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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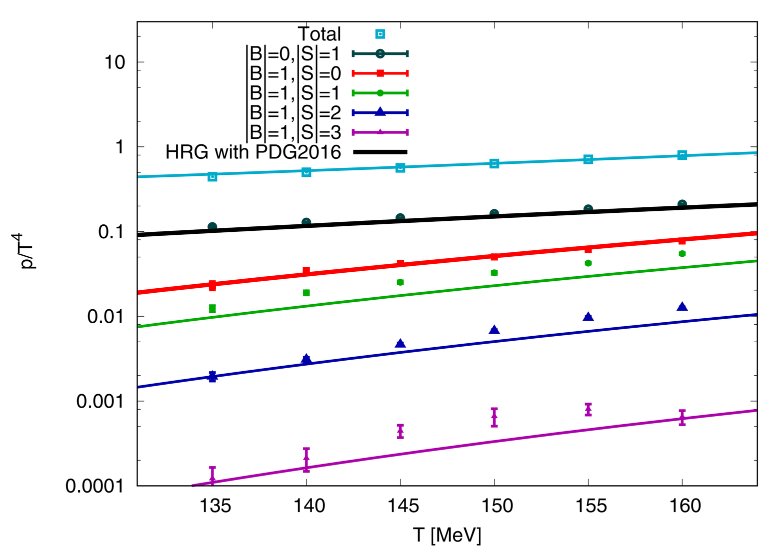
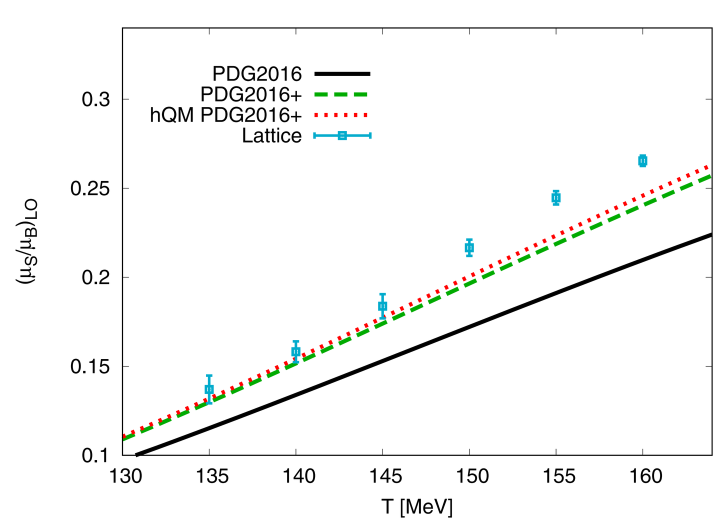
Why do we need additional strange resonances?

- **Additional resonances are needed in order to reproduce Lattice QCD (LQCD) results on partial pressures p/T^4** [1, 2];
- in the Hadron Resonance Gas model (HRG) the total pressure is given by the contributions from each hadron family with baryon number B and strangeness content S

$$P(\hat{\mu_B}, \hat{\mu_S}) = \sum_{i=reson.} P^{BS}_{b_i s_i} = P^{BS}_{00} + P^{BS}_{10}\cosh(\hat{\mu_B}) + P^{BS}_{01}\cosh(-\hat{\mu_S})$$
$$+ P^{BS}_{11}\cosh(\hat{\mu_B} - \hat{\mu_S}) + P^{BS}_{12}\cosh(\hat{\mu_B} - 2\hat{\mu_S}) + P^{BS}_{13}\cosh(\hat{\mu_B} - 3\hat{\mu_S})$$





- comparison of partial pressures $\mathbf{p/T^4}$ from **Wuppertal-Budapest LQCD** collaboration and Hadron Resonance Gas (HRG) model using **PDG2016** with only $^{****-***}$ states [3] ⇒ **need for additional strange states**
- hyperons in the $S = -1$ (e.g Λ) and $S = -2$ sector (e.g Ξ), are underestimated
- **PDG16** most up-to-date list of all $***-****$ states from the Particle Data Group
- **PDG16+** most up-to-date list of all $*-****$ states from the Particle Data Group
- only **strong decays** with non negligible branching ratios (≈1% or higher)
- if branching ratios do not sum to 100% ⇒ remaining decays $\mathbf{N_2 \to N_1 + \gamma}$ where N_2 and N_1 are hadrons with the same quantum numbers and N_1 is the next state in descending mass order with parity compatible for such a decay
- if no decay information available ⇒ **≲30% BR hadronic decays**, **≳70% radiative decays**

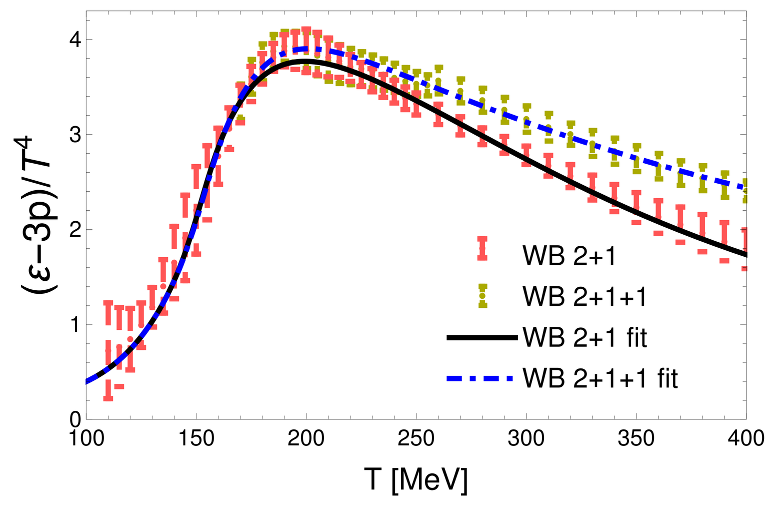
To leading order in the baryochemical potential μ_B, the ratio $\boldsymbol{\mu_S/\mu_B}$ reads

$$\left(\frac{\mu_S}{\mu_B}\right)_{LO} = -\frac{\chi^{BS}_{11}}{\chi^S_2} - \frac{\chi^{QS}_{11}}{\chi^S_2}\frac{\mu_Q}{\mu_B}.$$

Extremely sensitive to the amount of heavy strange and charged particles in the hadronic spectrum. **Additional strange states in PDG2016+ ⇑ the agreement with LQCD up to T ≈ 145 MeV.**

Lattice QCD based Equation of State

The Equation of State (EoS) is the fundamental input to the hydrodynamics evolution that allow us to **test the effect of the assumptions on the number of thermalized quarks**.



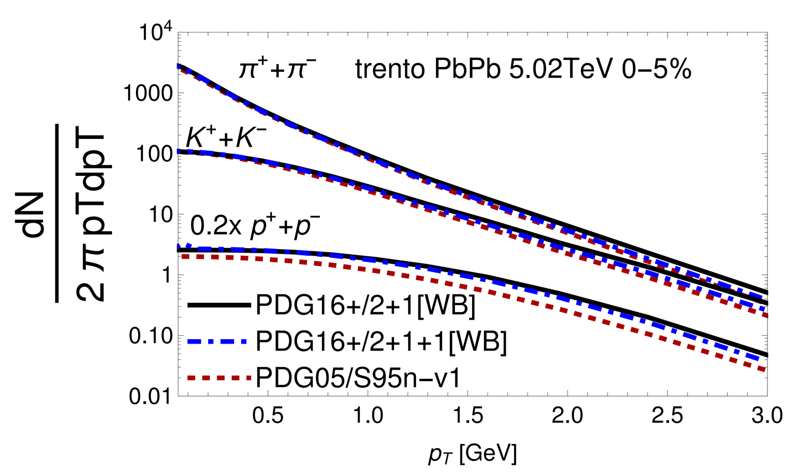
- **T < 153 MeV ⇒ HRG with PDG16+**;
- **T > 153 MeV ⇒ state-of-the art LQCD fitted EoS for 2+1** [4] **and 2+1+1** [5] **with thermalized charm degrees of freedom from WB collaboration**.

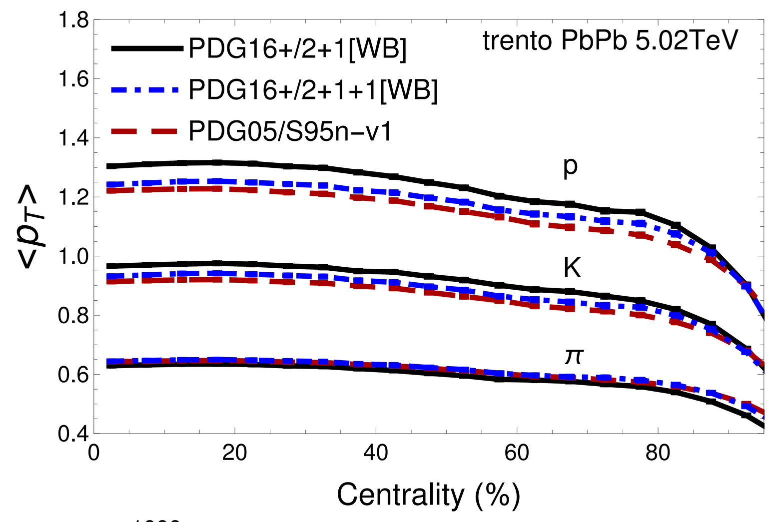
The hydrodynamical modeling

The parametrization for switching on/off of the hydrodynamics evolution has been chosen to be as consistent as possible with LQCD results.
Event-by-event viscous hydrodynamics **v-USPhydro** [6] with **TRENTO initial conditions** [7], assuming $\mathbf{T^{kin}_{FO} = T^{chem}_{FO}}$.
For the simulations both at RHIC Au-Au 200 GeV and ALICE Pb-Pb 5.02 TeV the hydrodynamics description is switched on at $\tau_0 = 0.6$ fm and the hadrons are formed at $T_{SW} = 150$ MeV.

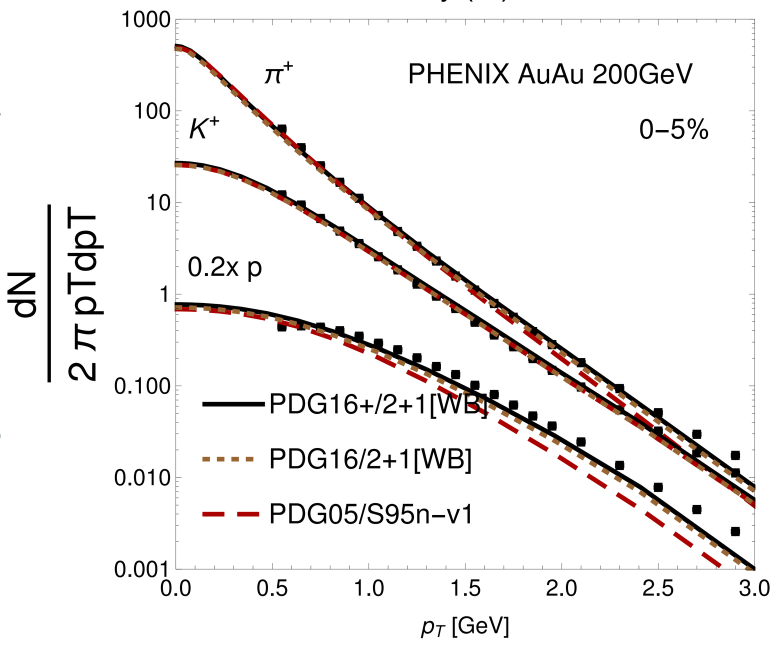
Results

Effects of the additional resonances on particle spectra and $< p_t >$

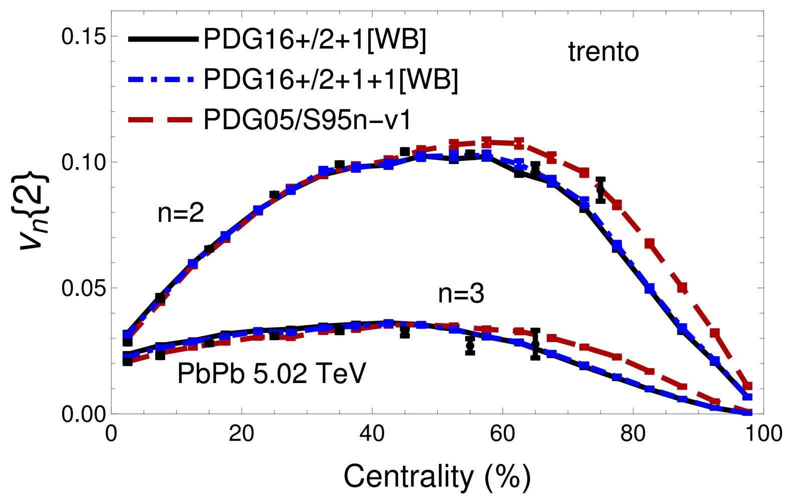




- **enhancement of p and K spectra at higher $\mathbf{p_t}$ for 2+1 EoS**;
- inclusion of charm quarks ⇒ less production of high p_t particles
- **inclusion of extra resonances ⇒ larger $< p_t >$**;
- inclusion of **charm quarks** ⇒ **smaller** $< p_t >$ **up to intermediate centrality range**
- inclusion of $*-**$ **states ⇒ increase of ≈ 5 − 15% in p_t spectra and up to ≈ 7% in $< p_t >$**;



Effects of the additional resonances on η/s and on flow harmonics



The shear viscosity η/s has been extracted from the comparison of our theoretical results obtained within different EoS to flow harmonics $v_2\{2\}$, $v_3\{2\}$ obtained from **STAR in Au-Au 200 GeV** [8] and **LHC run2 Pb-Pb 5.02 TeV** [9].

- at **RHIC** energies all three EoS describe the data quite well ⇒**no dependence on the chosen EoS, agreement with previous results based on Bayesian analysis [10]**;
- thermalized charmed quarks ⇒ smaller η/s value with respect to the 2+1 EoS.
- **higher temperatures probed at LHC run 2 (up to T 600 MeV)** ⇒ splitting between the **2+1** and **2+1+1** ⇒ **different values of η/s**

EoS	Au-Au 200 GeV	Pb-Pb 5.02TGeV
PDG05/S95n − v1 [11]	0.5	0.025
PDG16 + /2 + 1 [WB]	0.5	0.047
PDG16 + /2 + 1 + 1 [WB]	0.5	0.04

Conclusions

- EoS obtained by matching the **state-of-the-art LQCD calculations for 2+1/2+1+1 quark flavors** to a HRG model based **PDG2016+** spectrum containing extra resonances relevant for reproducing lattice data on partial pressures;
- **the inclusion of additional** $^{*-**}$ **states**:
  - **increase the agreement with LQCD data up to T ≈ 145 MeV, close to the crossover region**;
  - **enhance the production of particles at higher p_t and leads to a higher $< p_t >$**;
  - results for all three EoS obtained at RHIC energies are in agreement with previous Bayesian analysis;
  - **η/s ratio at LHC run2 energies depends on the EoS** and there is roughly a 15% difference in 2+1 and 2+1+1 EoS results which should increase at higher temperatures.

References

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