STRANGE STATES FROM LATTICE QCD THERMODYNAMICS

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Excited Hyperons in QCD Thermodynamics at Freeze-Out

BEST COLLABORATION

Lattice QCD

- Best first principle-tool to extract predictions for the theory of strong interactions in the non-perturbative regime

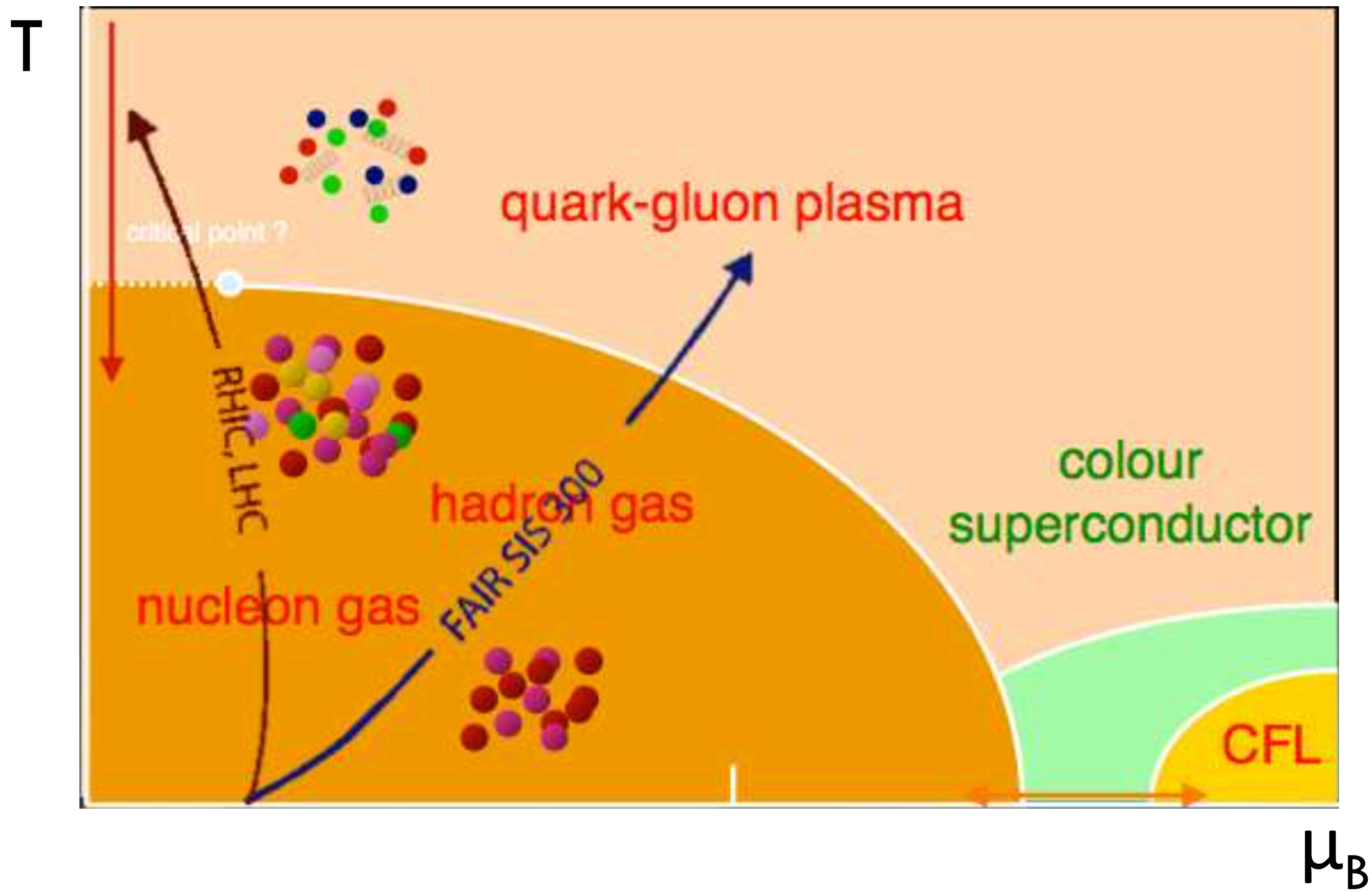
- Uncertainties:
  - Statistical: finite sample, error $\sim 1/\sqrt{\text{sample size}}$
  - Systematic: finite box size, unphysical quark masses

- Given enough computer power, uncertainties can be kept under control

- Unprecedented level of accuracy in lattice data

- Results can be compared to experimental measurements

QCD phase diagram



Low temperature phase: HRG model

Dashen, Ma, Bernstein; Prakash, Venugopalan, Karsch, Tawfik, Redlich

- Interacting hadronic matter in the ground state can be well approximated by a non-interacting resonance gas
- The pressure can be written as:

$$p^{HRG}/T^4 = \frac{1}{VT^3}\sum_{i\in\ mesons} \ln \mathcal{Z}^M_{m_i}(T,V,\mu_{X^a}) + \frac{1}{VT^3}\sum_{i\in\ baryons} \ln \mathcal{Z}^B_{m_i}(T,V,\mu_{X^a})$$

where

$$\ln \mathcal{Z}^{M/B}_{m_i} = \mp \frac{Vd_i}{2\pi^2}\int_0^\infty dk k^2 \ln(1 \mp z_i e^{-\varepsilon_i/T}) \quad ,$$

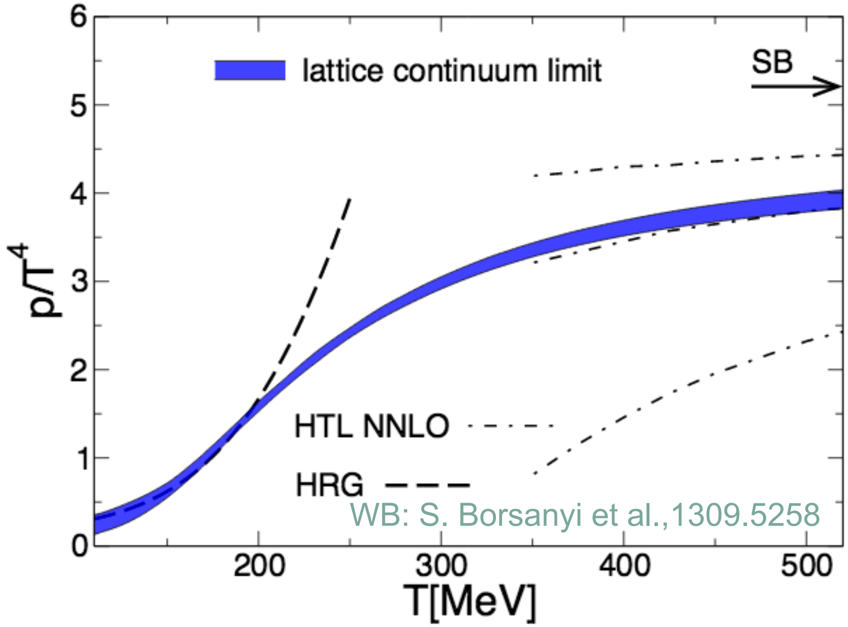
with energies $\varepsilon_i = \sqrt{k^2+m_i^2}$, degeneracy factors d_i and fugacities

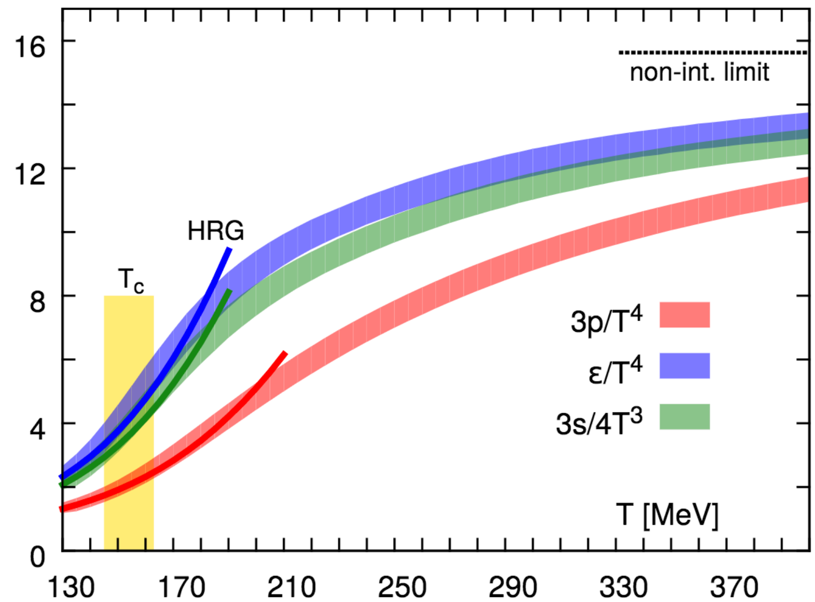
$$z_i = \exp\left((\sum_a X^a_i \mu_{X^a})/T \right) \; .$$

X^a: all possible conserved charges, including the baryon number B, electric charge Q, strangeness S.

- Input: hadronic spectrum

QCD Equation of state at μ_B=0

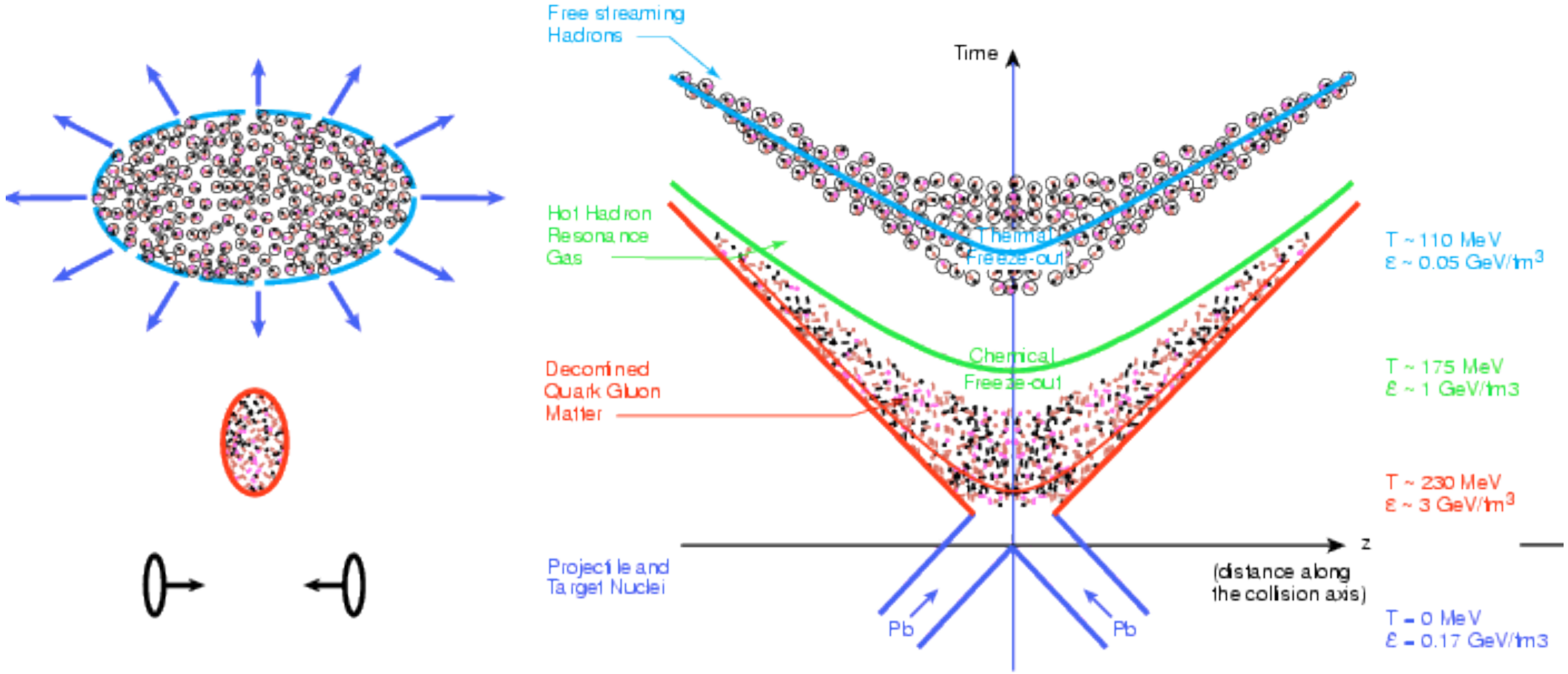




- EoS available in the continuum limit, with realistic quark masses
- Agreement with HRG model at low temperatures

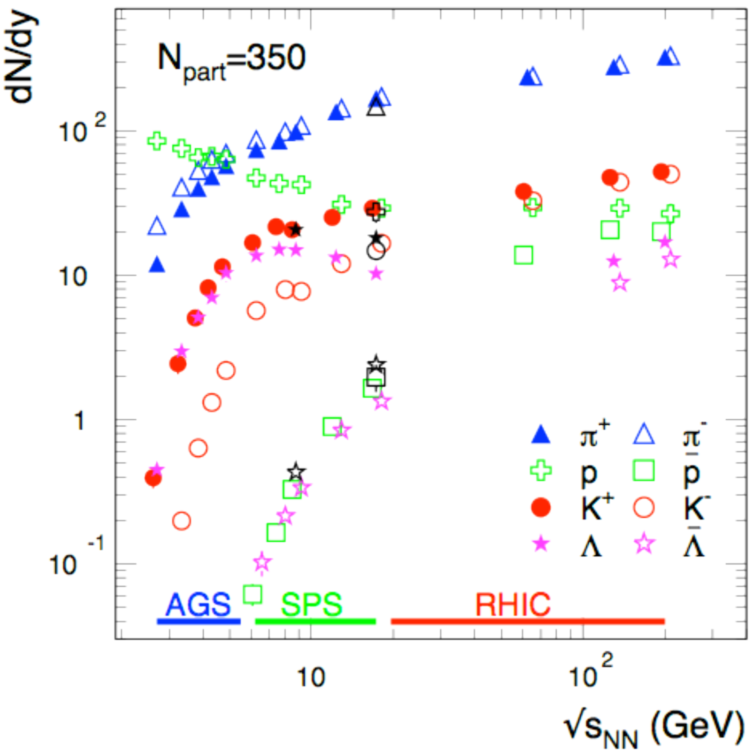
WB: S. Borsanyi et al., 1309.5258, PLB (2014)
HotQCD: A. Bazavov et al., 1407.6387, PRD (2014)

Evolution of a Heavy Ion Collision



- Chemical freeze-out: inelastic reactions cease: the chemical composition of the system is fixed (particle yields and fluctuations)
- Kinetic freeze-out: elastic reactions cease: spectra and correlations are frozen (free streaming of hadrons)
- Hadrons reach the detector

Hadron yields



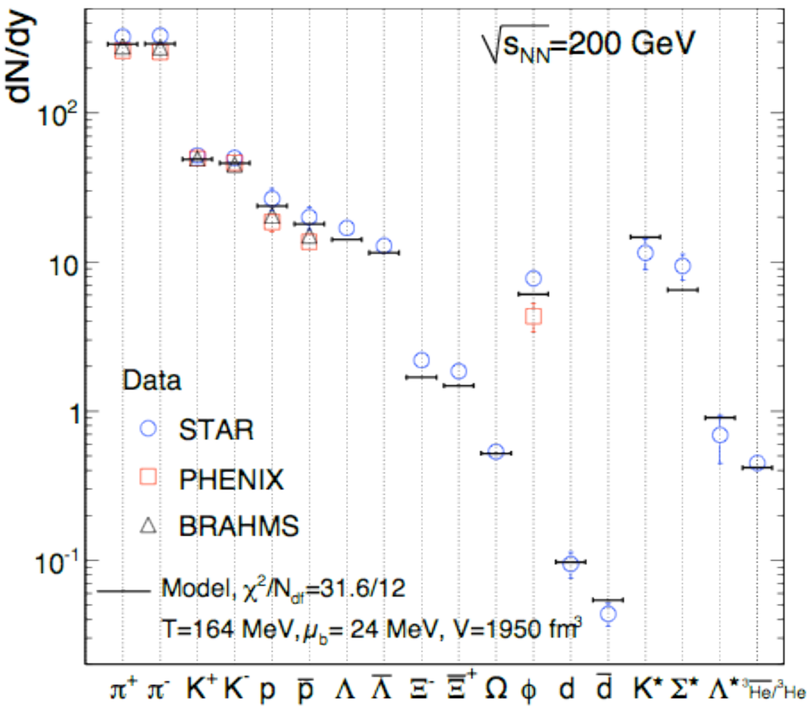
- E=mc^2: lots of particles are created
- Particle counting (average over many events)
- HRG model: test hypothesis of hadron abundancies in equilibrium

$$N_i = -T\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i V}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T]\pm 1}$$

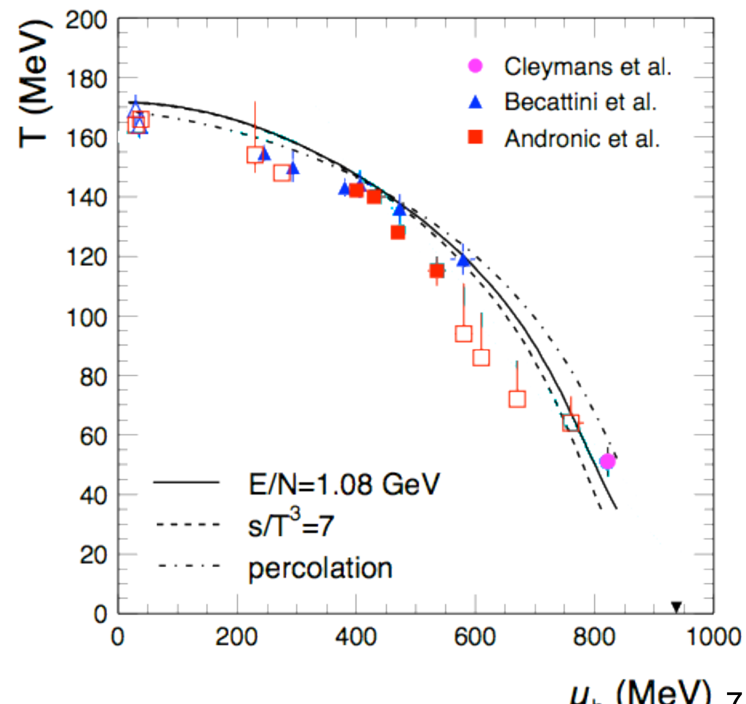
Resonances contribute to the effective number of stable species through their branching ratios $d_{r\rightarrow i}$.

$$\bar{N}_i = N_i + \sum_r d_{r\rightarrow i} N_r$$

The thermal fits

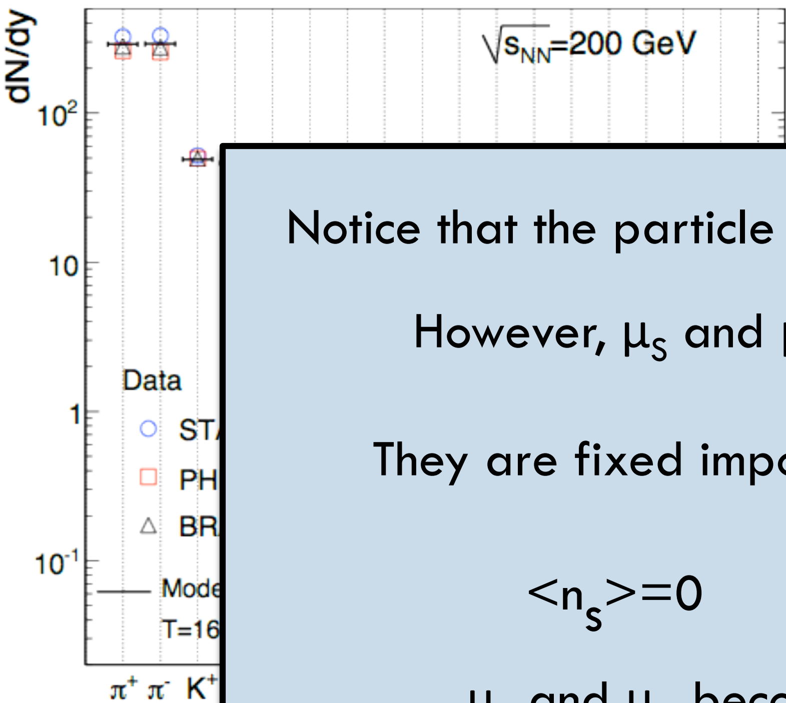


- Fit is performed minimizing the χ^2
- Fit to yields: parameters T, μB, V
- Fit to ratios: the volume V cancels out



- Changing the collision energy, it is possible to draw the freeze-out line in the T, μB plane
- The results depend dramatically on the hadronic spectrum: the freeze-out temperature was ~175 MeV in 2005 and is now ~156 MeV

The thermal fits



- Fit is performed minimizing the χ^2

B, V

ncels out

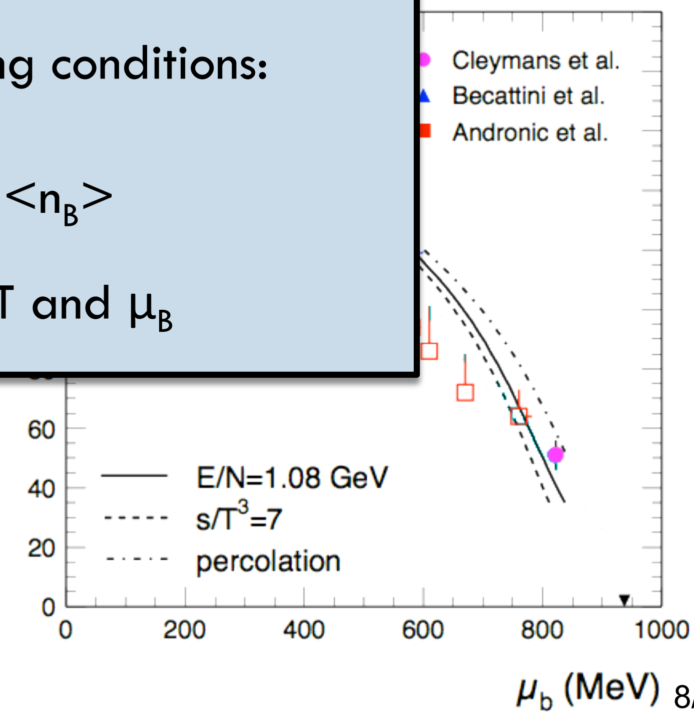
Notice that the particle yields also depend on μ_S and μ_Q

However, μ_S and μ_Q are not free parameters

They are fixed imposing the following conditions:

$$\langle n_S \rangle = 0 \qquad \langle n_Q \rangle = 0.4 \langle n_B \rangle$$

μ_S and μ_Q become functions of T and μ_B

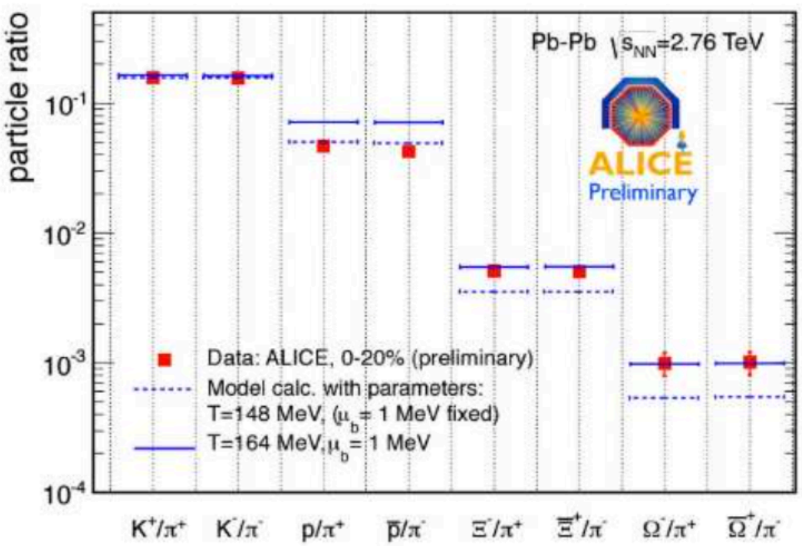


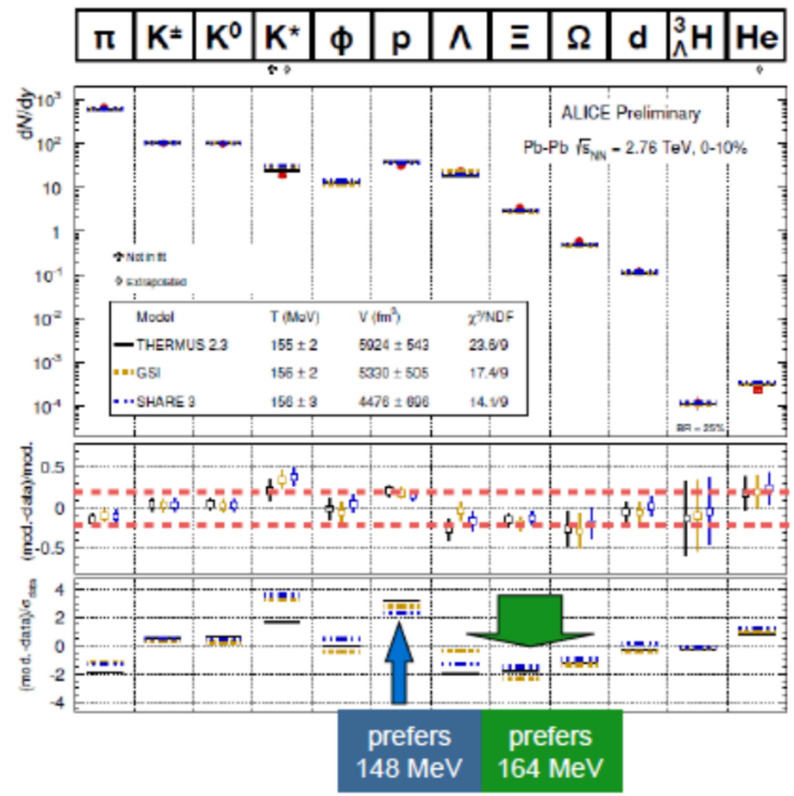
- Changi… draw the freeze-out line in the T, μB plane

- The results depend dramatically on the hadronic spectrum: the freeze-out temperature was ~175 MeV in 2005 and is now ~156 MeV

Do we have a common freeze-out line?

- Yield fits seem to hint at a higher temperature for strange particles



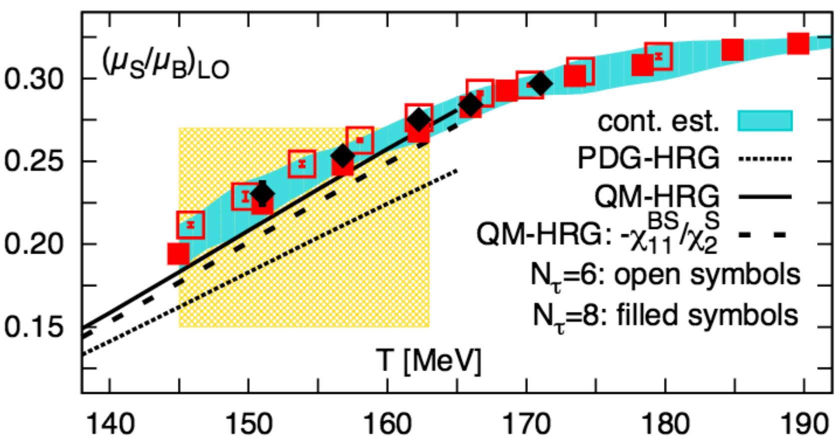


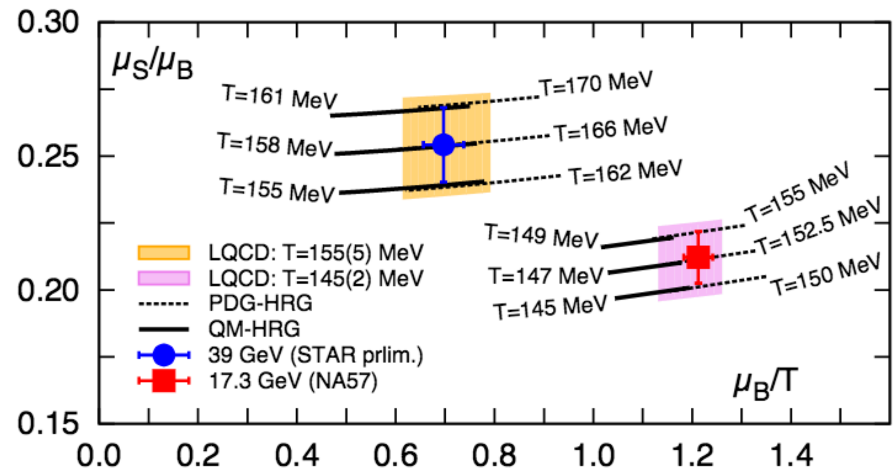
R. Preghenella for ALICE, SQM 2012

M. Floris, QM 2014.

Missing strange states?

- Quark Model predicts not-yet-detected (multi-)strange hadrons





- QM-HRG improves the agreement with lattice results for the baryon-strangeness correlator:

$$(\mu_S/\mu_B)_{LO}=-\chi_{11}^{BS}/\chi_2^S+\chi_{11}^{QS}\mu_Q/\mu_B$$

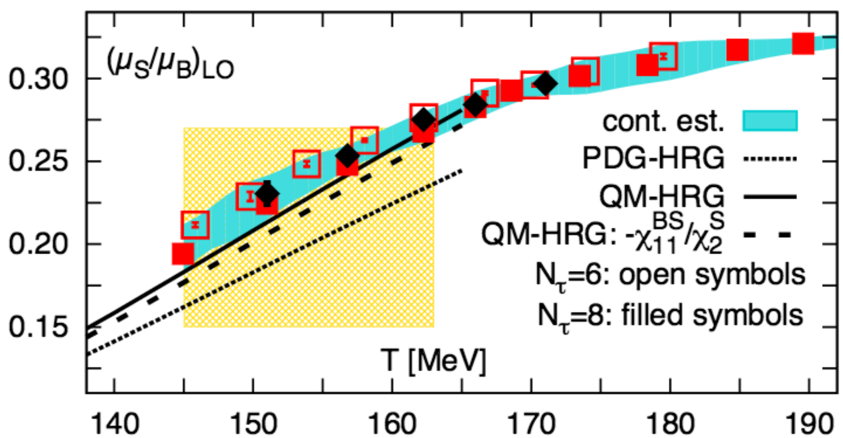
- The effect is only relevant at finite μ_B

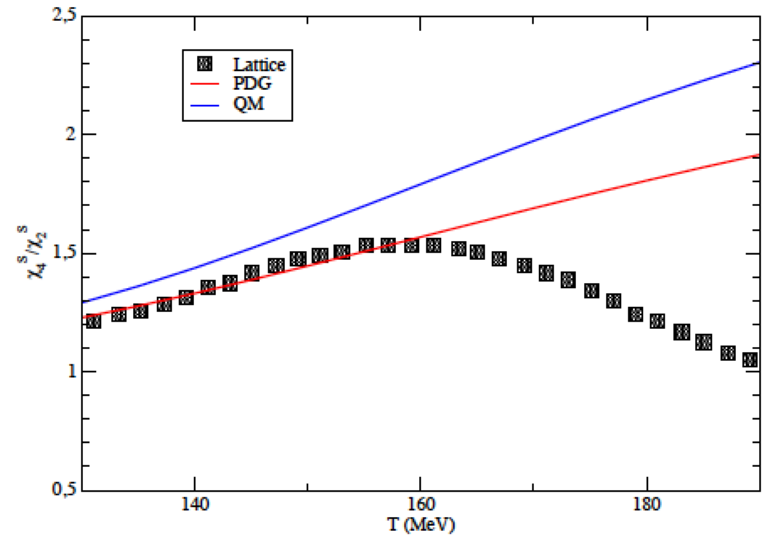
- Feed-down from resonance decays not included

A. Bazavov et al., PRL (2014); Quark Model states from Capstick and Isgur, PRD (1986) and Ebert, Faustov and Galkin, PRD (2009).

Missing strange states?

- Quark Model predicts not-yet-detected (multi-)strange hadrons





- The agreement with the HRG model improves with some observables but gets worse with others
- χ_4^S/χ_2^S is proportional to <S^2> in the system
- It seems to indicate that the quark model predicts too many multi-strange states

A. Bazavov et al., PRL (2014); Quark Model states from Capstick and Isgur, PRD (1986) and Ebert, Faustov and Galkin, PRD (2009).

Missing strange states?

- We took every state listed in the 2016 PDG (including * and ** states)
- We took two versions of the Quark Model: hypercentral Quark Model (hQM) and quark-diquark (qD)
- We constructed different spectra by merging the observed particles with the not-yet-detected ones
- We invented new observables which allow to separate the contributions of hadrons to the thermodynamics according to their quantum numbers
- We tested the predictions of the three different HRG models thus obtained by comparing them to lattice QCD results

Fluctuations of conserved charges

- Definition:

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

- Relationship between chemical potentials:

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

- They can be calculated on the lattice and compared to experiment

Missing strange states?

- Idea: define linear combinations of fluctuations which receive contributions only from particles with a given quantum number

- They allow to compare PDG and QM prediction for each sector separately

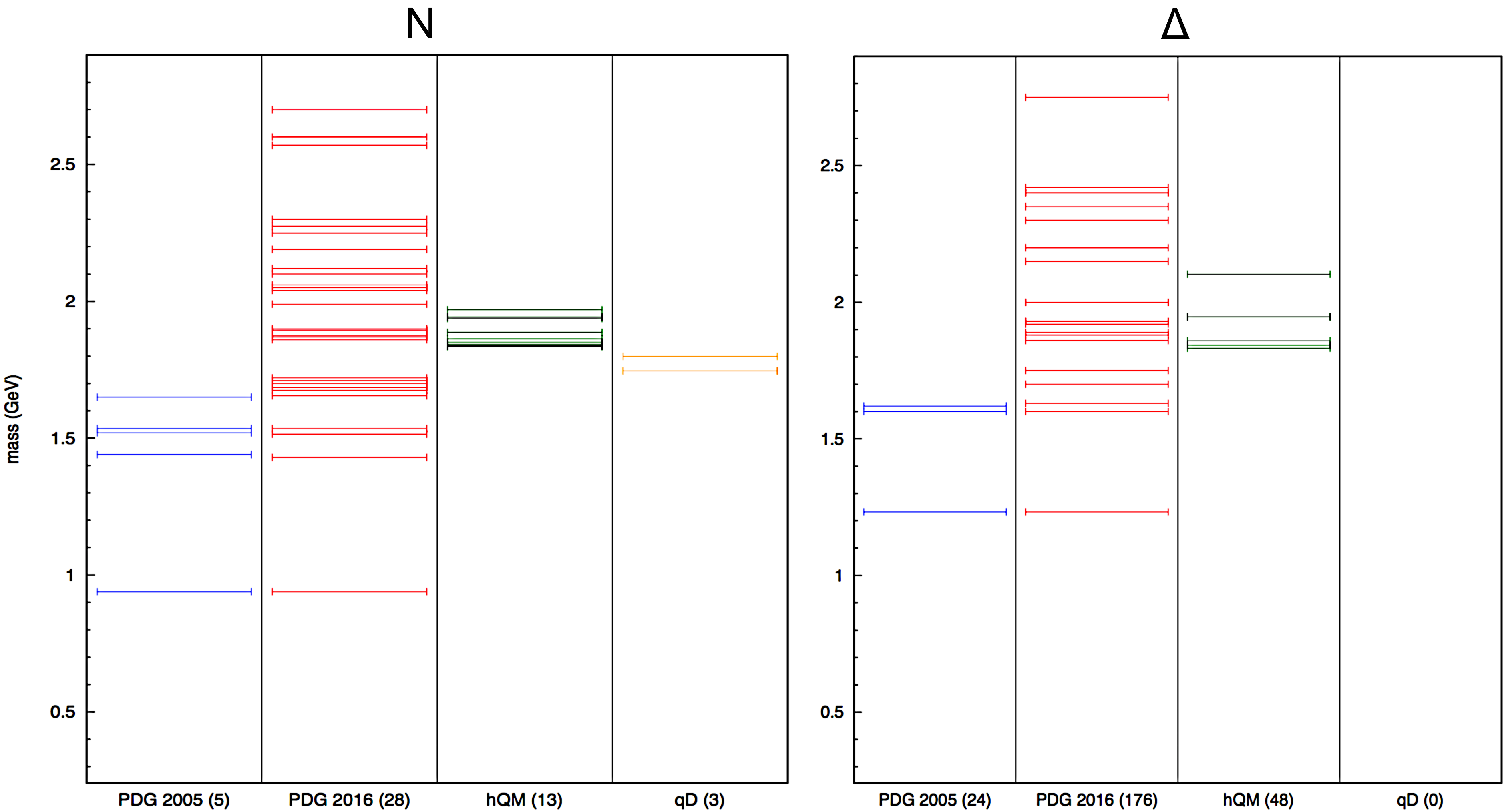
$$
\begin{aligned}
P_S(\hat{\mu}_B, \hat{\mu}_S) &= P_{0|1|} \cosh(\hat{\mu}_S) \\
&+ P_{1|1|} \cosh(\hat{\mu}_B - \hat{\mu}_S) \\
&+ P_{1|2|} \cosh(\hat{\mu}_B - 2\hat{\mu}_S) \\
&+ P_{1|3|} \cosh(\hat{\mu}_B - 3\hat{\mu}_S)
\end{aligned}
$$

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

A. Bazavov et al., PRL (2013)

How many states? |S|=0

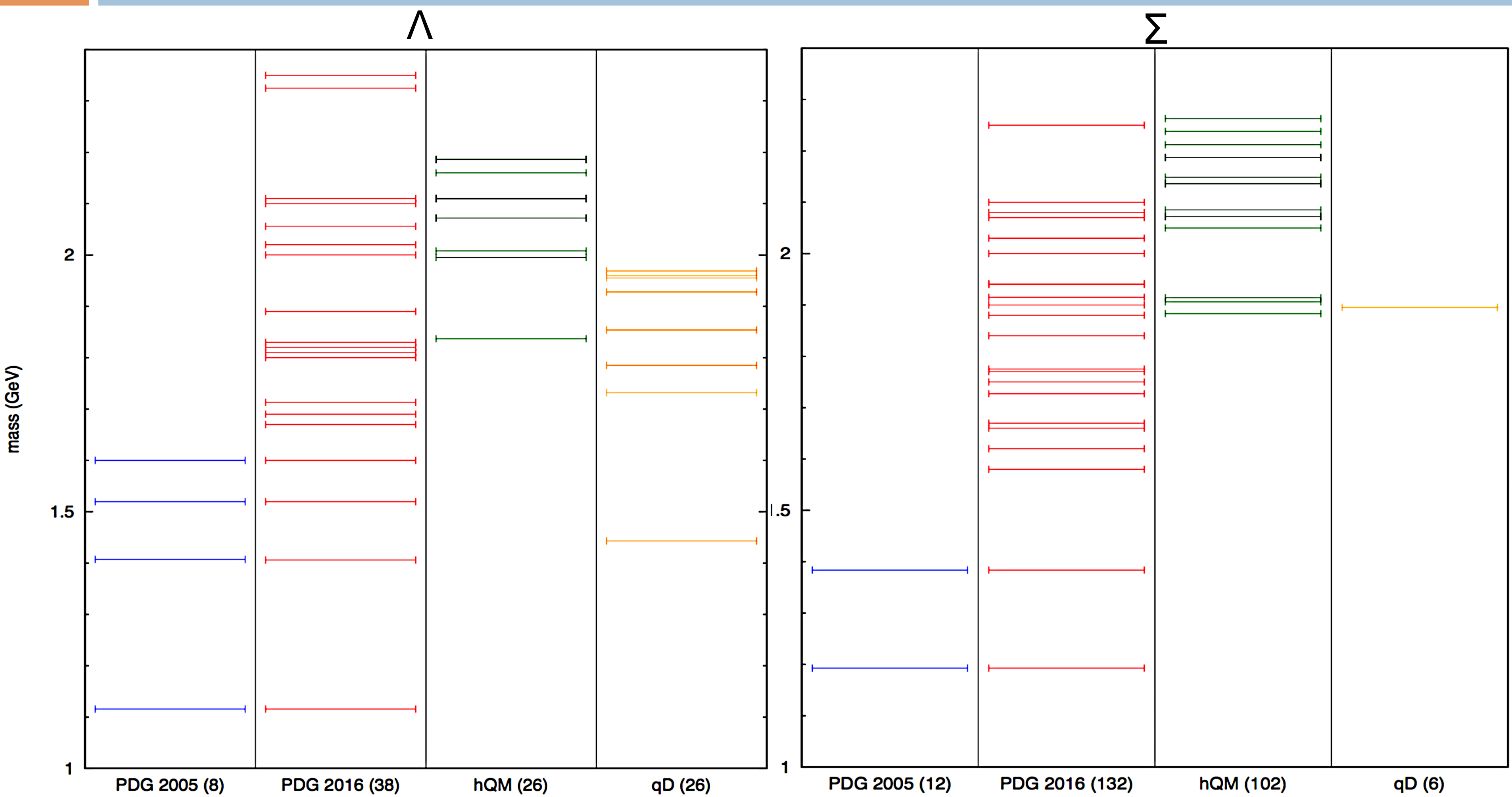
Santopinto et al. PLB (1995), PRC (2005), PRC (2015)



The columns hQM and qD contain additional states, not included in the PDG2016

How many states? |S|=1

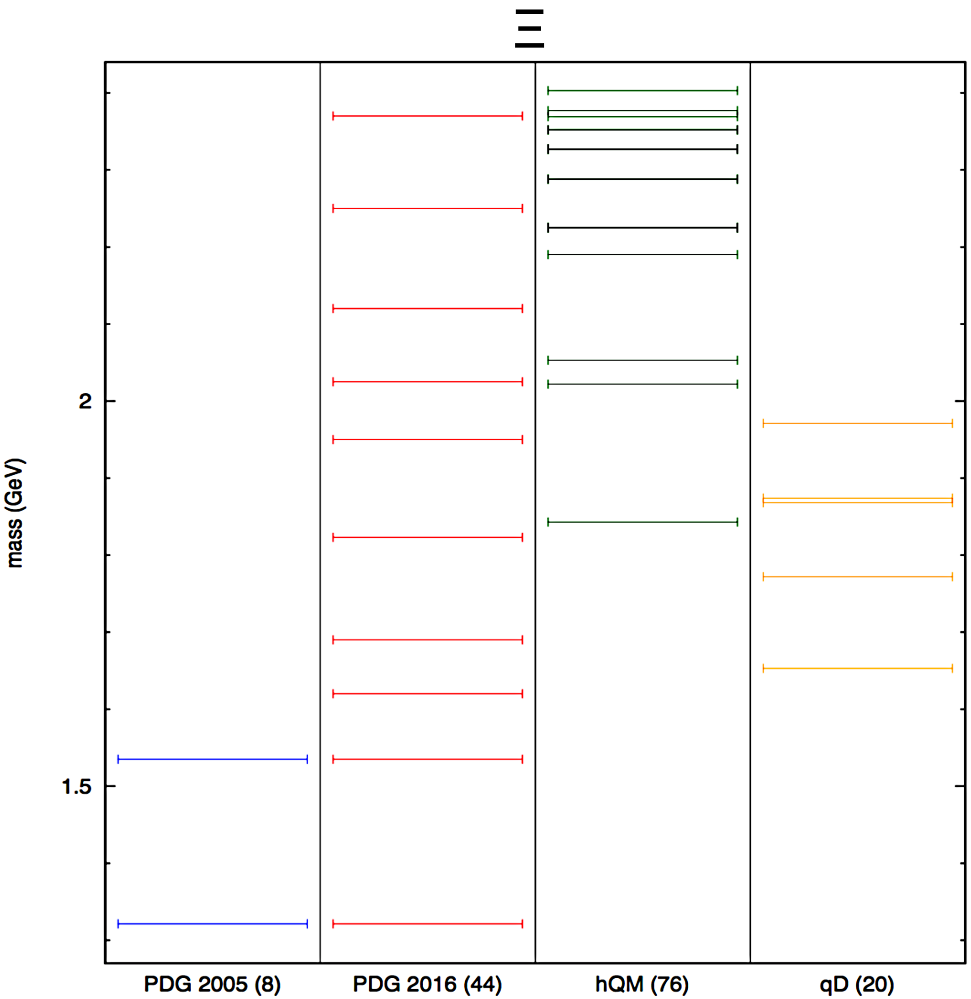
Santopinto et al. PLB (1995), PRC (2005), PRC (2015)

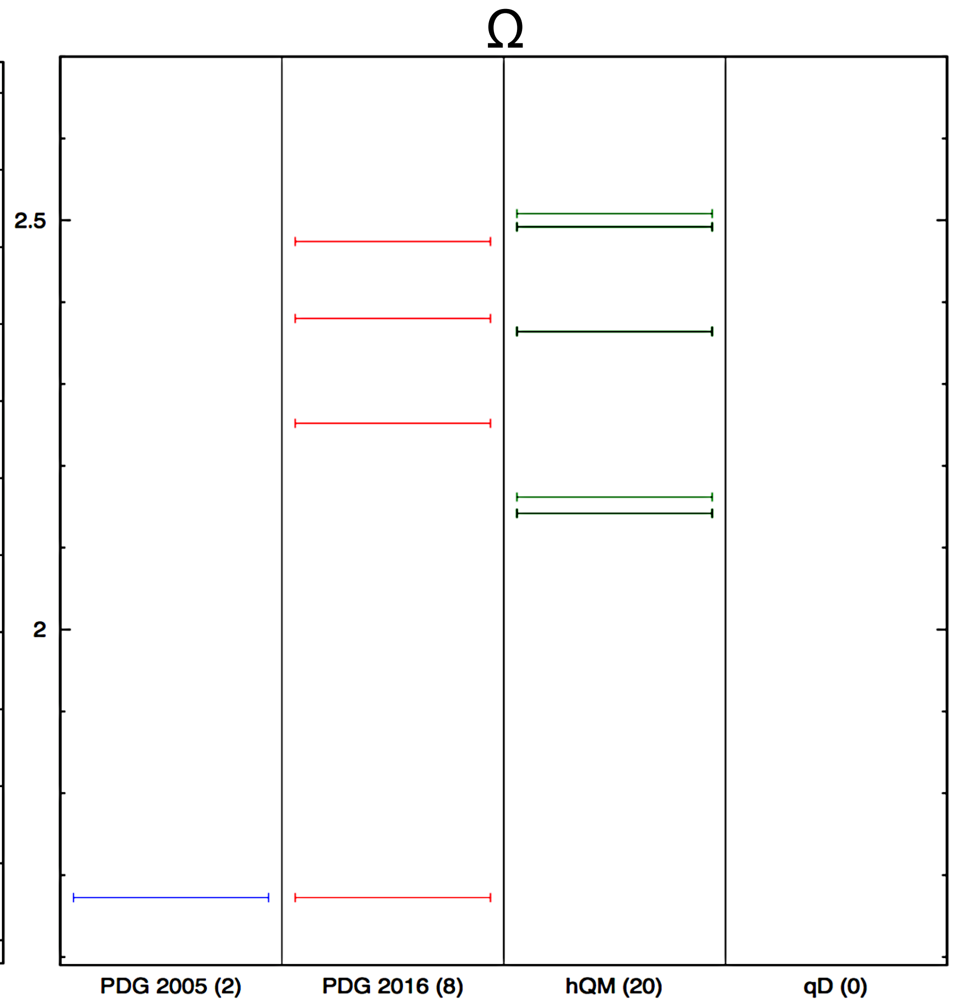


The columns hQM and qD contain additional states, not included in the PDG2016

How many states? |S|=2 and |S|=3

Santopinto et al. PLB (1995), PRC (2005), PRC (2015)





The columns hQM and qD contain additional states, not included in the PDG2016

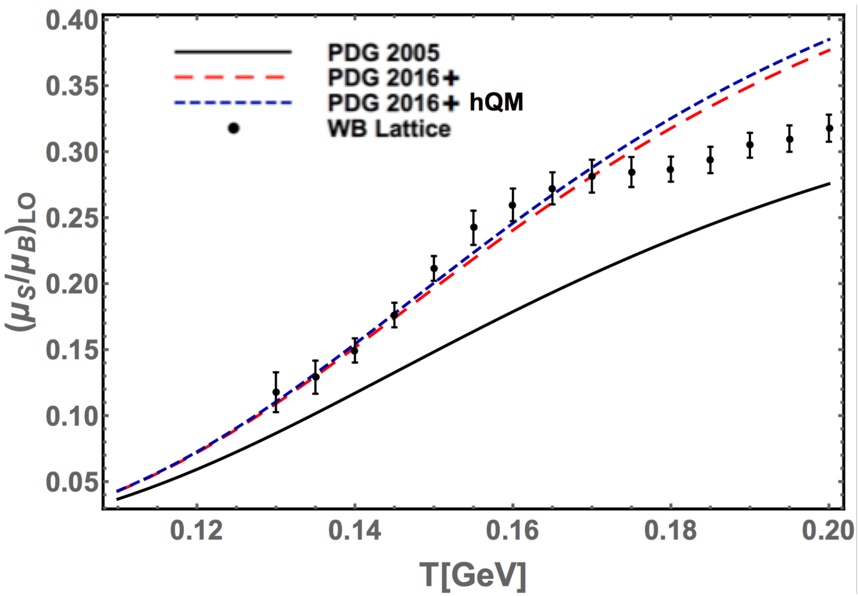
How many states?

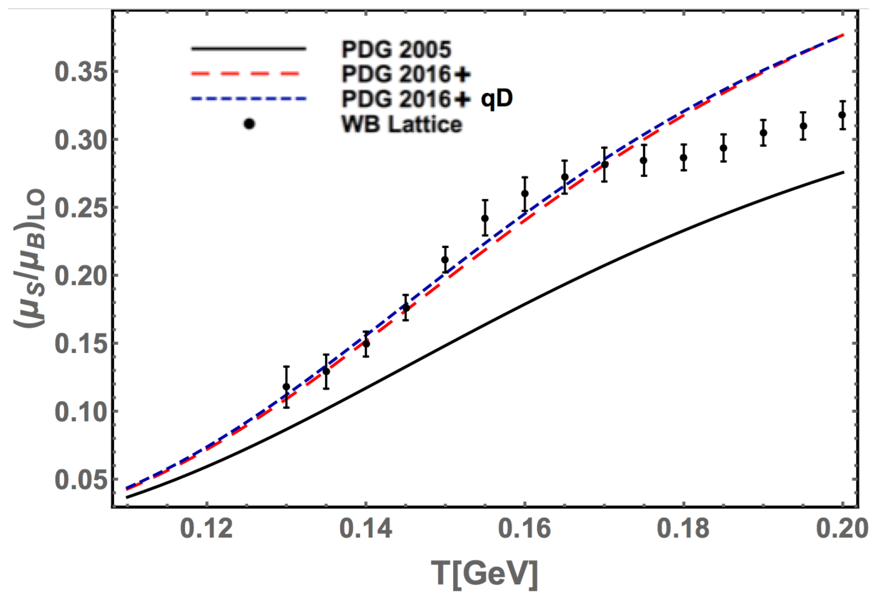
In total we have (isospin multiplicity and particle-antiparticle):

- PDG 2005: 144
- PDG 2016: 608 (**, *** and **** states)
- PDG 2016+: 738 (including also * states)
- hQM: 247 additional states (not included in PDG 2016+)
- qD: 79 additional states (not included in PDG 2016+)

Missing strange states?

- First observable: $(\mu_S/\mu_B)_{LO}$



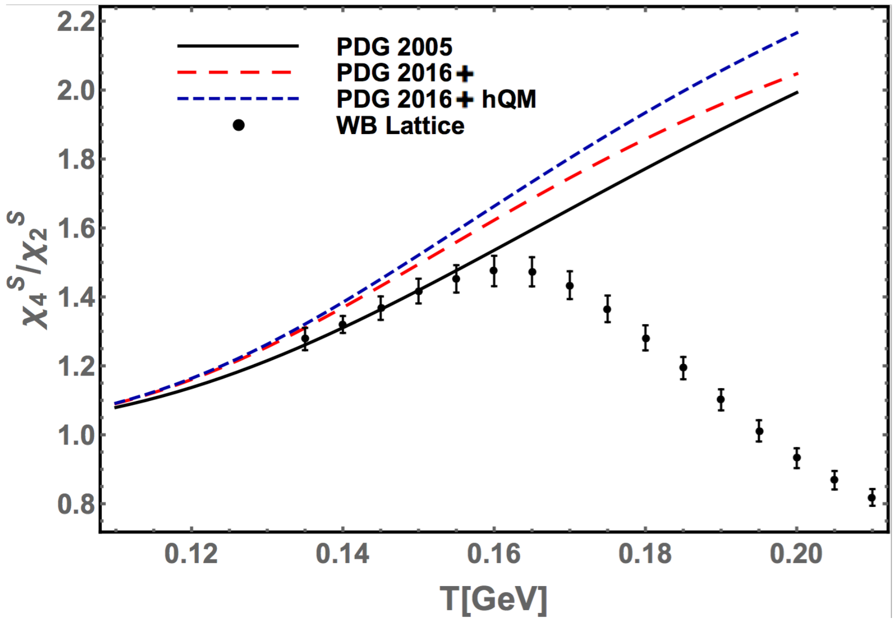


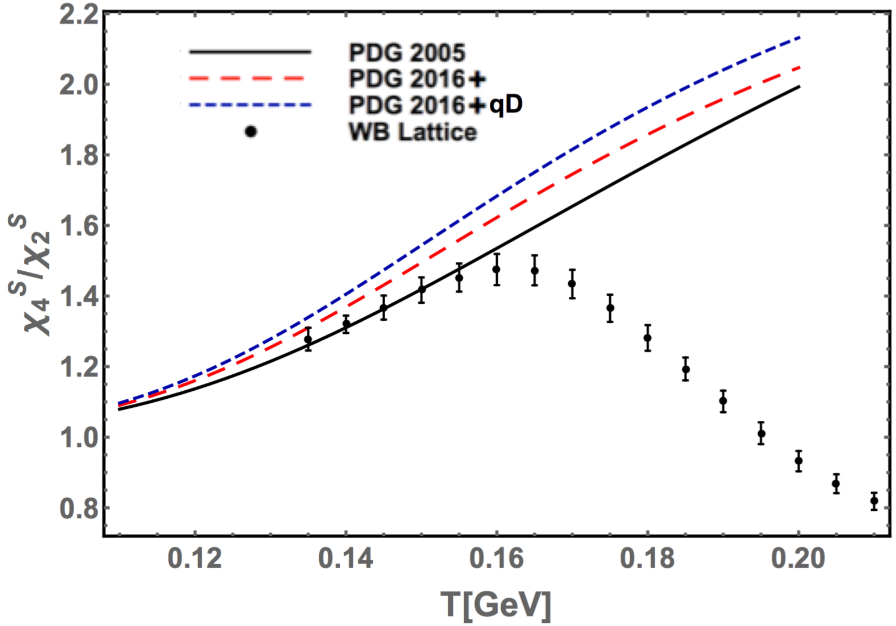
- Adding states to the spectrum allows to reproduce the lattice data
- Very small difference for this observable between PDG, PDG+hQM and PDG+qD

WB collaboration, in preparation

Missing strange states?

- Second observable: χ_4^S/χ_2^S

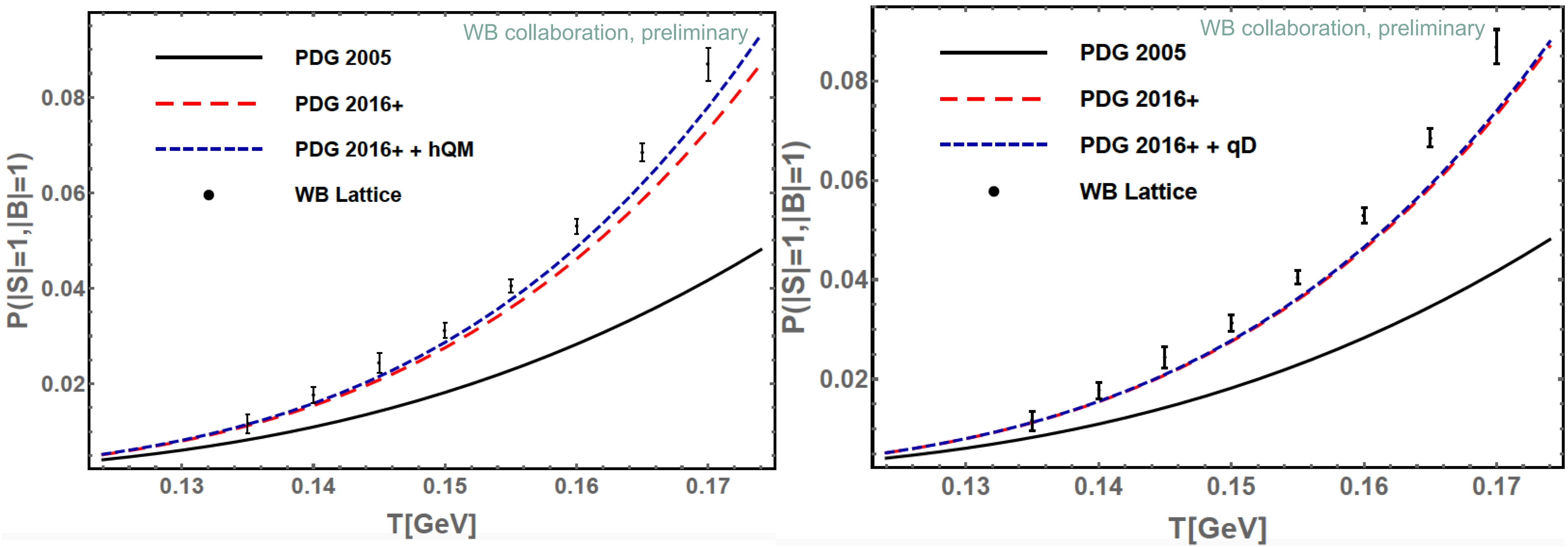




- This observable is extremely sensitive to the strangeness content of the system
- It looks like we need more |S|=1 states or less multi-strange ones

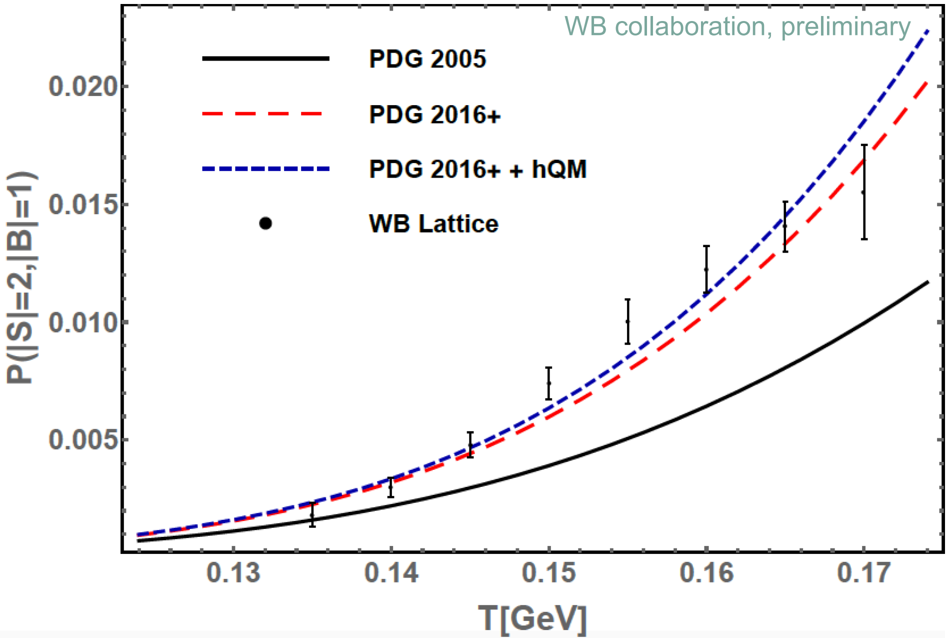
WB collaboration, in preparation

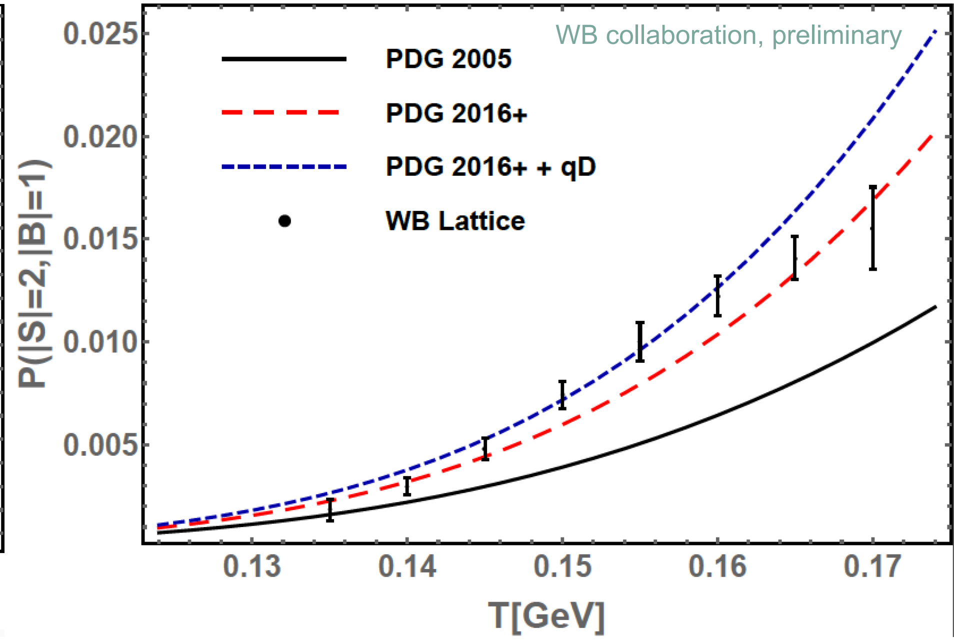
Missing strange states?



- The HRG model based on the PDG 2016 spectrum yields a good description of the data
- There is room to add more states beyond those predicted by the hQM or qD

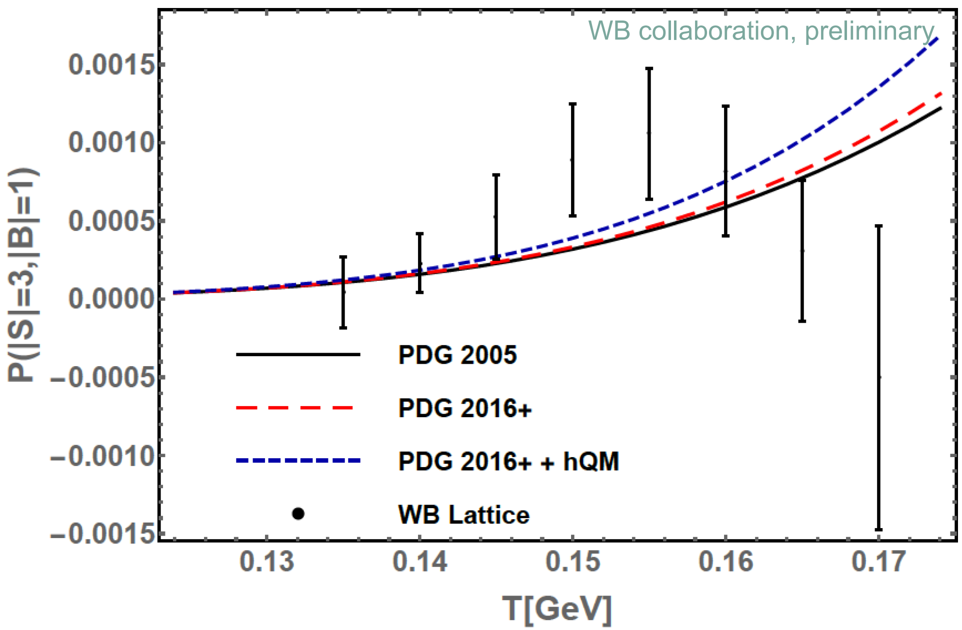
Missing strange states?

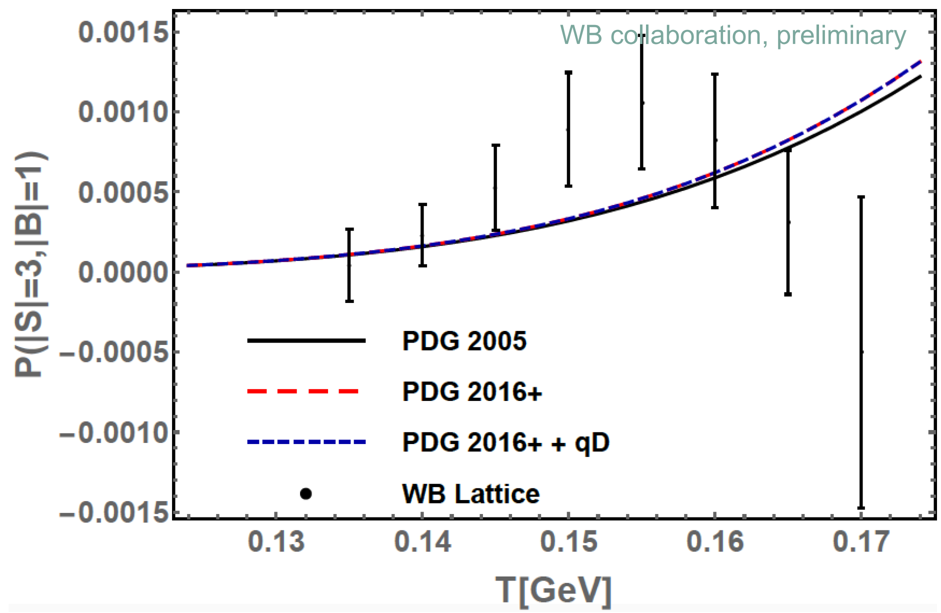




- The qD model adds |S|=2 states in the intermediate mass range

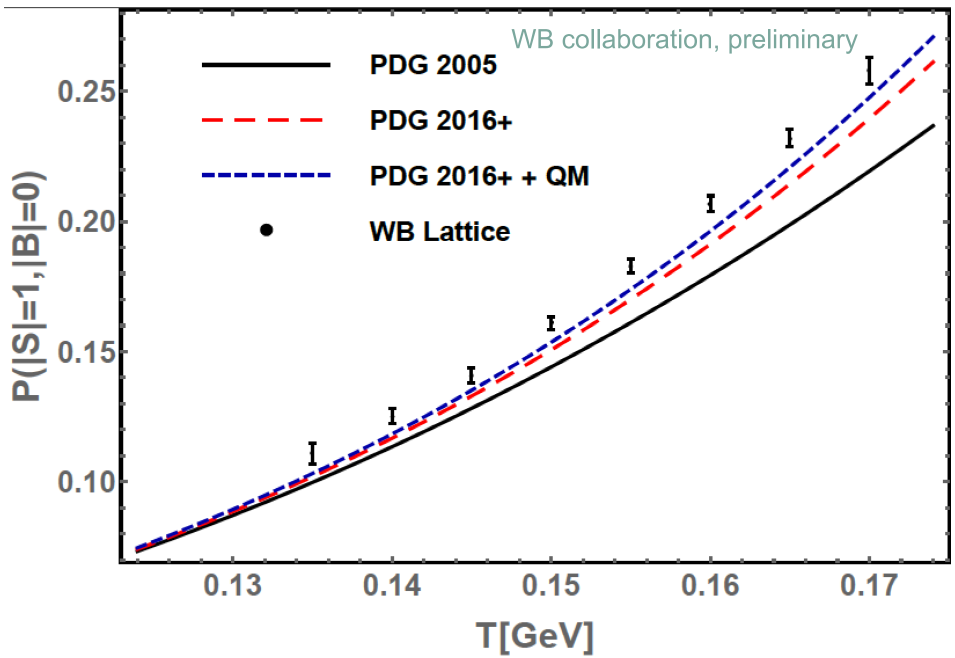
Missing strange states?

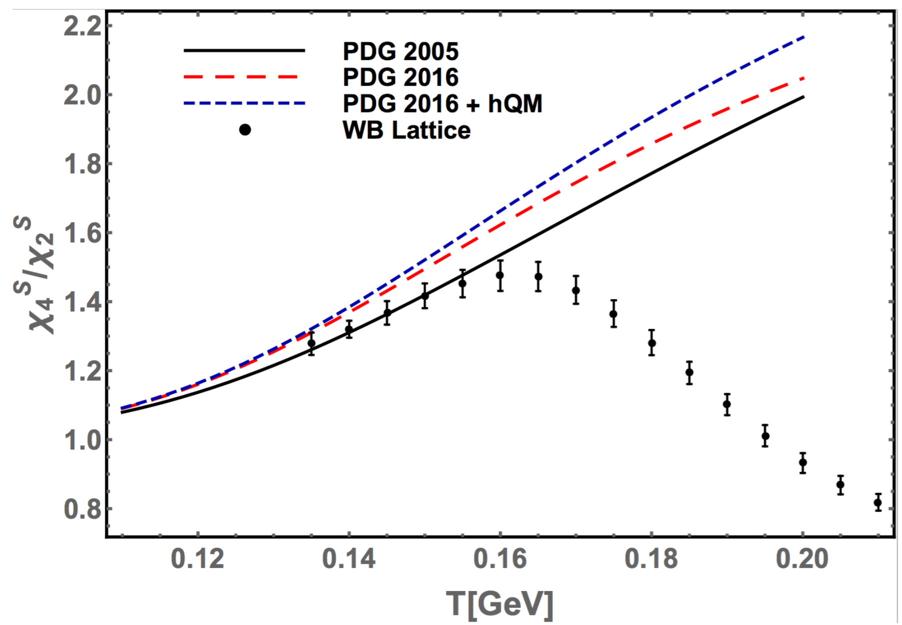




- It looks like we need more |S|=3 states

Not enough strange mesons

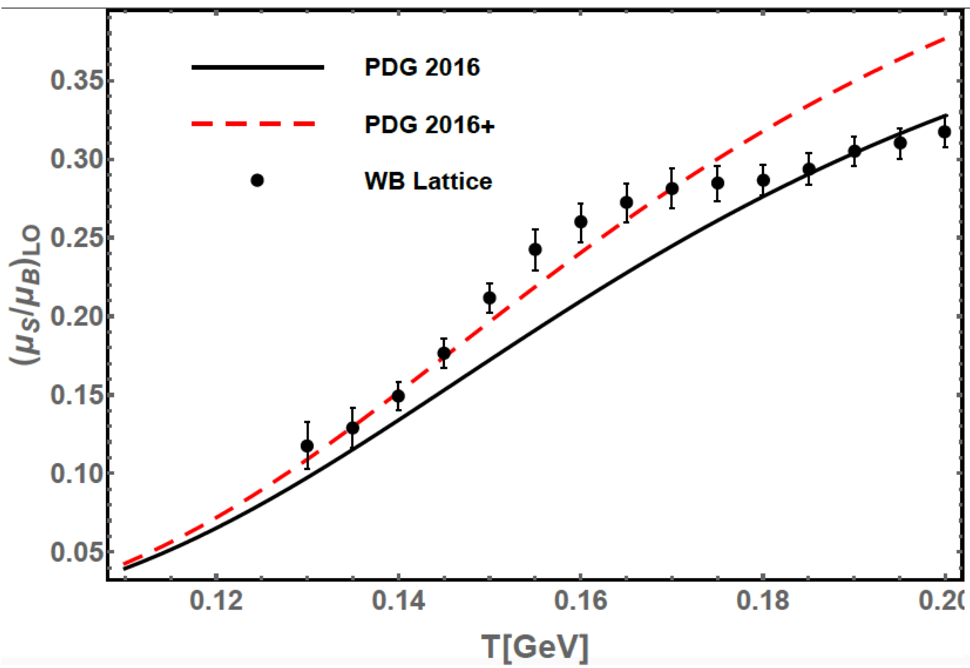


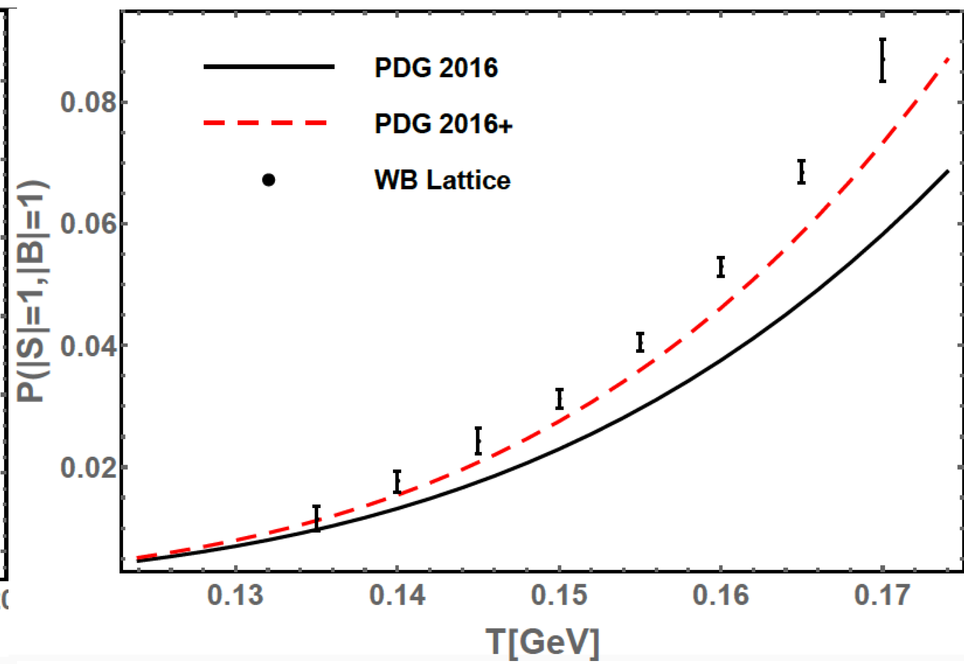


- Both Quark Model and PDG 2016 underestimate the partial pressure due to strange mesons
- This explains why the QM overestimates χ_4^S/χ_2^S: more strange mesons would bring the curve down

P.M. Lo, K. Redlich, C. Sasaki, PRc (2015)

Relevance of * states



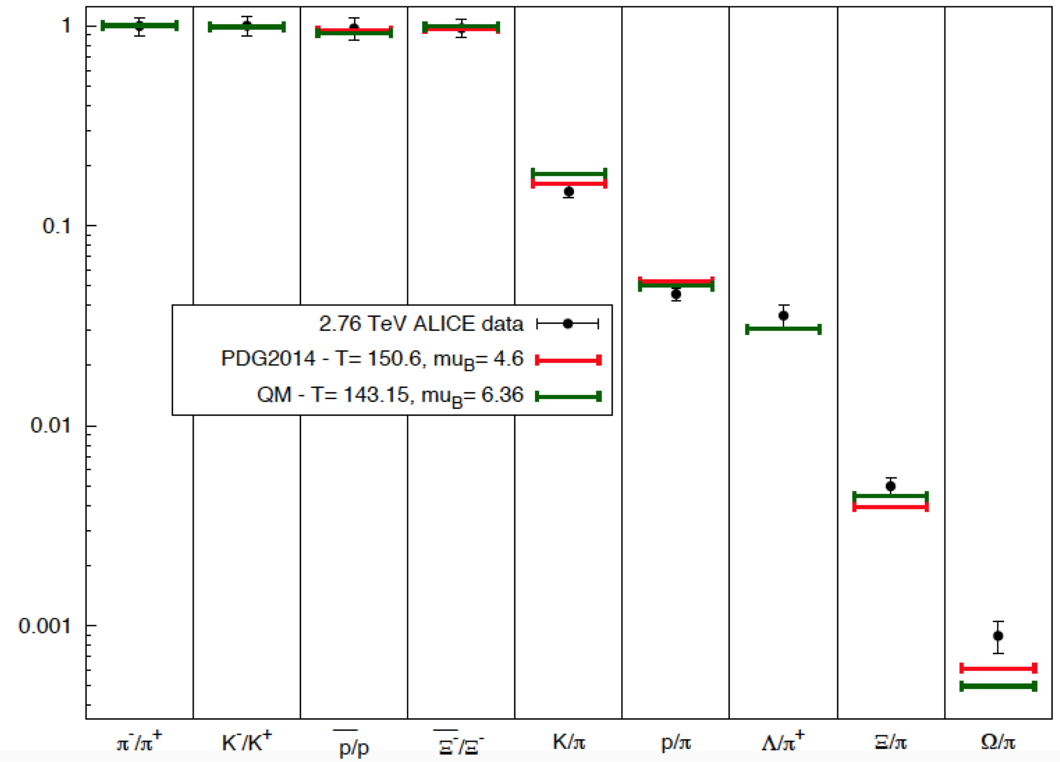


- Adding states to the spectrum allows to reproduce the lattice data
- We need the * states from the PDG 2016: the spectrum with only **, *** and **** states is not enough

WB collaboration, in preparation

Effect of resonance decays

- To extract the freeze-out parameters, we need to know how these additional states decay
- The decays have a big effect on the freeze-out parameters



P. Alba et al., in preparation

Conclusions

- Unprecedented precision in lattice QCD thermodynamics allows to extract information on the hadronic spectrum

- The most up-to-date PDG 2016 list with **, *** and **** states is not enough to reproduce the lattice results

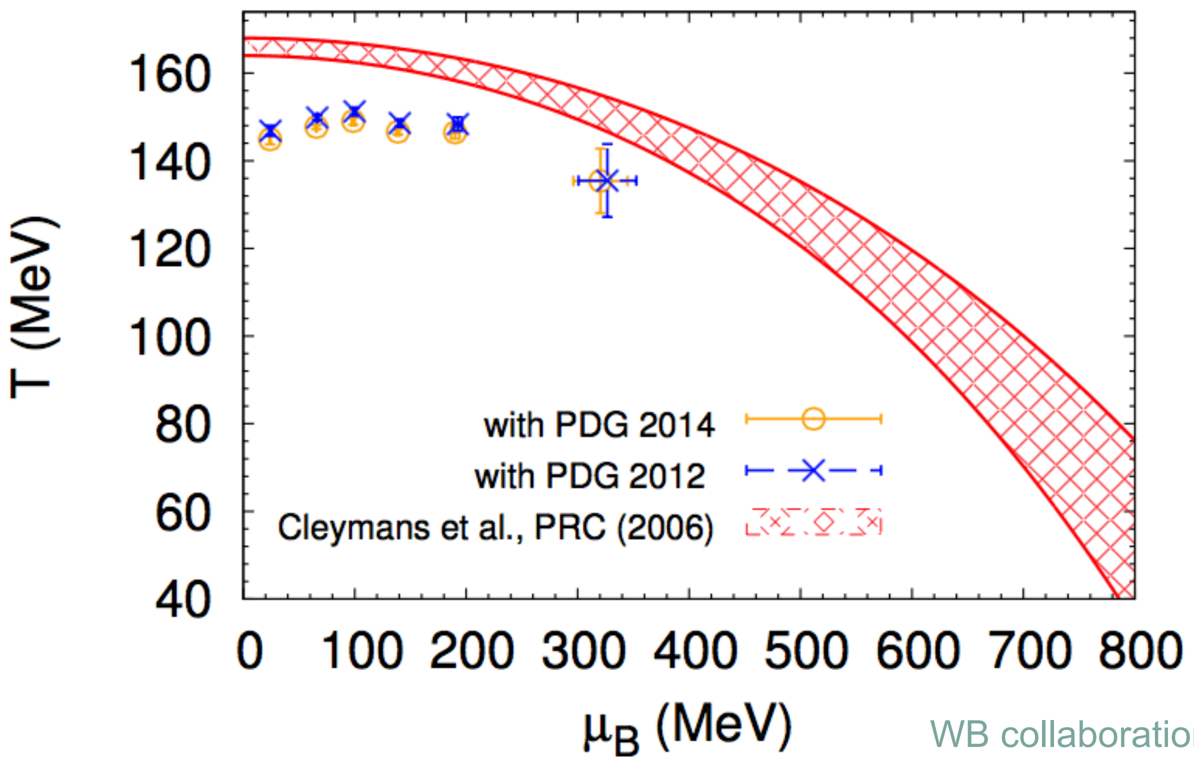
- Good agreement is found by including * states and/or Quark Model states

- Large effect of decays on freeze-out parameters from yields

- We need to know how these states decay, to use them in heavy ion physics

Effect of resonance decays

- We used the PDG2014 to estimate the effect of resonance decays on the fit to proton and charge fluctuations
- The results agree with the ones obtained with the PDG2012 within errorbars



WB collaboration, in preparation