangle\langle(\delta N_X)^2\rangle \\ &\quad +30\langle(\delta N_X)^2\rangle^3 \end{aligned}$$

cumulants of net-charge fluctuations

$\delta N_X \equiv N_X - \langle N_X \rangle$

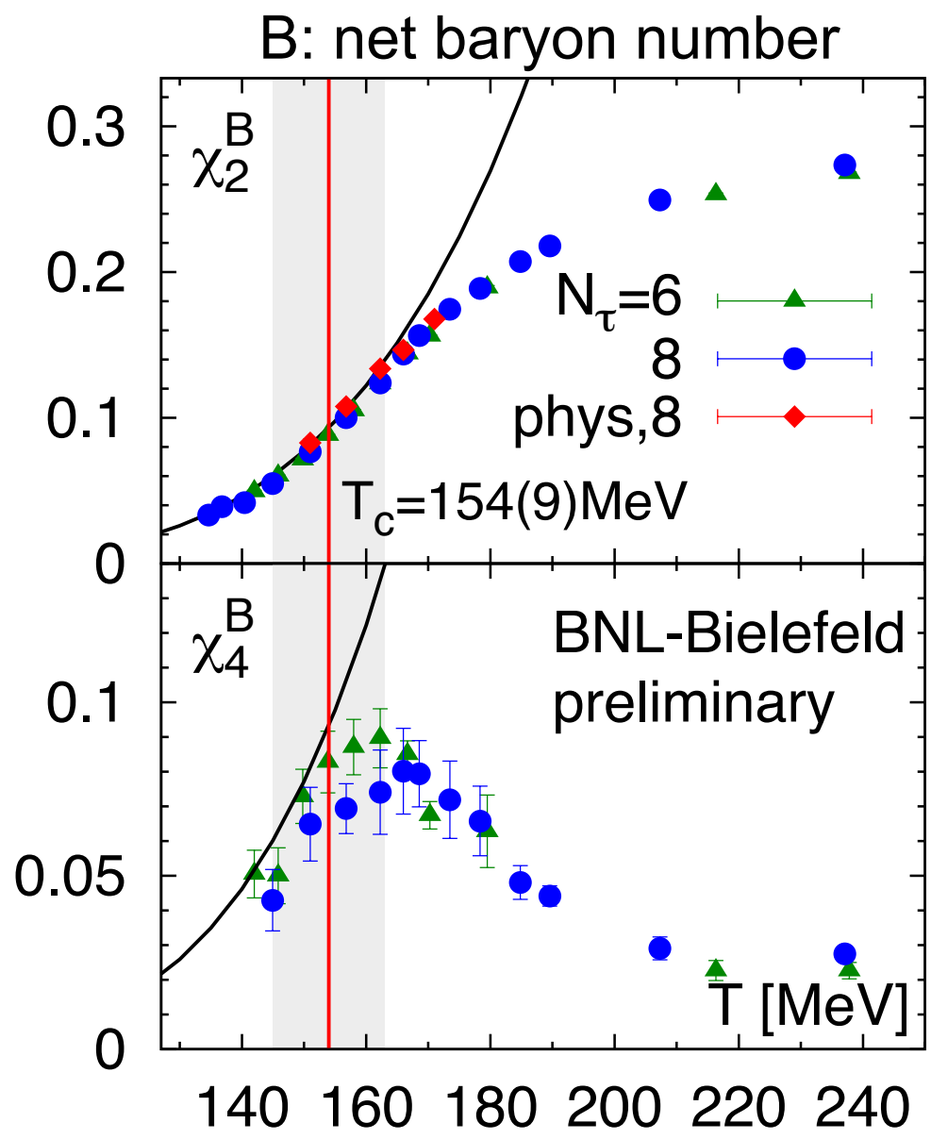
$\Rightarrow$ only at freeze-out ($\mu_f(\sqrt{s}), T_f(\sqrt{s})$)!

(lattice) QCD vs HRG

B,S diagonal cumulants up to 4th order

Lattice details

- (2+1)-flavor of highly improved staggered fermions (HISQ-action)
- a set of different lattice spacings ($N_\tau = 6, 8, 12$)
- two different pion masses: $m_\pi = 140, 160\ MeV$
- high statistics: $(10 - 16) \times 10^3$ configurations

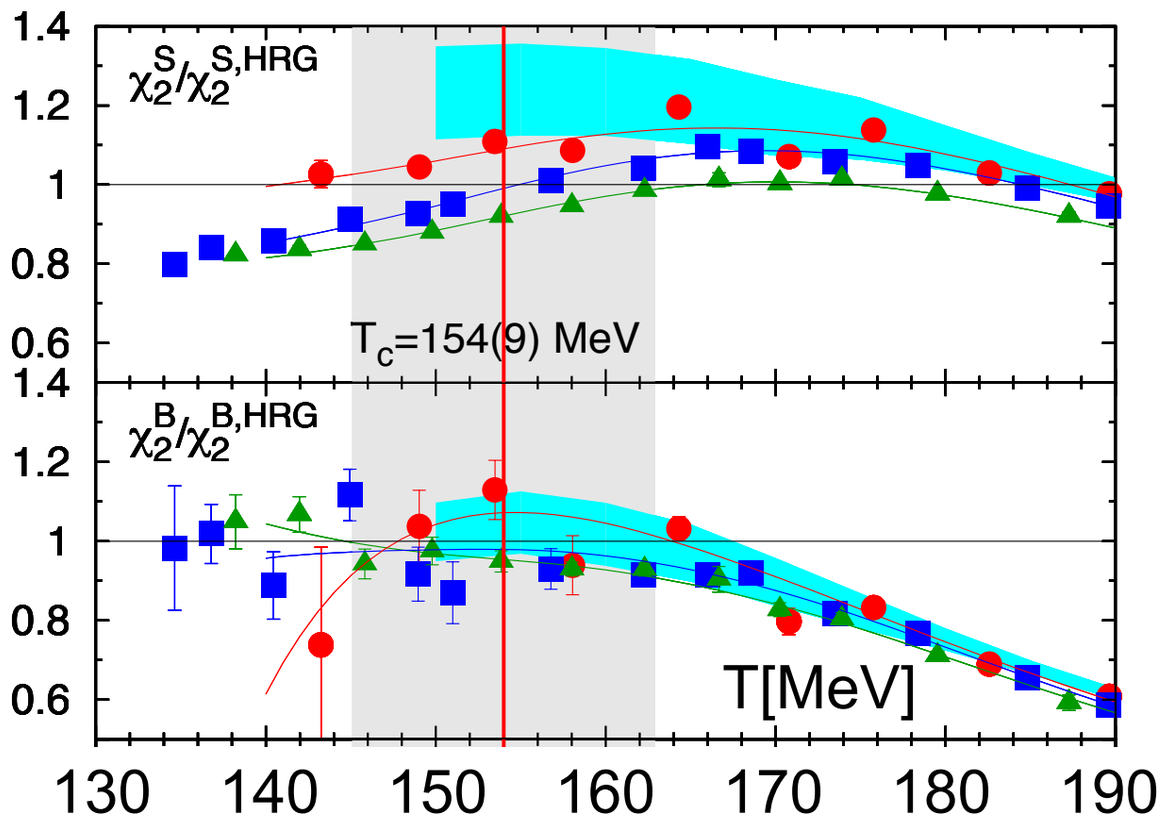


$\Rightarrow$ statistical and systematical errors are under control

$\Rightarrow$ In general: find good agreement with HRG model for T<155 MeV

(lattice) QCD vs HRG

However, some notable differences in the strangeness sector



$N_\tau = 12$ HISQ-Action

$N_\tau = 8$

$N_\tau = 6$

cyan bands indicate continuum extrapolations

HotQCD, PRD 86 (2012) 034509 [arXiv: 1203.0784]

HRG:

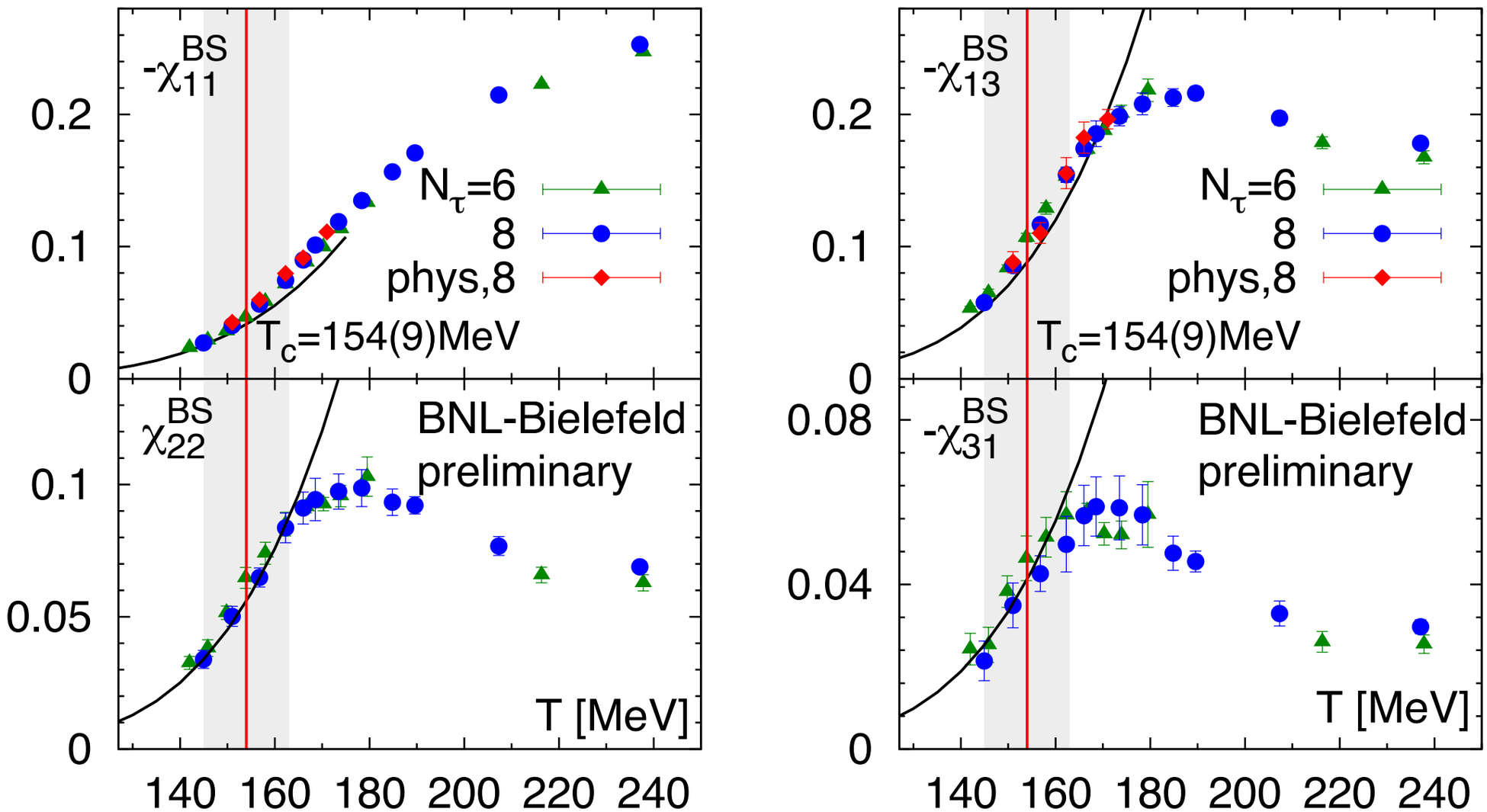
$$p^{\mathrm{HRG}} = \sum_{i \in \mathrm{mesons}} p^M_{m_i}(T, \mu_S) + \sum_{i \in \mathrm{baryons}} p^B_{m_i}(T, \mu_B, \mu_S)$$

hadron masses from PDG up to 2.5 GeV, and

$p^{M/B}_{m_i}$ pressure of free bosonic/fermionic quantum gas

(lattice) QCD vs HRG

Also apparent in B,S off-diagonal cumulants



$\Rightarrow$ overshooting of HRG in the crossover region and below

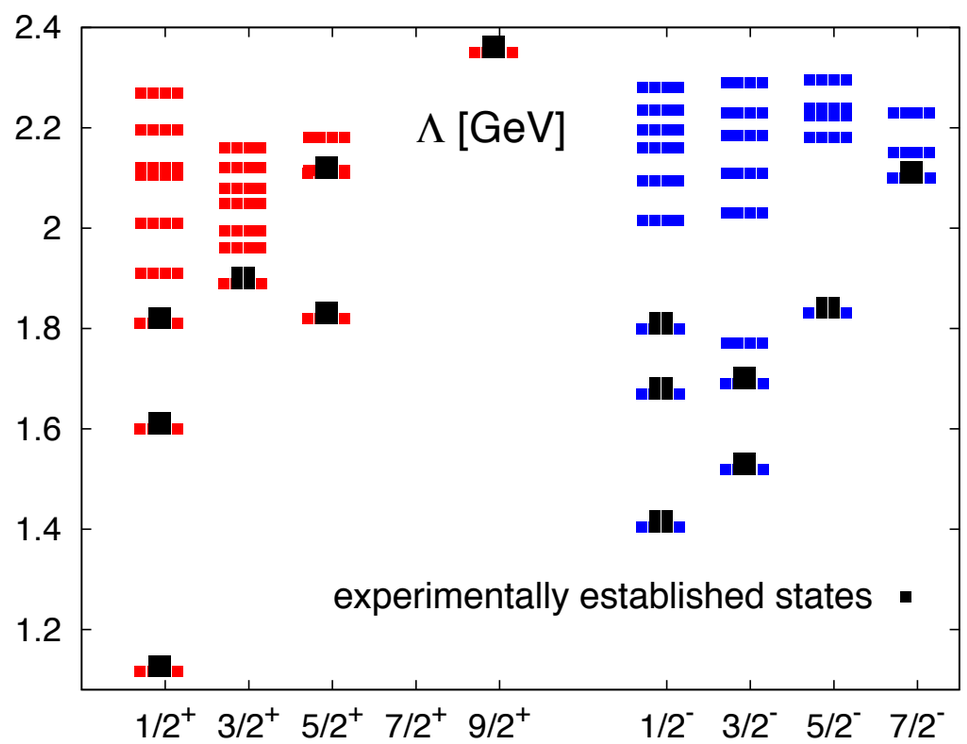
the QM-HRG

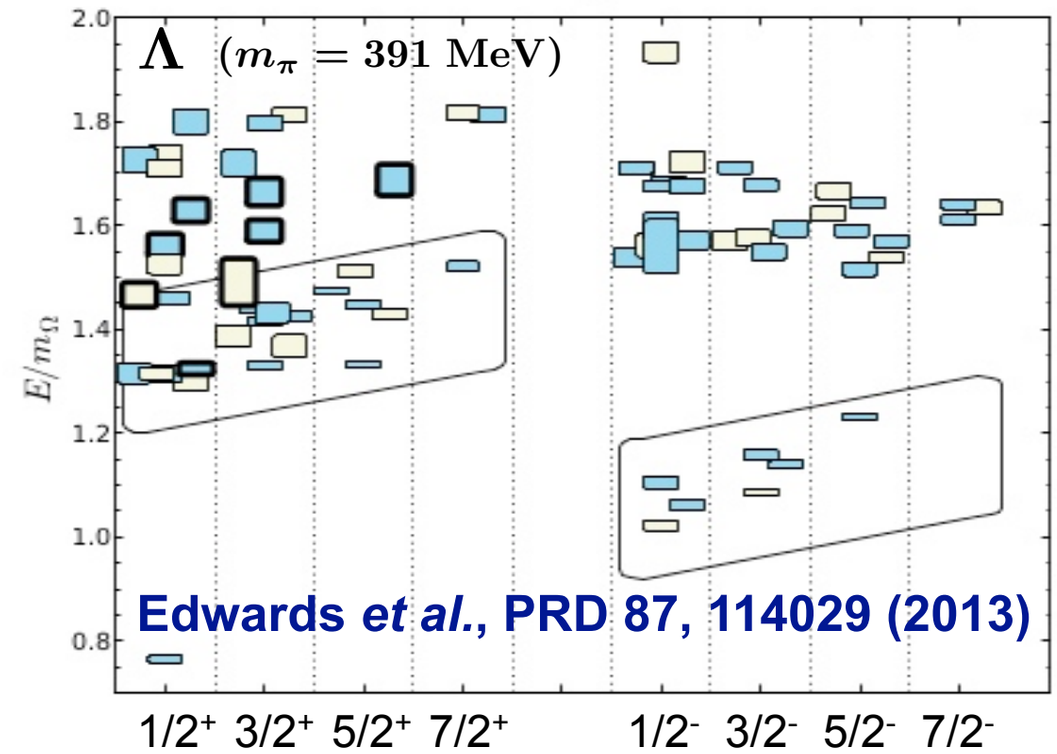
Are differences due to missing states in the PDG?

- Obvious in the charm sector (See Poster by S. Sharma)
- How large could be the effect of missing states in the strange sector?

$\Rightarrow$ construct **QM-HRG**, including additional states predicted by Quark-Model

- **Use mesonic states from:** **S. Capstick and N. Isgur, PRD 34, 2809 (1986)**.
- **Use baryonic states from:** **D. Ebert *et al.*, PRD 79, 114029 (2009)**





Edwards *et al.*, PRD 87, 114029 (2013)

- Similar to the spectrum of strange baryons on the lattice

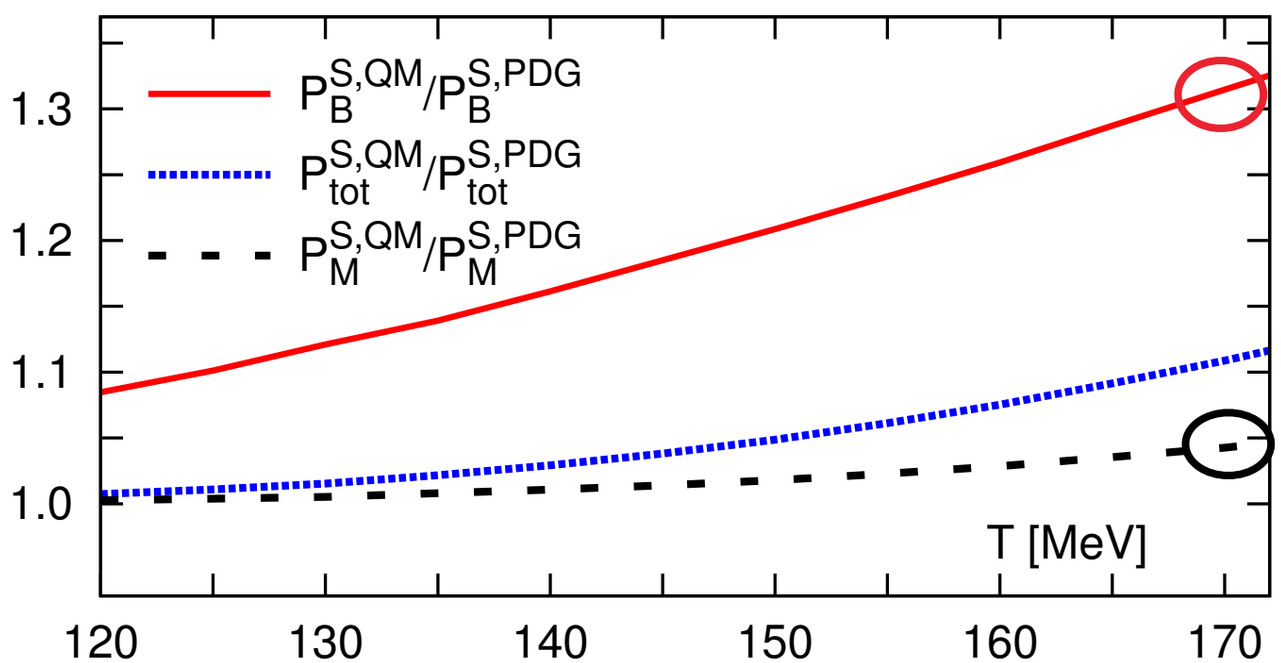
QM-HRG vs PDG-HRG

Partial pressure of strange mesons and baryons:

- Boltzmann approximation is used here and in the following

$$P^{S,X}_{M/B}(T,\vec{\mu}) = \frac{T}{2\pi^2}\sum_{i\in X} g_i \left(\frac{m_i}{T}\right)^2 K_2(m_i/T)\cosh(B_i\hat{\mu}_B + Q_i\hat{\mu}_Q + S_i\hat{\mu}_S)$$

with $X = \mathrm{PDG}, \mathrm{QM}$ and $\hat{\mu}_q = \mu_q/T,\ q = B, Q, S$



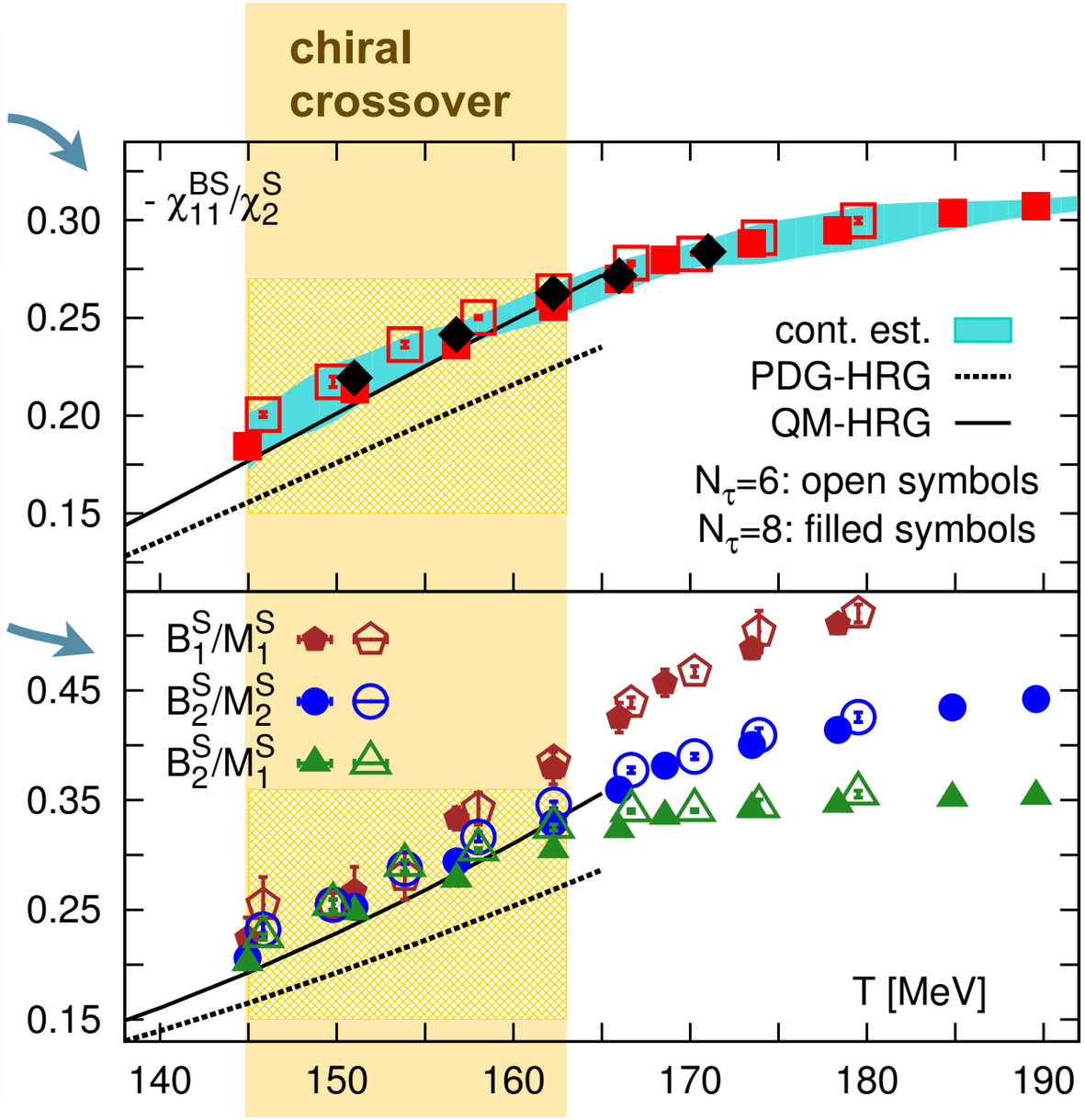
⇒ open strange baryon sector experimentally much less known, additional baryons contribute up to 30% at T=170 MeV

⇒ open strange meson sector experimentally well known

Evidence for more strange hadrons

- **BS-correlation** χ_{11}^{BS}
  at low T: weighted sum of partial pressure of strange baryons

- Different **linear combinations** of
  $$\chi_2^S, \chi_4^S, \chi_{11}^{BS}, \chi_{31}^{BS}, \chi_{22}^{BS}, \chi_{13}^{BS}$$
  are used to project onto partial pressure of strange baryons (B_i^S) and mesons (M_i^S) in the hadronic phase, e.g.
  $$B_1^S = -\frac{1}{6}(11\chi_{11}^{BS} + 6\chi_{22}^{BS} + \chi_{13}^{BS})$$
  $$B_2^S = \frac{1}{12}(\chi_4^S - \chi_2^S) - \frac{1}{3}(4\chi_{11}^{BS} - \chi_{13}^{BS})$$



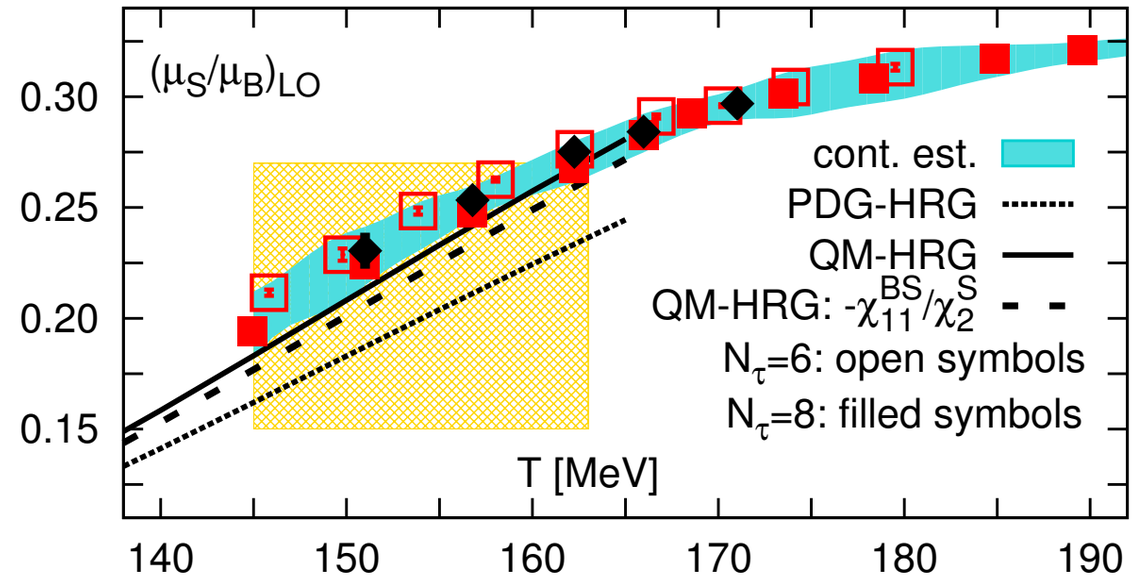
⇒ **QM-PDG provides more accurate description of lattice data**

⇒ Re-confirmation of our previous findings [PRL 111,082301]: onset of melting of open strange hadrons consistent with chiral crossover

Implications for freeze-out conditions

- in order to make contact to experiment: apply strangeness neutrality constraint $n_S = 0$ (and iso-spin $n_Q/n_B = 0.4$)

$\Rightarrow T, \mu_B, \mu_S, \mu_Q$ not independent



(Lattice) QCD: unique expansion

$$(\mu_S/\mu_B)(T) = s_1(T) + s_3(T)\hat{\mu}_B^2 + \mathcal{O}(\hat{\mu}_B^4)$$

$$\Rightarrow \left(\frac{\mu_S}{\mu_B}\right)_{\rm LO} \equiv s_1(T) = -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B}$$

- small corrections from $\mu_Q > 0$
- neglect NLO contribution, known to be small for $\mu_B \lesssim 200 MeV$ [PRL 111,082301]

HRG: $\mu_S(T, \mu_B)$ depends on relative abundance of open strange baryons and mesons

additional strange baryons
$\Rightarrow$ larger μ_S
(at fixed T, μ_B)

Implications for freeze-out conditions

Experiment:

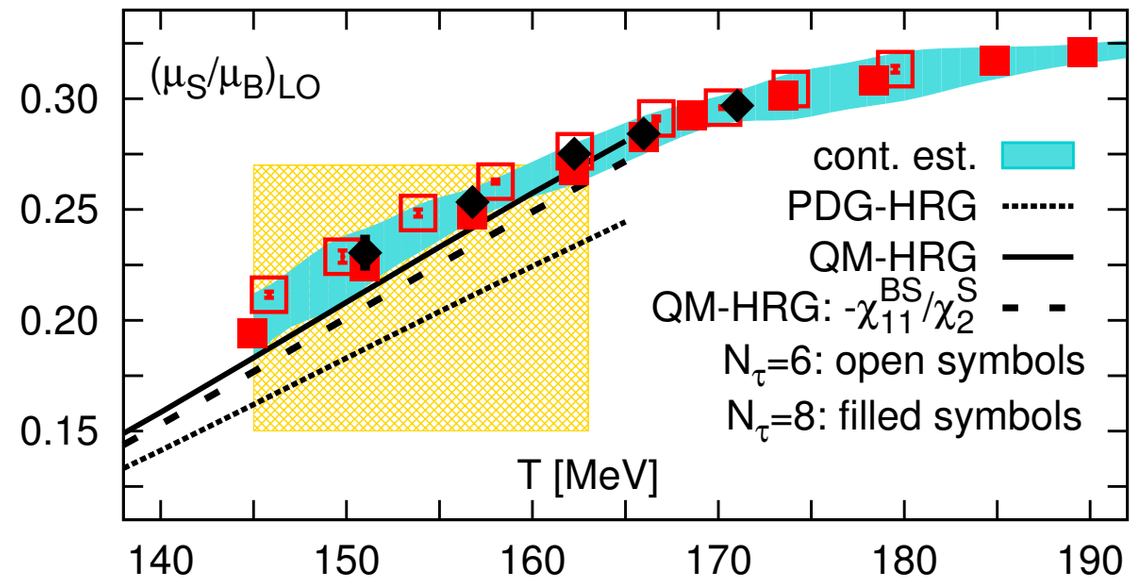
relative yields of strange anti-baryons to baryons at freeze-out are controlled by freeze-out parameter (T^f, μ_B^f, μ_S^f)

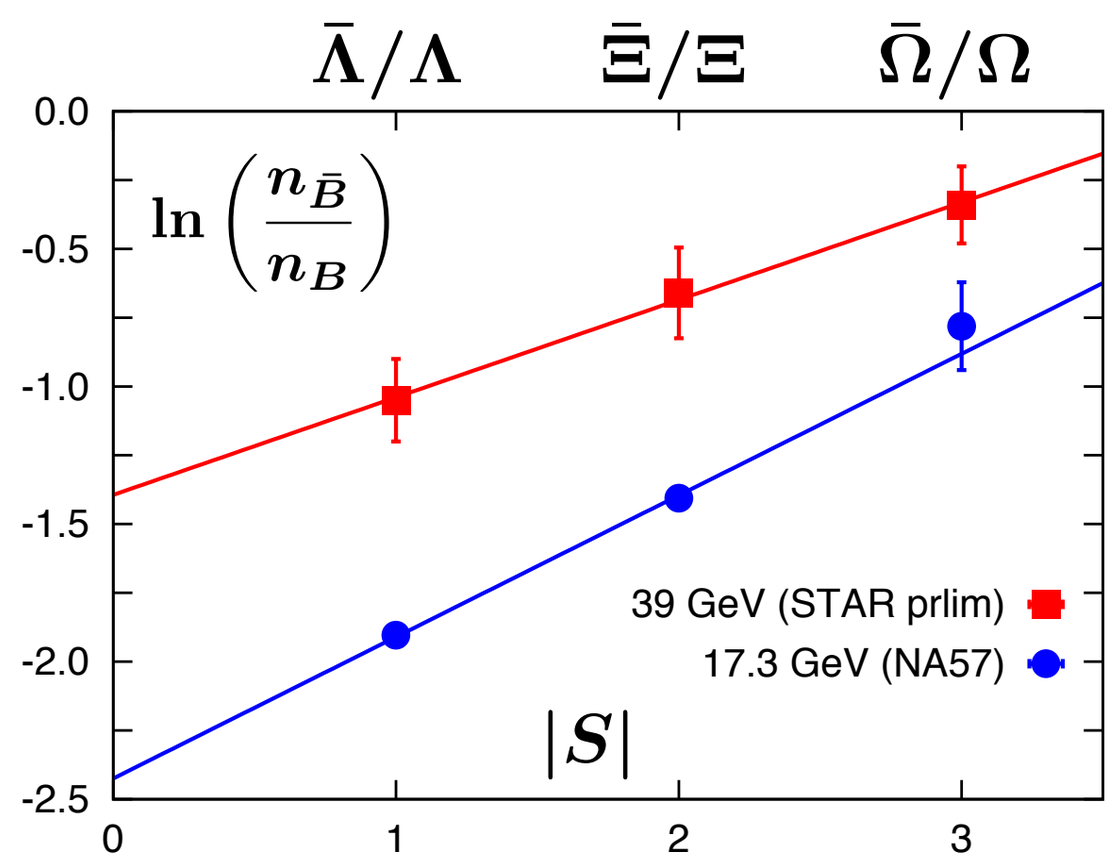
$$\frac{n_{\bar{B}}}{n_B} = \exp\left\{-\frac{2\mu_B^f}{T^f} + \frac{2\mu_S^f}{T^f}|S|\right\}$$

$$= \exp\left\{-\frac{2\mu_B^f}{T^f}\left(1 - \frac{\mu_S^f}{\mu_B^f}|S|\right)\right\}$$

$\Rightarrow$ μ_B^f/T^f and μ_S^f/μ_B^f can be obtained by fitting experimentally measured values of $\bar{\Lambda}/\Lambda$, $\bar{\Xi}/\Xi$ and $\bar{\Omega}/\Omega$

$\Rightarrow$ fit function independent of details of open strange hadron spectrum

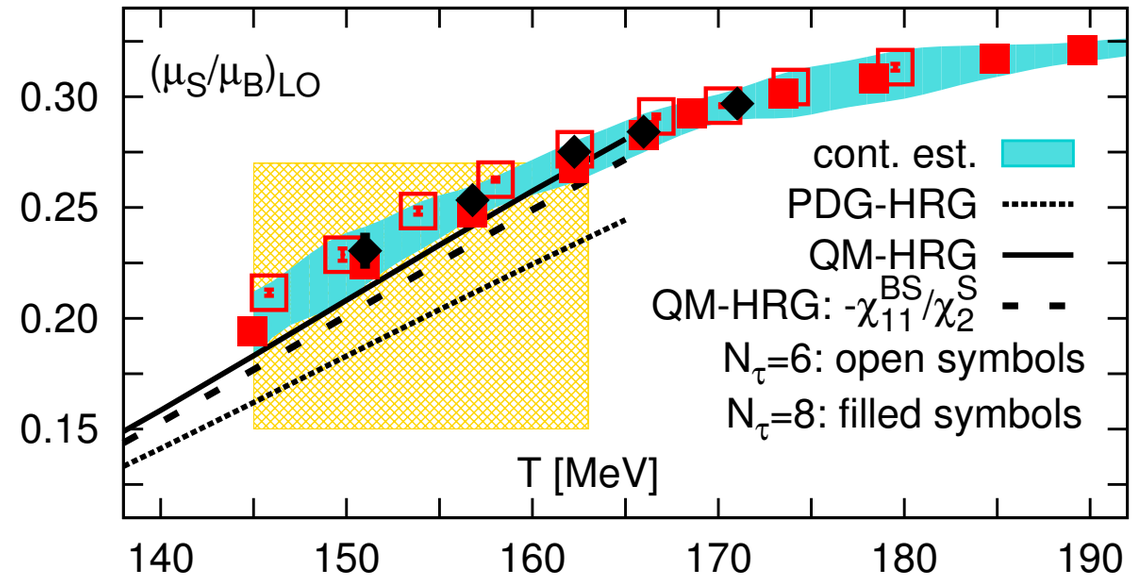


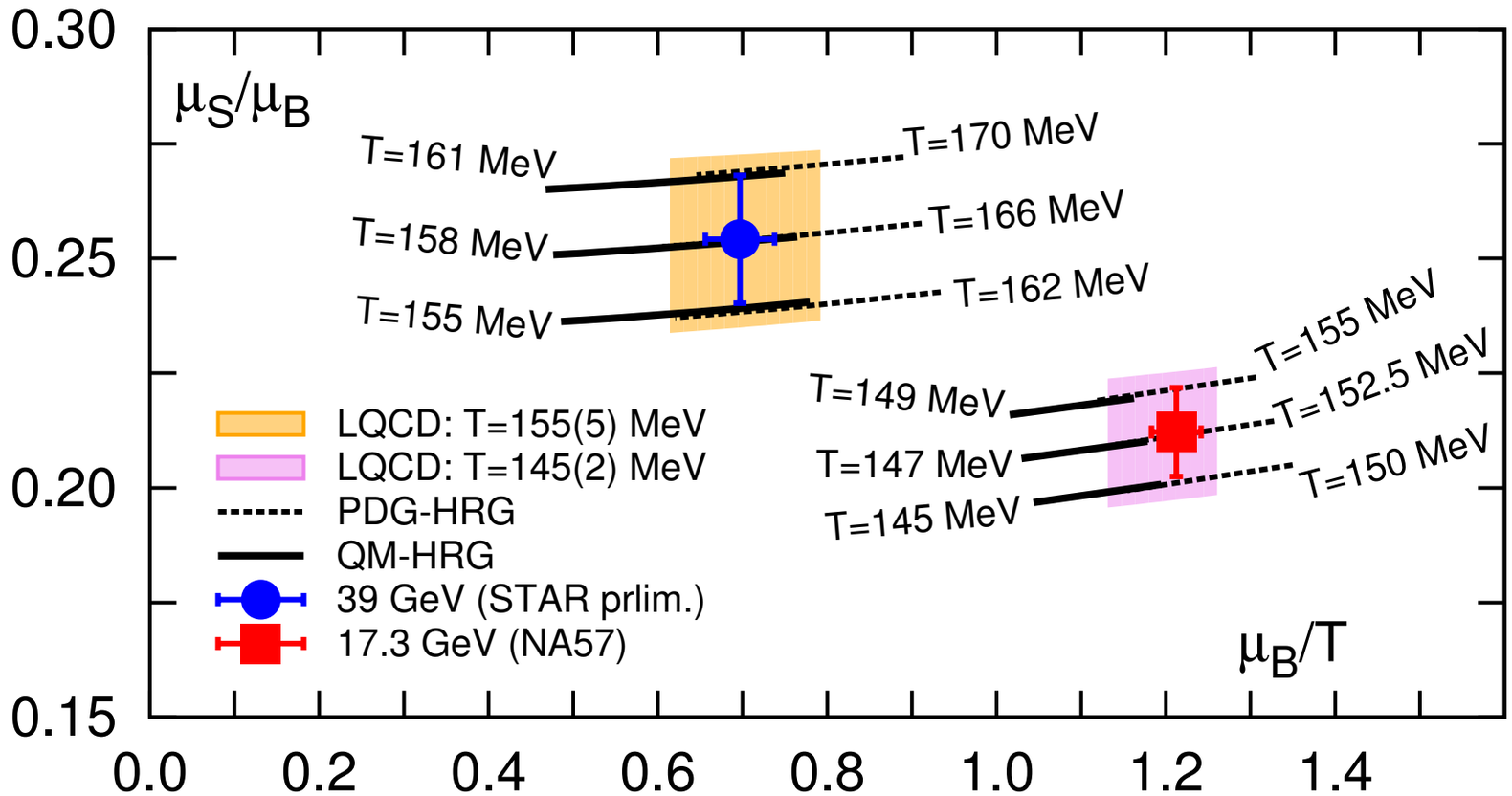


Implications for freeze-out conditions

Comparison:

vary T^f in order to mach μ_B^f/T^f and μ_S^f/μ_B^f





⇒ QM-PDG in agreement with (lattice) QCD

⇒ QM-HRG yields 5-8 MeV smaller freeze-out temperature than PDG-HRG

Summary and Conclusions

- correlations of net baryon number and net strangeness are sensitive probes of the strangeness content of the system

- partial pressure of strange baryons from QM-HRG and PDG-HRG differ by about 30% at T=170 MeV

  $\Longrightarrow$ additional strange baryons are thermodynamically relevant in the crossover region

- in the crossover region the QM-HRG provides a more accurate description of (lattice) QCD w.r.t. the conventionally used PDG-HRG

  $\Longrightarrow$ evidence for additional, experimentally not yet observed, strange baryons

- presence of additional strange hadrons get imprinted in the yields of ground state strange hadrons

  $\Longrightarrow$ significant reductions of freeze-out temperature of (5-8) MeV