

The onset of pion condensation in heavy-ion collisions at the LHC energies

Viktor Begun

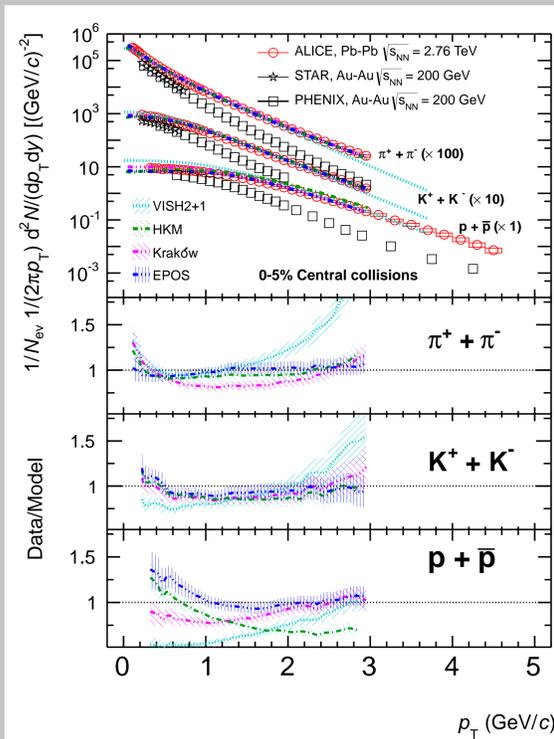
Jan Kochanowski University, Kielce, Poland & Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine



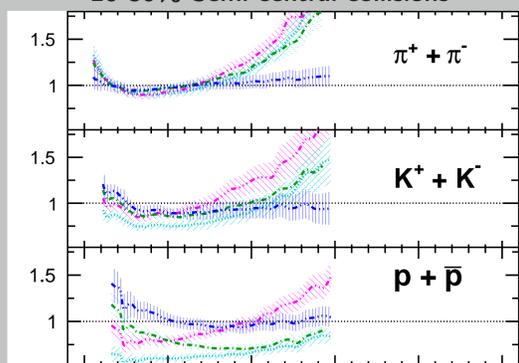
Motivation

- Statistical models of hadron production became a **cornerstone** of our understanding of heavy-ion collisions
- The measured **proton** abundances at sqrt(S) 2.76 TeV at LHC do **not agree** with the statistical models [1]
- The **low p_T pion spectra** show **enhancement** by about 25-50% with respect to the predictions of various models [1]

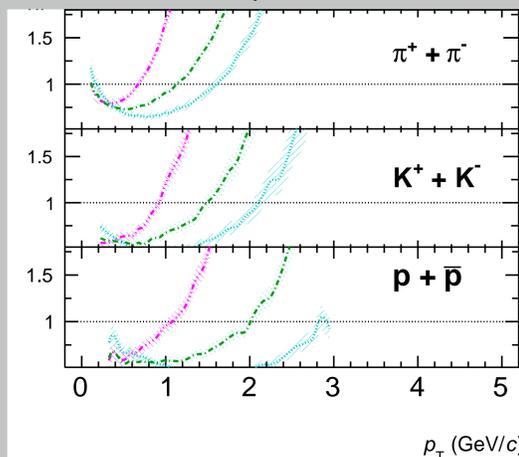
LHC data [ALICE] [1]:



20-30% Semi-central collisions



70-80% Peripheral collisions



The Cracow Model:

- Transverse-momentum distributions are calculated from the Cooper-Frye formula: $\frac{dN}{dyd^2p_T} = \int d\Sigma_\mu p^\mu f(\mathbf{p} \cdot \mathbf{u})$, where $d\Sigma_\mu$ is an element of the freeze-out hypersurface and
- \mathbf{u}^μ is the hydrodynamic Hubble-like flow at freeze-out: $\mathbf{u}^\mu = \mathbf{x}^\mu / \tau_f = (\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z}) / \tau_f$.
- The **primordial** distribution of the i -th hadron in the local rest frame has the form [2]:

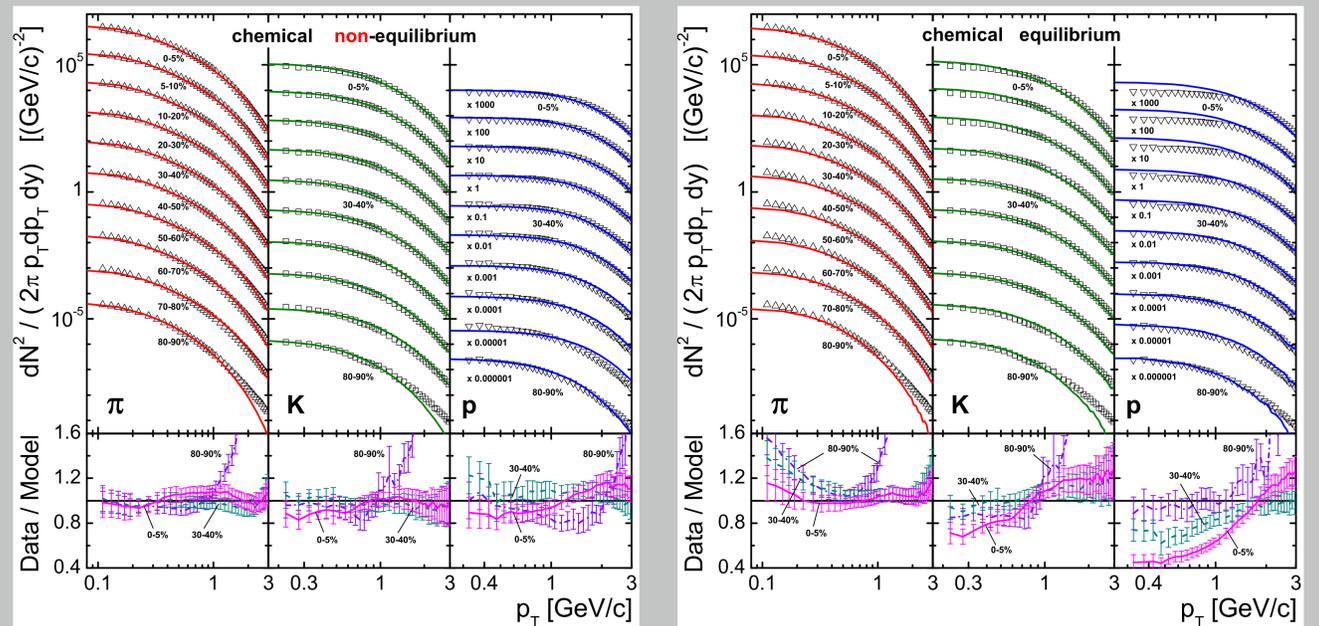
$$f_i = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\tau_i^{-1} \exp(\sqrt{p^2 + m_i^2}/T) \mp 1}, \quad \text{where} \quad \tau_i = \gamma_q^{N_q^i + N_{\bar{q}}^i} \gamma_s^{N_s^i + N_{\bar{s}}^i}.$$

Here g_i is the spin degeneracy factor, m_i – the mass of the particle, T – the system temperature, the $-1(+1)$ sign corresponds to bosons (fermions). We neglect small chemical potentials at the LHC.

- **Resonance decays** are handled by the THERMINATOR Monte-Carlo event generator [3].
- The N_j^i are the numbers of **light (u, d)** and **strange (s)** quarks and anti-quarks in the i -th hadron. The γ_q and γ_s parameters account for deviations from chemical equilibrium. We compare two cases: the **non-equilibrium**, $\gamma_j \neq 1$, and equilibrium, $\gamma_j = 1$, [2].
- Besides the thermodynamic parameters T , γ_q , γ_s and volume dV/dy that control the average multiplicities of particles [4] we have **only one additional parameter** to describe the spectra – maximal transverse radius over the invariant freeze-out time, r_{\max}/τ_f .

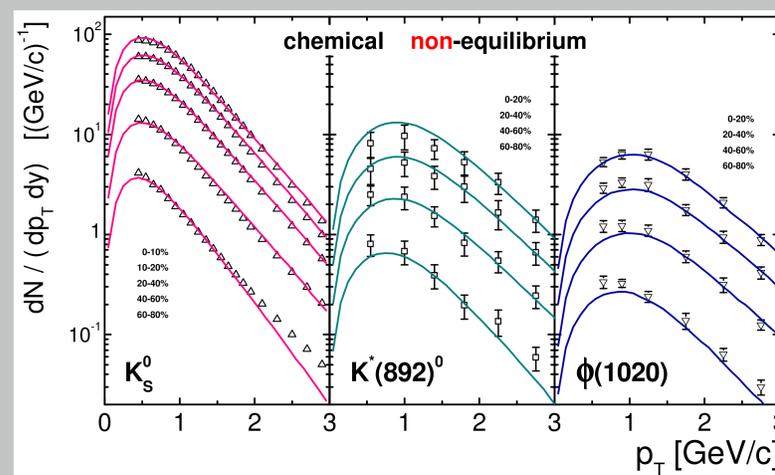
Pions, Kaons and Protons in Cracow model

We fit the **pion** and **kaon** spectra with only one parameter r_{\max}/τ_f and find a **remarkable agreement** with data

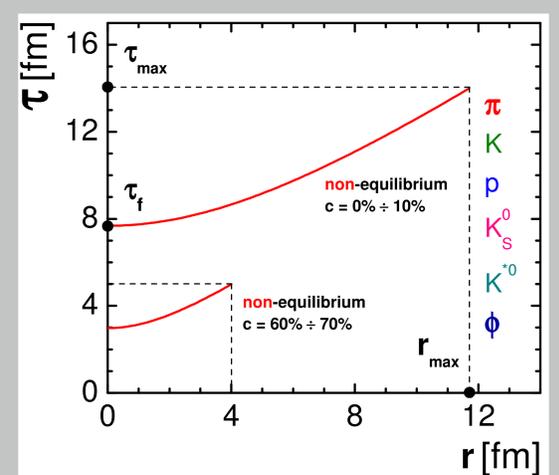


Protons are **not included** in the fit, however our **model explains** well their **spectrum**. The simultaneous description of the low p_T spectrum of pions and kaons (protons) is possible **only in non-equilibrium**.

Strange particles



Freeze-out Hypersurface



Using exactly the **same parameters**, we have obtained an **excellent description** of K_S^0 , K^{*0} , and ϕ . These particles have different lifetimes, masses and quark contents. Therefore their simultaneous description confirms the validity of the **single-freeze-out** concept of the Cracow model. According to it the **freeze-out for all particles** starts in the center of the fireball and spreads out along the **hyperbola** $\tau(r) = \sqrt{\tau_f^2 + r^2}$.

References:

- [1] B. Abelev *et al.*, PRC **88** (2013).
- [2] V. Begun, W. Florkowski and M. Rybczynski, arXiv:1312.1487.
- [3] M. Chojnacki *et al.*, Comput. Phys. Commun. **183** (2012).
- [4] M. Petran *et al.*, PRC **88** (2013).
- [5] B. B. Abelev *et al.*, arXiv:1404.0495.

Conclusions:

- We **connect** the **proton anomaly** with the **pion enhancement** effect and show that the two problems may be **solved** naturally within the **non-equilibrium Cracow single-freeze-out** model
- The obtained values of the non-equilibrium parameter γ_q are close to the **pion condensation limit** $(\gamma_q^{\text{cond}})^2 = e^{m_\pi/T}$. It may be interpreted as a signature of the onset of pion condensation in ultra-relativistic heavy-ion collisions at LHC