On Chemical Freeze-outs of Strange and Nonstrange Hadrons

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I Abstract

Two approaches to treat the chemical freeze-out of strange particles in hadron resonance gas model are analyzed. The first one employs their non-equillibration via the usual γ_s factor and such a model describes the hadron multiplicities measured in nucleus-nucleus collisions at AGS, SPS and RHIC energies with $\chi^2/dof \simeq 1.15$. Surprisingly, at low energies we find not the strangeness suppression, but its enhancement. Also we suggest an alternative approach to treat the strange particle freeze-out separately, but with the full chemical equilibration. This approach is based on the conservation laws which allow us to connect the freeze-outs of strange and non-strange hadrons. Within the suggested approach the same set of hadron multiplicities can be described better than within the conventional approach with $\chi^2/dof \simeq 1.06$.

II Hadron Resonance Gas Model

We consider the multicomponent HRGM [1, 2, 3], i.e. the hadron interaction is taken into account via hard-core radii, with the different values for pions, kaons, other mesons and baryons. The best fit values for such radii $R_b = 0.2$ fm, $R_m = 0.4$ fm, $R_\pi = 0.1$ fm, $R_K = 0.38$ fm were obtained in [3].
Consider the Boltzmann gas of N hadron species in a volume V that has the temperature T, the baryonic chemical potential μ_B, the strange chemical potential μ_S and the chemical potential of the isospin third component μ_{I3}. The system pressure p and the K-th charge density n_i^K ($K \in \{B, S, I3\}$) of the i-th hadron sort are given by the expressions [1]:

$$\frac{p}{T} = \sum_{i=1}^{N} \xi_i\,, \quad n_i^K = \frac{Q_i^K \xi_i}{1 + \frac{\xi^T \mathcal{B} \xi}{\sum_{j=1}^{N} \xi_j}}\,, \quad \xi = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \ldots \\ \xi_N \end{pmatrix}, \qquad (1)$$

where $\mathcal{B}$ denotes a symmetric matrix of the second virial coefficients with the elements $b_{ij} = \frac{2\pi}{3}(R_i + R_j)^3$ and the variables ξ_i are the solutions of the following system

$$\xi_i = \varphi_i(T) \exp\left[\frac{\mu_i}{T} - \sum_{j=1}^{N} 2\xi_j b_{ij} + \xi^T \mathcal{B} \xi \left[\sum_{j=1}^{N} \xi_j\right]^{-1}\right],$$

$$\varphi_i(T) = \frac{g_i}{(2\pi)^3} \int \exp\left(-\frac{\sqrt{k^2 + m_i^2}}{T}\right) d^3k. \qquad (2)$$

Here the full chemical potential of the i-th hadron sort $\mu_i \equiv Q_i^B \mu_B + Q_i^S \mu_S + Q_i^{I3} \mu_{I3}$ is expressed in terms of the corresponding charges Q_i^K and their chemical potentials, $\varphi_i(T)$ denotes the thermal particle density of the i-th hadron sort of mass m_i and degeneracy g_i, and ξ^T denotes the row of variables ξ_i.
The main fitting parameters are temperature T, baryonic chemical potential μ_B, the chemical potential of the third projection of isospin μ_{I3}, whereas the strange chemical potential μ_S is found from the vanishing strangeness condition.
γ_s fit. We follow the conventional way of introducing γ_s, suggested by J. Rafelski, and replace φ_i in Eq. (2) as

$$\varphi_i(T) \rightarrow \varphi_i(T) \gamma_s^{s_i}\,, \qquad (3)$$

where s_i is number of strange valence quarks plus number of strange valence anti-quarks.
SFO. Let us consider two freeze-outs instead of one.
T_{SFO}, T_{FO} are, respectively, the chemical freeze-out temperatures for strange and nonstrange particles,
$\mu_{B_{SFO}}$, $\mu_{B_{FO}}$ are, respectively, the baryonic chemical potentials for strange and nonstrange particles,
$\mu_{I3_{SFO}}$, $\mu_{I3_{FO}}$ are, respectively, the isospin third projection chemical potentials for strange and nonstrange particles,
V_{SFO}, V_{FO} are, respectively, the effective volumes of the freeze-out hypersurface for strange and nonstrange particles.

Conservation laws:

- $s_{FO} V_{FO} = s_{SFO} V_{SFO}$ – entropy conservation,
- $n_{FO}^B V_{FO} = n_{SFO}^B V_{SFO}$ – baryon charge conservation,
- $n_{FO}^{I3} V_{FO} = n_{SFO}^{I3} V_{SFO}$ – isospin projection conservation.

Resonances decays contributing:

$$\frac{N^{fin}(X)}{V_{FO}} = \sum_{Y \in FO} BR(Y \rightarrow X) n^{th}(Y) + \sum_{Y \in SFO} BR(Y \rightarrow X) n^{th}(Y) \frac{V_{SFO}}{V_{FO}}. \qquad (4)$$

Width correction is taken into account by averaging all expressions containing mass by the Breit-Wigner distribution having a threshold

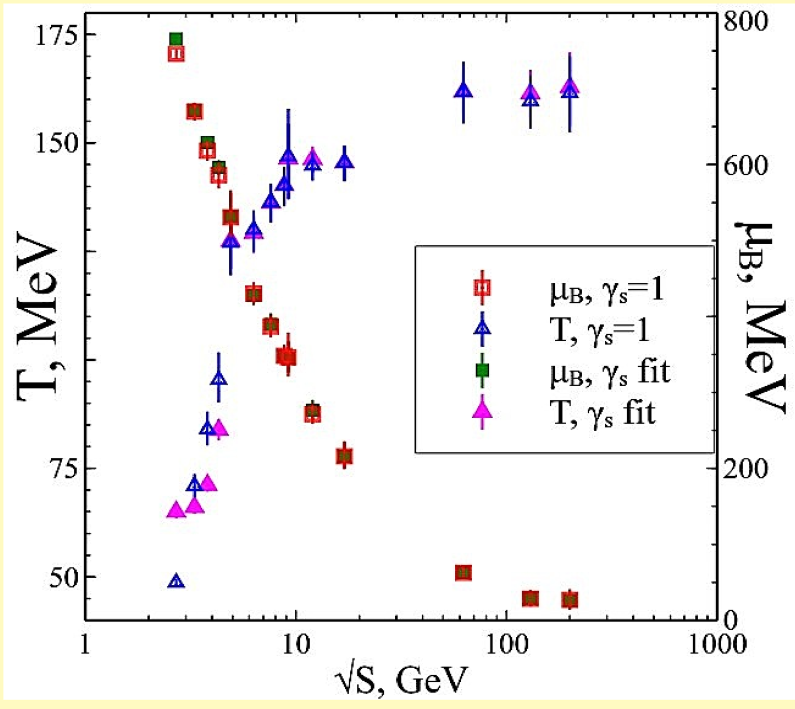
$$\int \exp\left(\frac{-\sqrt{k^2 + m_i^2}}{T}\right) d^3k \rightarrow \frac{\int_{M_0}^{\infty} \frac{dx_i}{(x - m_i)^2 + \Gamma^2/4} \int \exp\left(\frac{-\sqrt{k^2 + x^2}}{T}\right) d^3k}{\int_{M_0}^{\infty} \frac{dx_i}{(x - m_i)^2 + \Gamma^2/4}}. \qquad (5)$$

The effect of resonance decay $Y \rightarrow X$ on the final hadronic multiplicity is taken into account as $n^{fin}(X) = \sum_Y BR(Y \rightarrow X) n^{th}(Y)$, where $BR(X \rightarrow X) = 1$ for the sake of convenience. The masses, the widths and the strong decay branchings of all hadrons were taken from the particle tables used by the thermodynamic code THERMUS [4].

V Conclusions

- The fit of 111 hadron ratios measured at 14 values of the center of mass energy $\sqrt{s_{NN}}$ in the interval $\sqrt{s_{NN}}$= 2.7 - 200 GeV by our model gives $\chi^2/dof \simeq 1.15$ (for γ_s as a free parameter) and $\chi^2/dof \simeq 1.06$ (for separate freeze-outs for strange and for nonstrange particles approach);
- in contrast to earlier results [6] at low energies we find that in heavy ion collisions there is a sizable enhancement of strangeness with $\gamma_s \simeq 1.2 - 1.6$;
- γ_s fit allows us to essentially improve the Strangeness Horn description to $\chi^2/dof = 3.3/14$, i.e. better than it was done in [3] with $\chi^2/dof = 7.5/14$ and much better than it was done in [6];
- due to separate freeze-outs approach for the first time the HRGM is able to describe the multiplicity ratios of $\bar{\Lambda}/\Lambda$, $\bar{\Xi}/\Xi^-$, $\bar{\Omega}/\Omega$ and the $\bar{p}/\pi^-$ ratio with high quality;
- the obtained results allow us to conclude that an apparent deviation of γ_s from 1 is because strange hadrons have a separate chemical freeze-out compared to non-strange hadrons.

III γ_s approach



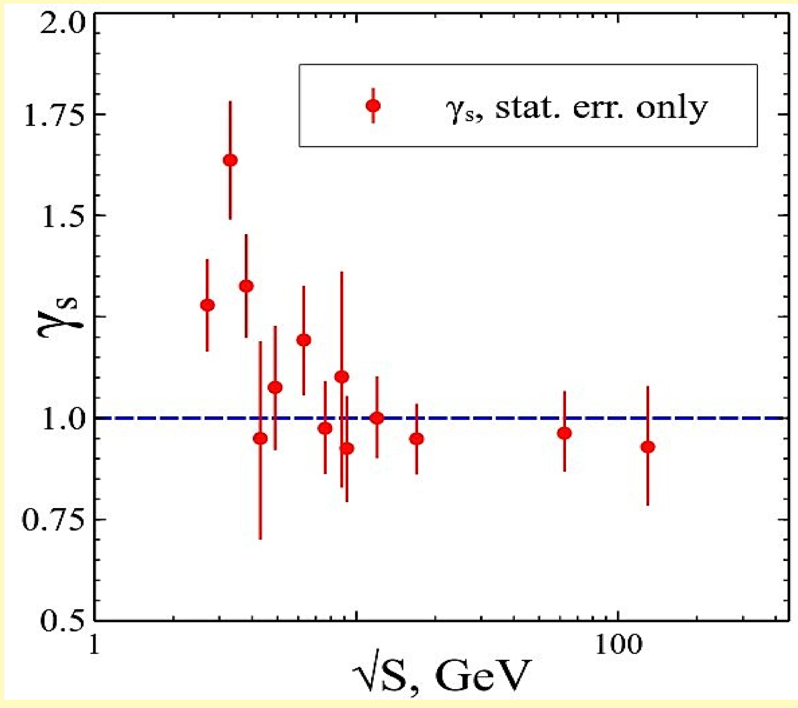


Fig.1. Behavior of parameters for the γ_s fit and for a single chemical FO with $\gamma_s = 1$. Upper panel: temperature T and baryo-chemical potential μ_B. Lower panel: γ_s.

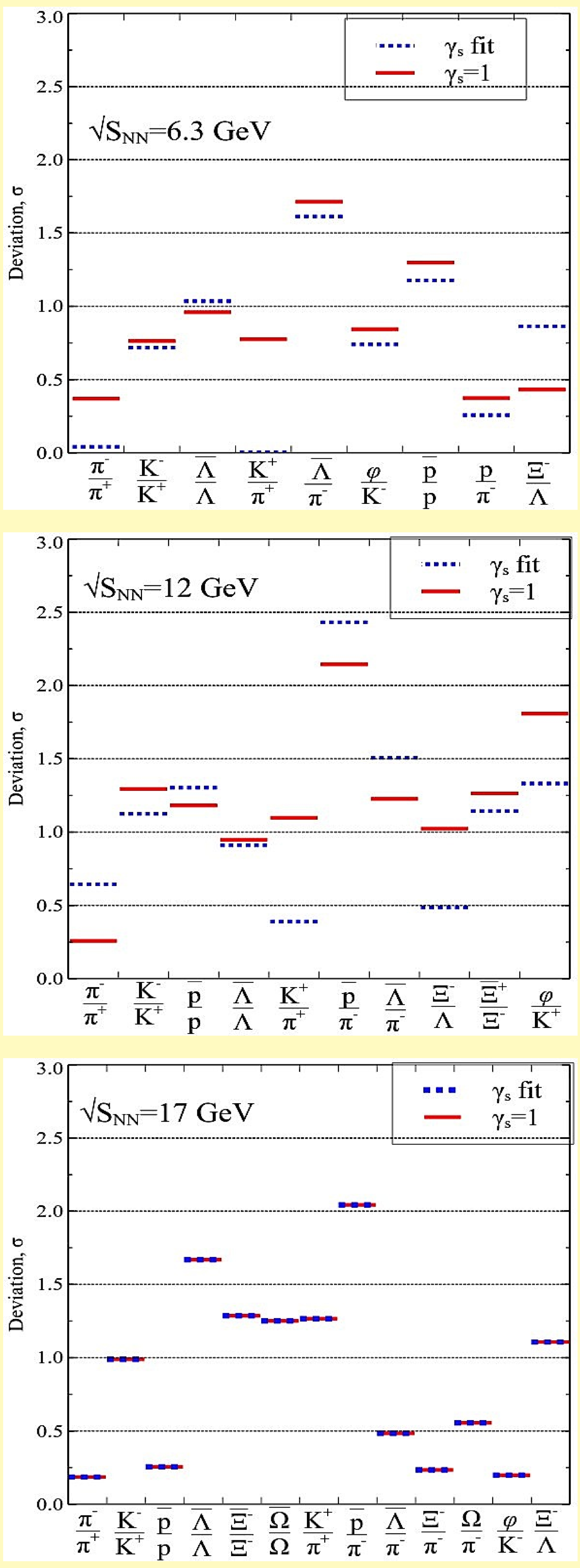


Fig.2. Relative deviation of theoretical description of ratios from experimental value in units of experimental error σ. The symbols on OX axis demonstrate the particle ratios. OY axis shows $\frac{|r^{theor} - r^{exp}|}{\sigma^{exp}}$, i.e. the modulus of relative deviation for $\sqrt{s_{NN}}$ = 6.3, 12 and 17 GeV. Solid lines correspond to the model with a single FO of all hadrons and $\gamma_s = 1$, while the dashed lines correspond to the model with γ_s fit.

IV Strange particle freeze-out

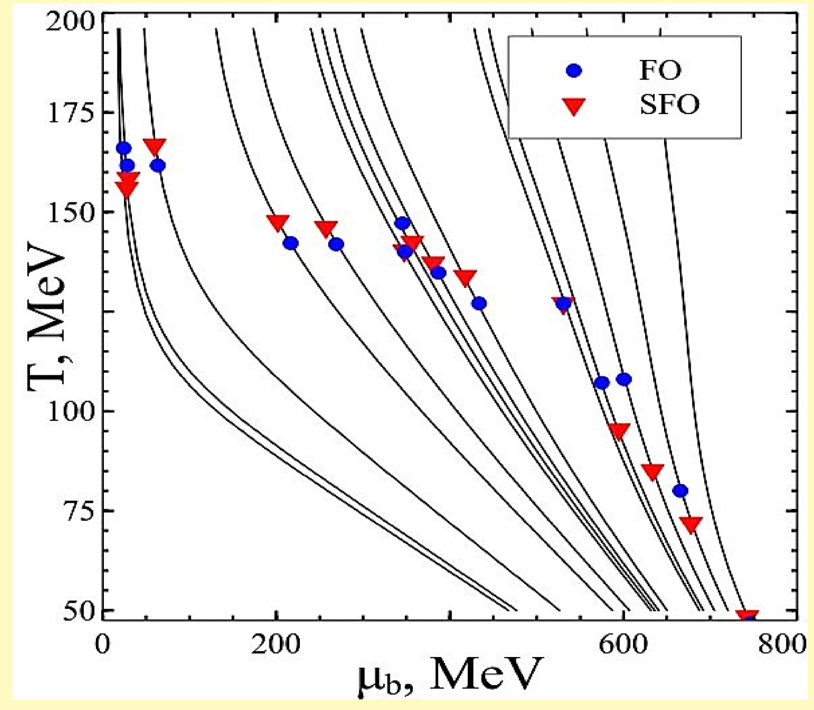


Fig.3. Parameters of chemical freeze-outs in the model with two freeze-outs. Triangles correspond to SFO, their coordinates are $(\mu_{B_{SFO}}, T_{SFO})$, while circles correspond to FO and their coordinates are $(\mu_{B_{FO}}, T_{FO})$. The curves correspond to isentropic trajectories $s/\rho_B = const$ connecting two freeze-outs.

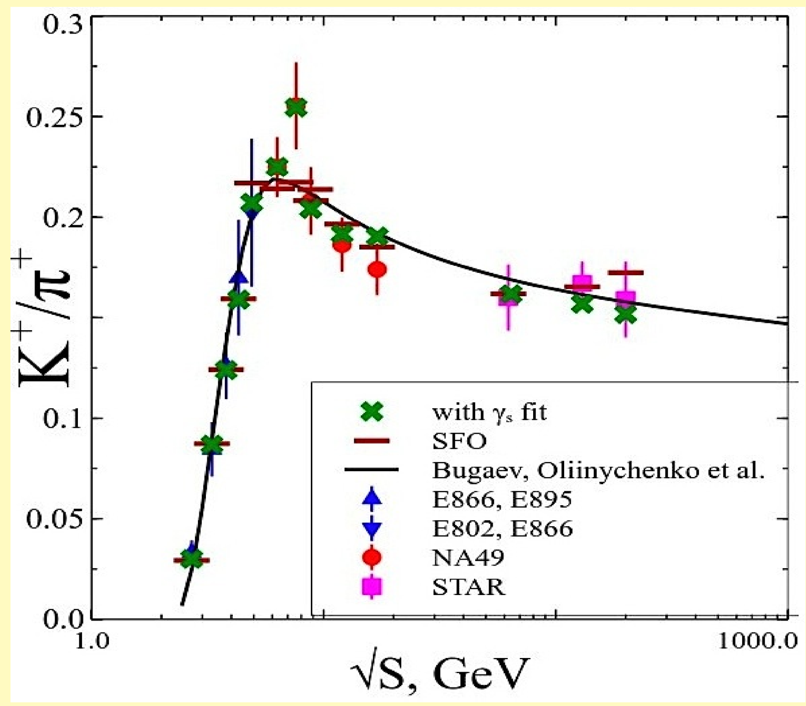


Fig.4. Description of K^+/π^+ ratio. Solid line is the result of [3]. Crosses stand for the case with γ_s fitted, while the horizontal bars correspond to SFO.

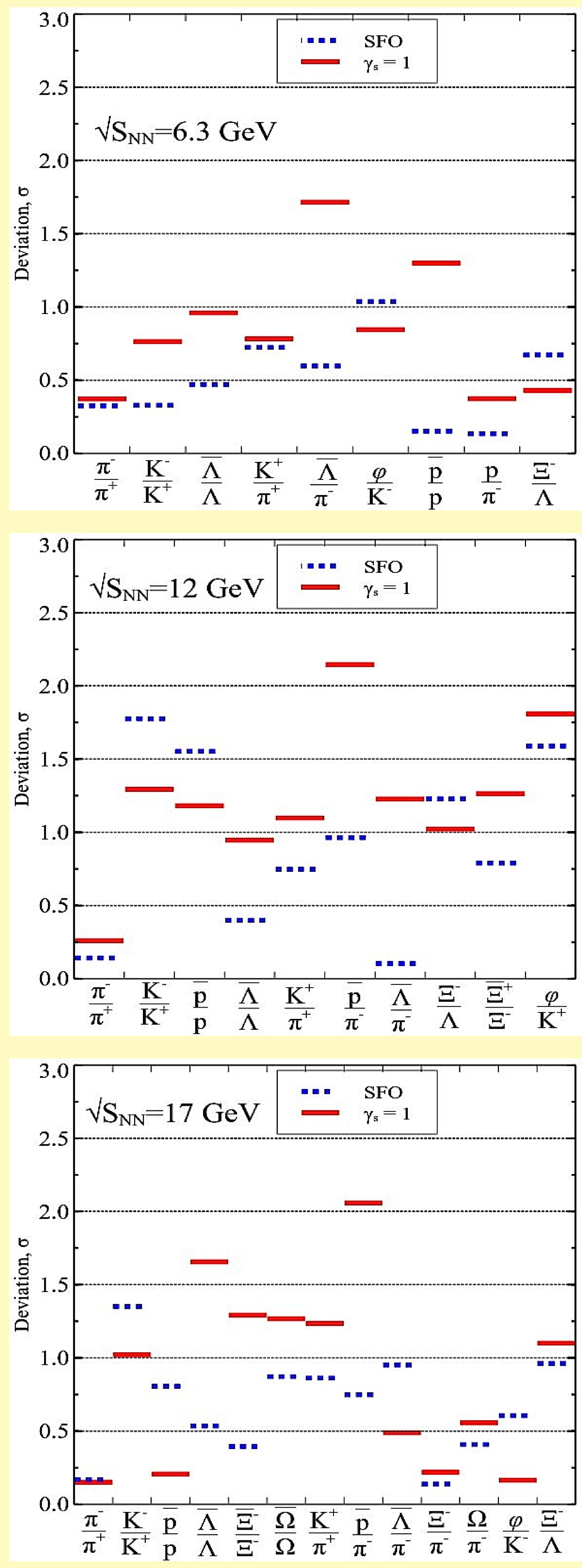


Fig.5. Same as in Fig. 2. Solid lines correspond to model without SFO and $\gamma_s = 1$, dashed lines correspond to model with SFO.

References

[1] Bugaev K. A. et al., EPL 104 22002 (2013).
[2] Andronic A., Braun-Munzinger P. and Stachel J., Nucl. Phys. A 772 167 (2006) and references therein.
[3] Bugaev K. A. et al., Eur. Phys. J. A 49 30–1-8 (2013) and references therein.
[4] Wheaton S., Cleymans J. and Hauer M., Comput. Phys. Commun. 180 84 (2009).
[5] Bugaev K. A. et al., arXiv:1312.5149 [hep-ph].
[6] Becattini F., Manninen J. and Gazdzicki M. Phys. Rev. C 673 044905 (2006).