Thermodynamic Signatures of Additional Strange and Charm Baryons

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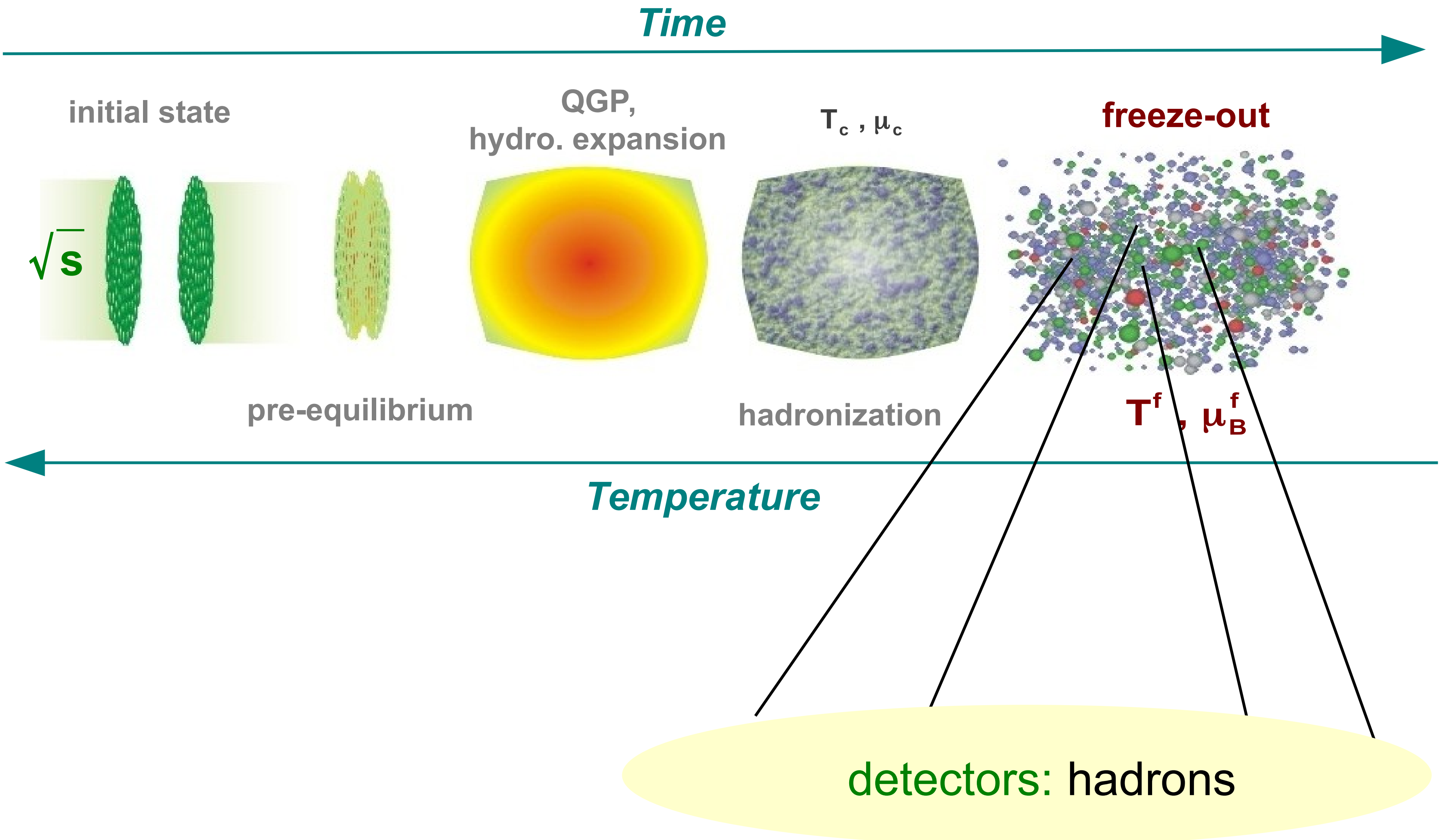
Heavy-ion collisions: a sketch



freeze-out stage

"observed" in HIC

Hadrons yields at the freeze-out

well described by: Hadron Resonance Gas (HRG)

thermal gas of uncorrelated hadrons with vacuum masses

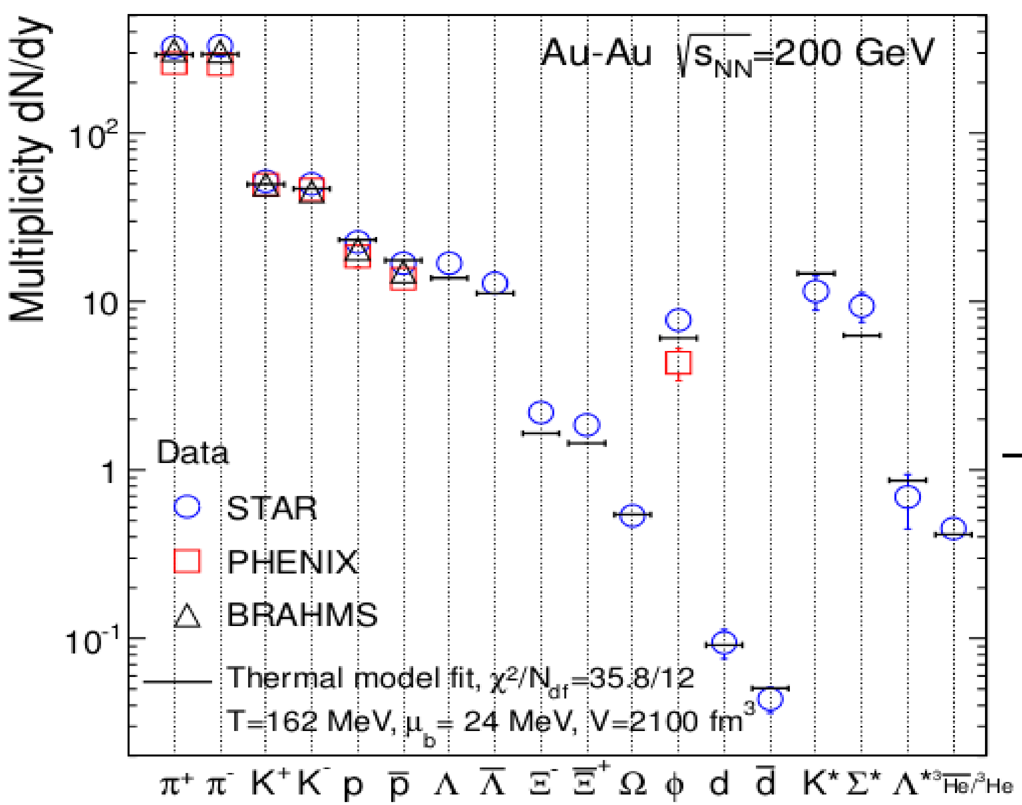
$$\hat{P}_h \sim f\left(\hat{m}_h\right) \cosh\left[B_h \hat{\mu}_B + Q_h \hat{\mu}_Q + S_h \hat{\mu}_S + C_h \hat{\mu}_C\right]$$

thermal abundance of hadrons

compare with expt. hadron yields

$$\hat{P}_{tot} = \sum_{\text{all hadrons}} \hat{P}_h$$

hat → dimensionless in T units



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

freeze-out parameters

$$\left(T^f, \mu_B^f, \mu_Q^f, \mu_S^f\right)$$

thermal conditions "observed" in HIC

LQCD: validity of hadronic description

baryon – charge/strangeness/charm correlations: $\chi_{BX}^{nm} = \left. \frac{\partial^{n+m} \hat{P}}{\partial^n \hat{\mu}_B \, \partial^m \hat{\mu}_X} \right|_{\vec{\mu}=0}$

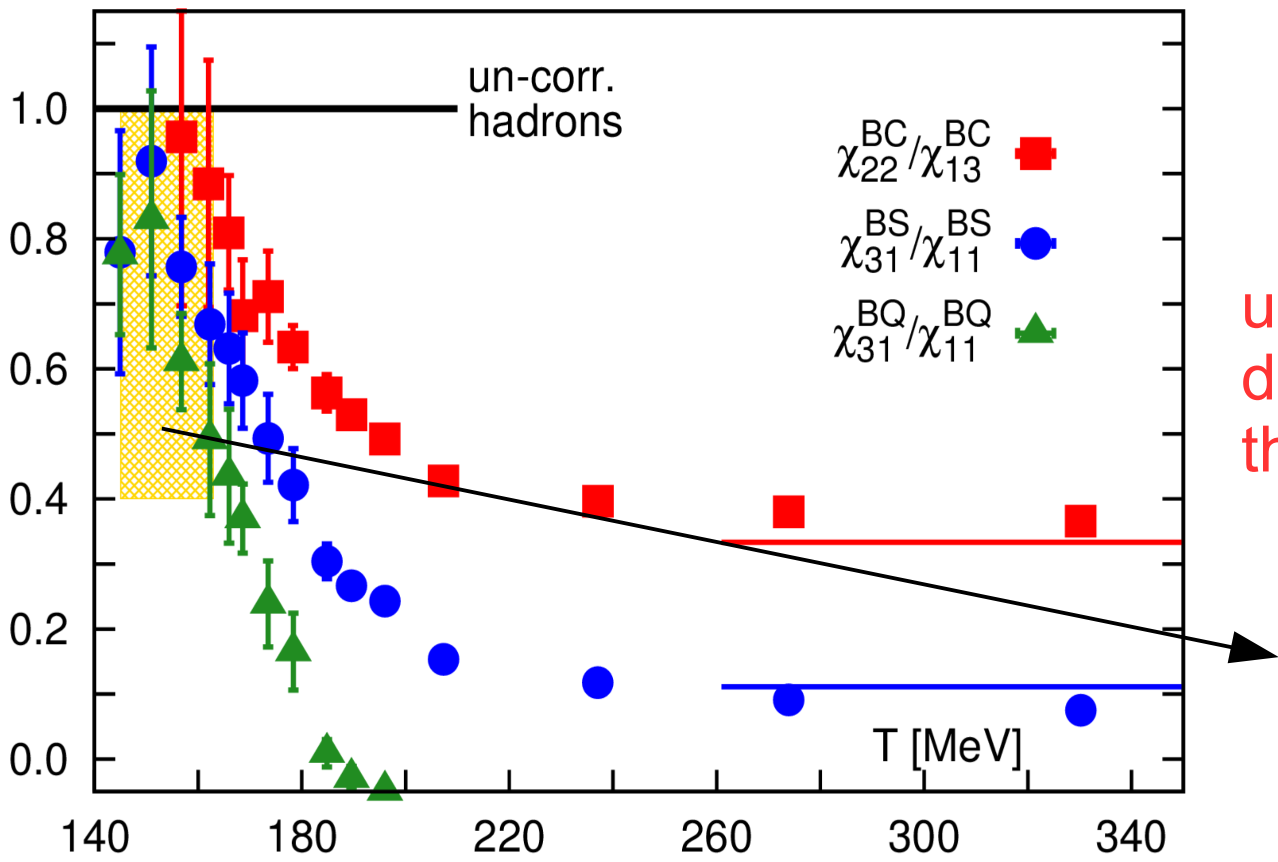
HRG: $\hat{P}_h \sim f(\hat{m}_h) \cosh[B_h \hat{\mu}_B + Q_h \hat{\mu}_Q + S_h \hat{\mu}_S + C_h \hat{\mu}_C]$ $\quad \chi_{BX}^{nm} = B^n \times F(\hat{m})$

$\chi_{BX}^{nm} / \chi_{BX}^{km} = B^{n-k}$

= 1, when dof are hadronic with B=1

< 1, when dof are quarks with B=1/3

independent of hadron mass spectrum, relies only on changing quantum number



uncorrelated hadron gas description is valid right till the QCD crossover region

chiral crossover:

$T_c = 154 \pm 9\,\text{MeV}$

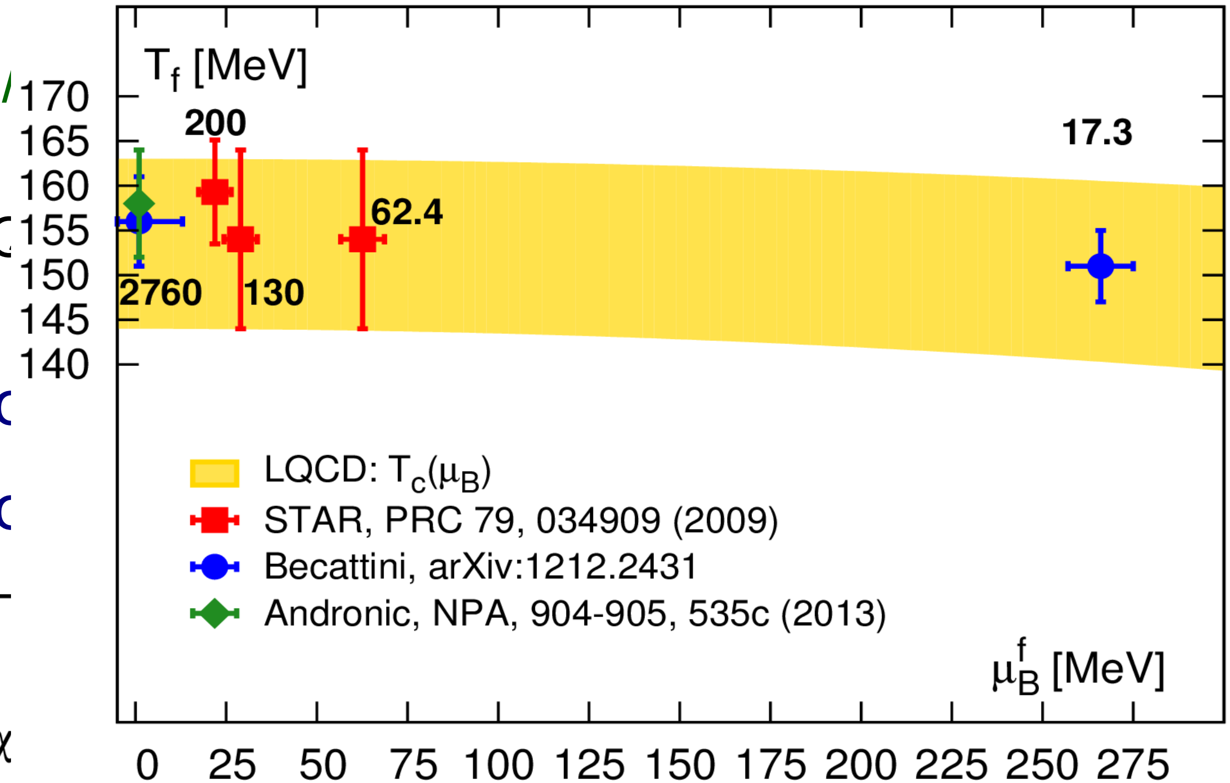
LQCD: validity of hadronic description

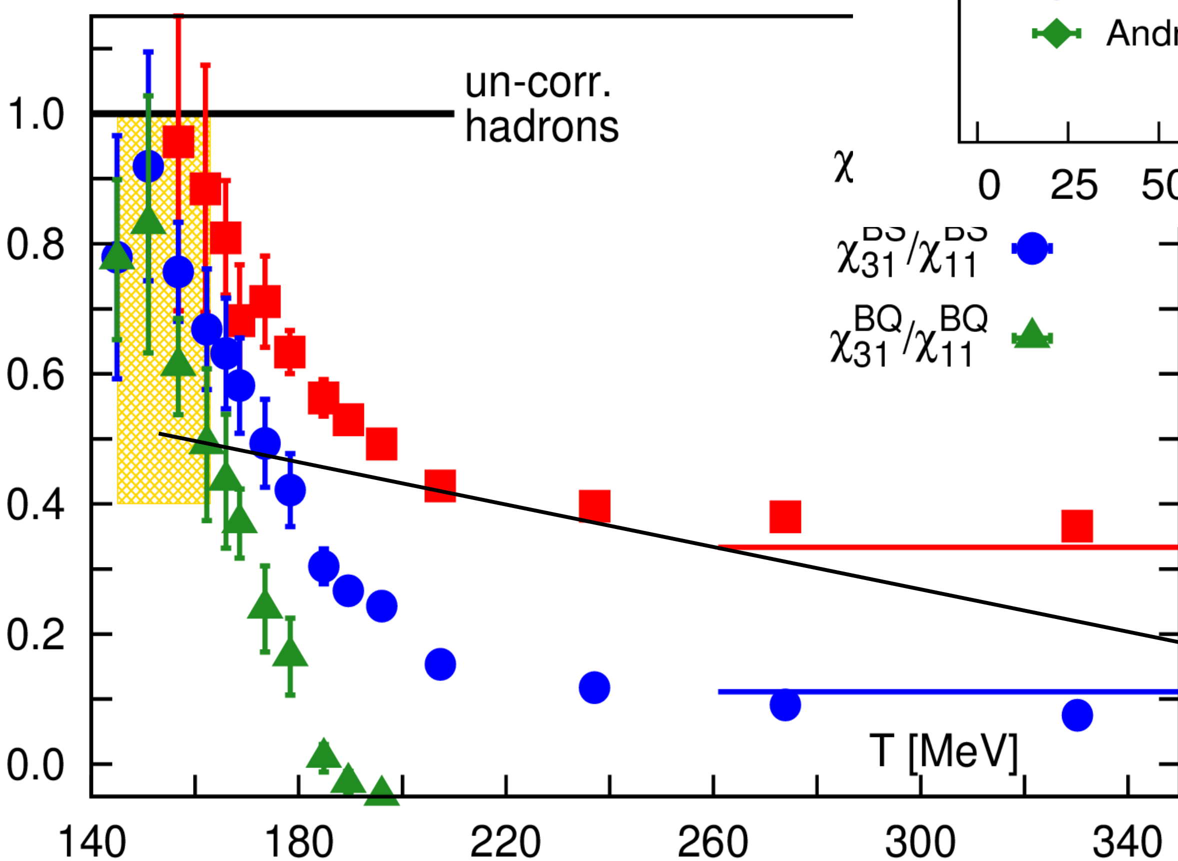
baryon – charge/strangeness/

HRG: $\hat{P}_h \sim f(\hat{m}_h)\ \cosh[B_h\hat{\mu}_B + C$

$\chi^{nm}_{BX}/\chi^{km}_{BX} = B^{n-k}$ = 1, when dc

< 1, when dc





uncorrelated hadron gas description is valid right till the QCD crossover region

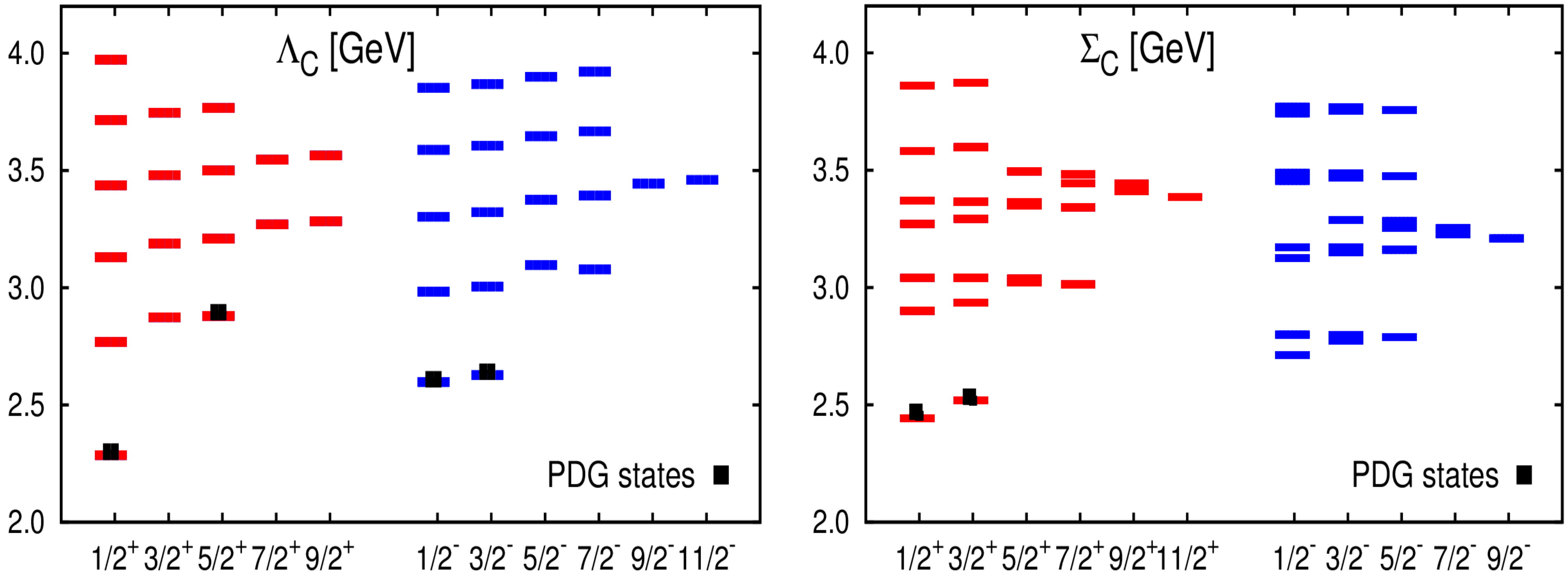
chiral crossover:

$T_c = 154 \pm 9\,\mathrm{MeV}$

Probing hadron spectrum using thermodynamics

hadronic pressure: $P^C = \sum_{h \in \text{all hadrons}} P_h$ ⟸ expt. observed hadrons + unobserved ones

Quark Model — charm baryons



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

Probing hadron spectrum using thermodynamics

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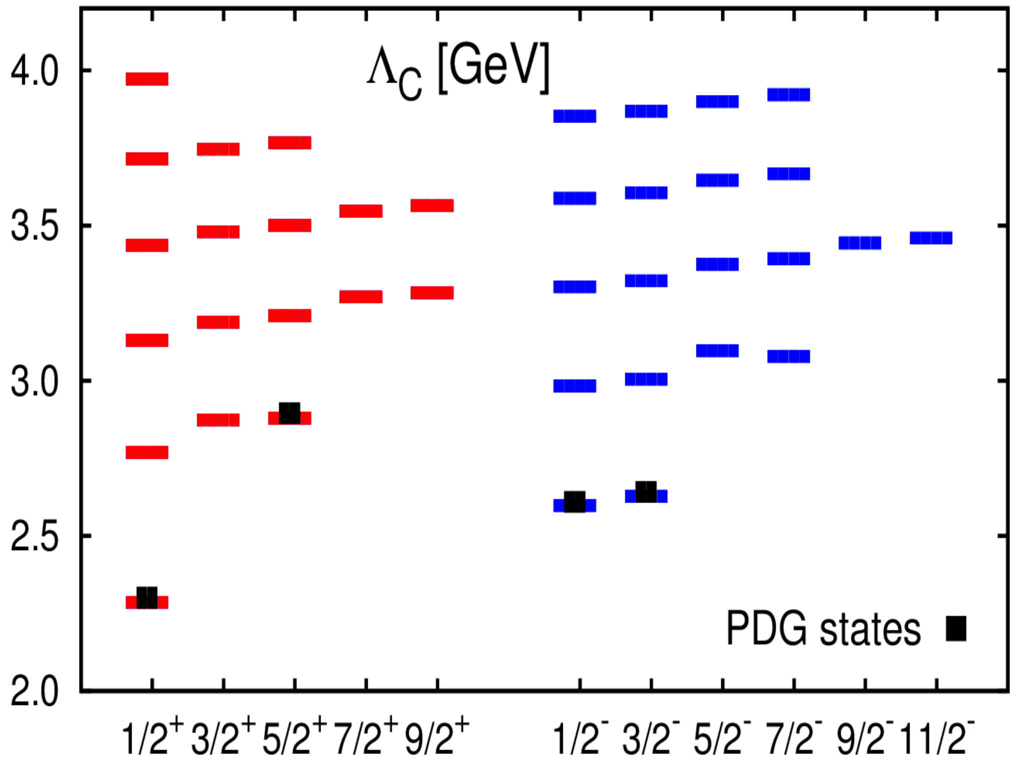
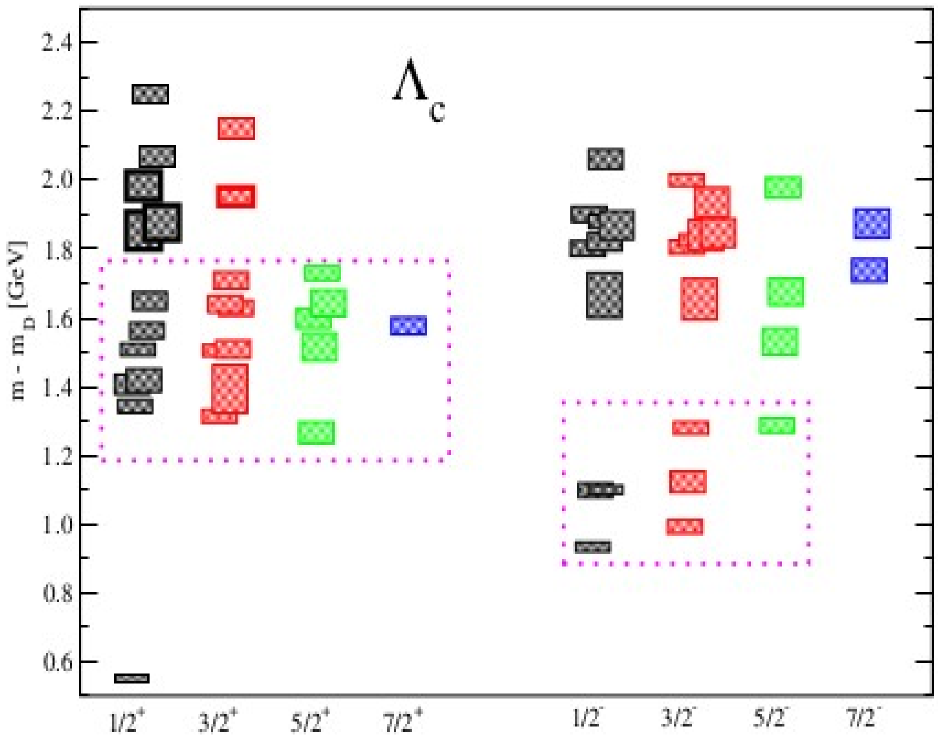
charm baryons

Quark Model



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

LQCD



Padmanath et.al.: arXiv:1311.4806 [hep-lat]

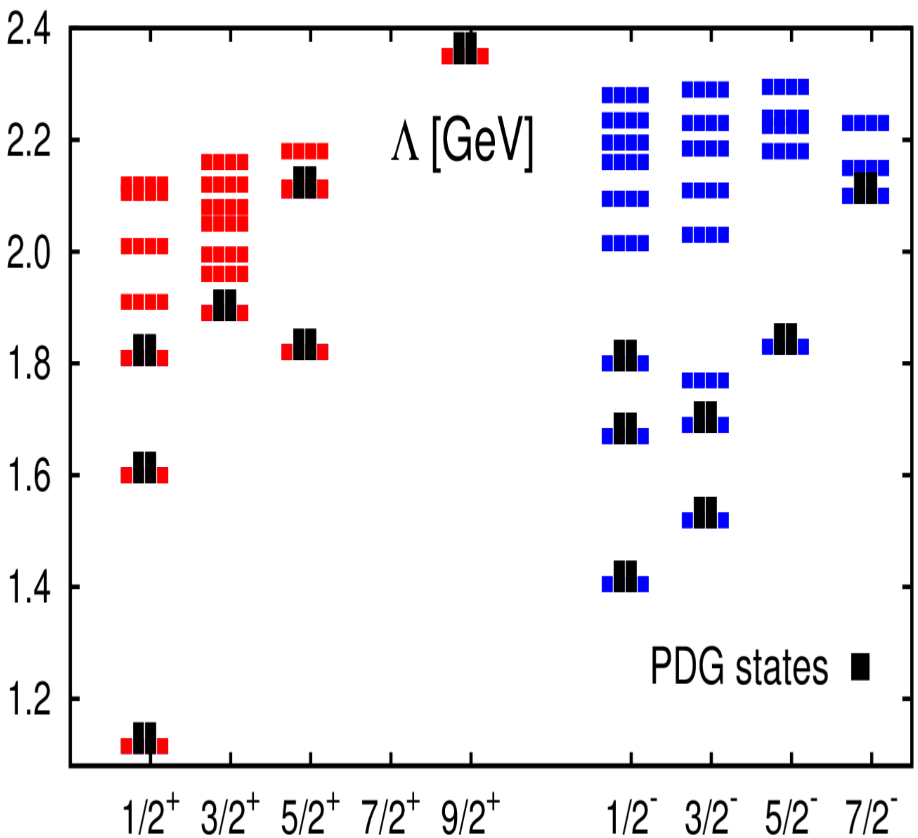
Probing hadron spectrum using thermodynamics

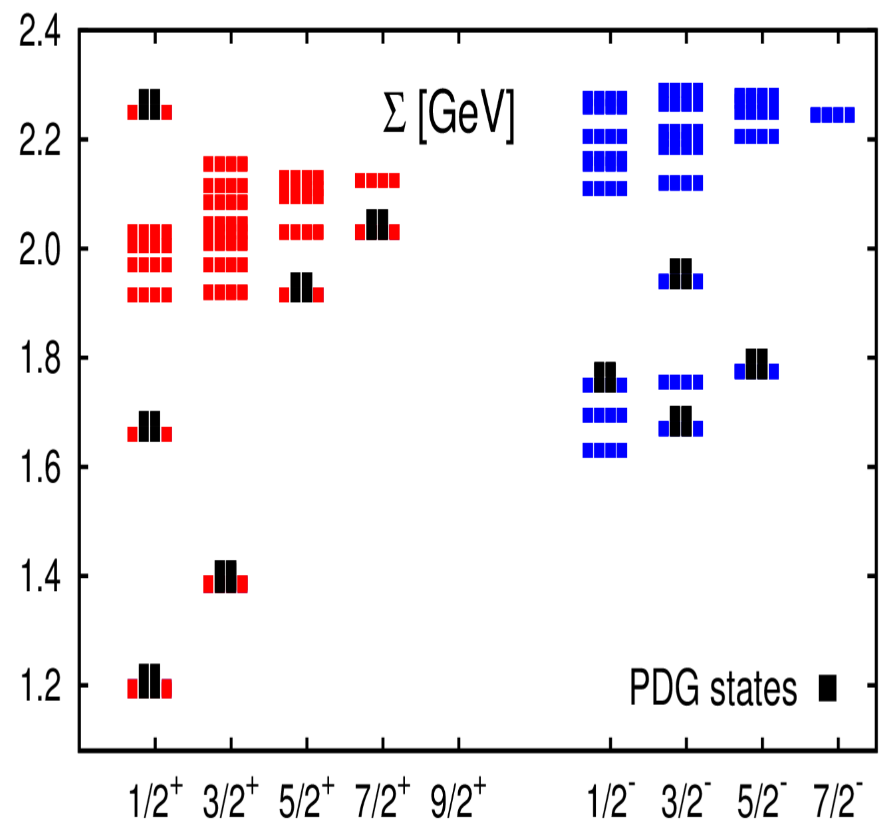
hadronic pressure: $P^S = \sum_{h \in \text{all hadrons}} P_h$

expt. observed hadrons
+ unobserved ones

Quark Model

strange baryons





Capstick-Isgur: Phys. Rev. D34, 2809 (1986)

Probing hadron spectrum using thermodynamics

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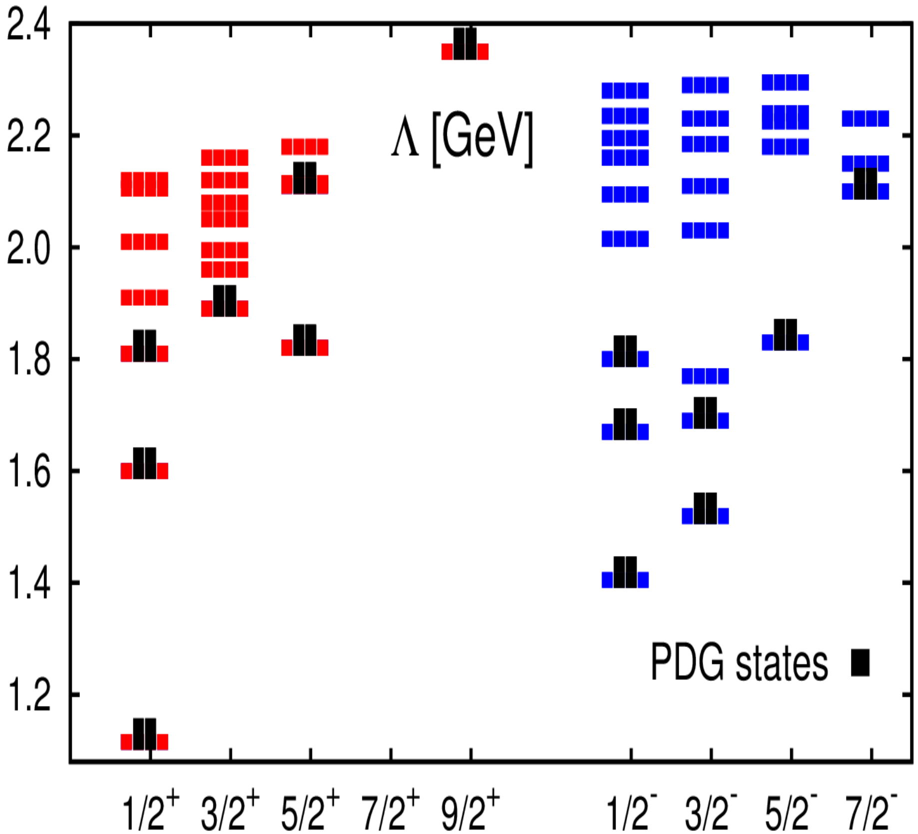
Quark Model | strange baryons | LQCD



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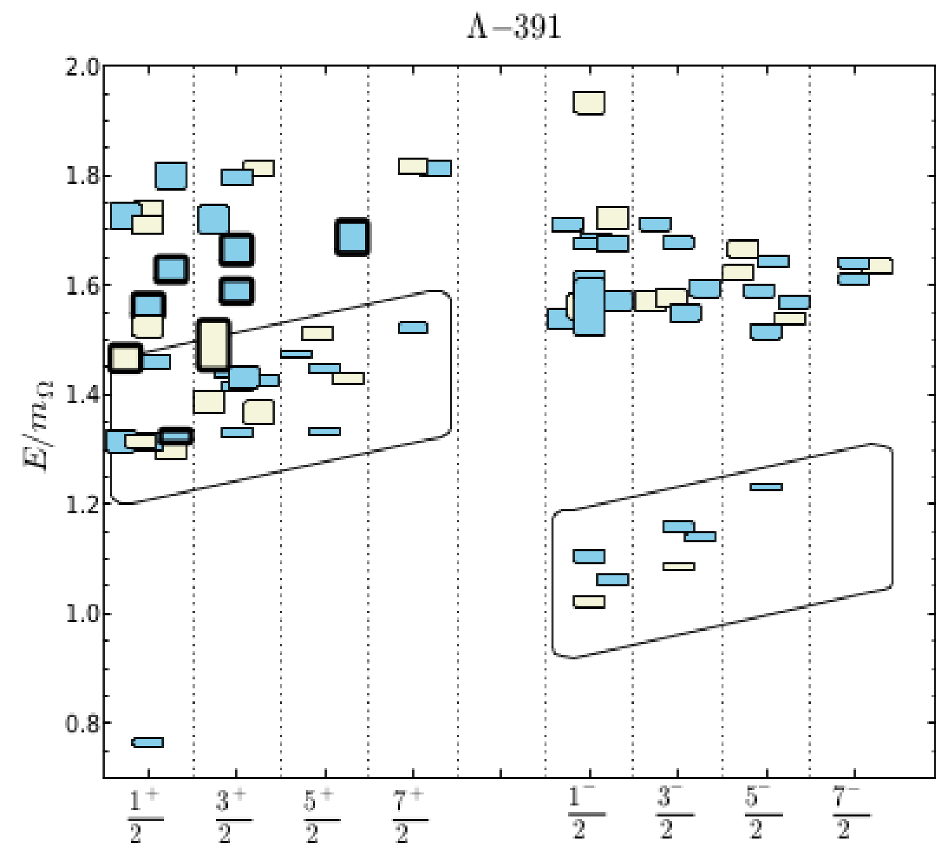
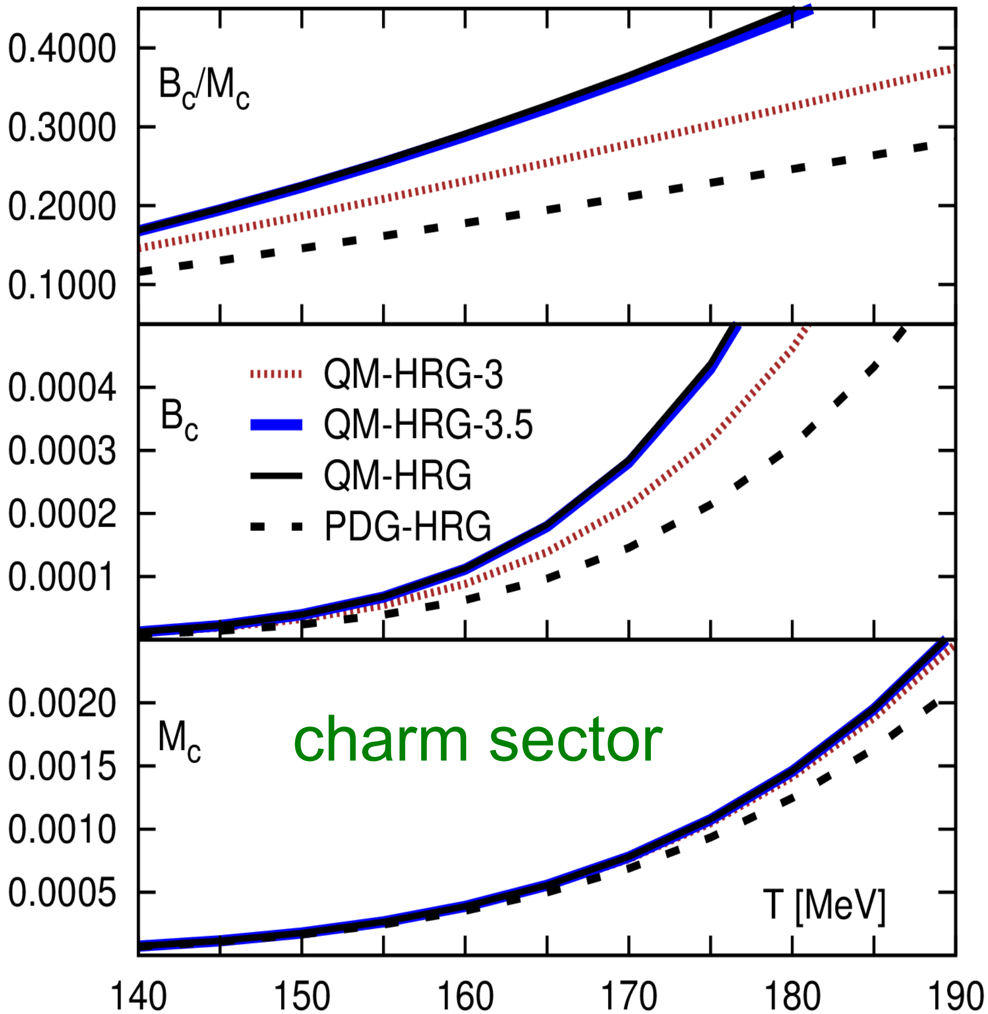
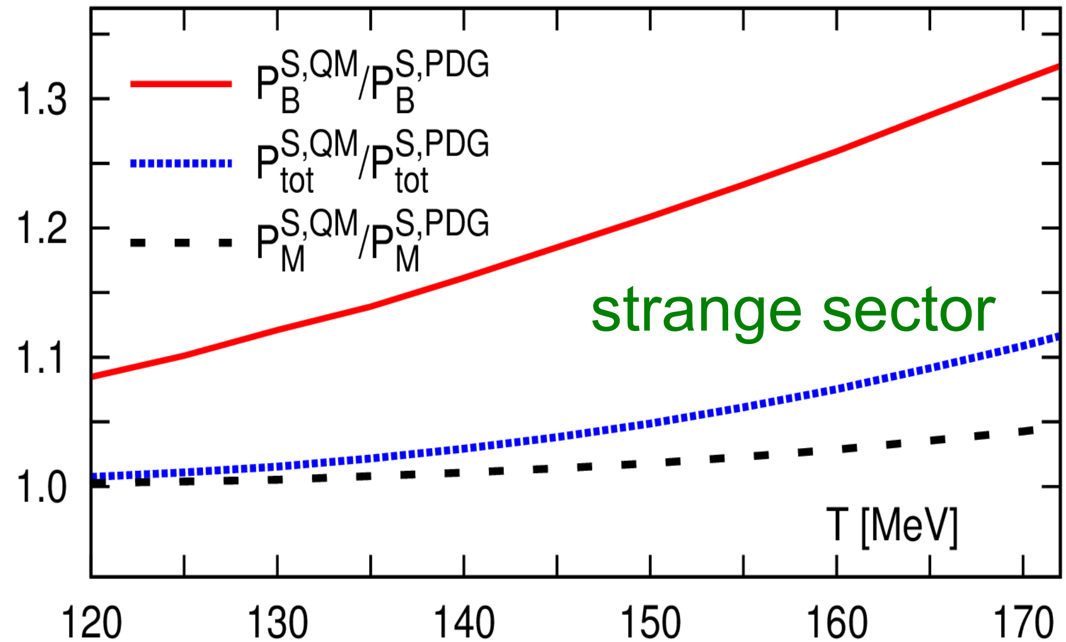


JLab: Phys. Rev. D87, 054506 (2013)

Probing hadron spectrum using thermodynamics





significant contributions of these unseen states to the ratios of partial pressures of baryon to meson near the QCD crossover

partial pressure of
baryon → B; meson → M

similar results with LQCD spectra

LQCD: operators to identify separate thermodynamic contributions of strange/charm baryons/mesons

Operators for partial pressures of baryons & mesons

suitable combinations of up to 4th order
baryon – charm/strangeness correlations

$$\chi_{BX}^{nm} = \left.\frac{\partial^{n+m}\hat{P}}{\partial^n \hat{\mu}_B \partial^m \hat{\mu}_X}\right|_{\vec{\mu}=0}$$

BNL-Bi: Phys. Lett. B737 (2014) 210; Phys. Rev. Lett. 111, 082301 (2013)

a simplified example:

hadron gas $\rightarrow$ $\hat{P}^C \sim P_M^C \cosh[\hat{\mu}_C] + P_B^C \cosh[\hat{\mu}_B + \hat{\mu}_C]$

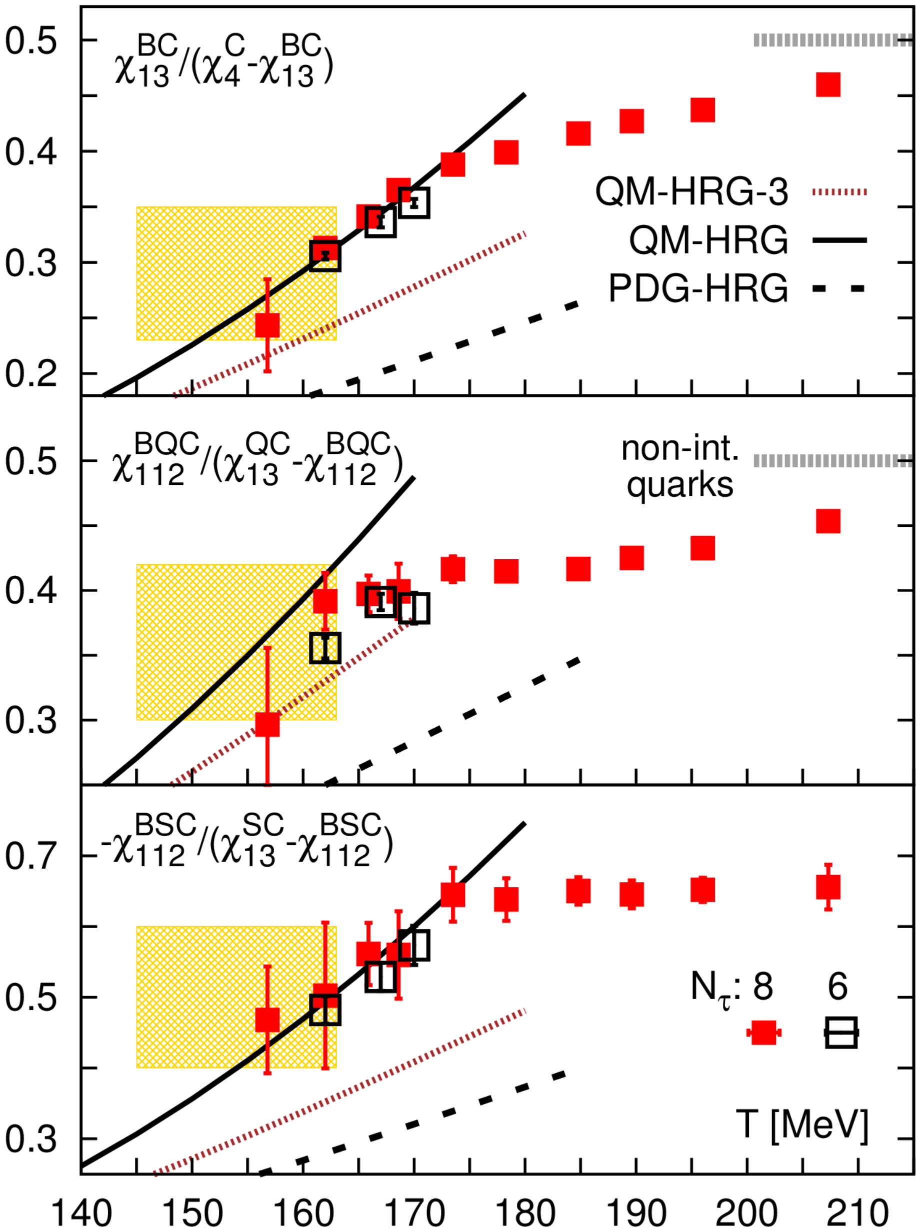
partial pressure of |C|=1 mesons

partial pressure of |C|=1 baryons

neglect contributions of heavier |C|=2,3 baryons, x1000 suppressed

$$\chi_k^C \simeq P_M^C + P_B^C \qquad \chi_{mn}^{BC} \simeq P_B^C$$

Signatures of additional charm baryons



BNL-Bi: Phys. Lett. B737 (2014) 210

relative contributions:

charm baryons to charmed mesons

$$\chi_{13}^{BC}/(\chi_4^C-\chi_{13}^{BC}) = P_B^C/P_M^C$$

charged charm baryons to charged charmed mesons

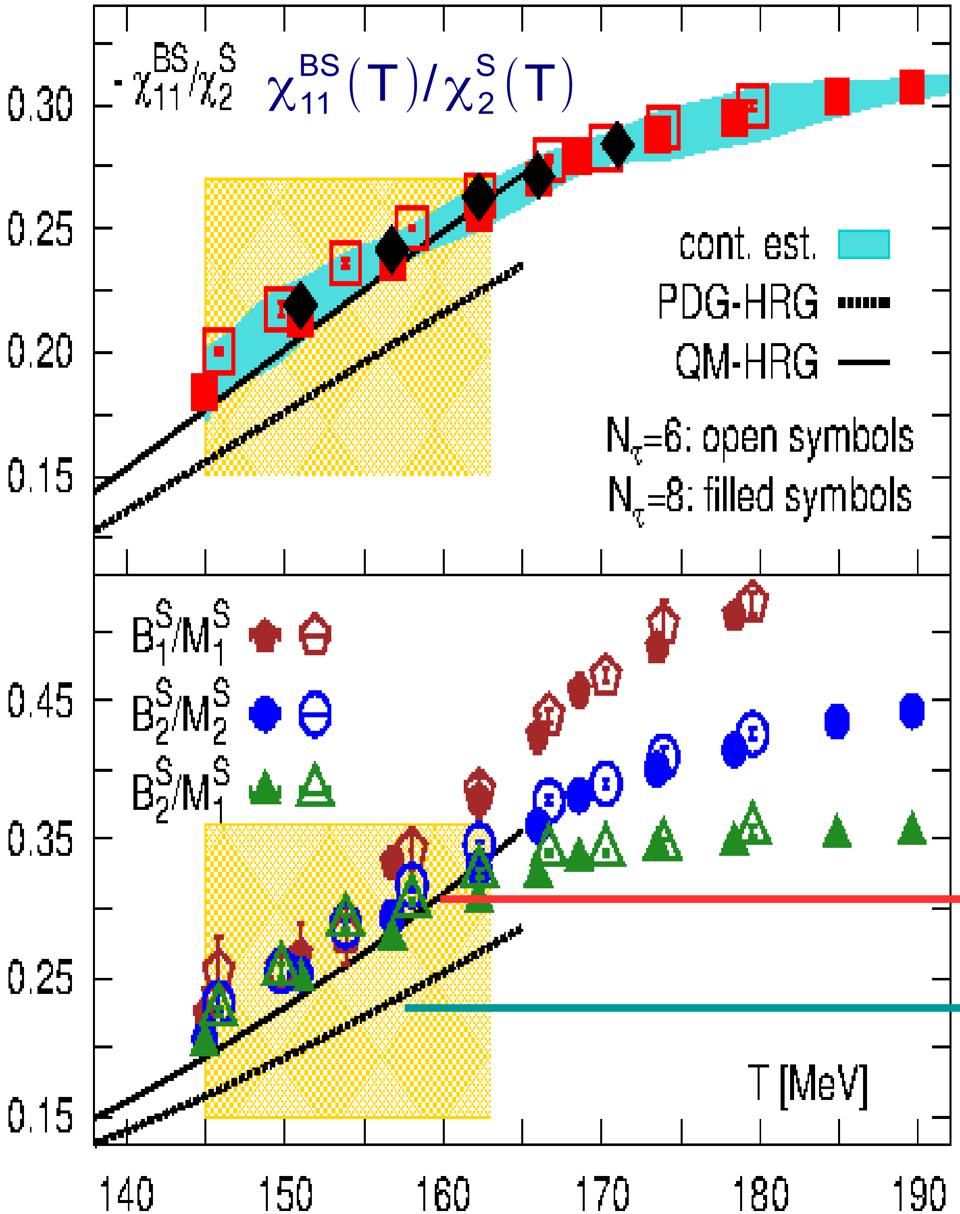
strange charm baryons to strange charmed mesons

signatures of additional, yet unobserved charm baryons from QCD thermodynamics

Thermodynamic contributions of additional strange baryons

relative contributions of strange baryons to strange mesons

BNL-Bi: Phys. Rev. Lett. 113 (2014) 072001



partial pressure of strange mesons:

$$M_1^S = \chi_2^S - \chi_{22}^{BS}$$

$$M_2^S = \frac{1}{12}\left(\chi_4^S + 11\,\chi_2^S\right) + \frac{1}{2}\left(\chi_{22}^{BS} + \chi_{13}^{BS}\right)$$

partial pressure of strange baryons:

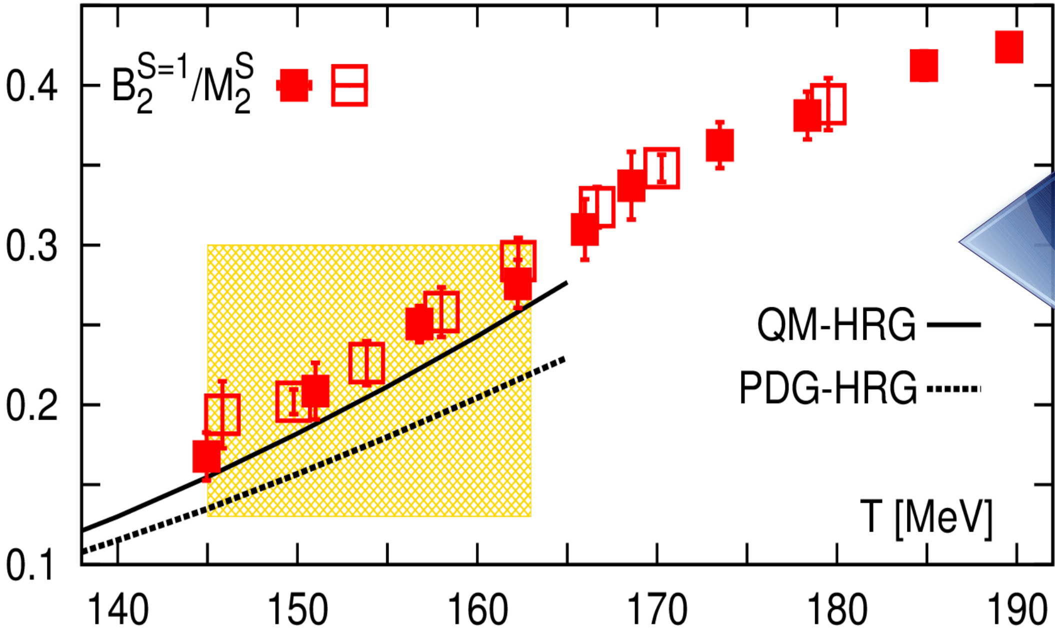
$$B_1^S = -\frac{1}{6}\left(11\,\chi_{11}^{BS} + 6\,\chi_{22}^{BS} + \chi_{13}^{BS}\right)$$

$$B_2^S = \frac{1}{12}\left(\chi_4^S - \chi_2^S\right) + \frac{1}{3}\left(4\,\chi_{11}^{BS} - \chi_{13}^{BS}\right)$$

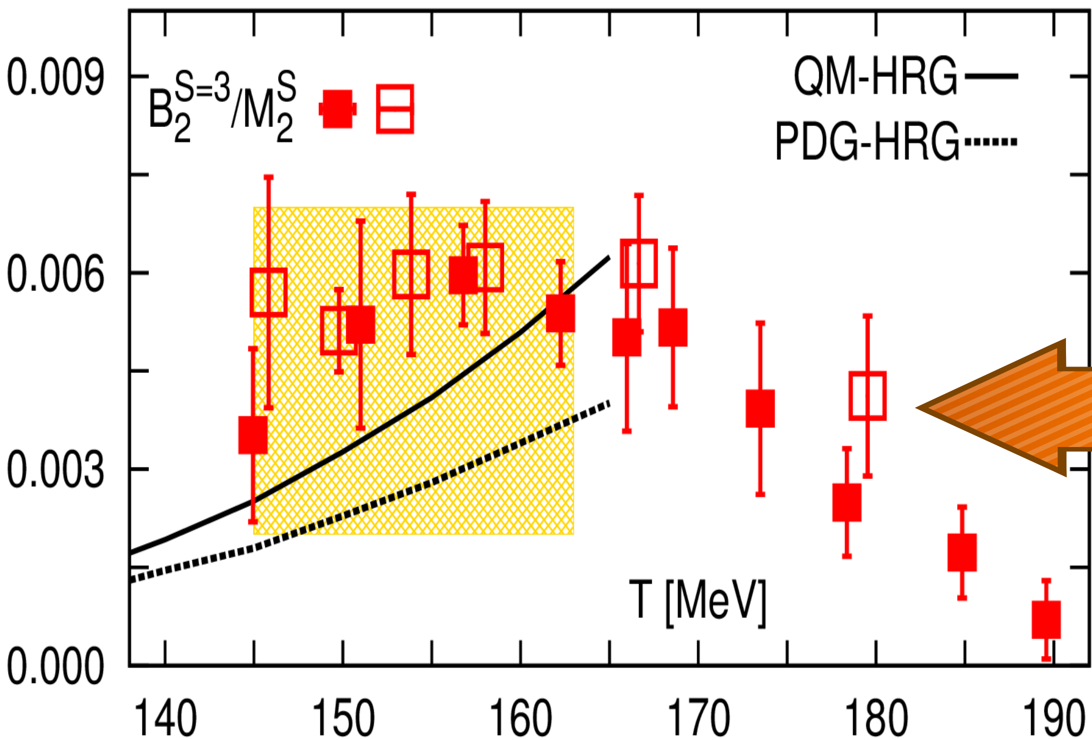
+ undiscovered strange baryons

contributions of all expt. observed strange hadrons

Thermodynamic contributions of additional strange baryons

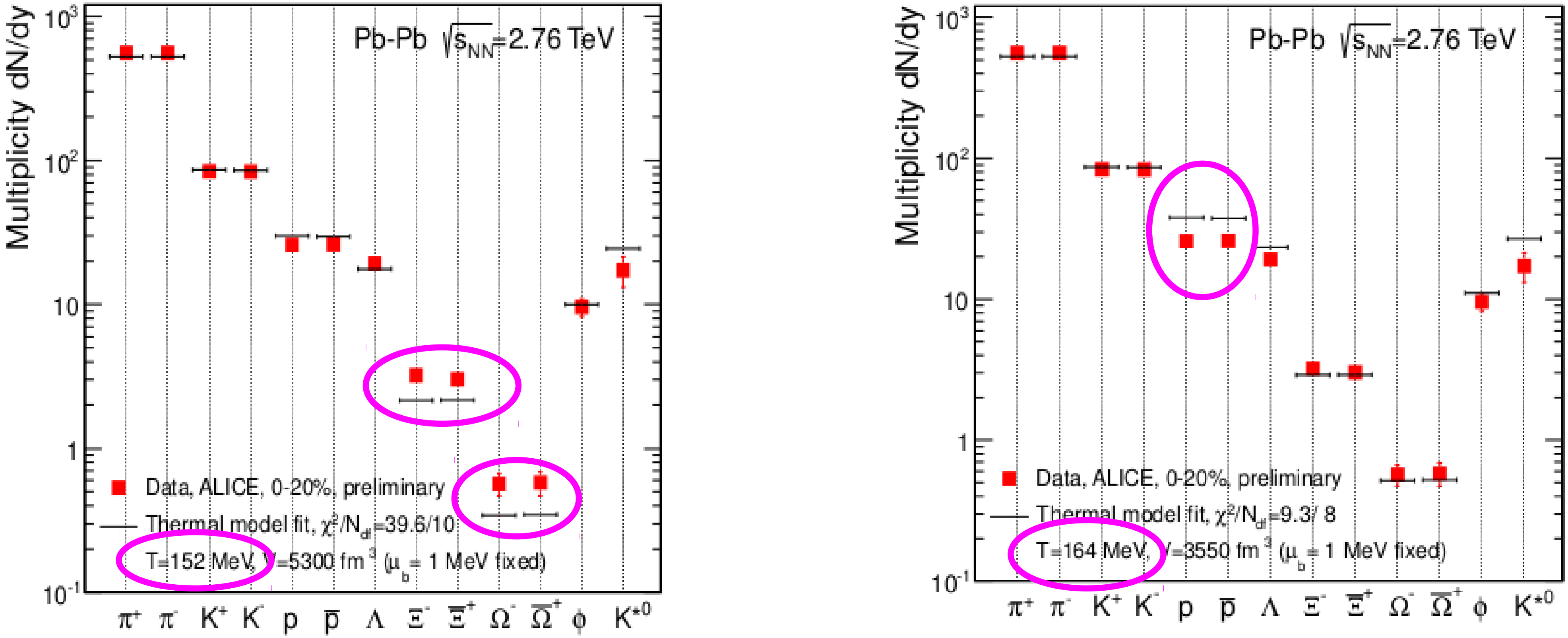


relative contributions of S=1 baryons to strange mesons



relative contributions of S=3 baryons to strange mesons

Hierarchical freeze-out of light & strange hadrons ?



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

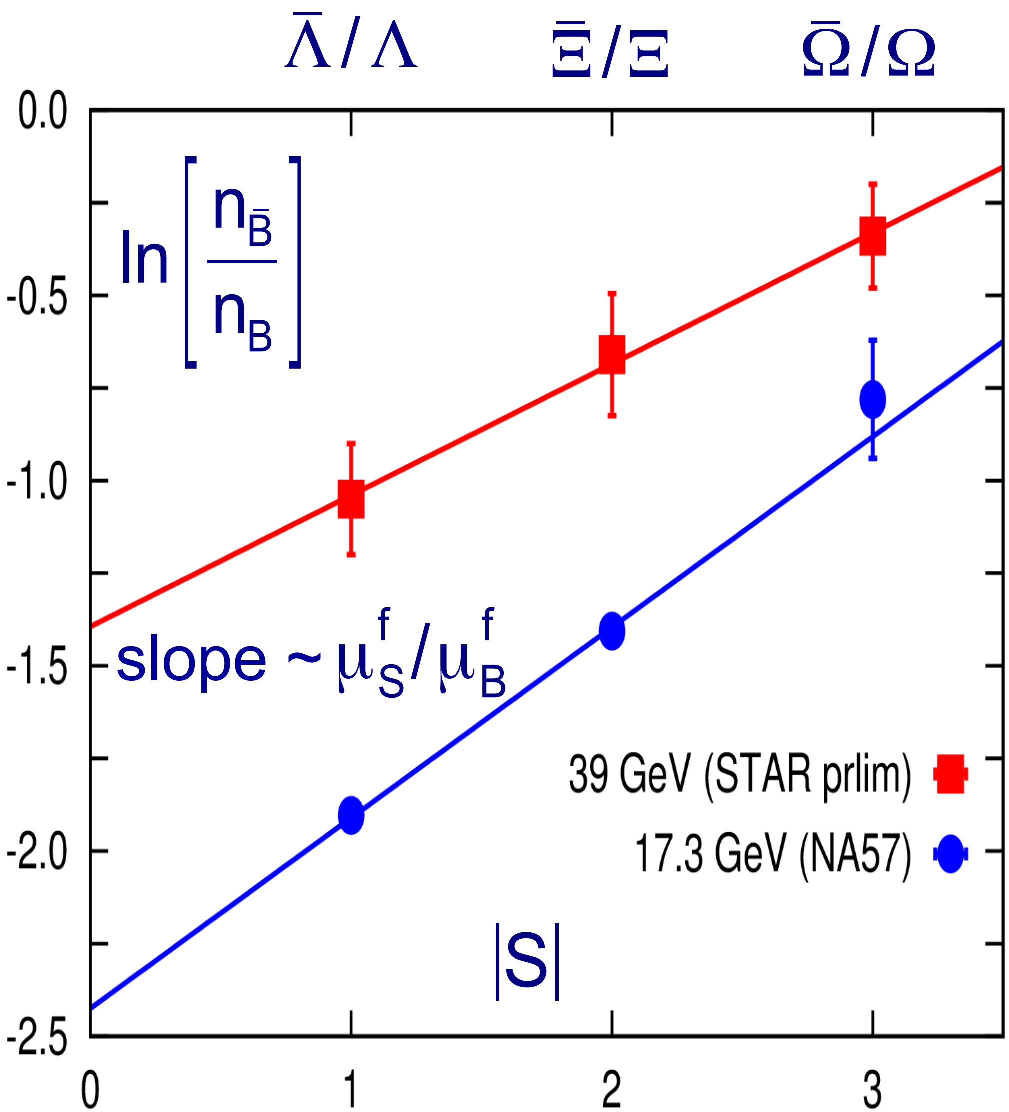
~10-5 MeV systematic difference in freeze-out T
from separate fits to light and strange hadrons

two separate freeze-out stages for light and strange hadrons ?

Phys. Rev. Lett. 111, 202302 (2013); Phys. Lett. B727, 554 (2013);
Europhys. Lett. 104, 22002 (2013) …

Strange baryon yields in heavy-ion collisions

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



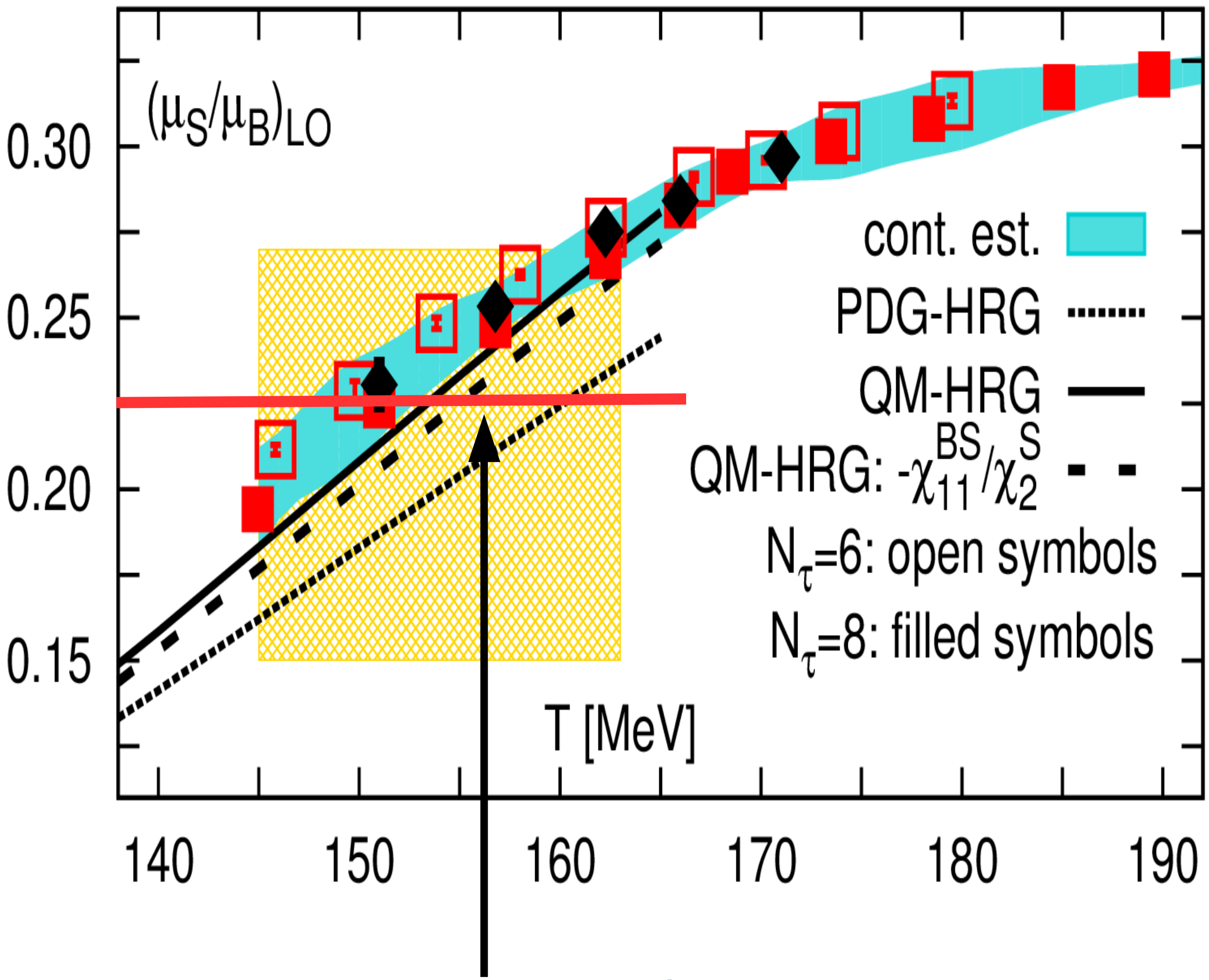
does not assume spectrum of hadron gas, only assumes hadron yields are thermal

Strangeness neutrality & strangeness chemical potential

medium formed in HIC is strangeness neutral: $\langle n_S \rangle = 0$

$$\frac{\mu_S}{\mu_B}(T, \mu_B/T) \simeq \frac{\chi_{11}^{BS}(T)}{\chi_2^S(T)} + \ldots$$

relative contribution of strange baryons to mesons



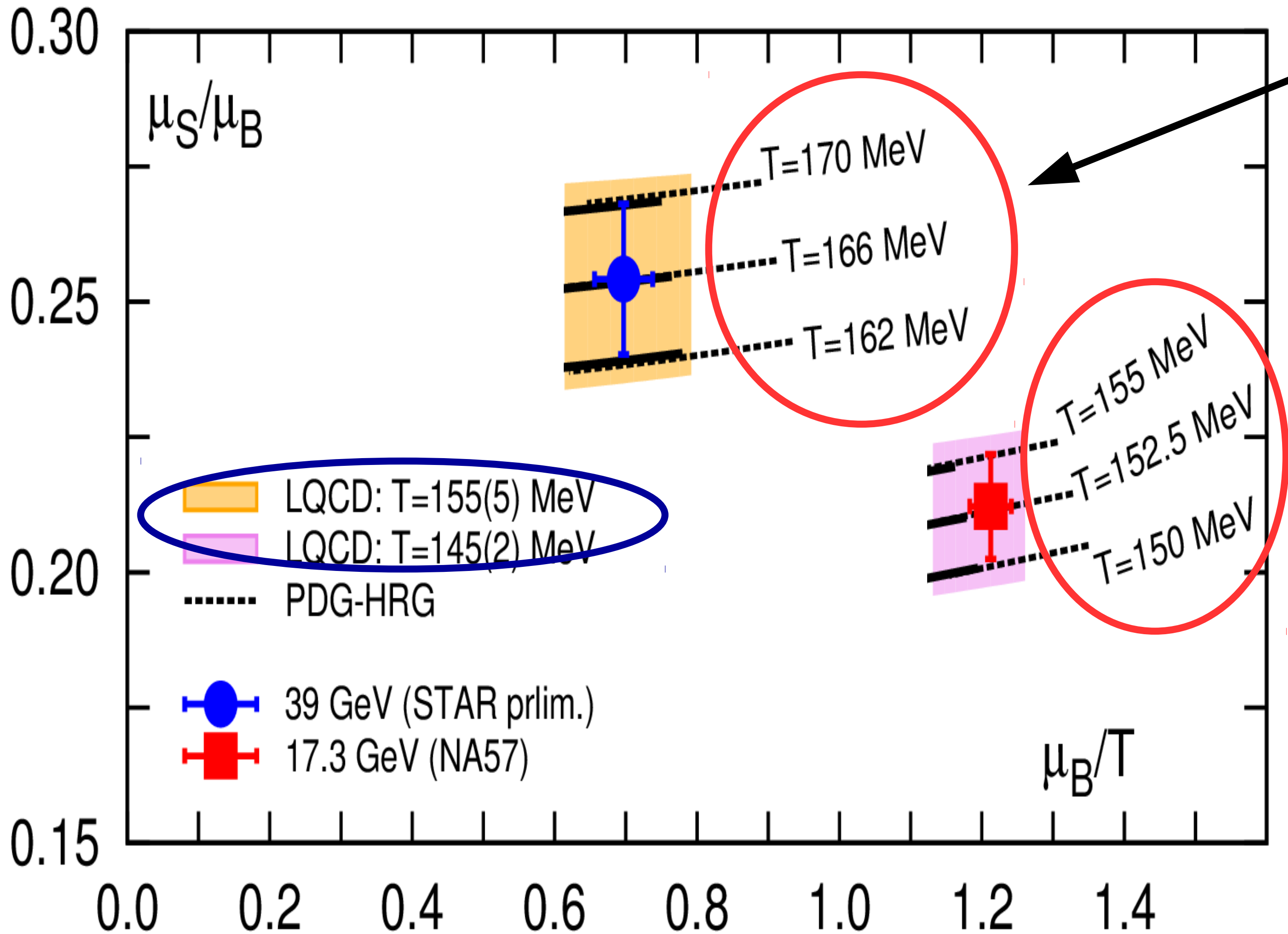
LQCD results are reproduced by including additional Quark Model states

a given value of μ_S/μ_B is realized at a lower temperature

BNL-Bi: Phys. Rev. Lett. 113 (2014) 072001

Strangeness, LQCD and freeze-out in HIC

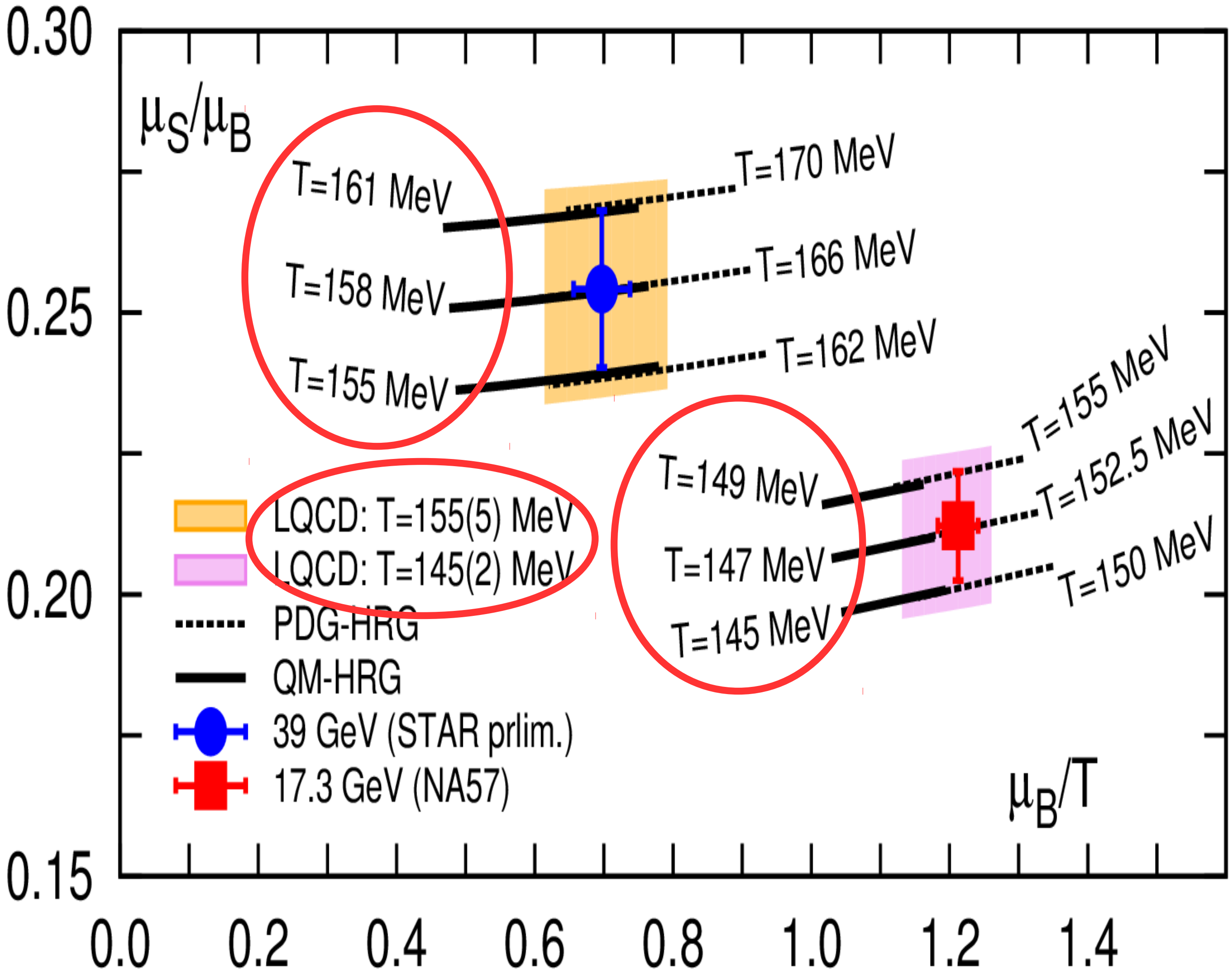
freeze-out T by comparing
μ_S/μ_B from LQCD and expt.



not reproduced by strangeness neutral hadrons gas with only PDG states

BNL-Bi: Phys. Rev. Lett. 113 (2014) 072001

Additional strange hadrons & freeze-out in HIC

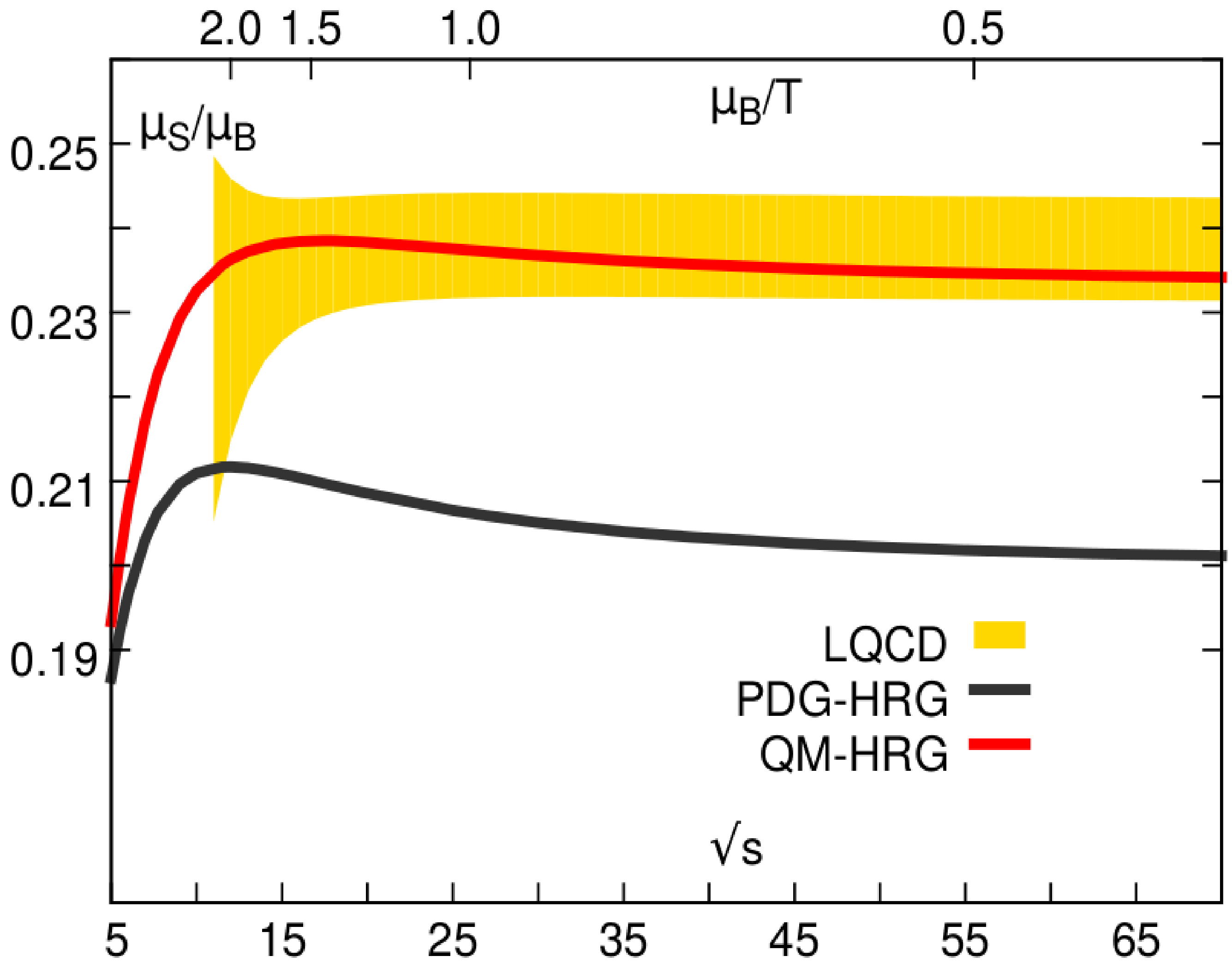


inclusion of additional strange hadrons reduces freeze-out T & agrees with LQCD+expt. determination

indirect evidence for so-far undiscovered strange baryons at RHIC ?

BNL-Bi: Phys. Rev. Lett. 113 (2014) 072001

Additional strange hadrons & RHIC BES



signature for unobserved strange baryons persists for RHIC BES-II

can also be extracted from expt. measured

$$\frac{\ln\left[N_{K^-}/N_{K^+}\right]}{\ln\left[N_{\bar{p}}/N_p\right]} = \frac{\mu_S^f}{\mu_B^f}$$

need accurate expt. measurements & feed-down corrections

Summary

hot-dense LQCD:

additional, yet unobserved strange & charm baryons become thermodynamically relevant near the QCD crossover

these additional strange baryons are important for determining the `observed' freeze-out temperatures of heavy-ion collision experiments

freeze-out temperatures for strange hadrons obtained comparing LQCD and HIC expt. favors presence of these additional hadrons