Collision energy dependence of the freeze-out parameters

Ivan Melo[a], Boris Tomášik[a,b]

[a] Žilinská univerzita, Žilina, Slovakia

[b] Univerzita Mateja Bela, Banská Bystrica, Slovakia

[c] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Czech Republic

boris.tomasik@umb.sk

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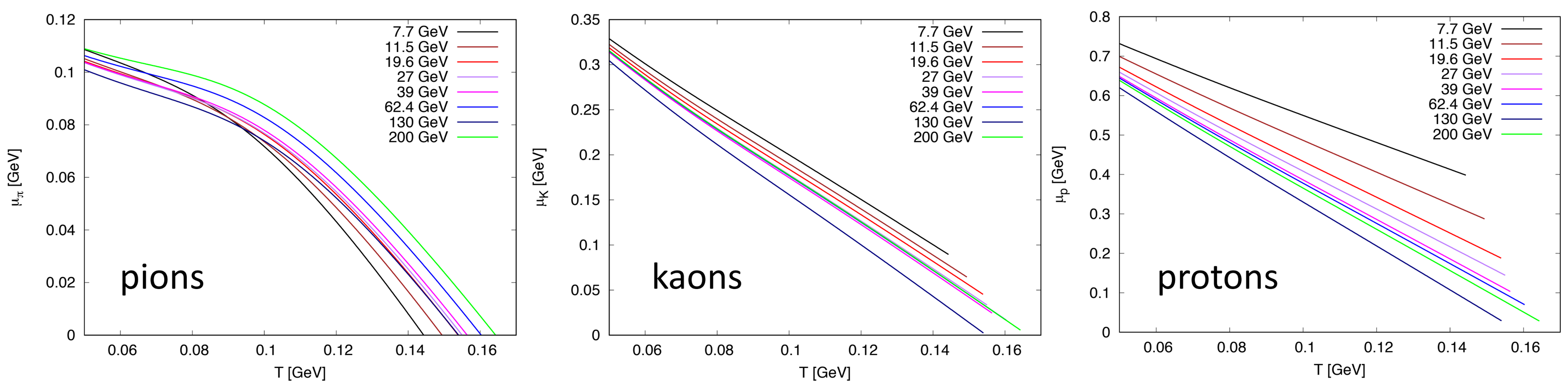
1. Partial chemical equilibrium

Transverse momentum spectra indicate kinetic freeze-out temperature lower than the chemical freeze-out temperature. The fireball in its hadronic phase cools down so that the final numbers of stable hadrons stay constant. For isentropic expansion this can be calculated via [1]

$$\frac{n_i(T)}{s(T)} = const$$

where $n_i(T)$ is the effective density of species i, and $s(T)$ the entropy density. The effective density includes also the stable particles which will be produced after all resonances in the system have decayed.

Below are the temperature dependences of the chemical potentials for pions, kaons, and protons, for different collision energies from the RHIC BES program and the LHC. They are evolved from the temperature of chemical freeze-out towards lower temperatures.



Theoretical spectra are generated with these chemical potentials.

2. The blast wave model

The features of the model are:

- Local thermal equilibrium with the temperature T, with Bose-Einstein or fermi-Dirac distribution
- Longitudinally boost-invariant expansion
- Transverse expansion with the velocity
  $$v_t(r) = \eta_f \left(\frac{r}{R}\right)^n \, , \qquad (1)$$
  where η_f is a model parameter, R is the radius of the fireball, and the power n is a model parameter
- Production includes also resonance decays. Resonances are produced according to the same blast-wave model.

In the fit we determine paramaters T, η_f, and n. We also calculate the mean transverse expansion velocity

$$\langle v_t \rangle = \frac{2}{n+2}\eta_f \qquad (2)$$

3. Results

We fitted transverse momentum spectra from collisions:

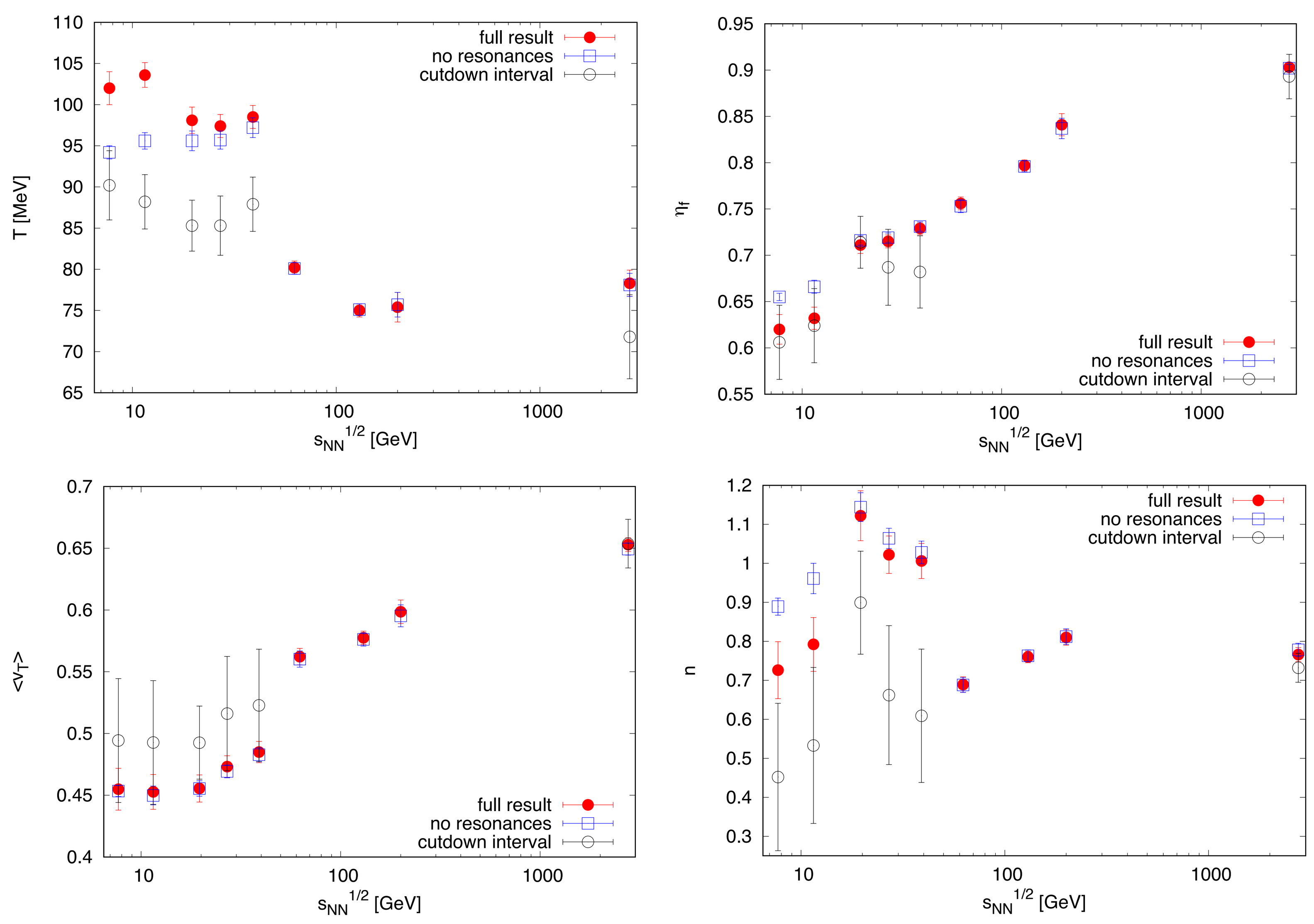
- Au+Au at $\sqrt{s_{NN}} = 7.7$, 11.5, 19.6, 27, and 39 GeV [2]
- Au+Au at $\sqrt{s_{NN}} = 62.4$, 130, 200 GeV [3]
- Pb+Pb at $\sqrt{s_{NN}} = 2760$ GeV [4]

Fits were done with the Bayesian technique with the help of the MADAI statistical package [5].

Below is the collision energy dependence of the freeze-out temperature, transverse flow gradient, and the exponent n. The mean transverse velocity is calculated from eq.(2).

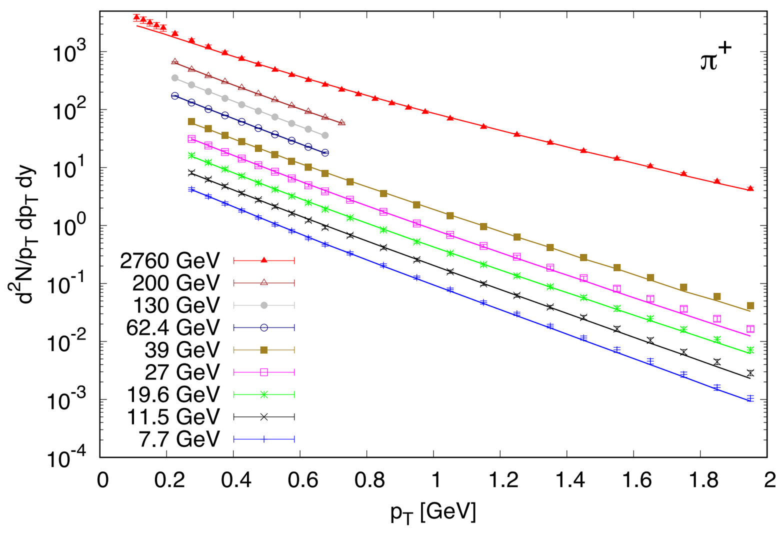
We show results for:

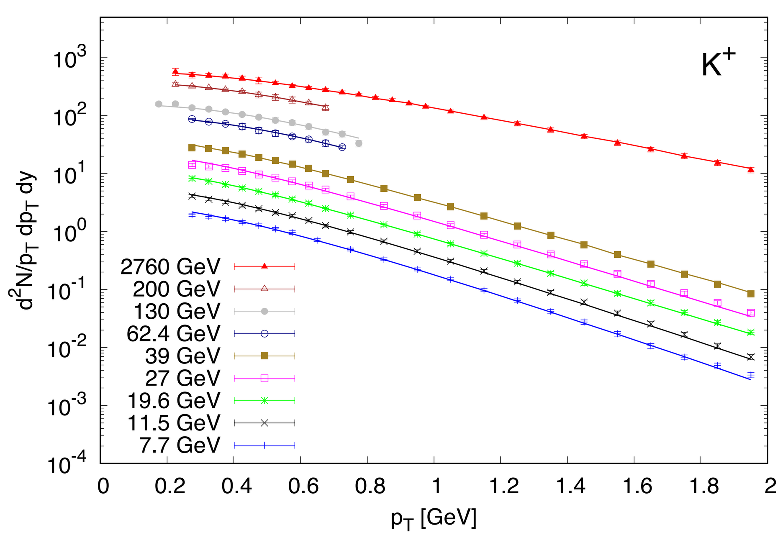
- Full fits with all resonances to the available range of p_T up to maximum 2 GeV
- Fits with no resonance production included
- Fits with imposed upper limit on p_T so that it matches data from [3] (see figures below)

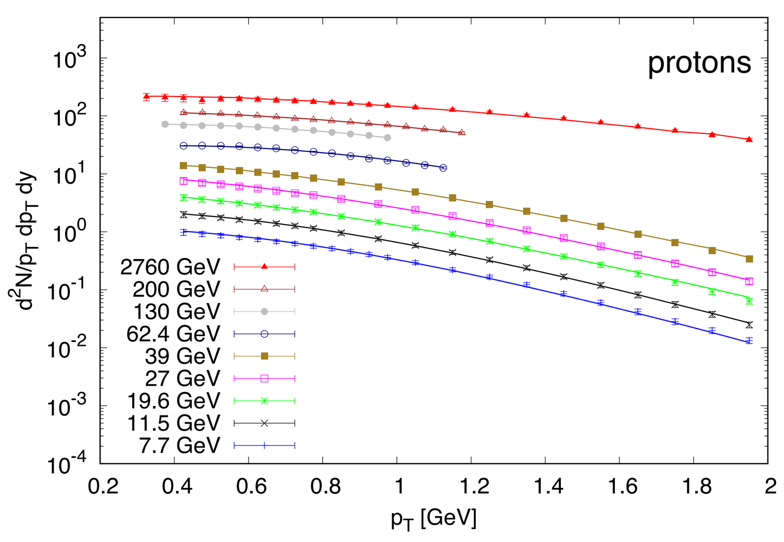


Examples of the fits to spectra

- At collision energies 62.4, 130, and 200 GeV data cover only limited p_T interval
- The first 6 p_T bins from ALICE are not included in fits
- Spectra are divided by subsequent factors of 2, for better visibility

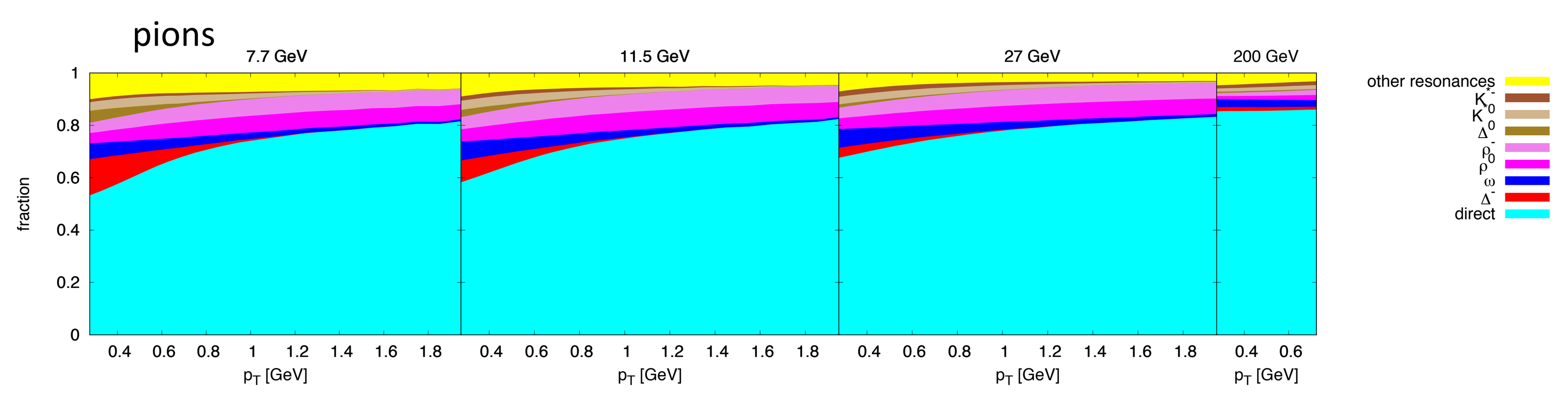


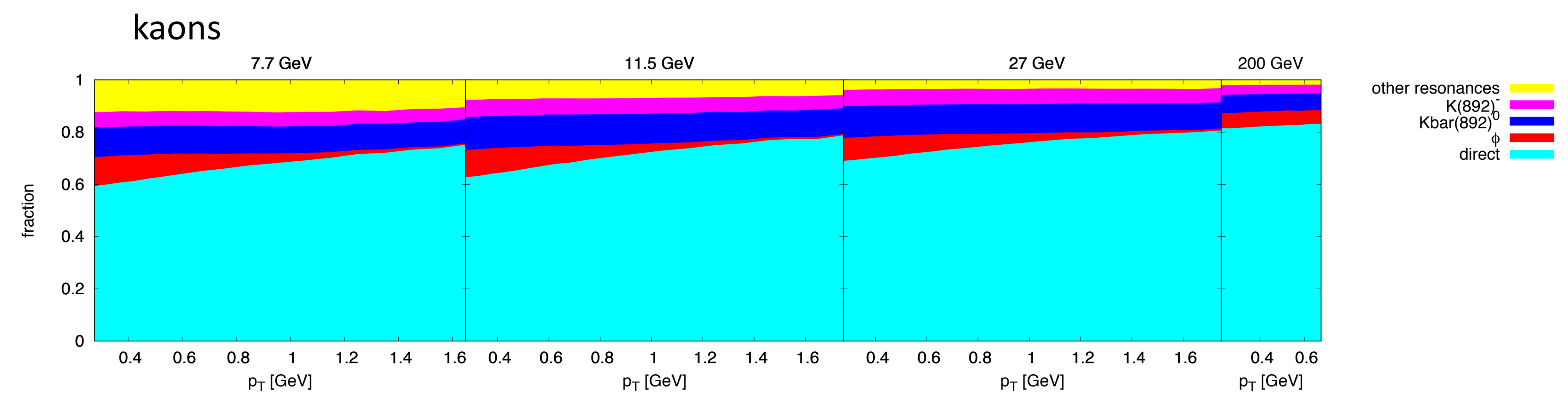


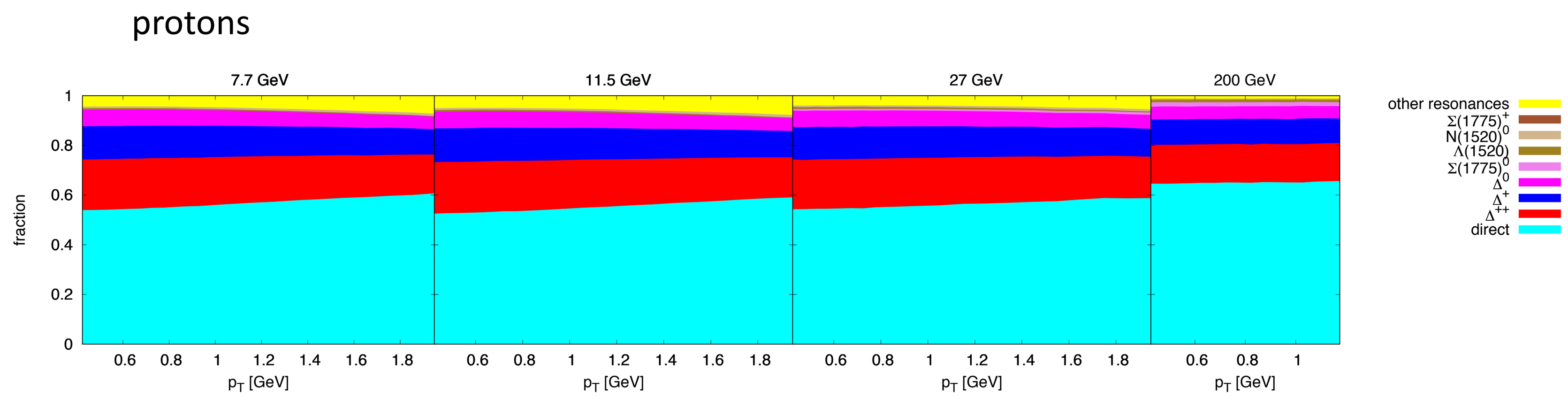


4. Anatomy of the spectra

Fit results seem to indicate weak dependence on whether resonance decays are accounted for or not. We show here the relative contributions to the transverse momentum spectra from direct thermal production and from most important resonance contributions.







At higher energies the p_T dependence of the composition is dominated by direct production, because thermal freeze-out happens at much lower temperature than the chemical freeze-out and particle number moves from resonances to direct production.

Mostly, the composition is rather flat. A dominance low p_T production happens in case of high mass resonances with decay channel with threshold just above the mass of the reonance.

5. Conclusions

- The kinetic freeze-out temperature steadily decreases as the collision energy is increased. The system at higher energy includes so much energy that it stays together longer until the final breakup.
- The kinetic freeze-out temperature is rather low, below ca 110 MeV, but even below 80 MeV at the highest collision energies.
- In partial chemical equilibrium resonance decays have little influence on the extracted parameters, because at low temperatures most particles are produced directly.
- The transverse flow increases with increasing collision energy

References

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