Fluctuations of identified particle numbers in partial chemical equilibrium

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Motivation - why partial chemical equilibrium?

- Statistical production can be used to describe hadron abundances and also their spectra
- (Simple) statistical model of interacting hadrons: interactions via inclusion of (free) resonance states [R. Dashen, S.K. Ma, H.J. Bernstein, Phys. Rev. 187 (1969) 345]

Chemical freeze-out

- Hadron abundances set by three (four) parameters: V, T_{ch}, μ_B, (γ_s)
- $T \sim 140 - 160$ MeV ($\sqrt{s_{NN}}$ dependent, above 7.7 GeV)

Kinetic freeze-out

- Sets the p_T spectra
- need transverse expansion
- slope due to T_k and $\langle v_t \rangle$
- $T_k \sim 80 - 120$ MeV (also higher)

How to build a scenario with chemical and kinetic freeze-out?

- need to freeze the effective numbers of stable hadrons—projected numbers after decays of all resonances $N_h^{eff} = \sum_r p_{r\to h} \langle N_r \rangle$
- Assumption: at chemical freeze-out inelastic collisions stop and elastic continue

Evolution of chemical potentials

Keep the (effective stable) particle numbers constant, as a function of temperature!

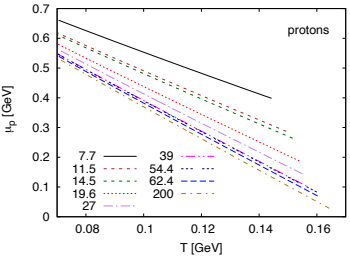
$$\langle N_h^{eff} \rangle = \sum_r p_{r\to h} V(T) n_r(T, \{\mu(T)\}), \qquad \frac{\mathrm{d}\langle N_h^{eff}\rangle}{\mathrm{d}T} = 0$$

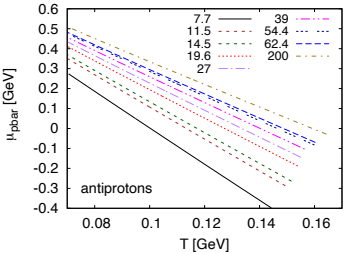
Entropy conservation: $0 = \mathrm{d}S/\mathrm{d}T = \mathrm{d}(sV)/\mathrm{d}T$
Equations for the evolution of chemical potentials

$$\frac{\sum_r p_{r\to h} \frac{\mathrm{d}n_r(T,\{\mu(T)\})}{\mathrm{d}T}}{\mathrm{d}s/\mathrm{d}T} = \frac{1}{s}\sum_r p_{r\to h} n_r(T, \{\mu(T)\})$$

Chemical potentials for resonances:

$$\mu_R = \sum_h p_{R\to h}\mu_h$$





[H. Bebie, P. Gerber, J.L. Goity, H. Leutwyler, Nucl. Phys. B 378 (1992) 95]

Net-proton number fluctuations from PCE

- cumulants of proton and antiproton number via $\left\langle (\Delta N)^l \right\rangle_c = \left. \frac{\mathrm{d}^l K(i\xi)}{\mathrm{d}(i\xi)^l} \right|_{\xi=0}$

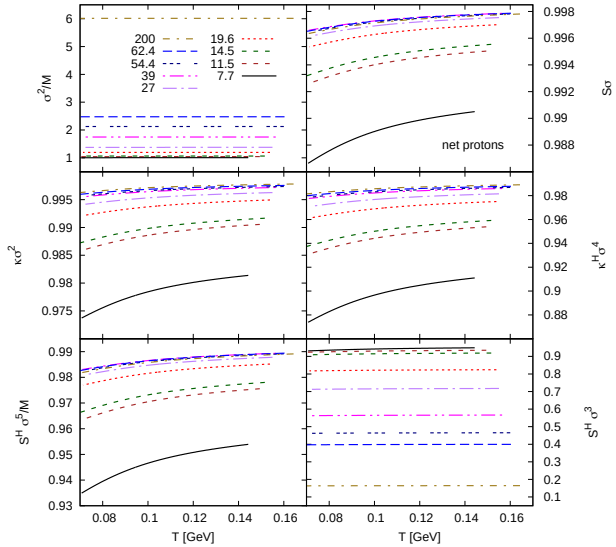
$$K(i\xi) = \ln \sum_{N=0}^{\infty} e^{i\xi N} P(N) = \sum_R \ln \left\{ \sum_{N_R=0}^{\infty} P_R(N_R) \left(e^{i\xi} p_R + (1-p_R) \right)^{N_R} \right\}$$

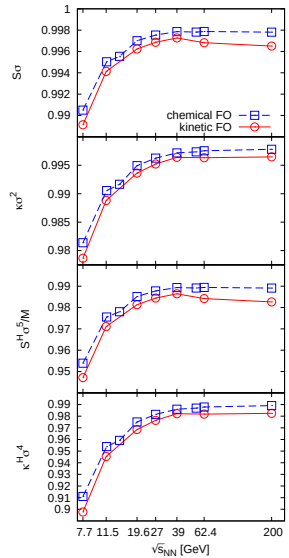
- $P_R(N_R)$: number probability of resonance R, furnished by statistical model
- Net-proton number cumulants obtained via $\left\langle (\Delta N_{p-\bar{p}})^l \right\rangle_c = \left\langle (\Delta N_p)^l \right\rangle_c + (-1)^l \left\langle (\Delta N_{\bar{p}})^l \right\rangle_c$
- Cumulants of the resonance number distributions

$$\left\langle (\Delta N_R)^l \right\rangle_c = \frac{g_R V}{2\pi^2} m_R^2 T \sum_{j=1}^{\infty} (\mp 1)^{j-1} j^{l-2} e^{j\mu_R/T} K_2 \left(\frac{j m_R}{T} \right) .$$

- first terms in the sums correspond to Boltzmann approximation (not BE or FD)
- In Boltzmann approximation, cumulants of all orders are the same!

Results for net-proton cumulants in PCE





Conclusions

- Partial Chemical Equilibrium
  - keeps effective numbers of stable species konstant independent of temperature
  - no reactions that would change one stable species into another (off equilibrium)
  - resonances in equilibrium with stable species
- Results from Partial Chemical Equilibrium on net-proton number fluctuations
  [B. Tomášik, P. Hillmann, M. Bleicher, Phys.Rev.C 104 (2021) 044907]
  - volume-independent ratios of cumulants of net-proton number are almost temperature independent $\Rightarrow$ they reflect values at chemical freeze-out
  - experimental data on cumulants at low energies are not reproduced
- Possible improvements to PCE
  - take into account entropy production
  - include hadron interactions via phase shifts