Resonances in a sudden chemical freeze-out model

Viktor Begun

Warsaw University of Technology, Faculty of Physics, Warsaw, Poland

continuation of the work done in collaboration with
Wojciech Florkowski and **Maciej Rybczynski**, see

arXiv: 1503.04040 (PRC 2015), 1405.7252 (PRC 2014), 1312.1487 (PRC 2014)

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The phase-space distribution of the primordial particles in the local rest frame:

$$f(p) = \frac{g_i}{\gamma_i^{-1}\exp(\sqrt{p^2+m_i^2}/T)\pm 1}, \quad \text{where} \quad \gamma_i = \gamma_q^{N_q^i+N_{\bar{q}}^i}\gamma_s^{N_s^i+N_{\bar{s}}^i}\exp\left(\frac{\mu_B B_i+\mu_S S_i}{T}\right),$$

where γ_q and γ_s are the **non-equilibrium** parameters, and N_q^i, N_s^i are the **numbers of** light (**u**, **d**) and strange (**s**) **quarks** in the i-th hadron, see SHARE model (Petran, Letessier, Rafelski, Torrieri, Comput. Phys. Commun. (2014)). It includes all well established resonances from PDG.

Single-freeze out model (Broniowski, Florkowski, PRL (2001)) is implemented in Monte-Carlo event generator THERMINATOR (Chojnacki, Kisiel, Florkowski, Broniowski, Comput. Phys. Commun. (2012))

The spectra are calculated from the Cooper-Frye formula at the freeze-out **hyper surface**

$$\frac{dN}{dy\,d^2p_T} = \int d\Sigma_\mu p^\mu f(p\cdot u), \qquad t^2 = \tau_f^2 + x^2 + y^2 + z^2, \qquad x^2+y^2 \le r_{\max}^2.$$

The **LHC Pb+Pb** data can be **well described** assuming the Hubble-like **flow**: $u^\mu = x^\mu/\tau_f$.

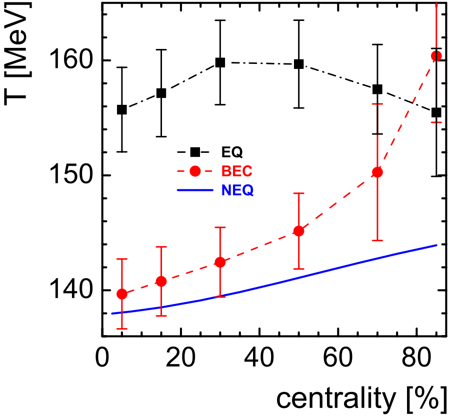
There is **only one** additional **parameter** in the model, because the product $V = \pi r_{\max}^2 \tau_f$ is the volume (per unit rapidity), while the ratio $r_{\max}/\tau_f$ **determines** the **slope** of the **spectra**.

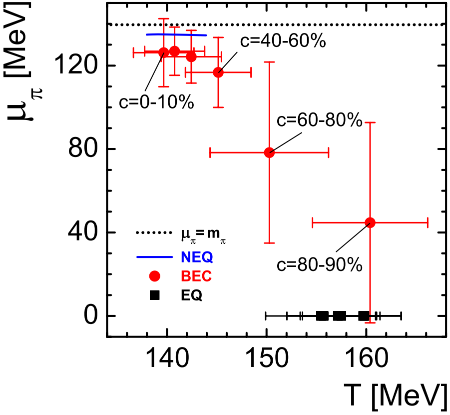
Reasons for non-equilibrium

- Non-equilibrium - **NEQ** - **explains smaller temperature at the LHC** compared to **RHIC** (Petran, Letessier, Petracek, Rafelski, PRC (2013)).
- It allows for a **better fit** of mean multiplicities in Pb+Pb at 2.76 TeV at the LHC: $\chi^2_{NEQ}/dof \sim 1$ versus $\chi^2_{EQ}/dof \sim 4$ in equilibrium - **EQ** (V.B., Florkowski, Rybczynski, PRC (2014)).
- The **slope parameter found for $\pi^{\pm}$ and $K^{\pm}$** only appears also very **good for $p+\overline{p}$, K^0_S, $K^*(892)^0$ and $\phi(1020)$!** (V.B., Florkowski, Rybczyński, PRC (2014)).
- It predicts an interesting phenomenon - **high temperature Bose-Einstein condensation of pions** - **BEC** - with about 5% of pions in the condensate (V.B., Florkowski, PRC (2015)).
- It can be a consequence of the **gluon condensation** (Blaizot, Gelis, Liao, McLerran, Venugopalan, NPA (2012)), or the **overcooling** of the **quark-qluon plasma** into the hadronic phase (Csorgo, Csernai, PLB (1994), Shuryak, arXiv:1412.8393).
- The recent analysis of two-, three-, and four-**pion correlations** done by **ALICE** Collaboration shows that a **coherent** fraction in charged **pion emission** may reach 32% (Abelev et al., PRC, (2014) 024911, Adam et. al., PRC (2016), 054908).

Non-equilibrium parameters

The fit to the **2.76 TeV Pb+Pb LHC data** in **equilibrium - EQ**, **non-equilibrium - NEQ**, and non-equilibrium with the possibility of **pion condensation - BEC** on the **ground state** in **hadron-resonance gas**, using modified **SHARE** code (V.B., Florkowski, PRC (2015), V.B. PRC (2016)):





- The system is closer to the **condensate** in **central collisions**.
- The uncertainty is large - more mean multiplicities are needed to constrain the fit.

At **large chemical potentials** **finite size effects** should be taken into account. In the thermodynamic limit, $V \to \infty$, the sum over momentum levels is transformed into the integral over momentum $\sum_{\mathbf{p}} \cdots \simeq (V/(2\pi)^3) \int d^3\mathbf{p}$, and the average number of particles is

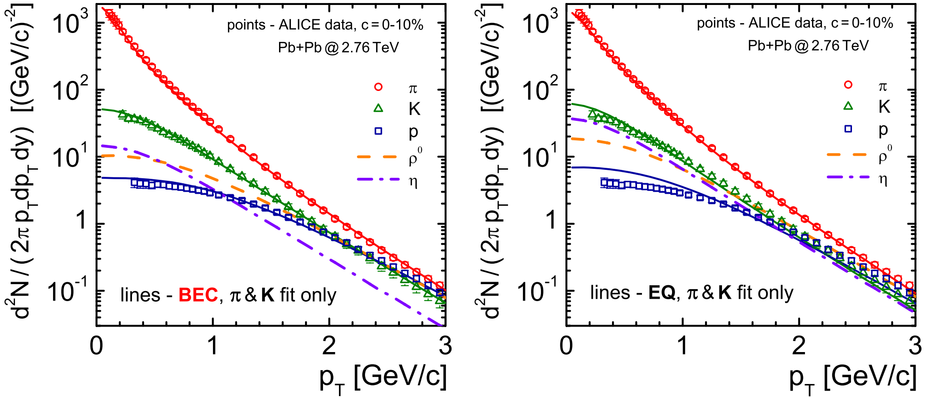
$$\langle N \rangle = \sum_p \langle n_p \rangle = \sum_n \frac{g_n}{\exp\left(\frac{\sqrt{p_n^2+m^2}-\mu}{T}\right) - 1} =$$

$$= \frac{g_0}{\exp\left(\frac{m-\mu}{T}\right) - 1} + \frac{g_1}{\exp\left(\frac{\sqrt{p_1^2+m^2}-\mu}{T}\right) - 1} + \ldots + V \int_{p_{\min}}^{\infty} \frac{d^3p}{(2\pi)^3} \frac{g}{\exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) - 1}$$

The momentum at the first excited level $p_1 \sim 1/V^{1/3}$ and the corresponding number of particles $N_1 \sim V^{2/3}$ vanish in the thermodynamic limit. While the **zero momentum level grows as fast as the volume** and survives (V.B., Gorenstein, PRC (2008), V.B. EPJ (2015)).

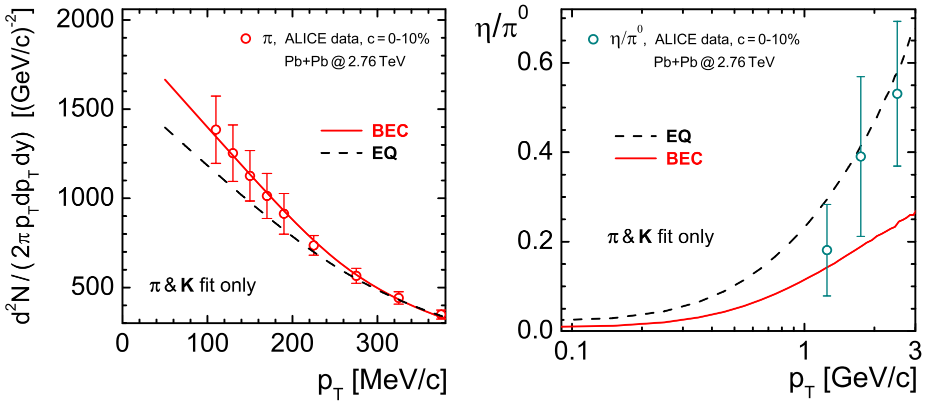
$$\langle N \rangle \simeq \frac{g}{\exp\left(\frac{m-\mu}{T}\right) - 1} + V \int_0^{\infty} \frac{d^3p}{(2\pi)^3} \frac{g}{\exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) - 1} = \langle N_{\mathrm{cond}} \rangle + \langle N_{\mathrm{norm}} \rangle,$$

where N_{cond} is the number of particles in Bose-Einstein condensate and N_{norm} is the number of particles in normal state.

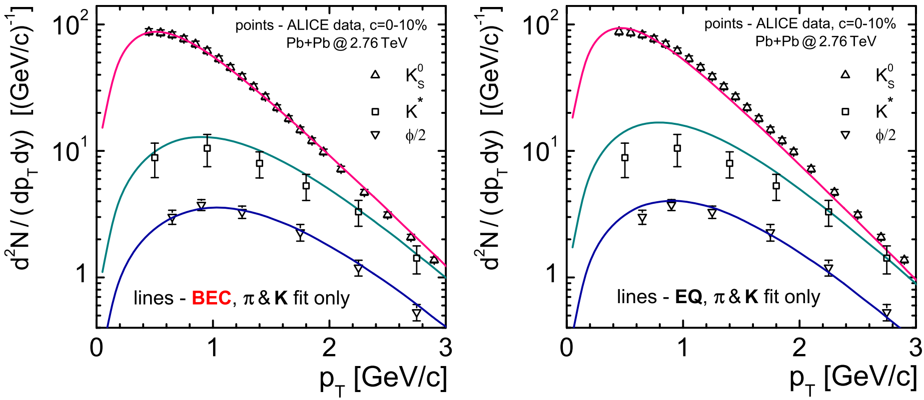


- The **BEC** fit of pion and kaon spectrum gives a good description of protons.
- Protons in **EQ** require a different freeze-out hypersurface.
- The amount and spectra of ρ^0 and η mesons are **significantly different** in **EQ** and **BEC**.

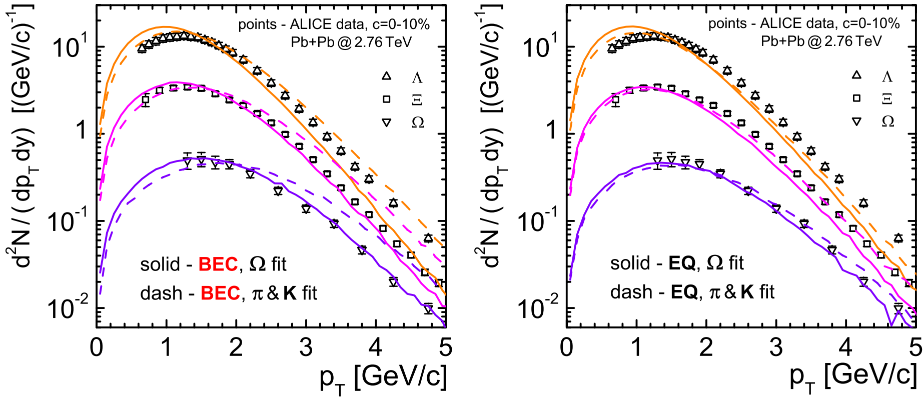
Low p_T charged pions versus η/π^0



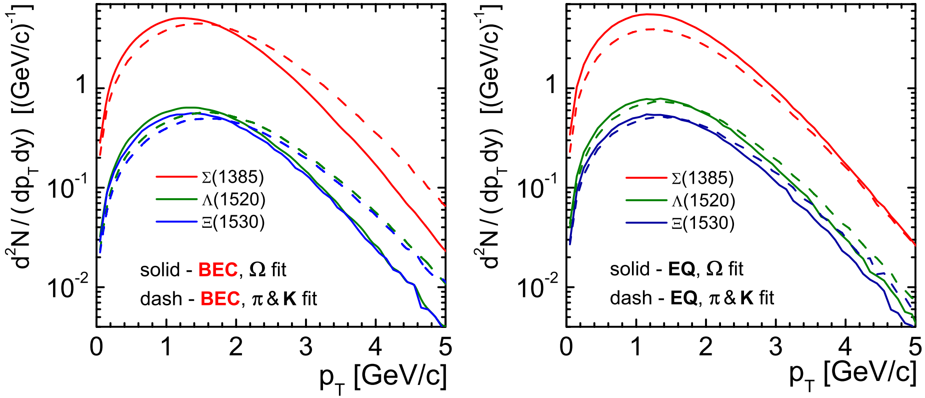
- **Charged pions favor BEC**. There is no other model that explained this low p_T excess together with proton spectra without giving pions and protons extra parameters since the data appearance in 2012.
- The η/π^0 **ratio favors EQ** (data from Morreale, J.Phys.Conf.Ser. (2017), arXiv:1609.06106).
- The **uncertainty** is **too large** to judge.



- Both **BEC** and **EQ explain** K^0_S and ϕ spectra **similarly good**.
- $K^*(892)^0$ **is close to BEC prediction!** Note, $K^*(892)^0$ was not included neither in the fit of mean multiplicities, nor in the fit of spectra (data: Adam et. al., PRC (2017), arXiv:1702.00555).
- It means that **BEC** can be treated as an **effective parameterizations** of the freeze-out.



- Strange baryons **require different freeze-out** hypersurface compared to that one for π, K, p, K^0_S, K^* and ϕ (see also Chatterjee, Mohanty, Singh, PRC (2015), Melo, Tomasik, JPG (2016)).
- There is the **mass dependance in BEC** - the heavier the baryon, the smaller is the slope, i.e. the flow, or, equivalently, smaller radius of the hypersurface.



- **BEC predicts similar multiplicities and spectra** of **Λ(1520)** and **Ξ(1530)**.
- **EQ predicts larger multiplicity** of **Λ(1520)** compared to **Ξ(1530)**.
- There is a **significant dependence** of the spectra **on the freeze-out hypersurface** for all particles in **BEC**, while in **EQ** only **Σ(1385)** is sensitive to the hypersurface.

Conclusions

- The π, K, K_S^0, and ϕ particles may have a **common freeze-out hypersurface in both BEC and EQ models**.
- The **BEC** additionally **allows to explain protons, low p_T pions,** and $K^*(892)^0$ **!**
- Strange baryons require different freeze-out in both models.
- The **predictions** for ρ^0, η, $\Sigma(1385)$, $\Lambda(1520)$, $\Xi(1530)$ are **significantly different** in **BEC** and **EQ**.