Transverse-momentum spectra of strange particles produced in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV in the chemical non-equilibrium model

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Strangeness in Quark Matter
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Statistical models of hadron production have become one of the cornerstones of our understaning of ultra relativistic heavy-ion collisions (and also of more elementary hadronic processes including e^+e^- annihilation)
(Becattini, Braun-Munzinger, Broniowski, Cleymans, Gaździcki, Gorenstein, Rafelski, Redlich, Satz, Stachel, Stock, ...)

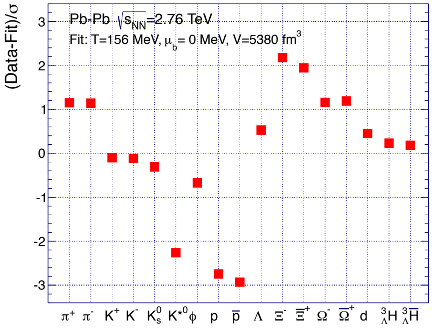
The data from the Large Hadron Collider (LHC) collected in Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV come as a big surprise: the measured proton abundances do not agree with the most common version of the thermal model based on the grand-canonical ensemble

Possible explanations:

- hadronic rescattering in the final stage
  (Becattini, Bleicher, Kollegger, Schuster, Steinheimer, Stock, PRL 111 (2013) 082302)
- hadronization and subsequent freeze-out taking place off chemical equilibrium
  (Petran, Rafelski, PRC 88 (2013) 021901; Petran, Letessier, Petracek, Rafelski, PRC 88 (2013) 034907)

Rusults of the thermal equilibrium model

(Stachel, Andronic, Braun-Munzinger, Redlich, J.Phys.Conf.Ser. 509 (2014) 012019)



Besides the proton anomaly, the same LHC data exhibits another interesting feature — the low-transverse-momentum pion spectra show enhancement by about 25%–50% with respect to the predictions of various thermal and hydrodynamic models

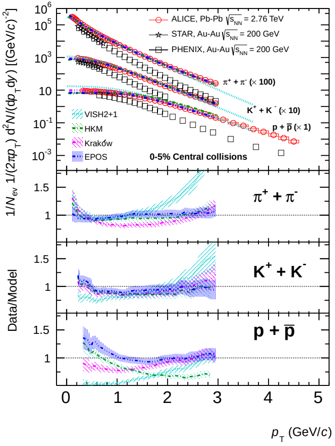
(ALICE papers compare experimental data to various hydro models, PRL 109 (2012) 252301, PRC 88 (2013) 044910)

Motivation 2

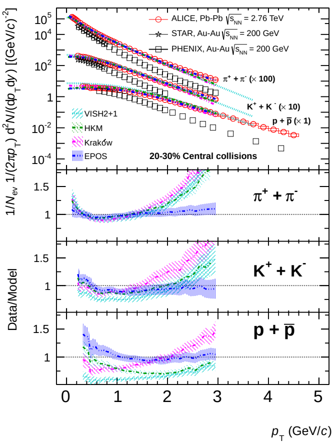
Problems of hydrodynamic models with the pion spectra

Theory vs. Hydro comparison (ALICE, PRC 88 (2013) 044910)

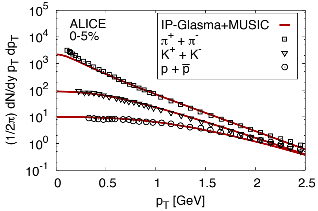
most central



semi central

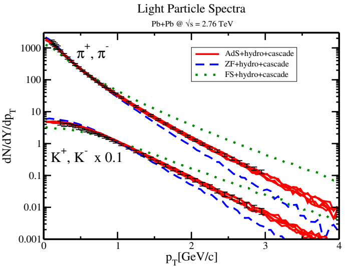


Gale, Jeon, Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 110 (2013) 012302



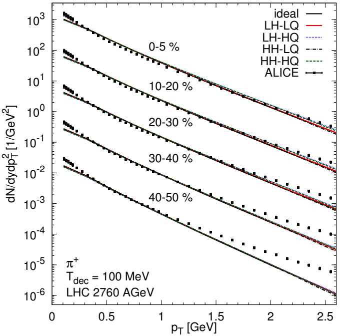
pion enhancement

W. van der Schee, P. Romatschke, S. Pratt, Phys.Rev.Lett. 111 (2013) 22, 222302



pions well described, protons?

P. Huovinen et al., arXiv:1407.8152
hydro with dynamical freeze-out



again pion enhancement

- Gluon condensate (Blaizot, Gelis, Liao, McLerran, Venugopalan, Nucl. Phys. A904-905 (2013) 829c Blaizot, Liao, McLerrran, Nucl. Phys. A920 (2013) 58, Blaizot, Lect. Notes Phys. 852 (2012) 1)
- Coherent pion production found in three-body correlations by ALICE (ALICE, Phys.Rev. C89 (2014) 024911)

Outline

In this talk I will argue that the two problems may be solved simultaneously within the chemical non-equilibrium model.

1. Cracow single-freeze out model
2. Non-equilibrium statistical model
3. Spectra of pions, kaons and protons
4. Spectra of other hadrons
5. Conclusions

Single-freeze out model (Broniowski, Florkowski, PRL 87 (2001) 272302)
Monte-Carlo implementations, THERMINATOR 1 & 2 (Kisiel, Taluc, Broniowski, Florkowski, Comput. Phys. Commun. 174 (2006) 669; Chojnacki, Kisiel, Florkowski, Broniowski, Comput. Phys. Commun. 183 (2012) 746)

The spectra are calculated from the Cooper-Frye formula

$$\frac{dN}{dyd^2p_T} = \int d\Sigma_\mu p^\mu f(p \cdot u)$$

The freeze-out hyper surface is defined by the conditions

$$t^2 = \tau_f^2 + x^2 + y^2 + z^2, \quad x^2 + y^2 \leq r_{\rm max}^2$$

The flow has the Hubble form

$$u^\mu = x^\mu / \tau_f$$

There are only two independent parameters in the model: the product $\pi \tau_f r_{\rm max}^2$ defines the volume (per unit rapidity), the ratio $r_{\rm max}/\tau_f$ determines the shape (slope) of the spectra

The phase-space distributions include all well established resonances from PDG, the primordial distributions in the local rest frame have the form

$$f_i = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\Upsilon_i^{-1} \exp(\sqrt{m^2 + p^2}/T) \pm 1}$$

Parameterization of the fugacity as in SHARE

(Torrieri, Steinke, Broniowski, Florkowski, Letessier, Rafelski, Comput. Phys. Commun. 167 (2005) 229)

$$\Upsilon_i = \left(\lambda_q \gamma_q\right)^{N^i_q} \left(\lambda_s \gamma_s\right)^{N^i_s} \left(\lambda_{\bar{q}} \gamma_{\bar{q}}\right)^{N^i_{\bar{q}}} \left(\lambda_{\bar{s}} \gamma_{\bar{s}}\right)^{N^i_{\bar{s}}}$$

$\lambda_q = \lambda_{\bar{q}}^{-1}, \lambda_s = \lambda_{\bar{s}}^{-1}, \gamma_q = \gamma_{\bar{q}}, \gamma_s = \gamma_{\bar{s}}$

N^i_q and N^i_s are the numbers of light (u, d) and strange (s) quarks in the ith hadron, while $N^i_{\bar{q}}$ and $N^i_{\bar{s}}$ are the numbers of the antiquarks in the same hadron

using the Gell-Mann–Nishijima formulas one finds

$\lambda_q = \exp(\mu_B/3T)$ and $\lambda_s = \exp((-3\mu_S + \mu_B)/3T)$, which gives

$$\Upsilon_i = \gamma_q^{N^i_q + N^i_{\bar{q}}} \gamma_s^{N^i_s + N^i_{\bar{s}}} \exp\left(\frac{\mu_B B_i + \mu_S S_i}{T}\right)$$

At the LHC, in the central rapidity region the baryon number density and strangeness are negligible, $\mu_B \approx \mu_S \approx 0$

$$\Upsilon_i \approx \gamma_q^{N_q^i + N_{\bar{q}}^i} \gamma_s^{N_s^i + N_{\bar{s}}^i}$$

The parameters γ_q and γ_s are equivalent to the chemical potentials $\mu_q/T = \ln \gamma_q$ and $\mu_s/T = \ln \gamma_s$

$$\Upsilon_i \approx = \exp\left(\frac{\mu_q \left(N_q^i + N_{\bar{q}}^i\right) + \mu_s \left(N_s^i + N_{\bar{s}}^i\right)}{T} \right)$$

The new potentials are connected with the conservation of the SUM of the number of quarks and antiquarks during the hadronization process, similarly as μ_B and μ_S are connected with the conservation of the DIFFERENCE of the quark and antiquark numbers. Rafelski: This must be so, since the entropy is conserved during the hadronization process (the entropy is a measure of the sum of the quarks and antiquarks). This argument is convincing if the hadronization process is fast and there is no significant volume expansion

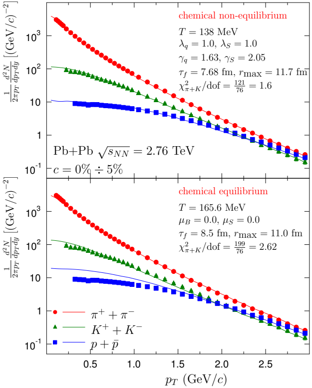
There is an upper bound on γ_q and γ_s because of Bose-Einstein condensation, the singularities may appear in the Bose-Einstein distributions of primordial pions and kaons.

For pions, the value of γ_s is irrelevant, and

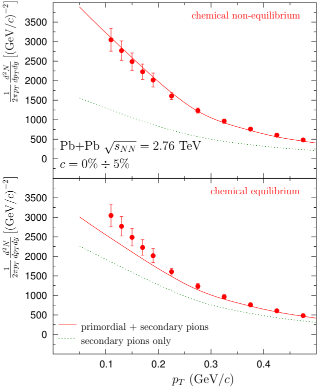
$$\gamma_q^{\rm critic} = \exp\left(\frac{m_{\pi^0}}{2T}\right)$$

Interestingly, the fits to the ratios of hadron abundances yield γ_q which is very close to the critical value.

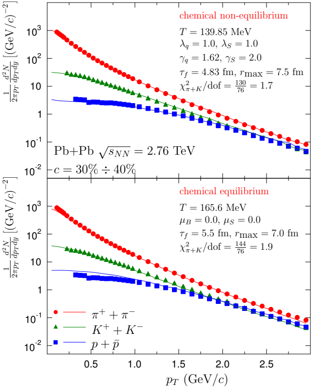
most central events



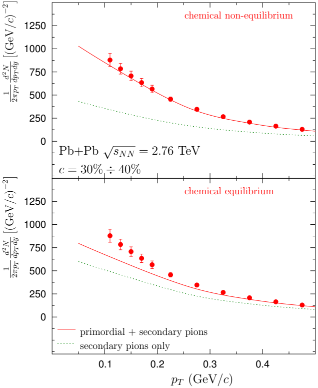
linear scale



semi central events

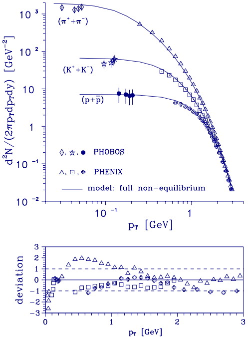


linear scale

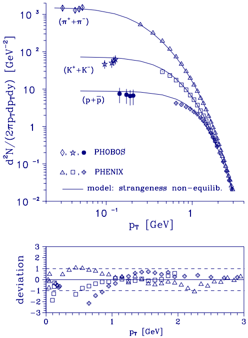


Dariusz Prorok, Phys.Rev. C75 (2007) 014903, the same approach but applied for RHIC

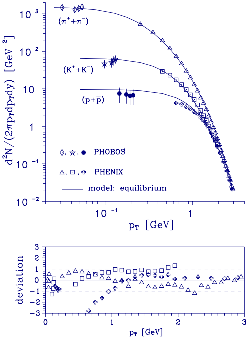
chemical non-equilibrium



strangeness non-equilibrium



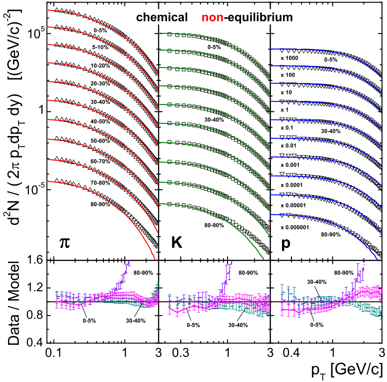
chemical equilibrium



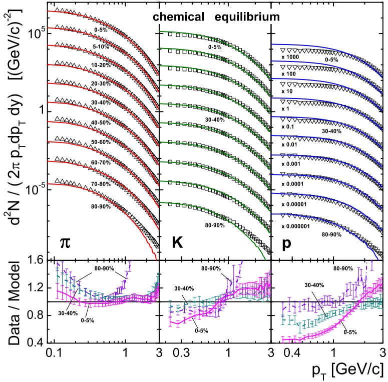
situation opposite to that at the LHC!

Complete set of pion, kaon, and proton spectra for different centralities

Chemical non-equilibrium

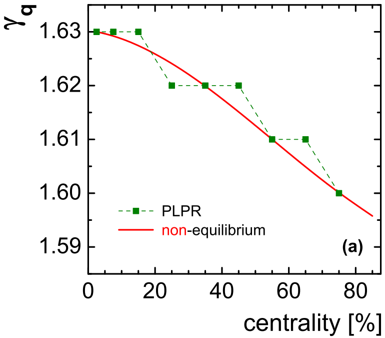


Chemical equilibrium

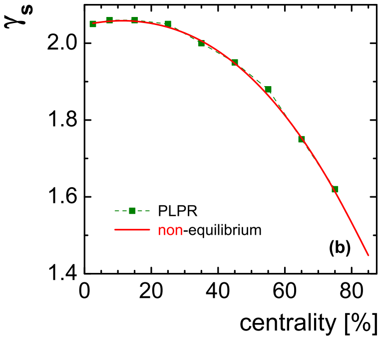


Centrality dependence of γ's inferred from the fit to the pion, kaon and proton spectra

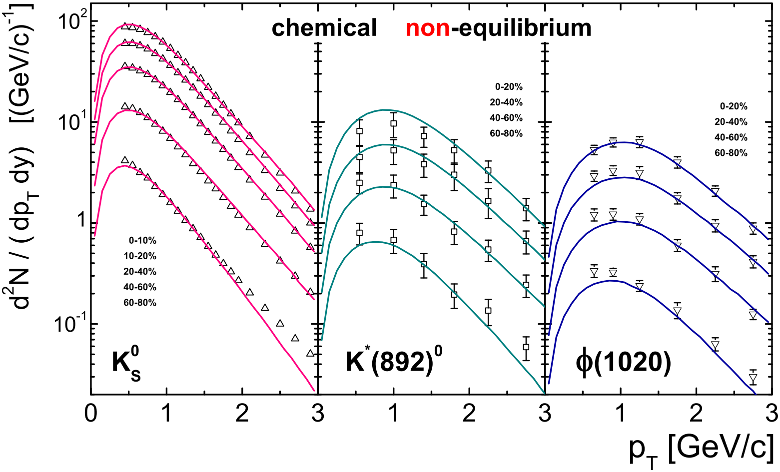
γ_q



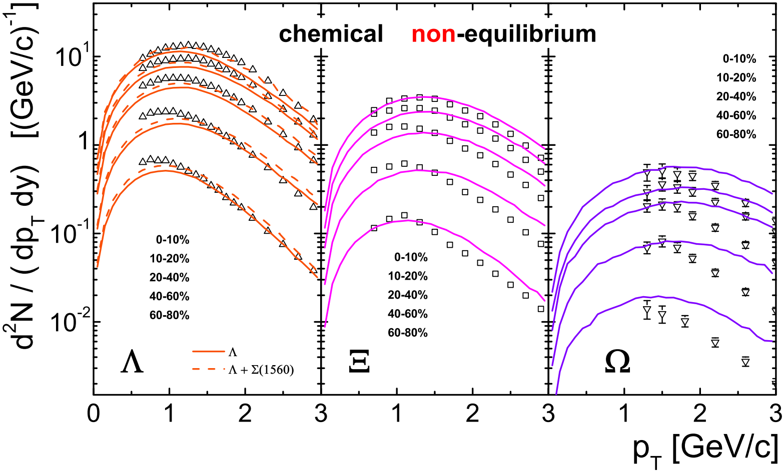
γ_s



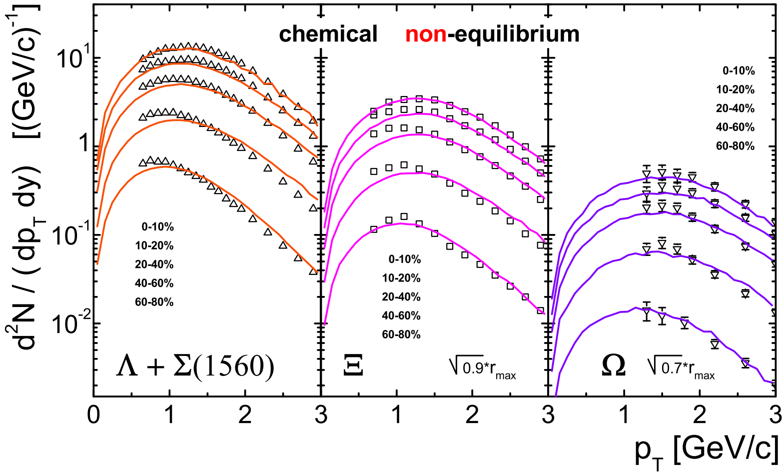
Predictions for other hadrons



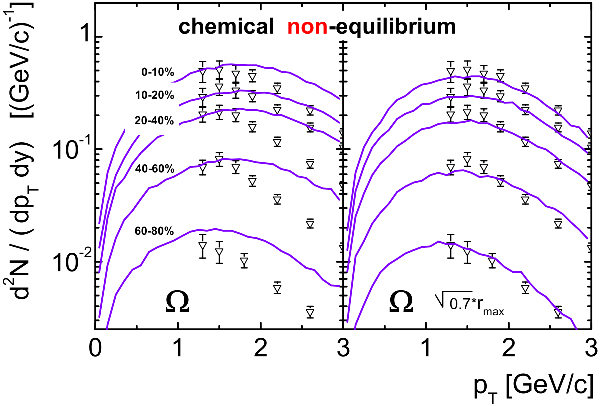
Predictions for other hadrons – hyperons



Predictions for other hadrons – hyperons
Ξ's and Ω's emitted from a smaller volume



Predictions for other hadrons – hyperons
Ω's emitted from a smaller volume



- The non-equilibrium thermal model combined with the single-freeze-out scenario explains very well the spectra of pions, kaons, and protons.
- It eliminates the proton anomaly and explains the low-p_T enhancement of pions.
- This enhancement may be interpreted as a signature of the onset of pion condensation in heavy-ion collisions at the LHC energies.
- It would be interesting to measure the pion spectrum at smaller values of p_T than those available at the moment.