Effect of the QCD equation of state and strange hadronic resonances on multiparticle correlations in heavy ion collisions
(nucl-th:1711.05207)

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Outline

• Why do we need additional resonances
• Inclusion of additional states in the hadronic spectrum
• Lattice QCD based Equation of State (EoS)

Results:
• Particle spectra and mean $p_t$
• $\eta/s$ and flow harmonics: comparison with STAR results in QM18

Conclusions
Heavy-ion collisions evolution

Valentina Mantovani Sarti (TUM Physics Department – E62)
Why do we need additional states?

Baryon-Strangeness correlator

\[
\left( \frac{\mu_S}{\mu_B} \right)_{LO} = - \frac{\chi_1^{BS}}{\chi_2^S} - \frac{\chi_1^{QS}}{\chi_2^S} \frac{\mu_Q}{\mu_B}.
\]

- **QM-HRG** improves the agreement with LQCD data
- **QM** predicts **not-yet-detected strange states** ⇒ overestimate other strangeness related observables as \(X_4/X_2\)

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**Adding *-* ** States from Up-to-Date PDG List?**

Bazazov et al. PRL 113(2014)
QM: Capstick, Isgur PRD (1986)
Additional states from up-to-date PDG list

- PDG 2005: 144
- PDG 2016: 608
- PDG 2016+: 738 (including also * states)

P. Alba PRD96 (2017)
• Sensitive to the strangeness content

![Graph showing partial pressures from LQCD](image)

- Total
- $|B|=0, |S|=1$
- $|B|=1, |S|=0$
- $|B|=1, |S|=1$
- $|B|=1, |S|=2$
- $|B|=1, |S|=3$

HRG with PDG2016

$\frac{p}{T^4}$ vs. $T$ [MeV]

P. Alba PRD96 (2017)
Baryon-strangeness fluctuations from LQCD

\[
\left( \frac{\mu_S}{\mu_B} \right)_{LO} = -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS} \mu_Q}{\chi_2^S \mu_B}.
\]

\[
\frac{\chi_4^S}{\chi_2^S} \propto |S|^2
\]

P. Alba PRD96 (2017)
Lattice QCD based Equation of State

\[
\left( \frac{\varepsilon - 3p}{T^4} \right)_{\text{all}} = \left( \frac{\varepsilon - 3p}{T^4} \right)_{\pi} \frac{1 + \text{tanh} \left[ b(T - T_{\text{HRG+Latt}}) / \pi \right]}{2} \left[ \left( \frac{\varepsilon - 3p}{T^4} \right)_{\text{HRG+Latt}} - \left( \frac{\varepsilon - 3p}{T^4} \right)_{\pi} \right]
\]

- \( T < 153 \text{ MeV} \) ⇒ HRG with PDG16+
- \( T > 153 \text{ MeV} \) ⇒ state-of-the art

LQCD fitted EoS for 2+1 (PLB730, 2014) /2+1+1 (Nature 539, 2016) with thermalized quark charm, from WB collaboration

PDG16+: Chin. Phys. C40 (2016)
Hydrodynamical evolution in a nutshell

Initial Conditions
Quantum fluctuations in the position of protons, neutrons, quarks, and gluons

τ₀ initial time to switch on hydro

Hydrodynamics
(for heavy-ions collisions) in a nutshell

Hydrodynamics viscosity and thermodynamics

Hadron Gas: number of hadrons, decays, interactions etc

Pressure, energy, entropy

Tsw temperature at which the Quark Gluon Plasma switches to hadrons

(J.Norohna-Hostler slides)
Results
Particle spectra: additional states & charm quarks

- Inclusion of **additional states** ⇒ better agreement for $p$ and $K$ at high $p_t$
- Inclusion of **charm quarks** ⇒ less high $p_t$ particles

PDG05/S95n-v1: Huovinen et al. Nucl. Phys., A837:26–53, 2010
\(<p_t>: \) additional states & charm quarks

- Inclusion of extra resonances ⇒ larger \(<p_t>\)
- Inclusion of charm quarks ⇒ smaller \(<p_t>\) up to intermediate centralities
Particle spectra and $<p_t>$: *-** states effect

- Increase of $\approx 5$-$15\%$ in $p_t$ spectra
- Up to $\approx 7\%$ in $<p_t>$

PHENIX Collaboration, PRC69 (2004)
How is $\eta/s$ affected by the new EoS?

- $\eta/s$ from fit to **STAR 200 GeV** (nucl-ex: 1701.06496) and **ALICE RUN2 5.02 TeV** (PRL116,2016)
- LHC energies more sensitive to different EoS
How is $\eta/s$ affected by the new EoS?

| EoS                      | Au-Au 200 GeV | Pb-Pb 5.02TGeV |
|-------------------------|--------------|---------------|
| PDG05/S95n – v1 [11]    | 0.05         | 0.025         |
| PDG16 + /2 + 1 [WB]     | 0.05         | 0.047         |
| PDG16 + /2 + 1 + 1 [WB] | 0.05         | 0.04          |

- No EoS dependence at RHIC $\Rightarrow$ agreement with Bayesian analysis (PRC94, 2016)
- LHC energies $\Rightarrow$ decrease of 50% for old EoS
  $\Rightarrow$ charm contribution leads to a smaller $\eta/s$
- higher temperatures probed at LHC run 2 (up to $T \approx 600$ MeV)
  $\Rightarrow$ splitting between the 2+1 and 2+1+1 EoS
Shear viscosity and flow harmonics: *-** states

- *-** states act as «viscosity»
- ~2-10% decrease in $v_2\{2\}$
- ~1-8% decrease in $v_3\{2\}$
Flow harmonics: comparison to STAR results

- Agreement with $v_2\{2\}, v_2\{4\}$ at 200 GeV
- Slightly underestimating the ratio $v_2\{4\}/v_2\{2\}$ ⇒ non-linear effects? (BES)

QM18 talk by Niseem Magdy-STAR Coll.
Flow harmonics: comparison to STAR results

- Ratio $v_3\{2\}/v_3\{4\}$ mildly affected by medium and does not depend on the colliding system ⇒ probe to investigate properties of initial state

QM18 talk by Niseem Magdy-STAR Coll.
NS cumulants: comparison to STAR results

\[ NSC(m, n) = \frac{\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\langle v_m^2 \rangle \langle v_n^2 \rangle} \]

- NSC ⇒ insight into medium and initial state
- **NSC(2,3)** independent of viscous effects
- **NSC(4,2)** sensitive to viscosity

QM18 talk by Niseem Magdy-STAR Coll.
Conclusions & Outlooks (for more details: [nucl-th]:1711.05207)

• EoS based on additional strange hadronic states (PDG2016+) and state-of-the-art LQCD calculations for $2+1/2+1+1$ quark flavors ⇒ partial pressures analysis

• inclusion of additional *-*-** states:
  • increase the agreement with LQCD data up $T \approx 145$ MeV, close to the crossover region
  • enhance the production of particles at higher $p_t$ and leads to a higher $<p_t>$

• Shear viscosity and new EoS:
  • 50% increase wrt to old EoS at LHC energies
  • at LHC run2 energies sensitive to EoS ⇒ 15% difference in 2+1 and 2+1+1 EoS results which should increase at higher temperatures

• Flow harmonics and NSC at STAR 200 GeV:
  • Nice agreement with recent results presented at QM18 by STAR collaboration

• Outlooks: thermal fit analysis on STAR and LHC yields and ratios to study QCD flavour hierarchy and transport coefficients near phase transition (in preparation)
Outlooks:

• Thermal fit analysis based on this new-up-to-date spectrum for particle yields at RHIC and LHC data (in preparation)
BACKUP SLIDES
Building the EoS: HRG model at low $T$

Theoretical Description

Perturbative Quantum Chromodynamics

Gluon self-interactions

Lattice Quantum Chromodynamics

Hadron Resonance Gas Boltzmann Equation

$T_c \approx 155$ MeV

$\sim 1.8 \times 10^{12}$ K

(J.Norohna-Hostler slides)
Building the EoS: HRG model at low T

\begin{equation}
N(m) \sim \text{Exp} \left[ \frac{m}{T_H} \right]
\end{equation}

(J.Norohna-Hostler slides)
In this paper, we perform an analysis of several strange–nonstrange hadronic lists currently available, which include states with two, three, and four stars as listed in the PDG2016. Experimentally established states from the PDG2016 are included, along with one-star states from the PDG2016. One-star states are predicted by the QM, providing information on the decay properties of such particles. However, the basic QM description does not provide any flavor, spin, and momentum configurations. Many of the states predicted by the QM have masses between 1.5 and 2.5 GeV. When we merge the nonrelativistic QM states, we find 1517 states. In total, when we also include the one-star states, the overall increase is much larger, with a total of 985 in the list which adds to the ones listed in the PDG2016. In the QM, particles and antiparticles and their isospin multiplicity are imposed. The total number of measured particles and antiparticles is 24,052. For most of the predicted states, no mass cutoff has been imposed. The quarks in the bound state, and the decay modes are listed. The latter contains fewer states than the ones found in the PDG2016+ Quark Model hQM (magenta).

• Sensitive to the strangeness content

\[
P_S(\hat{\mu}_B, \hat{\mu}_S) = P_{0|1|} \cosh(\hat{\mu}_S) + P_{1|1|} \cosh(\hat{\mu}_B - \hat{\mu}_S) + P_{1|2|} \cosh(\hat{\mu}_B - 2\hat{\mu}_S) + P_{1|3|} \cosh(\hat{\mu}_B - 3\hat{\mu}_S)
\]

\[
P_{0|1|} = \chi_2^S - \chi_2^{BS}
\]

\[
P_{1|1|} = \frac{1}{2} (\chi_4^S - \chi_2^S + 5\chi_1^{BS} + 7\chi_2^{BS})
\]

\[
P_{1|2|} = -\frac{1}{4} (\chi_4^S - \chi_2^S + 4\chi_1^{BS} + 4\chi_2^{BS})
\]

\[
P_{1|3|} = \frac{1}{18} (\chi_4^S - \chi_2^S + 3\chi_1^{BS} + 3\chi_2^{BS})
\]

The model results based on the PDG2016 spectrum are extrapolated. In all cases, the solid lines correspond to the HRG model results based on the PDG2016 spectrum. For all other cases, the data are properly continuum extrapolated. In all cases, the solid lines correspond to the HRG model results based on the PDG2016 spectrum. For all other cases, the data are properly continuum extrapolated. The figure shows a logarithmic plot illustrating the many orders of magnitude that the partial pressures studied in this paper cover. The total pressure is taken from Ref. 34. From this analysis, a consistent picture emerges: all pressures are present, although experiments and lattice QCD may disfavor such a state. A more drastic reduction can be achieved by assuming a diquark structure for the state. A diquark structure is not yet fully established, and strangeness states. The full observables confirm the need for not yet detected, or at least weakly established states, which span many orders of magnitude, as can be seen in the figure. The main result of this paper is a lattice QCD study which systematically tests the results for different particle species, observables, and quark models. This is done in order to get differential information on the missing states, based on their strangeness content. The observables which allow a more stringent test of the QM states compared to the PDG2016 are the strangeness-related observables, by comparing the lattice QCD results to those of the HRG model based on different observables. Moreover, all observables confirm the need for not yet detected, or at least weakly established, strangeness states. The full observables confirm the need for not yet detected, or at least weakly established, strangeness states. The full observables confirm the need for not yet detected, or at least weakly established, strangeness states. The full observables confirm the need for not yet detected, or at least weakly established, strangeness states.
Hydrodynamical evolution

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Hydrodynamics
viscosity and thermodynamics

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Hydrodynamics
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τ₀ initial time to switch on hydro

Tsw temperature at which the Quark Gluon Plasma switches to hadrons

• E-b-E v-USPHydro + TRENTO I.C. +T_{kin}=T_{chem}
• On/off hydro chosen to be consistent as possible with LQCD
• \( \tau_0 = 0.6 \text{ fm, } T_{sw} = 150 \text{ MeV} \)

(J.Norohna-Hostler slides)
Partial pressures from LQCD: Kaons
Partial pressures from LQCD: N states and Hyperons

\[ N, \Lambda, \Sigma, \Xi, \Omega \]
Shear viscosity and hadronic spectrum

\[ \eta/s(T) \]

- \( r_{\text{all}} = 0.1 \text{ fm PDG05} \)
- \( r_{\text{all}} = 0.1 \text{ fm PDG16+} \)
- \( r_{\text{all}} = 0.25 \text{ fm PDG16+} \)

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