Soft pion production signals of new phenomena at the LHC
Viktor Begun  Jan Kochanowski University, Kielce, Poland

Motivation:
- The LHC data on hadron production, transverse-momentum spectra, and particle correlations in Pb+Pb collisions indicate a possibility of a coherent emission of pions with low momenta [1, 2, 3, 4].
- It can be a consequence of the gluon condensation [5, 6], or the cooling of the quark- gluon plasma into the hadronic phase [7].
- In both cases a possible consequence is the formation of the Bose-Einstein condensate (BEC) of pions at the freeze-out.
- If this is the case, then its density is higher, volume is smaller, the interaction forces are different, and the temperature exceeds the one in the BEC of atoms by $10^{12}$.

LHC Data [ALICE] [1]:

The Cracow Model:
- The primordial distribution of the $i$-th hadron in the local rest frame has the form [3]:
  \[ f_i = \frac{1}{(2\pi)^3 \sqrt{T_i}} \exp\left(-\frac{1}{T_i} \frac{p^2 + m_i^2}{T_i} \right), \]
  where $T_i = T \gamma_i N_{\text{light}} + N_{\text{strange}}$.
- Here $g_i$ is the spin degeneracy factor, $m_i$ is the mass of the particle, $T$ is the system temperature, the $-1(1)$ sign corresponds to bosons (fermions). We neglect the small chemical potentials at the LHC.
- Resonance decays are handled by the THERMINATOR Monte-Carlo event generator.
- The $N_j$ are the numbers of light ($u$, $d$) and strange ($s$) quarks and anti-quarks in the $i$-th hadron. The $\gamma_\text{non}$ and $\gamma_\text{equ}$ parameters account for deviations from chemical equilibrium. We compare two cases: the non-equilibrium, $\gamma_\text{non} = 1$, and equilibrium, $\gamma_\text{equ} = 1$, [3].
- Besides the thermodynamic parameters $T$, $\gamma_\text{non}$, $\gamma_\text{equ}$ and volume $dV/\,dt$ that control the average multiplicities of particles we have only one additional parameter to describe the spectra – maximal transverse radius over the invariant freeze-out time, $r_{\text{max}}/T$.

Protons and Pions in the Cracow Model with Pion Condensate [3, 4]:
- We fit the pion and kaon spectra and find a remarkable agreement with data.

\[ \frac{dN}{dp_T} \propto \frac{1}{p_T} \left( \frac{p_T}{T} \right)^3 \exp\left(-\frac{m}{T} \right), \]
- The solid lines are for the non-equilibrium with Bose condensate, while the dashed lines are for the equilibrium without the condensate. 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, kaons and protons is possible only in the non-equilibrium. Using exactly the same one parameter for all particles, we have obtained an excellent description of the spectra for $\pi^\pm$, $K^\pm$, $K^0$, $K^{*0}$, and $\phi$ [3, 4].

Charged Pions at low $p_T$ and the Condensate Rate [6]:
- The gray bands indicate the 10% deviation of the $\chi^2/N_{\text{df}}$ from the best fit of the mean multiplicities for all measured particles. The step at the low $p_T$ appears because of the assumption that all condensed particles are accumulated on the ground state $p_T = 0$ in the local rest frame of the fluid. At the detector the condensed particles have the momentum $p_T < p_T^{\text{max}}$ because of the flow at the freeze-out.
- The attempt to explain the low $p_T$ enhancement of pions by the proper treatment of the $\sigma$ meson, $f_0(500)$, leads to the conclusion that the $\sigma$ should not be included in thermal models at all, see [8], and the poster by F. Giacosa.

Conclusions:
- The combined analysis of the hadronic multiplicities and the pion transverse momentum spectra indicates that about 5% of pions at each centrality of the collision could be in the condensate at the LHC [4].
- Perhaps it is worth clarifying this interesting issue [7].

References:

The Cracow Model:
- Transverse-momentum distributions are calculated from the Cooper-Frye formula:
  \[ \frac{dN}{dp_T} = \int d\Sigma_{p_T} f(p, \omega), \]
- where $d\Sigma_{p_T}$ is an element of the freeze-out hypersurface and
- $u^\mu$ is the hydrodynamic Hubble-like flow at freeze-out: $u^\mu = x^\mu/\tau = (t, x, y, z)/\tau$. 

The grid bands indicate the 10% deviation of the $\chi^2/N_{\text{df}}$ from the best fit of the mean multiplicities for all measured particles. The step at the low $p_T$ appears because of the assumption that all condensed particles are accumulated on the ground state $p_T = 0$ in the local rest frame of the fluid. At the detector the condensed particles have the momentum $p_T < p_T^{\text{max}}$ because of the flow at the freeze-out. The attempt to explain the low $p_T$ enhancement of pions by the proper treatment of the $\sigma$ meson, $f_0(500)$, leads to the conclusion that the $\sigma$ should not be included in thermal models at all, see [8], and the poster by F. Giacosa.

Conclusions:
- The combined analysis of the hadronic multiplicities and the pion transverse momentum spectra indicates that about 5% of pions at each centrality of the collision could be in the condensate at the LHC [4].
- Perhaps it is worth clarifying this interesting issue [7].

References: