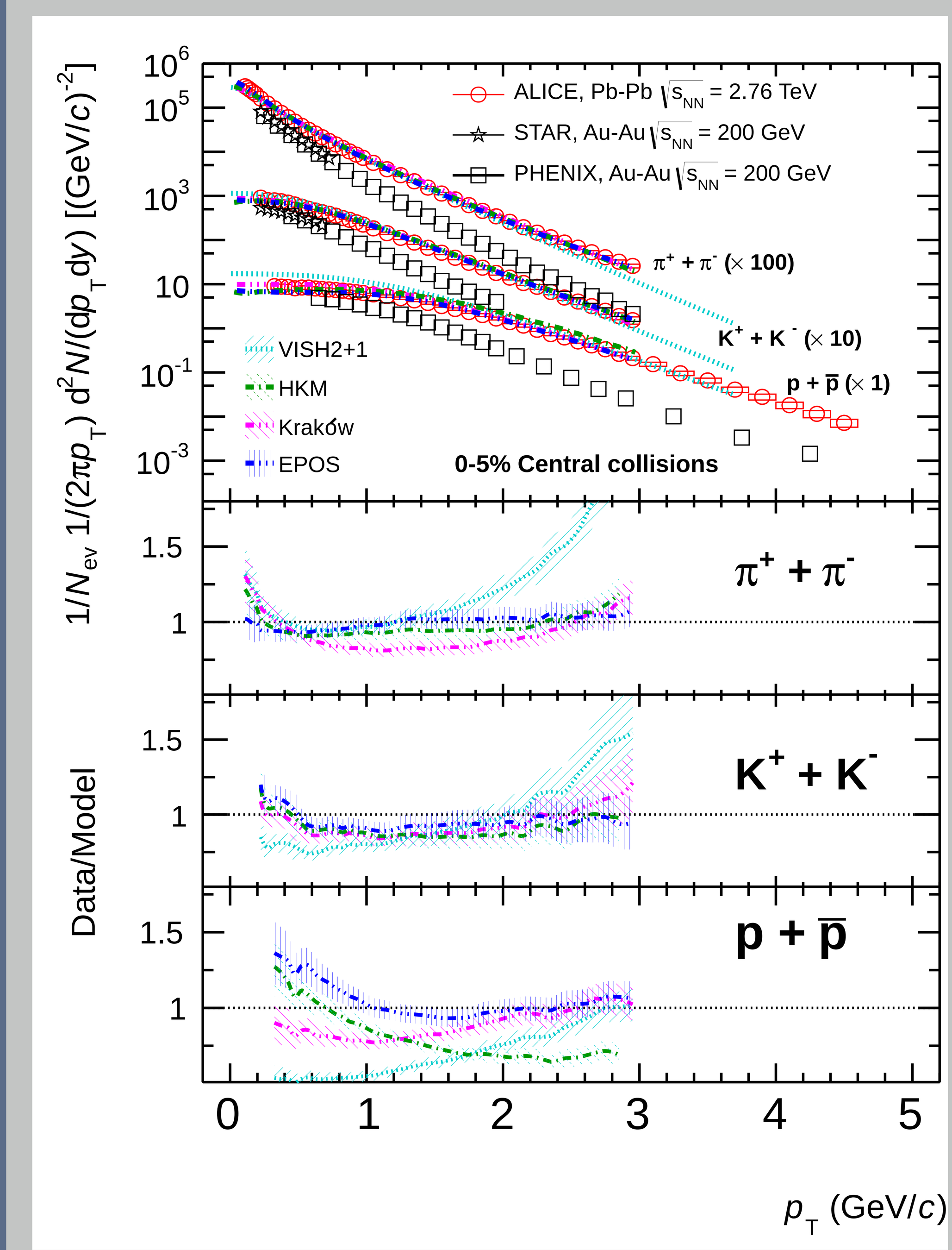
Soft pion production signals of new phenomena at the LHC

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 overcooling 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 $\mathbf{10^{12}}$.

LHC Data [ALICE] [1]:



References:

[1] B. Abelev *et al.* [ALICE Collaboration], Phys. Rev. C **88**, 044910 (2013)

[2] B. B. Abelev *et al.* [ALICE Collaboration], Phys. Rev. C **89**, 024911 (2014)

[3] V. Begun, W. Florkowski and M. Rybczynski, Phys. Rev. C **90**, 014906 (2014); Phys. Rev. C **90**, 054912 (2014)

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[5] J. P. Blaizot, F. Gelis, J. F. Liao, L. McLerran and R. Venugopalan, Nucl. Phys. A **873**, 68 (2012)

[6] F. Gelis, Nucl. Phys. A **931**, 73 (2014)

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[8] W. Broniowski, F. Giacosa and V. Begun, Phys. Rev. C **92**, 034905 (2015)

The Cracow Model:

- Transverse-momentum distributions are calculated from the Cooper-Frye formula: $\frac{dN}{dyd^2p_T} = \int d\Sigma_\mu p^\mu f(p\cdot u)$, where $d\Sigma_\mu$ is an element of the freeze-out **hypersurface** and
- u^μ is the hydrodynamic Hubble-like **flow** at freeze-out: $u^\mu = x^\mu/\tau_f = (t,x,y,z)/\tau_f$.

The Cracow Model:

- The primordial distribution of the i-th hadron in the local rest frame has the form [3]:

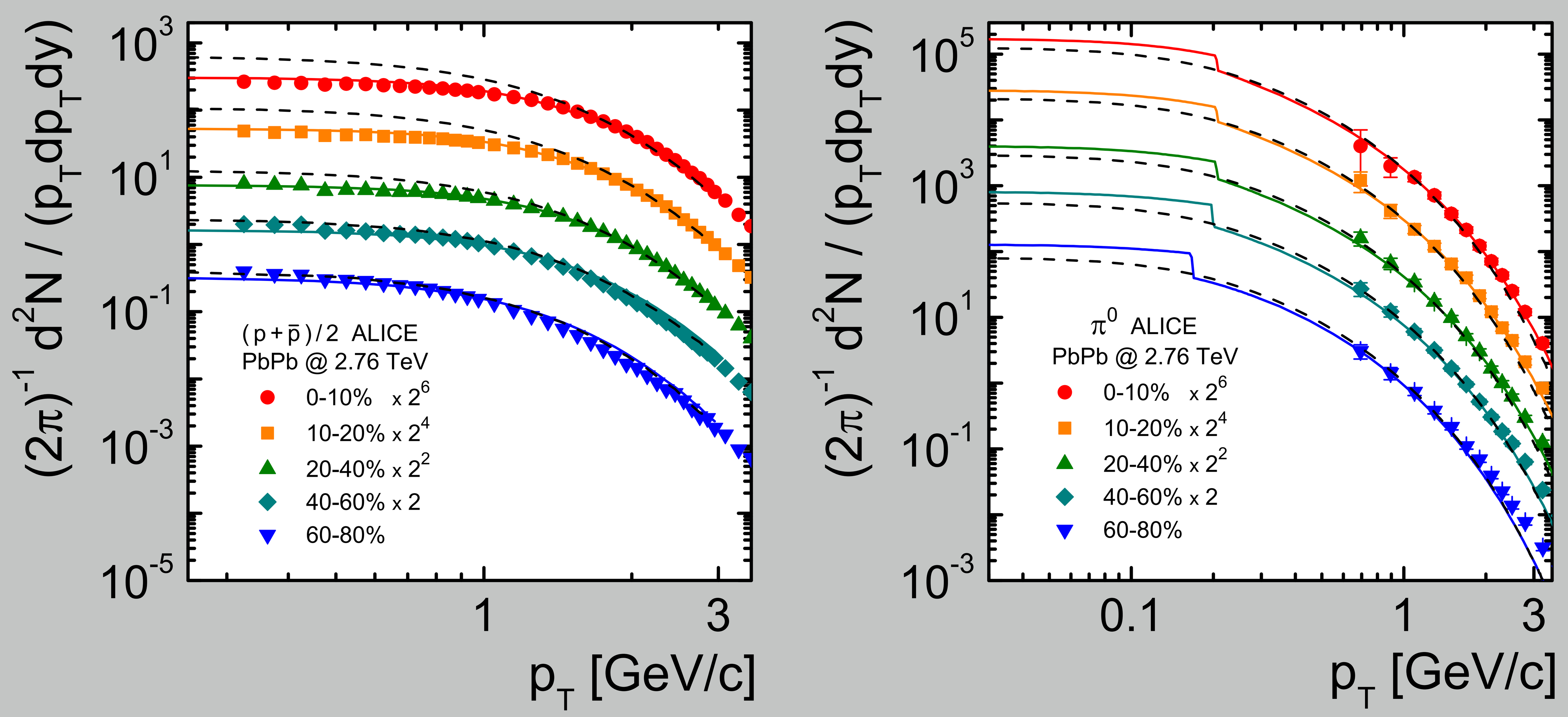
$$f_i = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\Upsilon_i^{-1} \exp\left(\sqrt{p^2+m_i^2}/T\right) \mp 1}, \quad \text{where} \quad \Upsilon_i = \gamma_q^{N_q^i+N_{\bar{q}}^i} \gamma_s^{N_s^i+N_{\bar{s}}^i}.$$

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 the small chemical potentials at the LHC.

- Resonance decays are handled by the THERMINATOR Monte-Carlo event generator.
- 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, $\gamma_j = 1$, [3].
- Besides the thermodynamic parameters T, γ_q, γ_s and volume dV/dy 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, $r_{\max}/\tau_f$.

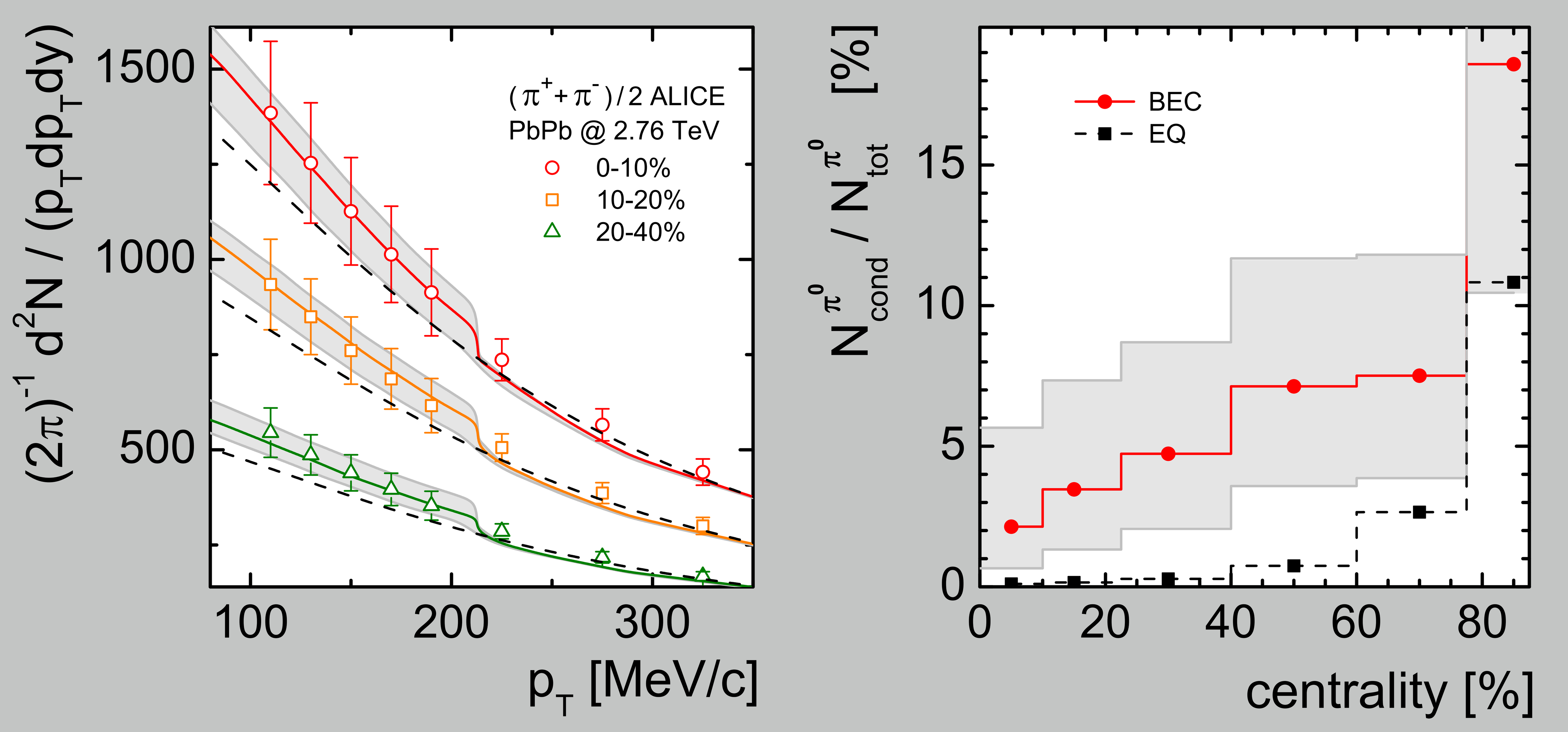
Protons and Pions in the Cracow Model with Pion Condensate [3, 4]

We fit the pion and kaon spectra and find a remarkable agreement with data.



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 π^0, $\pi^\pm$, K, p, K_S^0, K^{*0}, and ϕ [3, 4].

Charged Pions at low p_T and the Condensate Rate [4]



The gray bands indicate the 10**%** deviation of the χ^2/N_{dof} 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 $p_0 = 0$ in the local rest frame of the fluid. At the detector the condensate particles have the momentum $p_T < p_T^{max} = m_\pi\, r_{max}/\tau_f$ 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 σ meson, $f_0(500)$, leads to the conclusion that the σ **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].

 viktor.begun@gmail.com