Additional Strange Hadrons and Freeze-out in Heavy Ion Collisions

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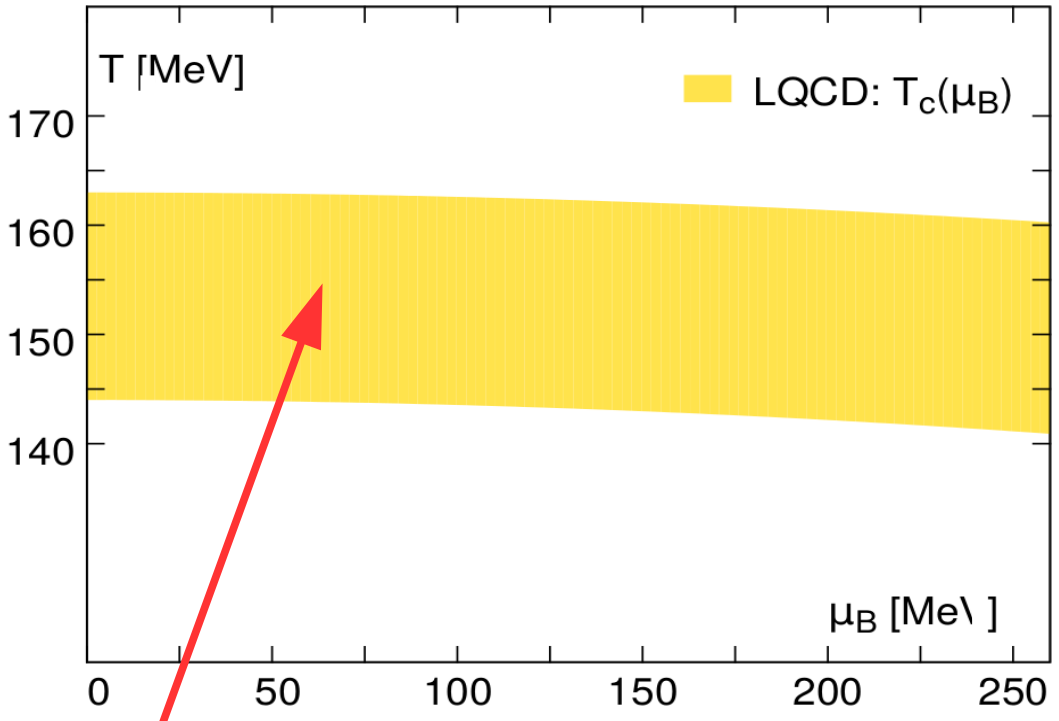
Mapping out the QCD phase diagram



phase boundary in T, μ_B plane

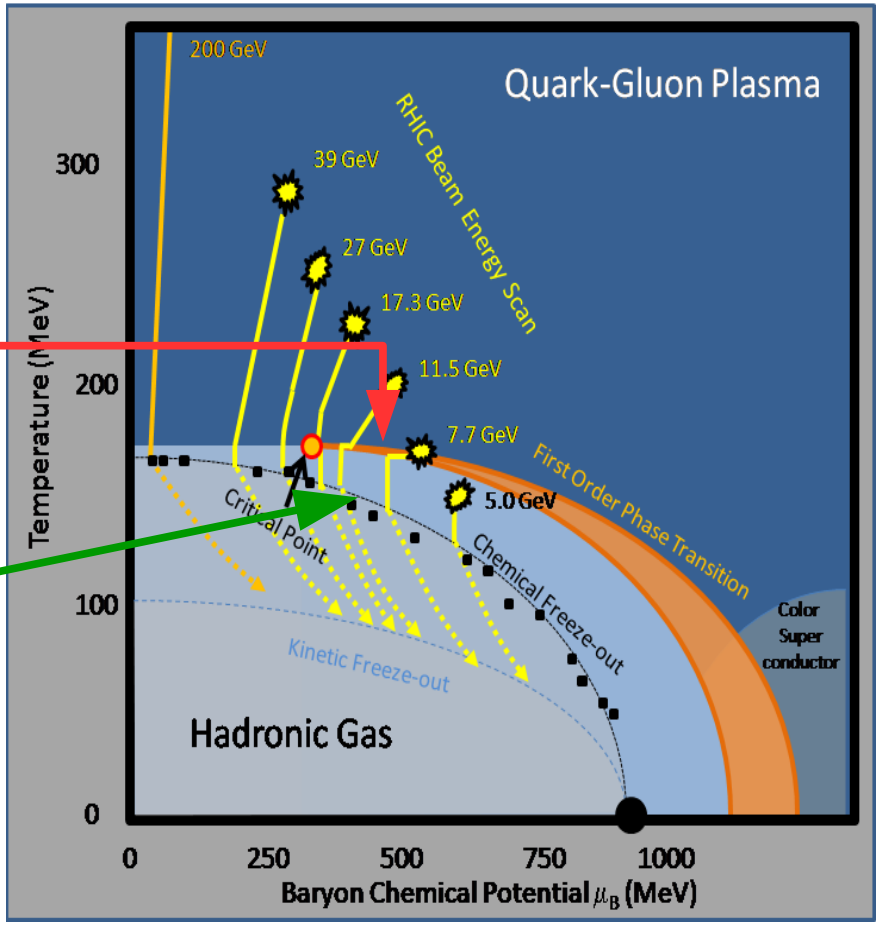
BNL-Bi: Phys. Rev. D83, 014504 (2011)

freeze-out T^f, μ_B^f

phase boundary & freeze-out line must be close to probe the QCD phase diagram

RHIC Beam Energy Scan probing QCD phase diagram

$\sqrt{s} \Leftrightarrow (T, \mu_B)$??



Cumulants of conserved charge fluctuations

LQCD: conserved charge susceptibilities

$$\sqrt{s} \Leftrightarrow \left(T, \mu_B\right)$$

$$\chi_n^x(T,\mu_x) = \frac{\partial^n\left(p(T,\mu_x)/T^4\right)}{\partial(\mu_x/T)^n}$$

$$\chi_n^x(T,\mu_x) = \sum_n \frac{1}{k!}\,\chi_{k+n}^x(T)\left(\frac{\mu_x}{T}\right)^n$$

can be compared directly with experimentally measured cumulants of charge fluctuations

$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\chi_1^Q(T,\mu_B)}{\chi_2^Q(T,\mu_B)}$$

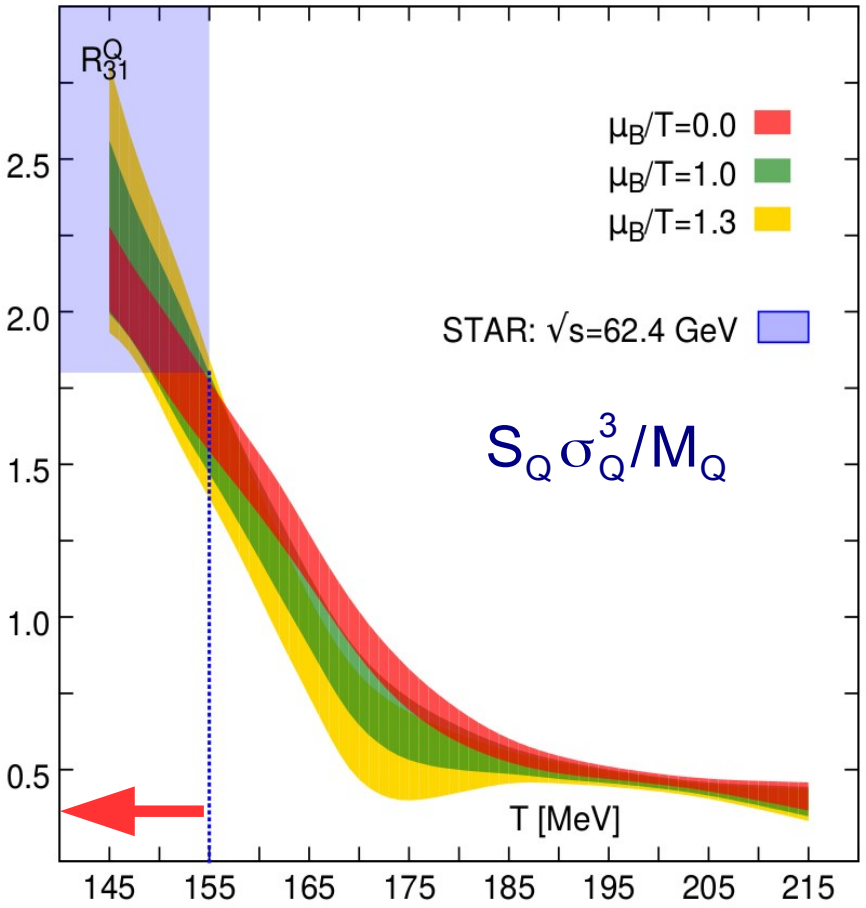
$$\frac{S_Q(\sqrt{s})\,\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\chi_3^Q(T,\mu_B)}{\chi_1^Q(T,\mu_B)}$$

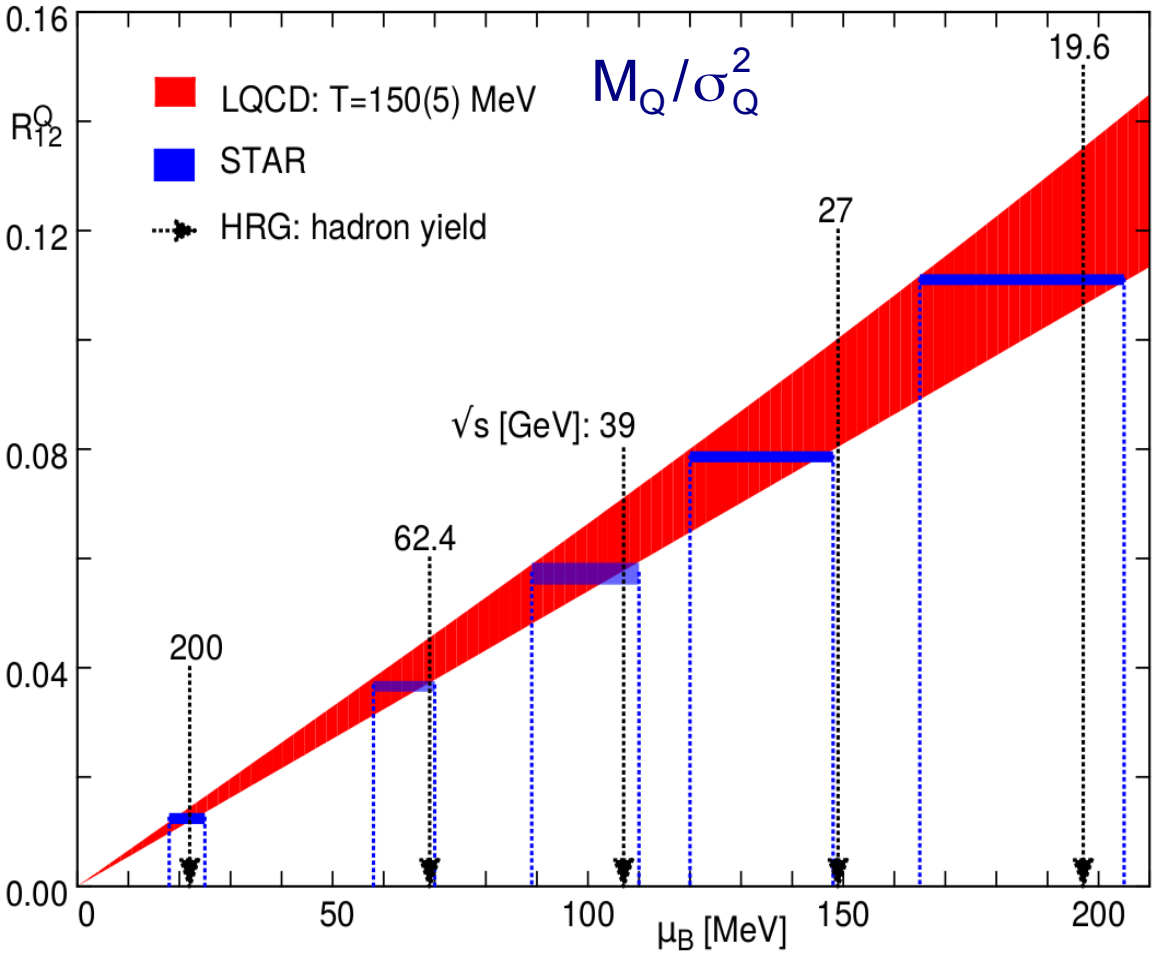
Expt.: mean: M_Q
variance: σ_Q^2
skewness: S_Q
kurtosis: κ_Q

can be used to extract freeze-out parameters

BNL-Bi: Phys. Rev. Lett. 109, 192302 (2012)

Charge fluctuations, LQCD and freeze-out in HIC





thermometer: T^f

$T^f \leqslant 155$ MeV

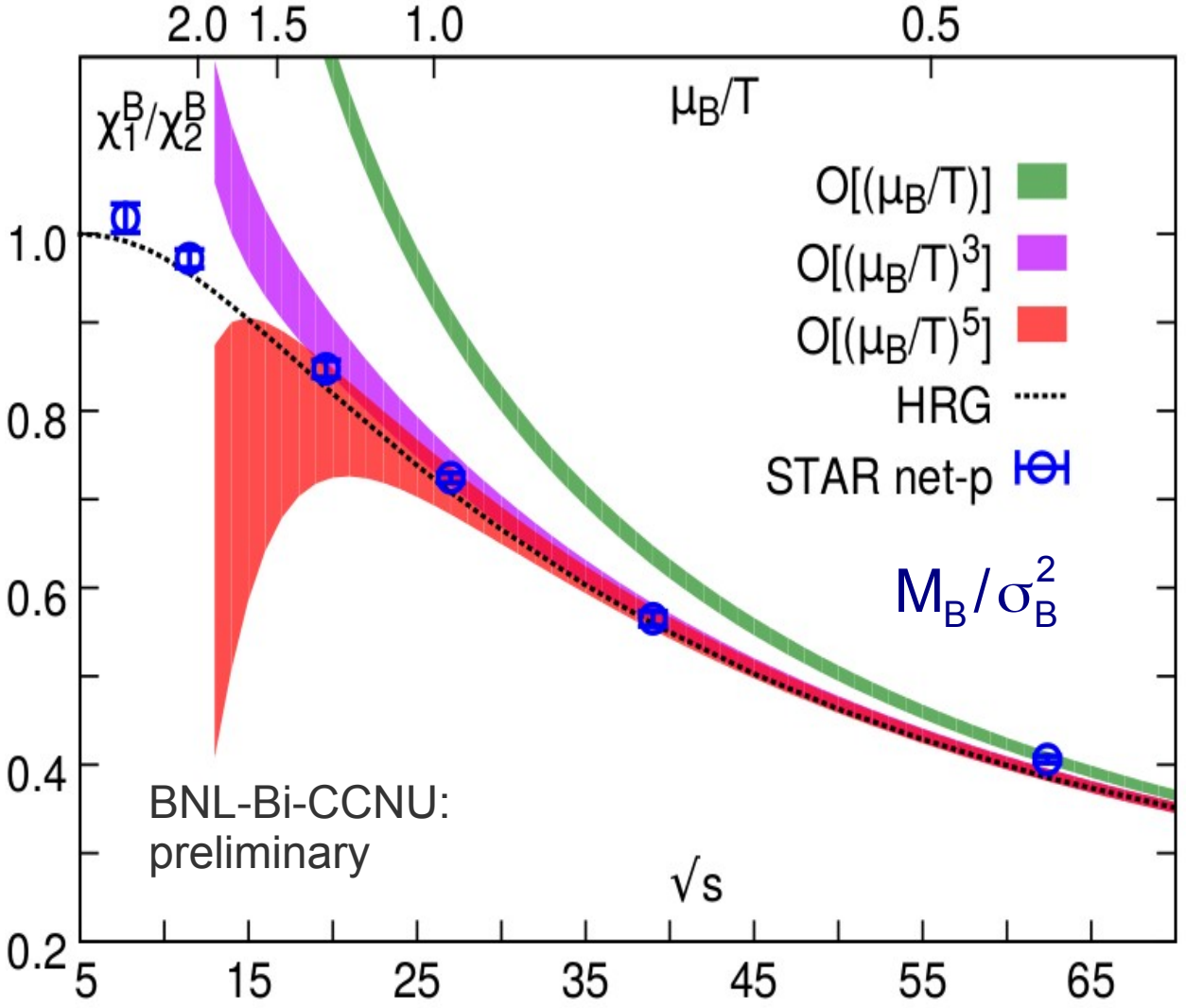
baryometer: μ_B^f

need more precise measurements from BES-II

STAR: Phys.Rev.Lett. 113 (2014) 092301

BNL-Bi: Phys. Rev. Lett. 109, 192302 (2012)

Baryon number fluctuation along the freeze-out

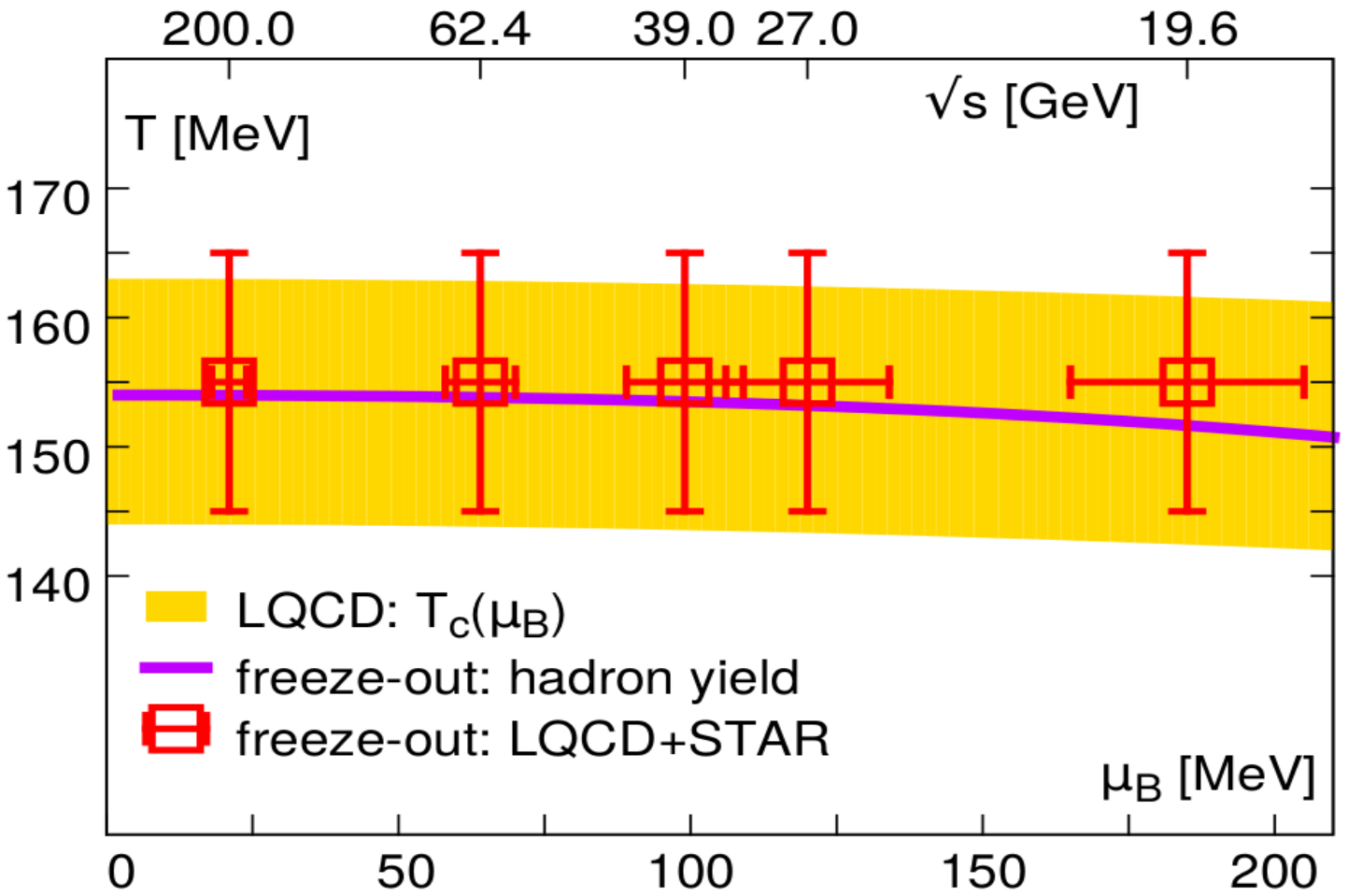


once freeze-out parameters are fixed using QCD, parameter-free comparison with QCD calculations possible

consistent with electric charge fluctuations

STAR: Phys. Rev. Lett. 112 (2014) 3, 032302

Freeze-out at RHIC



need better T^f determination

freeze-out in RHIC takes place close to the phase boundary

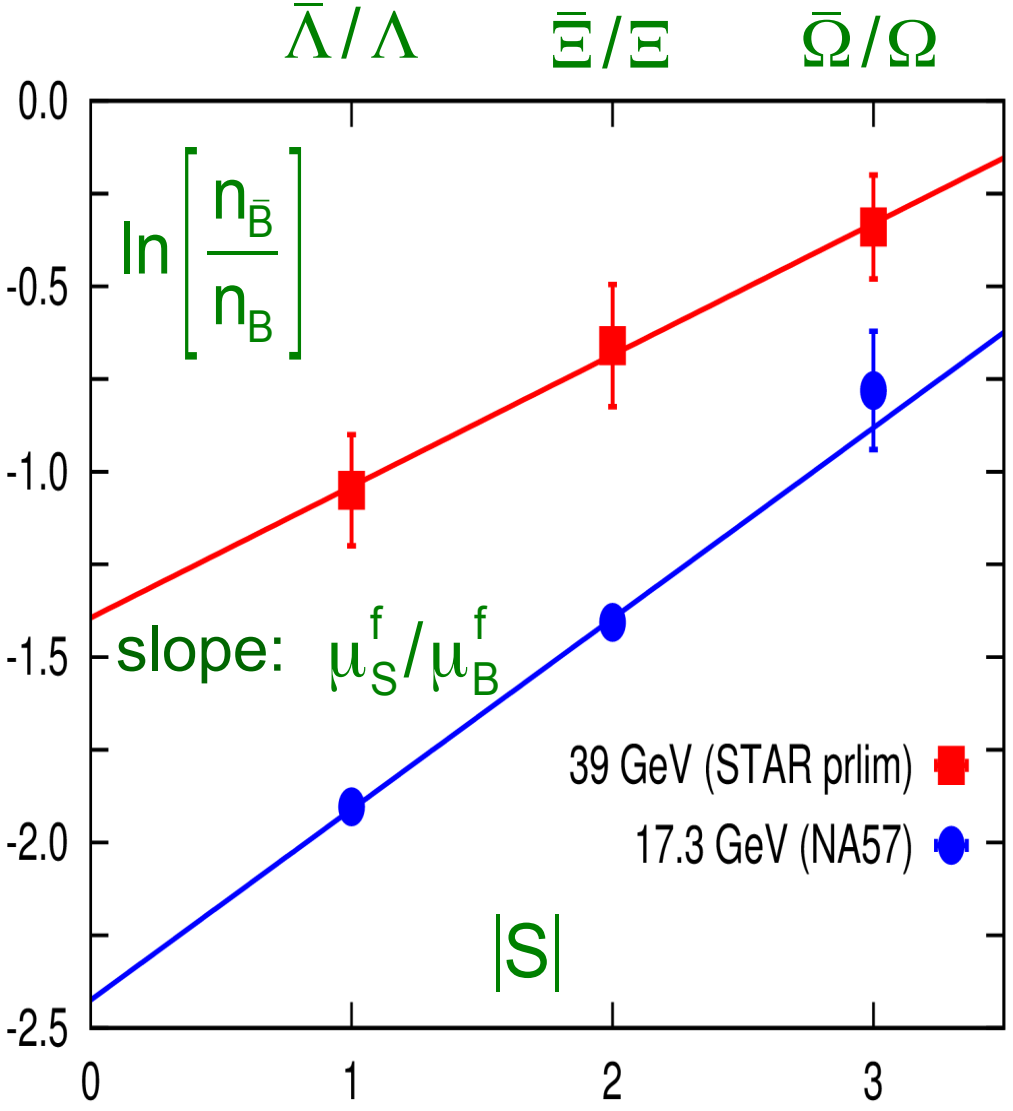
freeze-out from hadron yield parametrization:
Andronic et.al., J. Phys. G38, 124081 (2011),
with $T^f(\sqrt{s}\to\infty)=154$ MeV

Strangeness, LQCD and freeze-out in HIC

medium formed in HIC is strangeness neutral: $\langle n_S \rangle = 0 \Rightarrow \mu_S(T, \mu_B)$

$$\frac{\mu_S}{\mu_B}(T, \mu_B/T) \simeq \frac{\chi_{11}^{BS}(T)}{\chi_2^S(T)} + O\left[(\mu_B/T)^2\right]$$

can be calculated from LQCD



can be extracted from expt.:

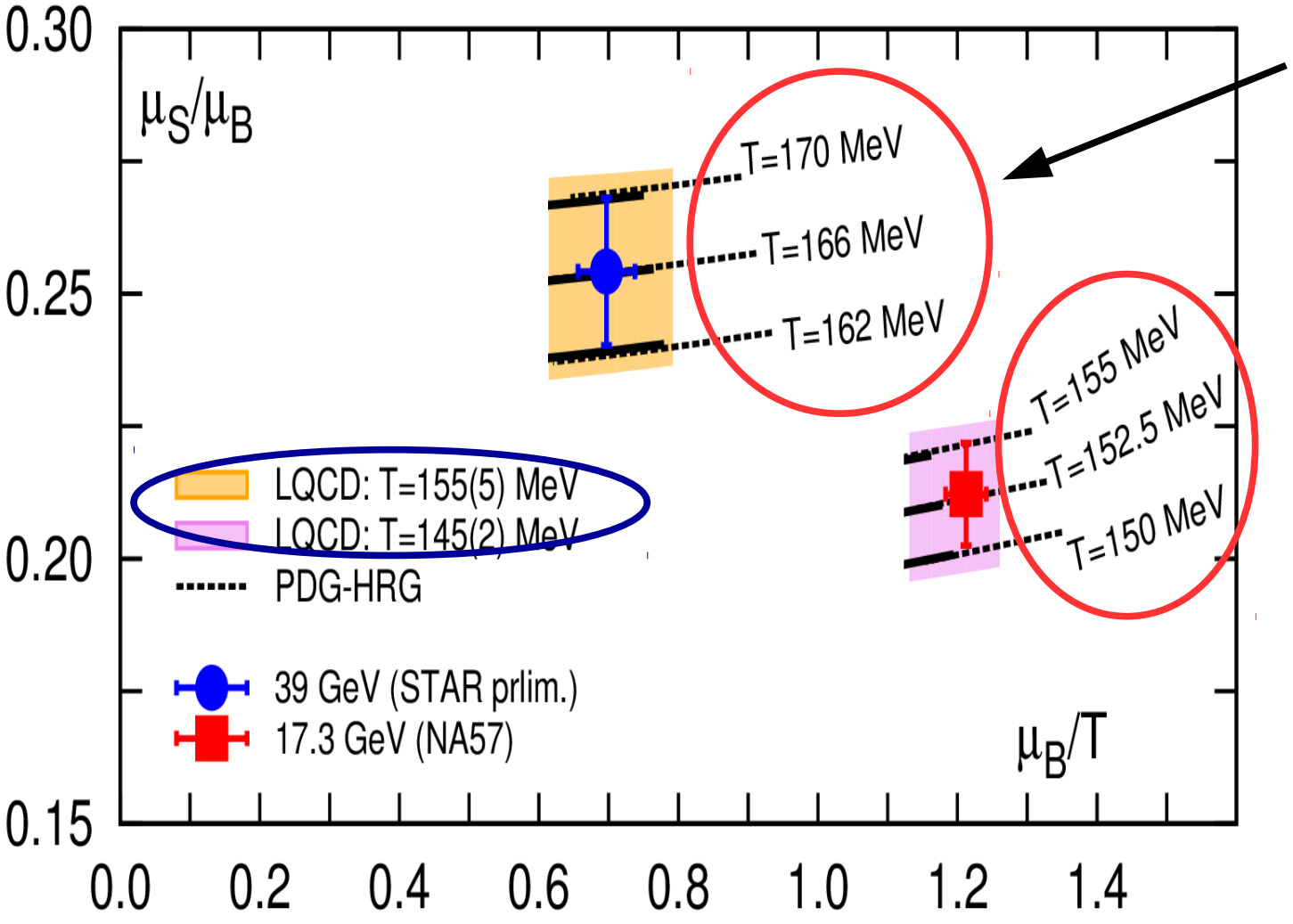
$$\frac{n_{\bar{\Lambda}}}{n_\Lambda}, \frac{n_{\bar{\Xi}}}{n_\Xi}, \frac{n_{\bar{\Omega}}}{n_\Omega} = \exp\left[-\frac{2\mu_B^f}{T^f}\left(1 - \frac{\mu_S^f}{\mu_B^f}|S|\right)\right]$$

freeze-out T by comparing (L)QCD and expt.

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

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

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

relative contribution of strange baryons to strange mesons

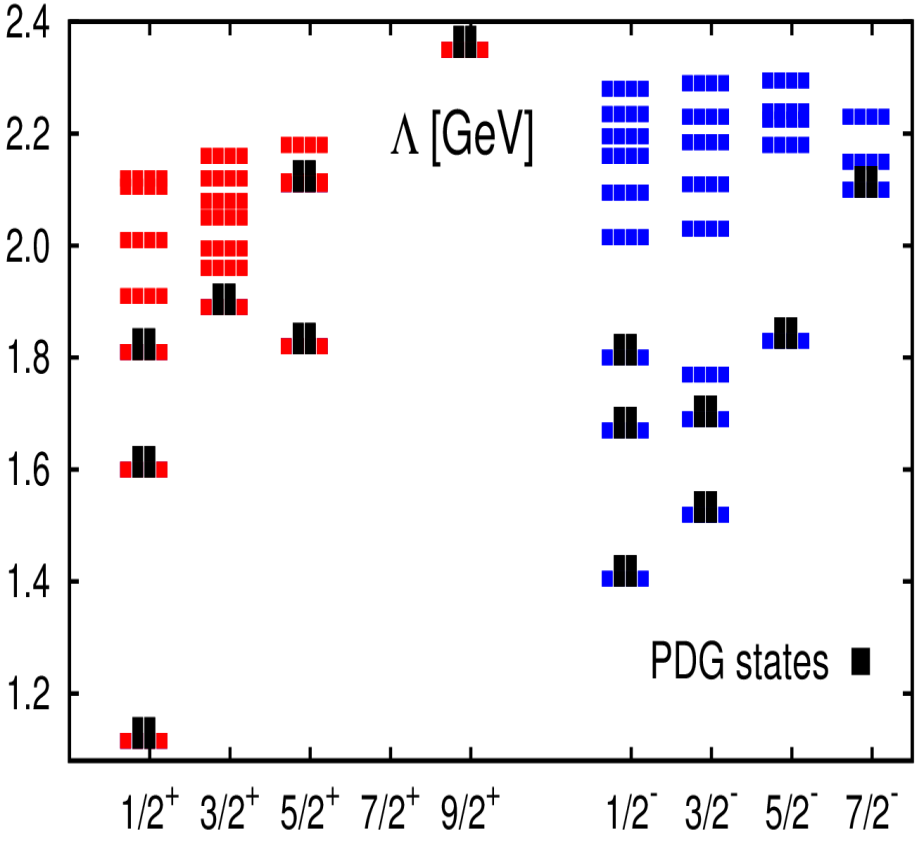
BNL-Bi-CCNU: Phys. Rev. Lett. 113 (2014) 072001

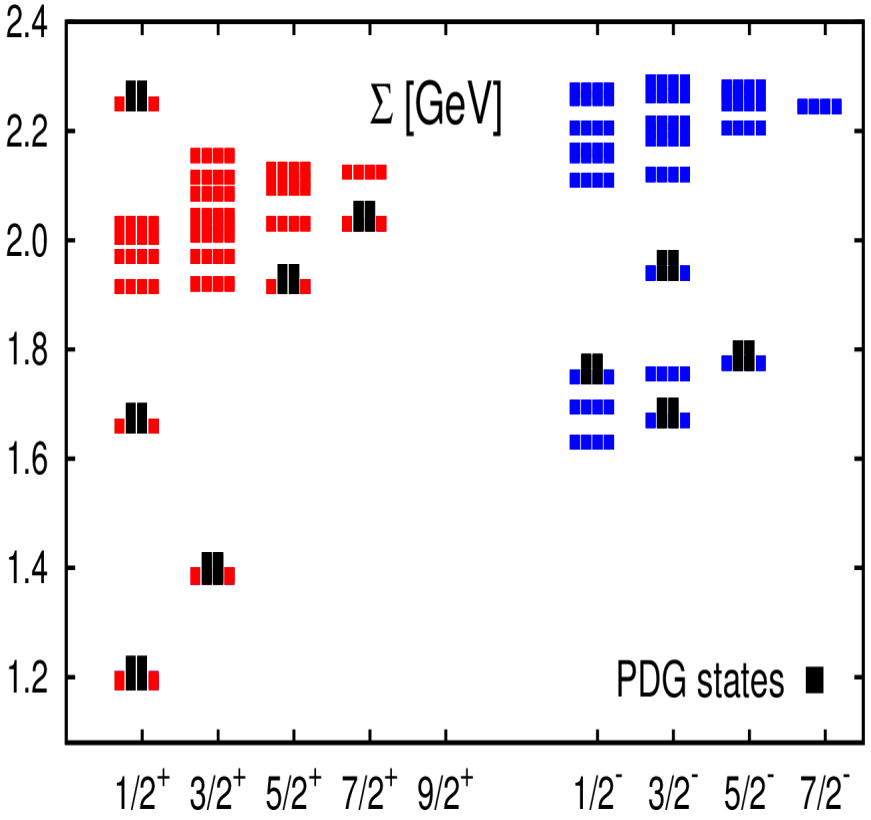
Role of additional strange hadrons

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

expt. observed hadrons
+ unobserved ones

Quark Model





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

Role of additional strange hadrons

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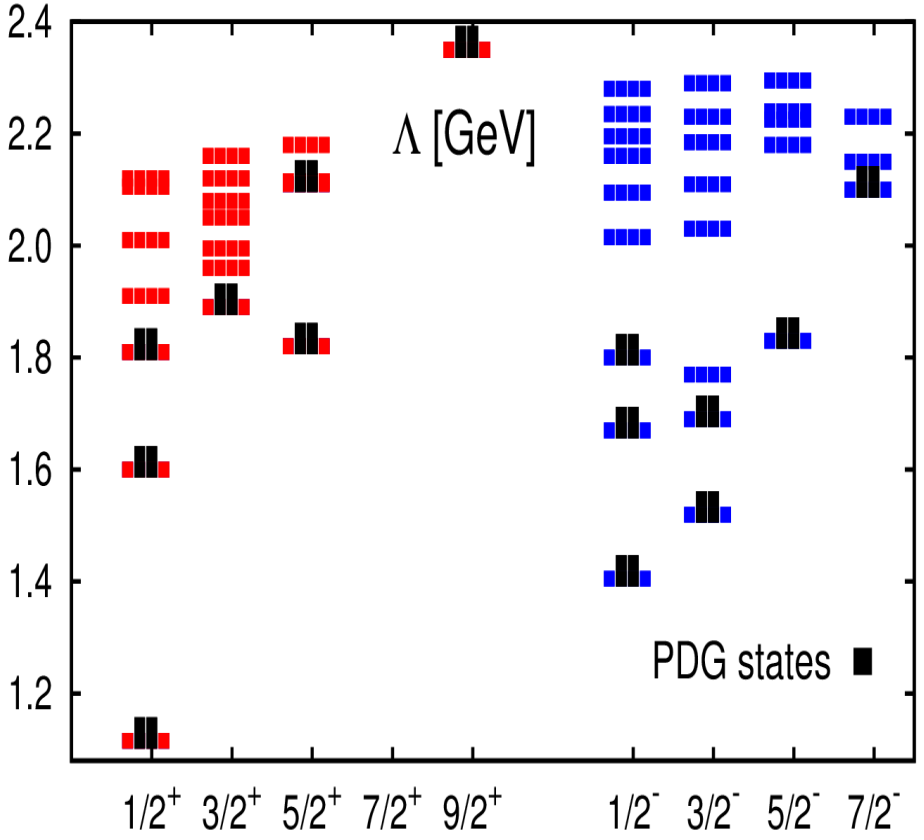
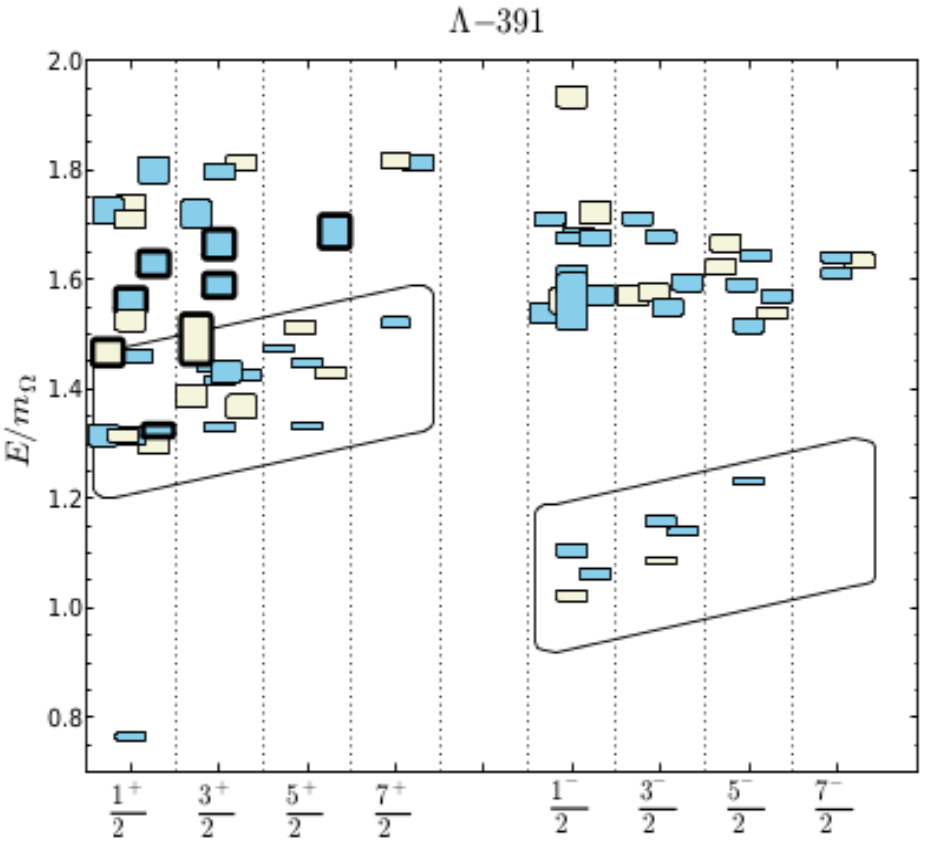
Quark Model



LQCD



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

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

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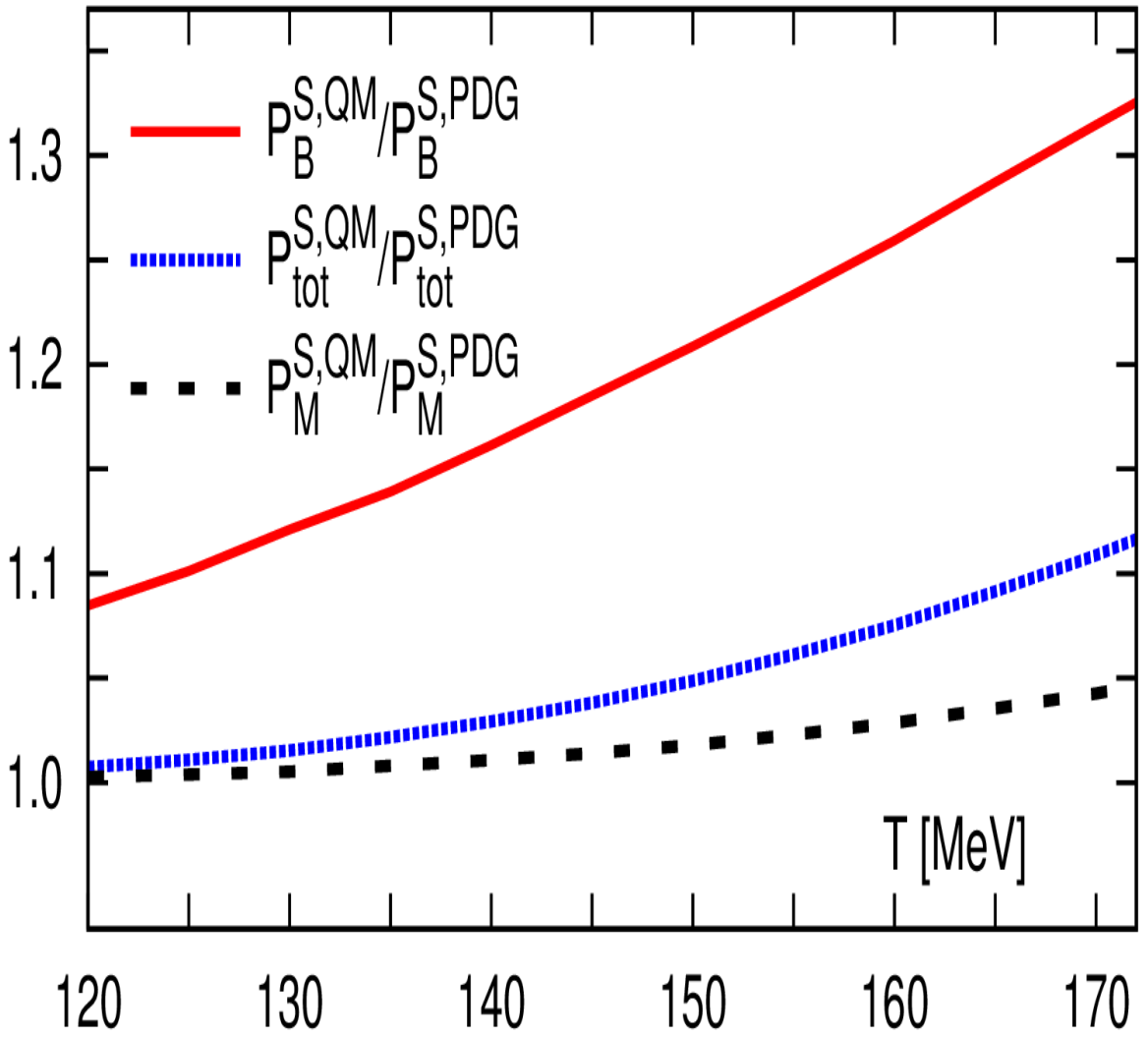
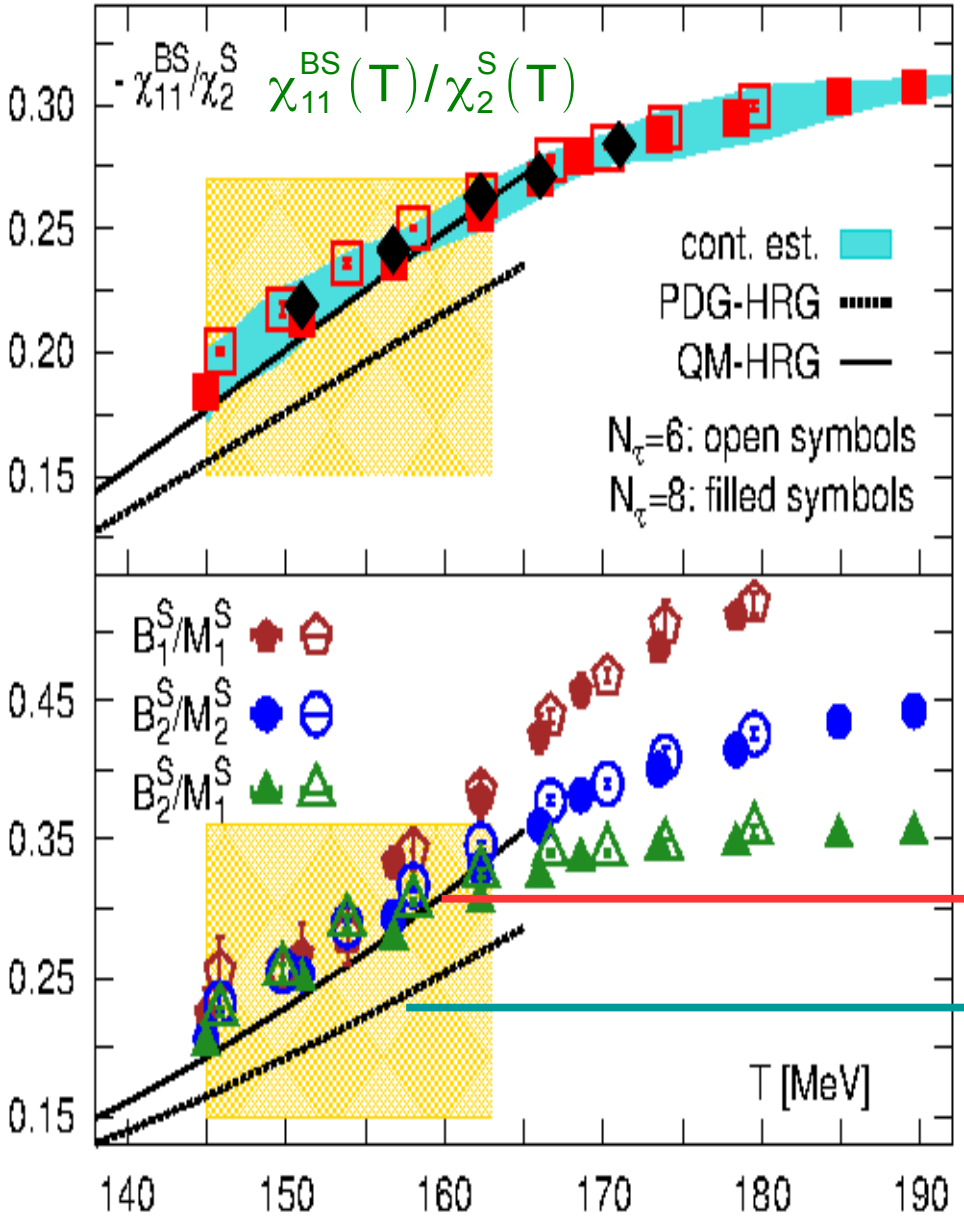


significant contribution of additional, unobserved strange baryons close to the QCD crossover

B ← strange baryons, M ← strange mesons

Thermodynamic contributions of additional strange hadrons

relative contributions of strange baryons to strange mesons



BNL-Bi-CCNU:
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:

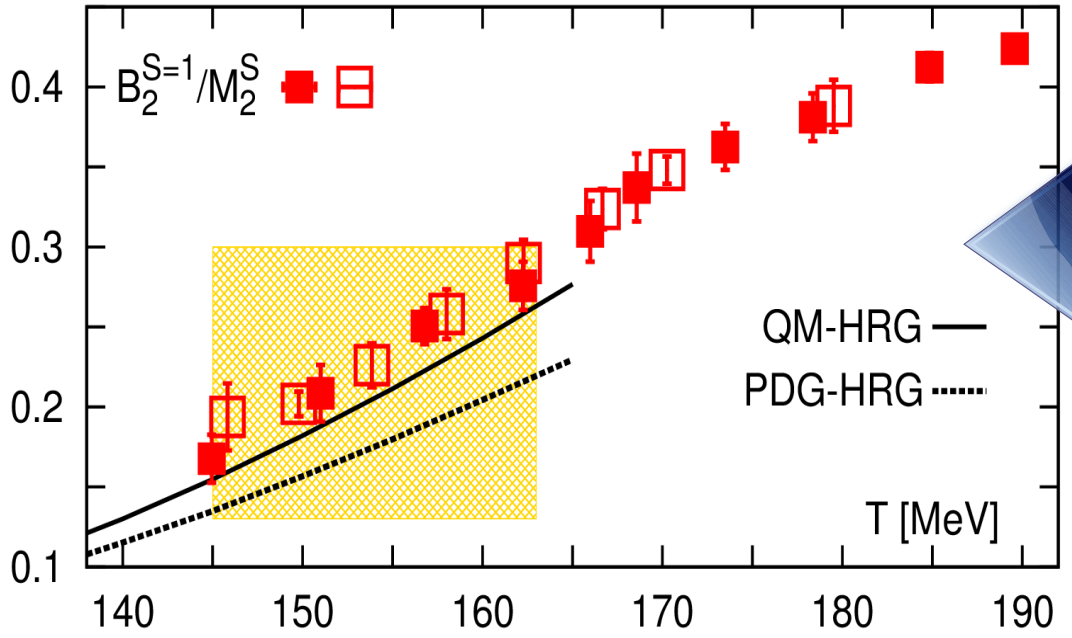
$$B_1^S = -\frac{1}{6}\left(11\,\chi_{11}^{BS} + 6\,\chi_{22}^{BS} + \chi_{13}^{BS}\right)$$

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

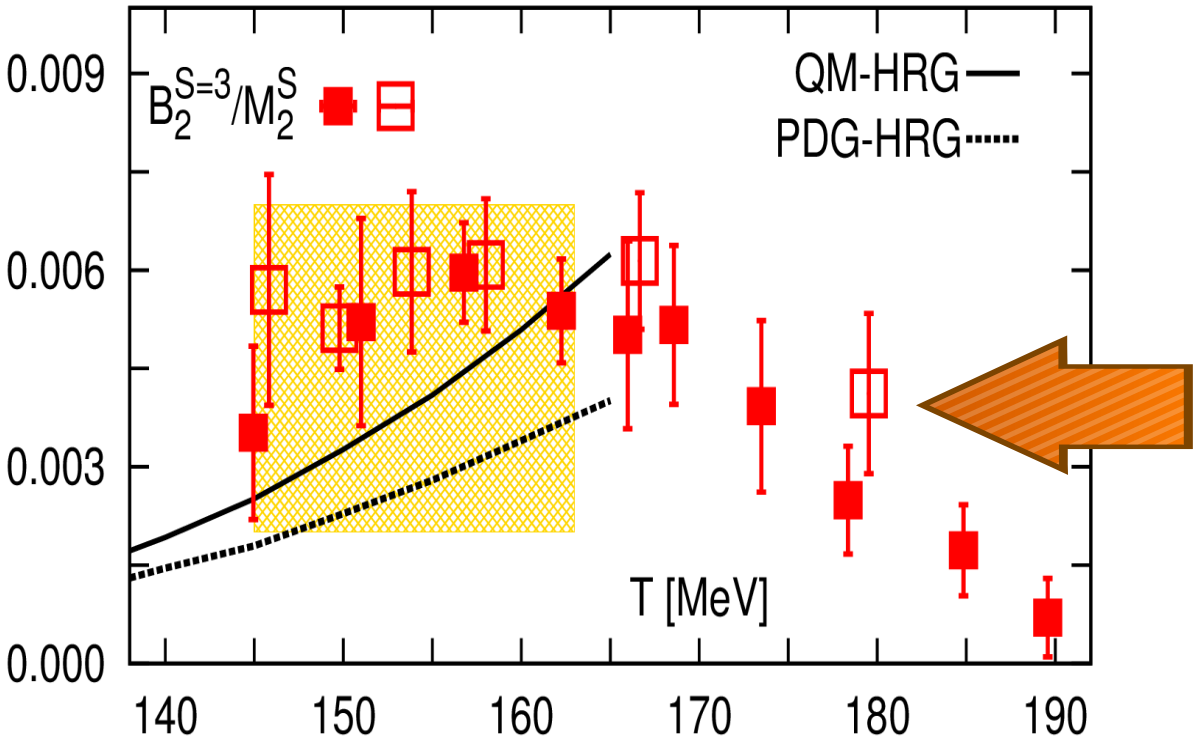
+ undiscovered strange baryons

contributions of all expt. observed strange hadrons

Thermodynamic contributions of additional strange hadrons



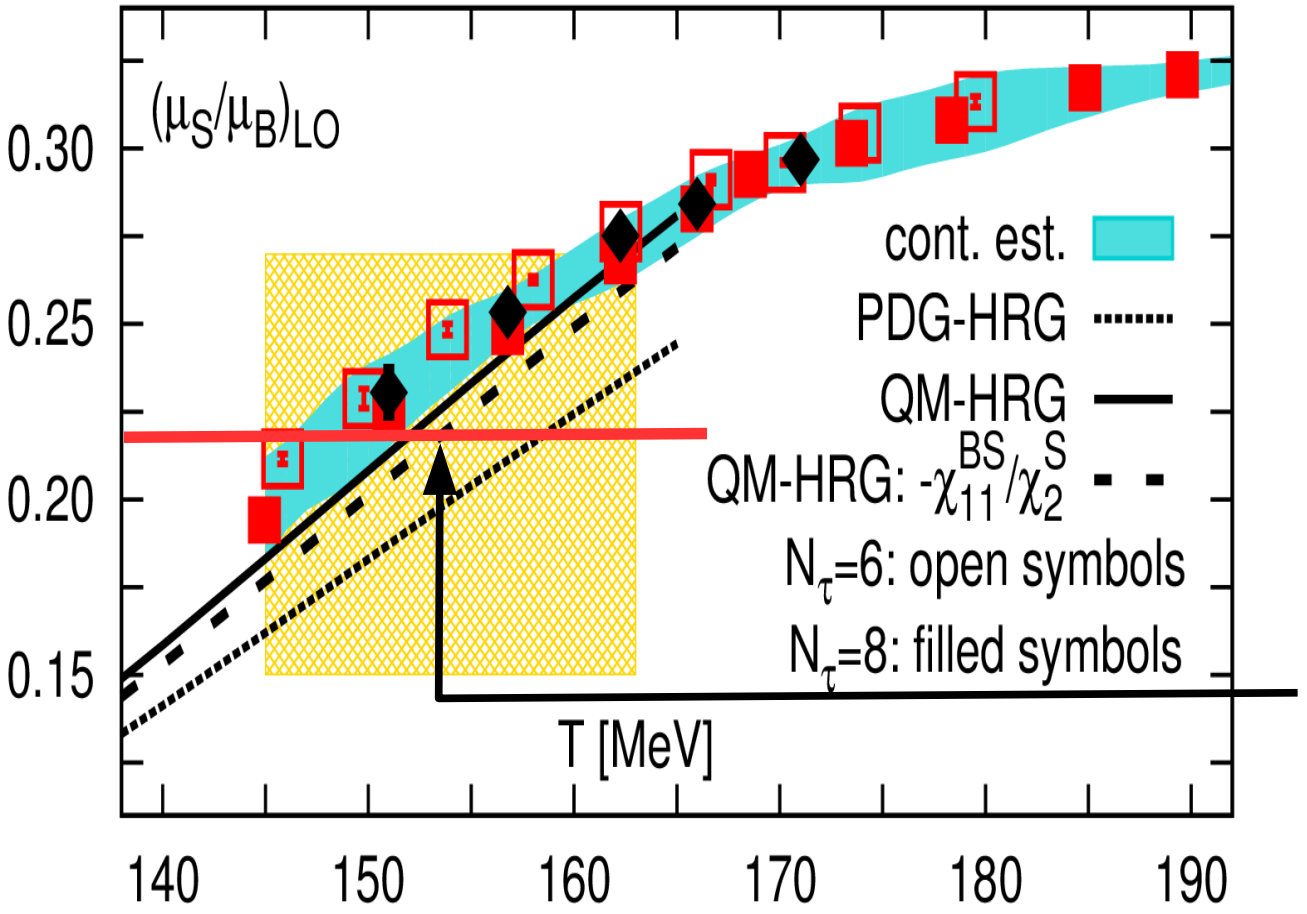
relative contributions of S=1 baryons to strange mesons



relative contributions of S=3 baryons to strange mesons

Additional strange hadrons & strangeness neutrality

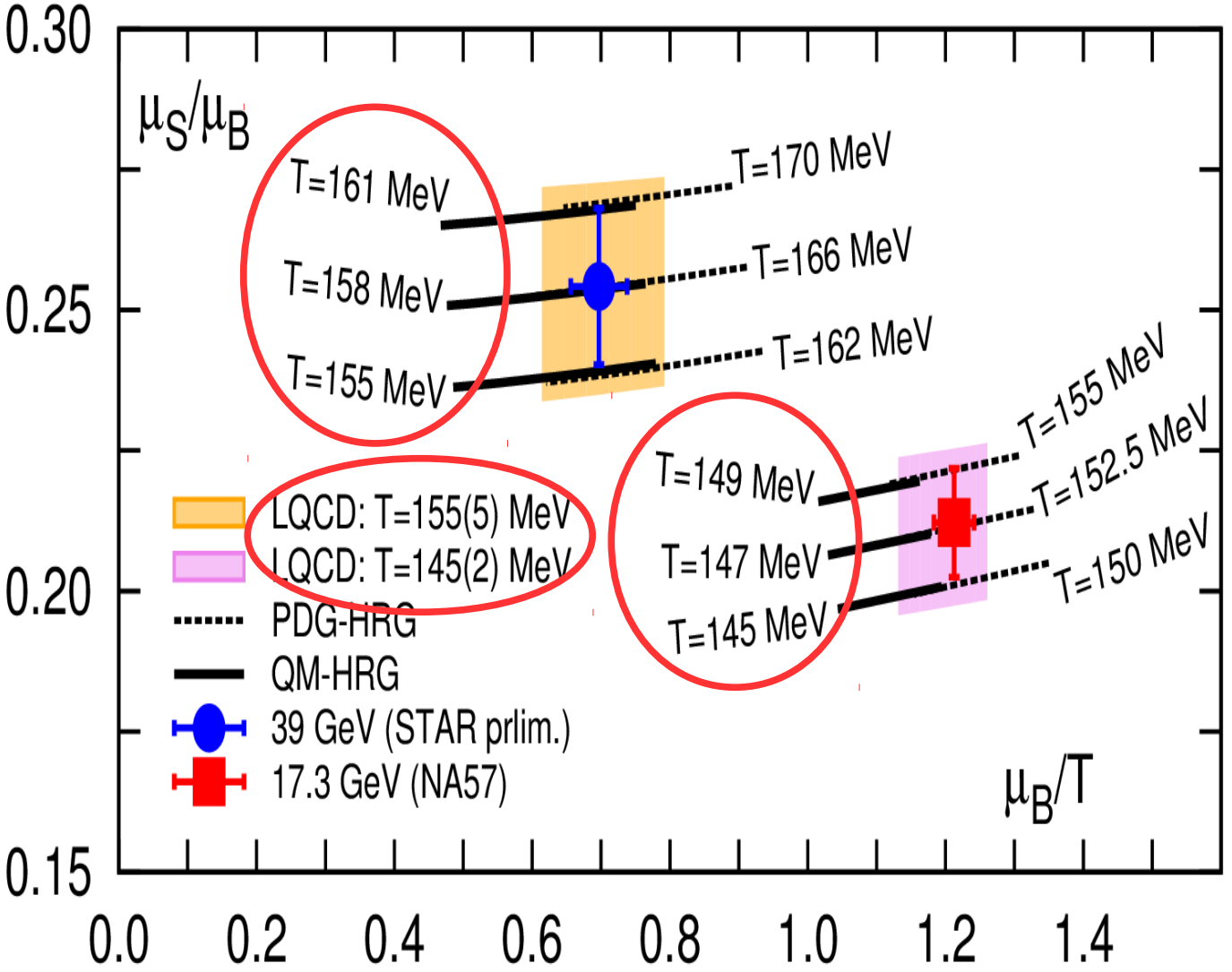
$$\langle n_S \rangle = 0 \Rightarrow \frac{\mu_S}{\mu_B}(T, \mu_B/T) \simeq \frac{\chi_{11}^{BS}(T)}{\chi_2^S(T)} + O[(\mu_B/T)^2]$$



LQCD results are reproduced by including additional Quark Model states

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

Additional strange hadrons & freeze-out in HIC

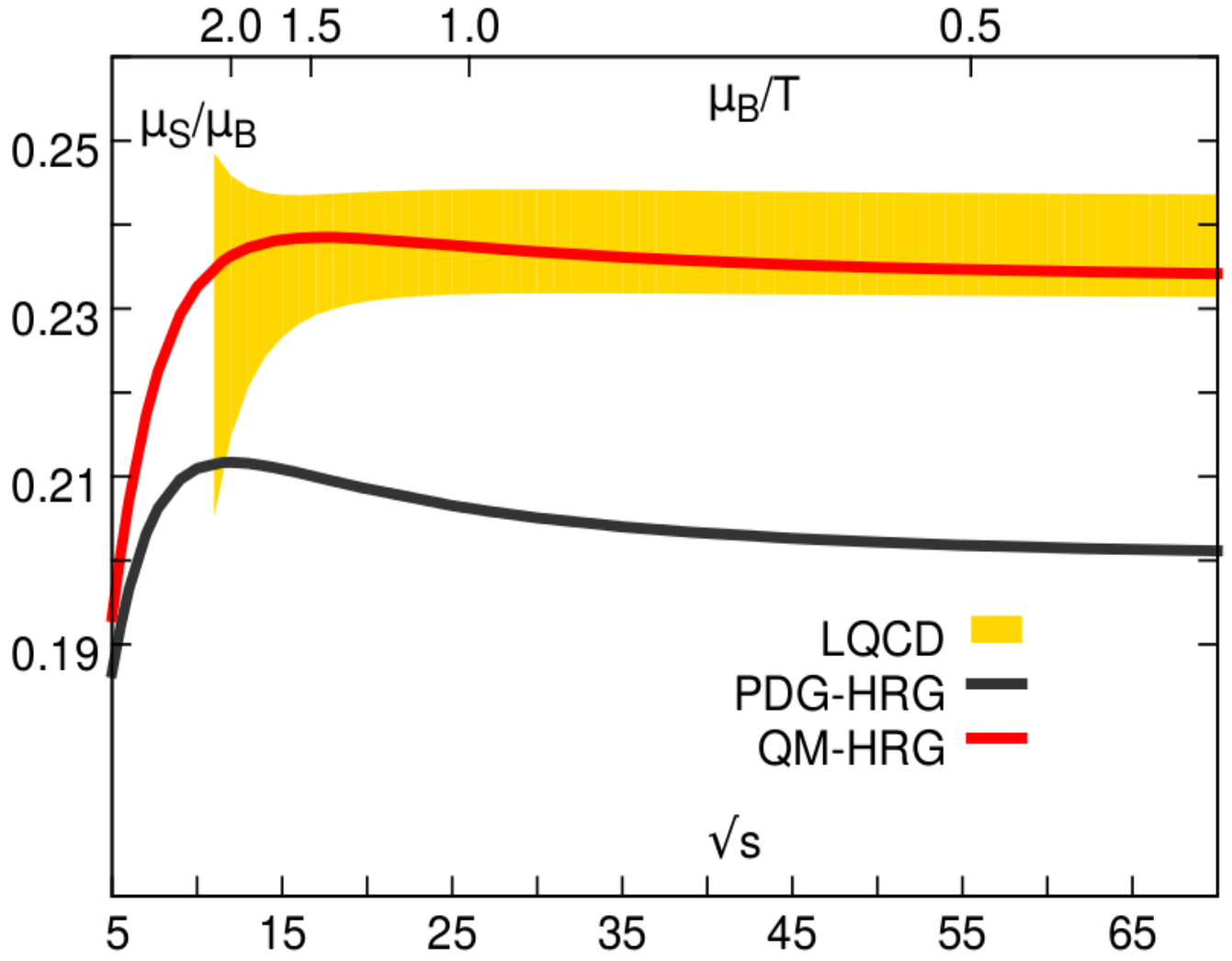


inclusion of additional strange hadrons reduces freeze-out T & agrees with LQCD+expt. determination

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

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

Additional strange hadrons & RHIC BES



BNL-Bi-CCNU: preliminary

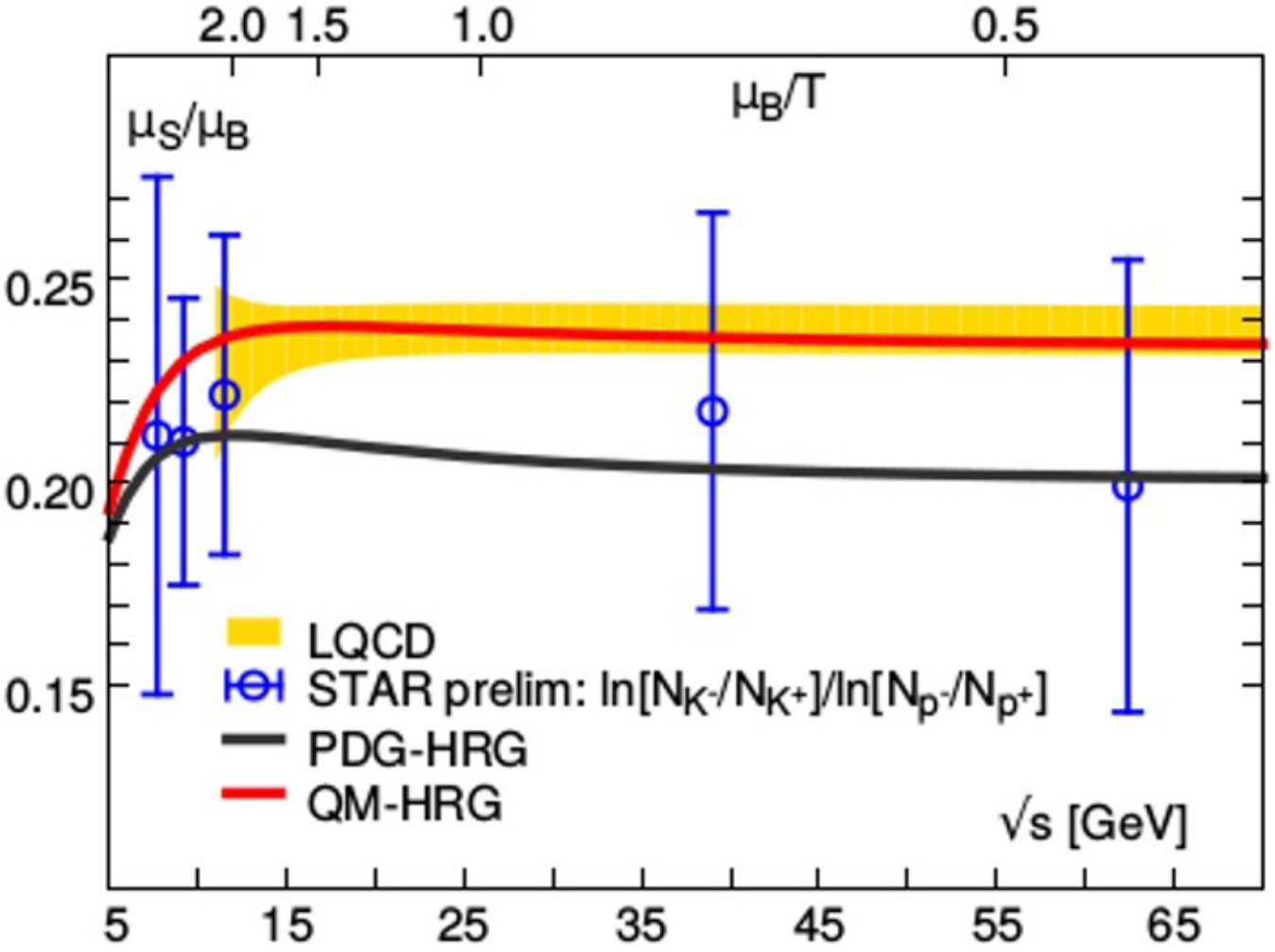
signature for unobserved strange baryons persists for RHIC BES-II

chosen:

$T^f(\sqrt{s}\to\infty)=154$ MeV

need accurate measurements of strange anti-baryon to baryon ratios

Additional strange hadrons & RHIC BES

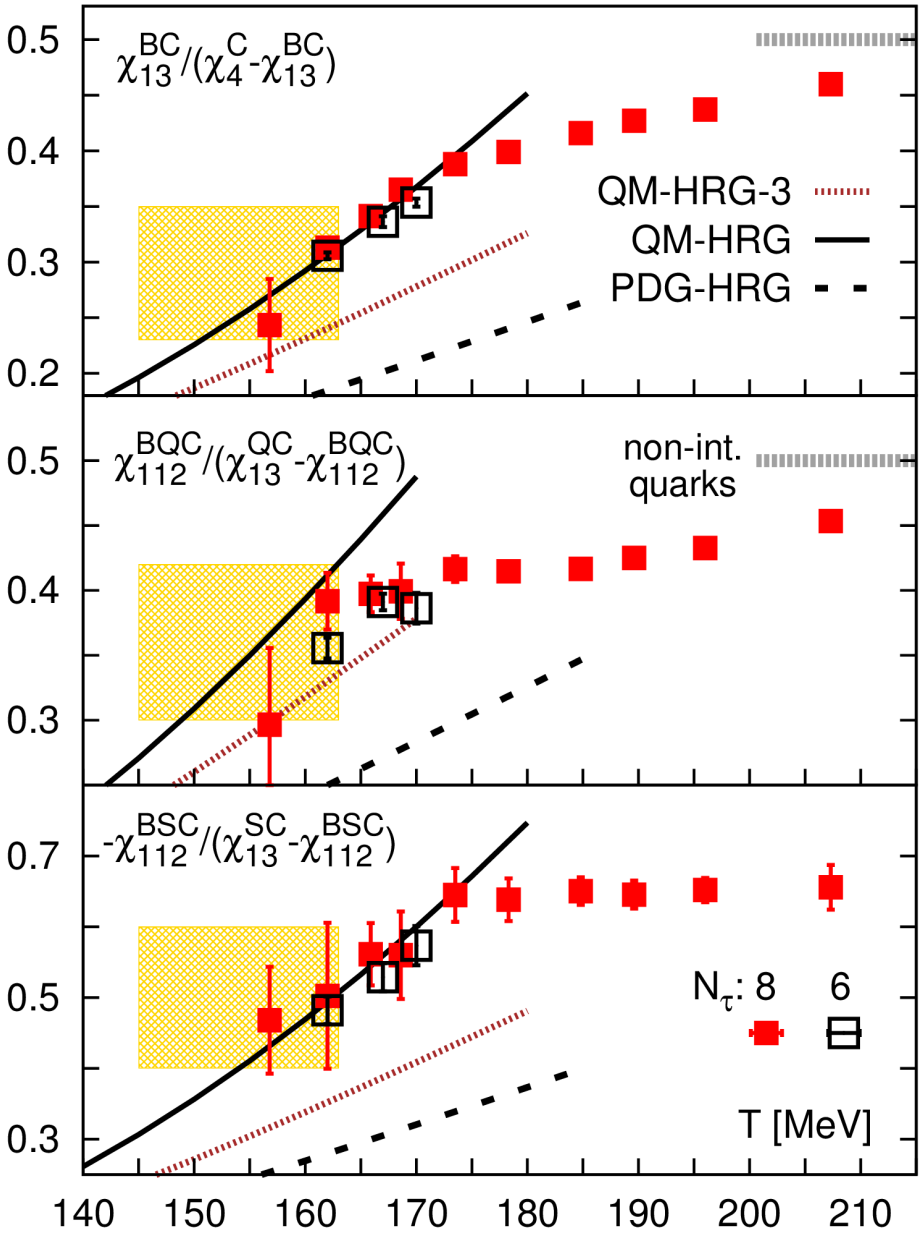


BNL-Bi-CCNU: preliminary

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

need accurate experimental measurements and feed-down corrections

Thermdynamic signature of unobserved charm baryons



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

relative contributions:

charm baryons to charmed mesons

charged charm baryons to charged charmed mesons

strange charm baryons to strange charmed mesons