Chemical Freeze-Out of Hadrons Within the Induced Surface Tension Hadron Resonance Gas Model

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Motivation

The primary goal of ultrarelativistic heavy ion collisions is to recreate strongly interacting matter in the laboratory to study its properties and the QCD phase diagram. These experiments aim to understand particle production in high-energy collisions, explore the QCD phase diagram, detect signals of color deconfinement, chiral symmetry restoration, and locate the critical endpoint. To achieve these objectives, we need robust tools to analyze the data. Specifically, analyzing STAR experimental data on hadron multiplicities highlights the importance of accounting for weak decay contributions for different particle species, enabling correct descriptions of the experimental results.

Induced Surface Tension Equation of State (EOS)

IST EOS is a thermodynamically self-consistent equation of state, it is a system of coupled equations between the pressure p of considered system and the induced surface tension coefficient Σ, which are as follows [1]:

$$p = \sum_{k=1}^{N} p_k^{Id}(T, \nu_k^P), \qquad \Sigma = \sum_{k=1}^{N} R_k p_k^{Id}(T, \nu_k^S)$$

Particle number density of k-th sort:

$$n_k = \frac{a_{22} n_k^{Id}(T, \nu_k^P) - a_{12} R_k n_k^{Id}(T, \nu_k^S)}{a_{11}a_{22} - a_{12}a_{21}}$$

$$a_{11} = 1 + \sum_{k=1}^{N} V_k n_k^{Id}(T, \nu_k^P), \qquad a_{12} = \sum_{k=1}^{N} S_k n_k^{Id}(T, \nu_k^P)$$

$$a_{21} = \sum_{k=1}^{N} V_k R_k n_k^{Id}(T, \nu_k^S), \qquad a_{22} = 1 + \alpha \sum_{k=1}^{N} S_k R_k n_k^{Id}(T, \nu_k^S)$$

$$n_k^{Id}(T, \mu) = \frac{g_k}{2\pi^2\hbar^3} \int_0^{\infty} \frac{p^2 dp}{\exp\left[(E-\mu)/T\right] \pm 1},$$

$$p_k^{Id}(T, \mu) = \frac{g_k}{2\pi^2\hbar^3} \int_0^{\infty} \frac{p^4 dp}{3E} \frac{1}{\exp\left[(E-\mu)/T\right] \pm 1}$$

Effective chemical potentials:

$$\nu_k^P = \mu_k - pV_k - \Sigma S_k, \qquad \nu_k^S = \mu_k - pV_k - \alpha\Sigma S_k$$

- IST EOS allows one to go beyond the Van der Waals approximation, since it reproduces 2-nd, 3-rd and 4-th virial coefficients of the gas of hard spheres for $\alpha = 1.245$.
- Number of equations in IST EOS is 2 and it does not depend on the number of different hard-core radii.

Results for Chemical Freeze-out Parameters

For fitting were used experimental data of the E686, E895, E891, NA49 and STAR Collaborations for energies: 2.7 - 200 GeV. Local fit parameters for each collision energy (5): T, μ_B, μ_{I_3}, μ_S, γ_S. Global fit parameters are 5 radii for different partcile species, which are fixed in this work. $R_\pi = 0.15$ fm, $R_K = 0.395$ fm, $R_{mesons} = 0.42$ fm, $R_{baryons} = 0.365$ fm, $R_\Lambda = 0.085$ fm. It is crucial that inclusion of weak decays should be made according to experimental analysis.

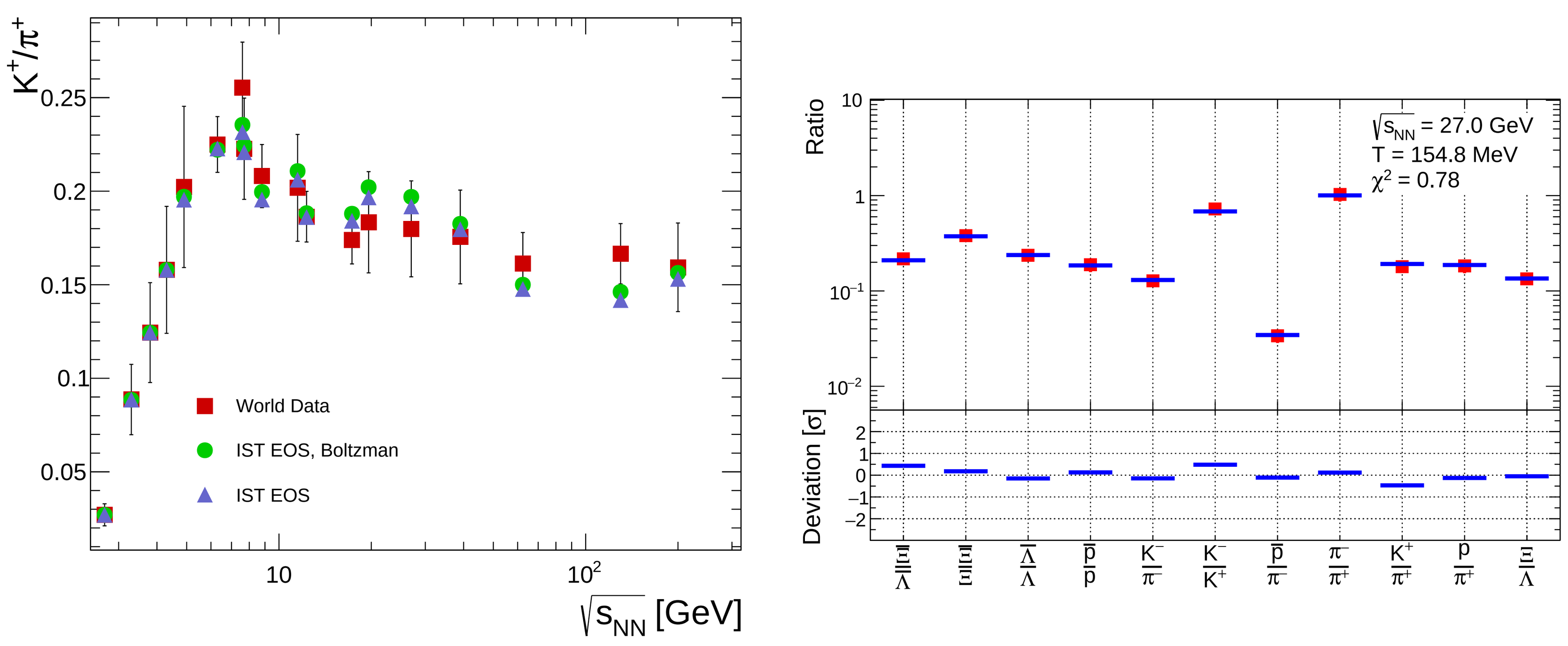

Figure 1: (left) Energy dependence of K^+/π^+ ratio for the measured world data and obtained with the IST EOS at $\sqrt{s} = 2.7 - 200$ GeV. (right) Particle ratios (upper) and (lower) deviation of the theoretical description obtained by IST EoS from the data ratio measured at $\sqrt{s} = 27$ GeV by STAR Collaboration.

K^+/π^+ is the most problematic ratio for description by different models. Inclusion of weak decays greatly improves the description of particle ratios in the experimental data and decrease temperature of chemical freeze-out by 10 MeV! IST EOS with additional radii for kaons and pions provides a good description of available experimental data.

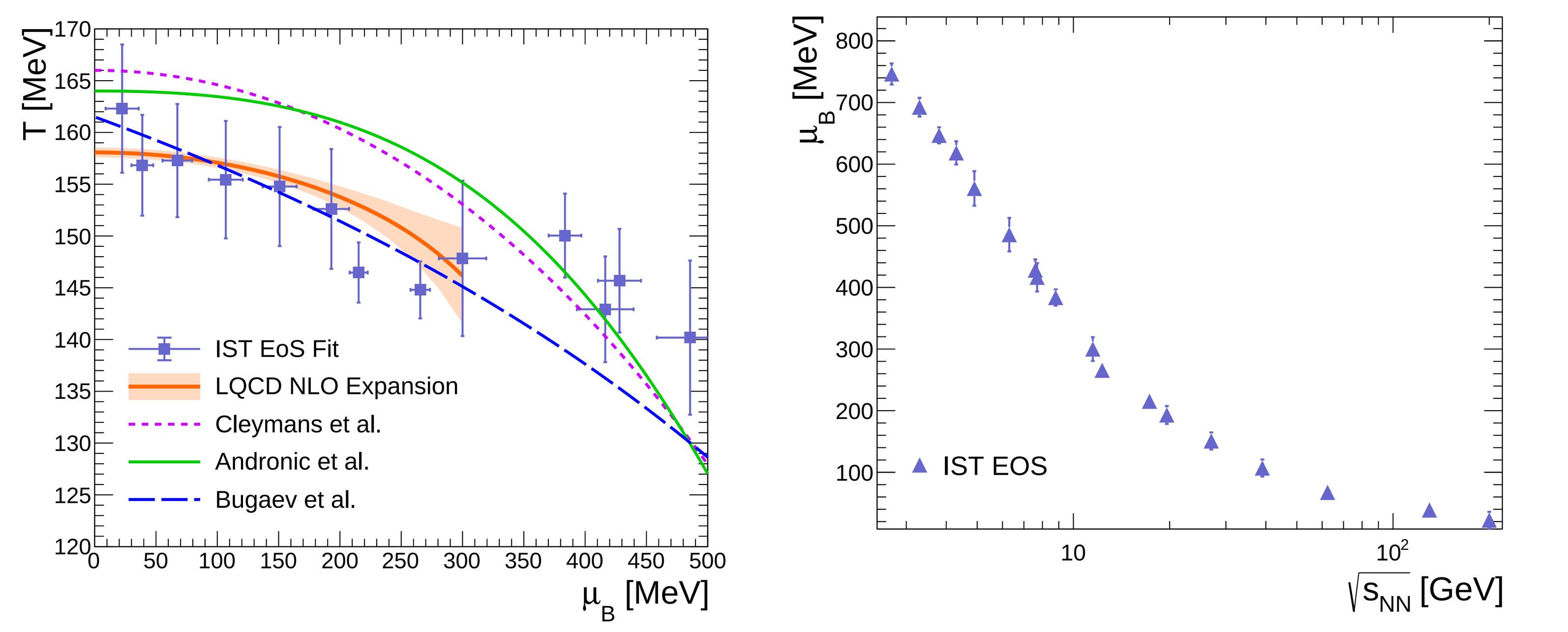

Figure 2: (left) Parametrization of the chemical freeze-out temperature (T_{ch}) on baryon chemical potential (μ_B) dependence made by J. Cleymans and A. Andronic [3, 4] (left) and obtained with the IST EOS [5]. (right) Energy dependence of μ_B obtained with the IST EOS.

Conclusions

The IST EOS is a good tool to describe the particle yields and to get chemical freeze-out parameters. An updated version of this model allows the fitting of ratios among different hadrons, taking into account both inclusive and exclusive feed-down corrections consistently with experimental analysis. Moreover, inclusion of weak decays:

- Brings the chemical freeze-out temperature to the right track. It gets lower than LQCD predictions for pseudocritical T
- Provides a good description of the particle ratios from the existing experimental data
- The chemical freeze-out parameters from the IST EOS fits for STAR and NA49 data are close to the LQCD calculations.

References

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