High temperature Bose-Einstein condensation

Viktor Begun

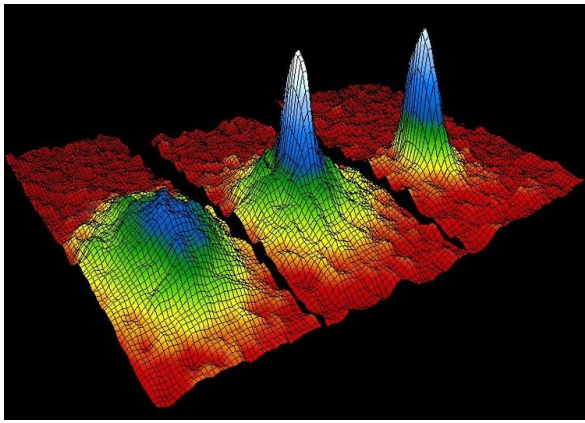
Jan Kochanowski University, Kielce, Poland

in collaboration with

W. Broniowski, W. Florkowski, F. Giacosa, M. Gorenstein, M. Rybczynski

Bose-Einstein condensation

- 1924 - Bose statistics discovered
- 1925 - Bose-Einstein condensation predicted
- 1995 - two experimental groups created BEC
- 2001 - leaders of the groups, Cornell, Wieman, and Ketterle, won the Nobel Prize



Velocity profile of the first BEC (left to right): $T > T_C$, $T < T_C$, $T \ll T_C$

The density of bosons is calculated from

$$\rho = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp[(\sqrt{p^2+m^2}-\mu)/T]-1}$$

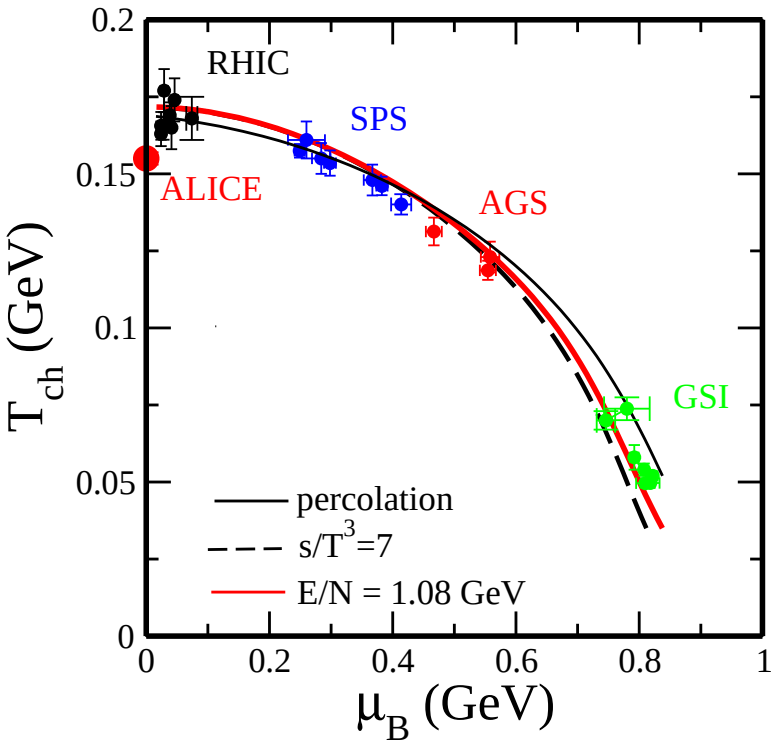
The BEC temperature for $T/m \ll 1$ is $T_C \sim m^{-1}\rho^{2/3}$. The density depends on the proper particle radius as $\rho \sim r^{-3}$. Then the ratio of the BEC temperature in the atomic gases, $T_C(A)$, to that in the pion gas, $T_C(\pi)$, in non-relativistic approximation

$$\frac{T_C(\pi)}{T_C(A)} \cong \frac{m_A}{m_\pi}\left(\frac{r_A}{r_\pi}\right)^2 \cong \frac{m_A}{m_\pi}10^{10}$$

- The BEC of atoms is achieved at temperatures $T_C \sim 10^{-8}K$
- The **BEC** of **pions** would have 10^{12} **higher temperature** and very **different properties** due to different interaction forces involved, much smaller volumes, and higher densities

The LHC Puzzle

- Thermal model gives the freeze-out curve
- The prediction was too high for ratios to **pions**, especially proton to pion ratio
- The best fit of the **LHC** data still gives three standard deviations for protons
- The low-transverse-momentum **pion spectra** show up to 50% enhancement compared to hydrodynamic models
- The fit of the LHC data gives the parameters that **fall out** to the "wrong" side



Cleymans, Redlich, et. al., PRC (2006); EPJ (2015)

Possible explanations:

- hadronization and freeze-out in chemical **non-equilibrium** (Rafelski et al., PRC (2013))
- hadronic rescattering in the final stage (Becattini, Stock et al., PRL (2013))
- incomplete list of hadrons (Noronha-Hostler, Greiner, 1405.7298; NPA (2014))

Reasons for the non-equilibrium:

- overcooling of the QGP (Shuryak, 1412.8393)
- gluon condensation in Color Glass Condensate (Gelis, NPA (2014))

Cracow single freeze-out thermal model

The phase-space distribution of the primordial particles has the form:

$$f_i = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\gamma_i^{-1} \exp(\sqrt{p^2+m^2}/T) \pm 1}, \quad \text{where} \quad \gamma_i = \gamma_q^{N_q^i + N_{\bar{q}}^i} \gamma_s^{N_s^i + N_{\bar{s}}^i} \exp\left(\frac{\mu_B B_i + \mu_S S_i}{T}\right),$$

and N_q^i, N_s^i are the numbers of light (u, d) and strange (s) quarks in the ith hadron. It includes all well established resonances from PDG. Resonance decay according to their branching ratios.

Single-freeze out model (Broniowski, Florkowski, PRL (2001))
Monte-Carlo implementations, THERMINATOR (Chojnacki, Kisiel, Florkowski, Broniowski, Comput. Phys. Commun. (2012))

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

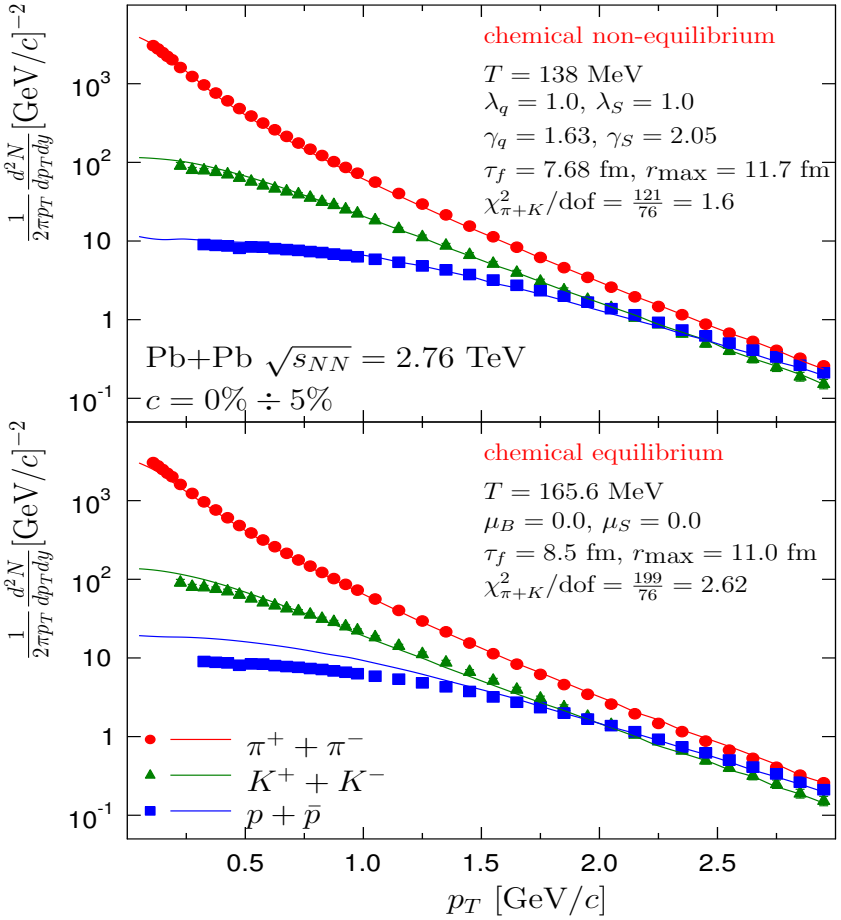
$$\frac{dN}{dy d^2p_T} = \int d\Sigma_\mu p^\mu f(p \cdot u), \qquad t^2 = \tau_f^2 + x^2 + y^2 + z^2, \qquad x^2 + y^2 \le r_{\max}^2,$$

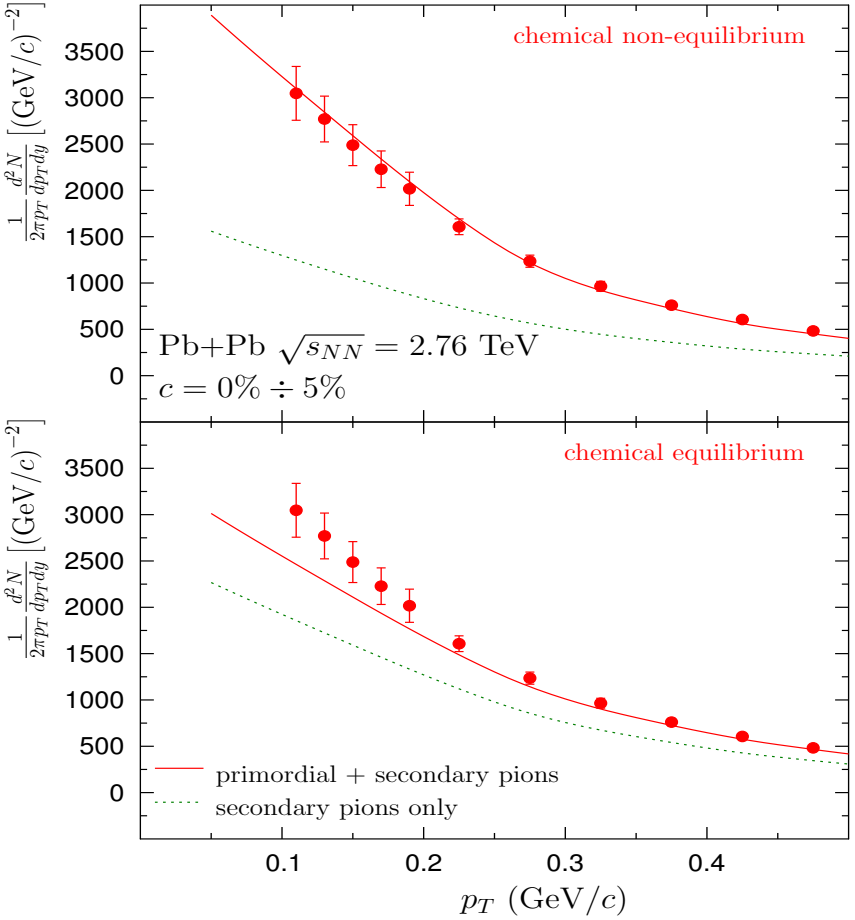
assuming the Hubble-like **flow**: $u^\mu = x^\mu / \tau_f$.

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

Spectra of pions kaons and protons in Cracow model at the LHC

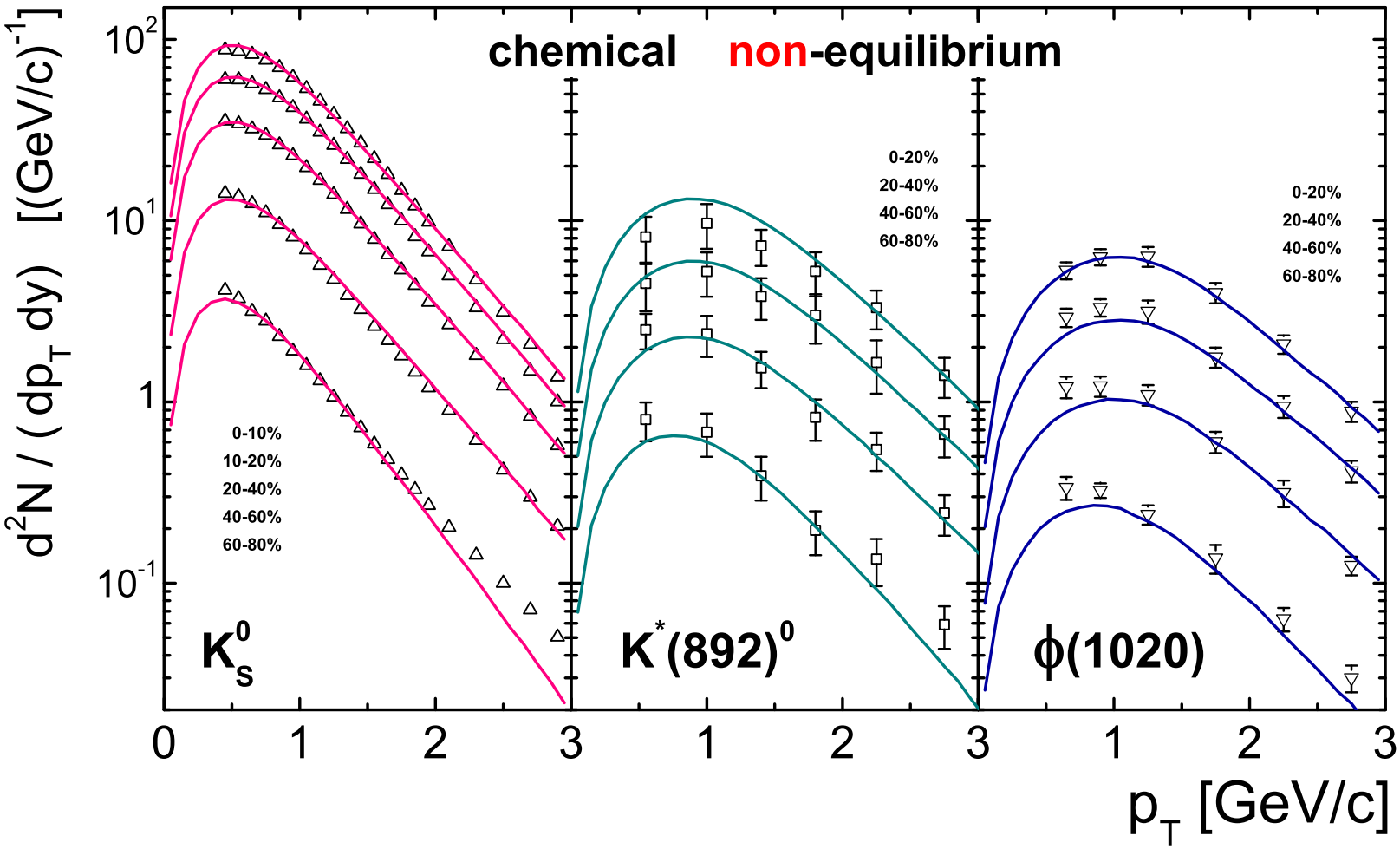
The fits to the ratios of hadron abundances (Rafelski et al., PRC (2013)) yield γ_q which is very close to the critical pion chemical potential: $\mu_\pi = \mathbf{2T} \ln \gamma_\mathbf{q} \simeq \mathbf{134}$ MeV $\simeq \mathbf{m}_{\pi^0} \simeq \mathbf{134.98}$ MeV





The **spectra** favor the **non-equilibrium** model. It may suggest that a substantial part of π^0 **mesons form** the **condensate** (V.B., Florkowski, Rybczynski, PRC (2014))

Spectra of strange particles in Cracow model at the LHC

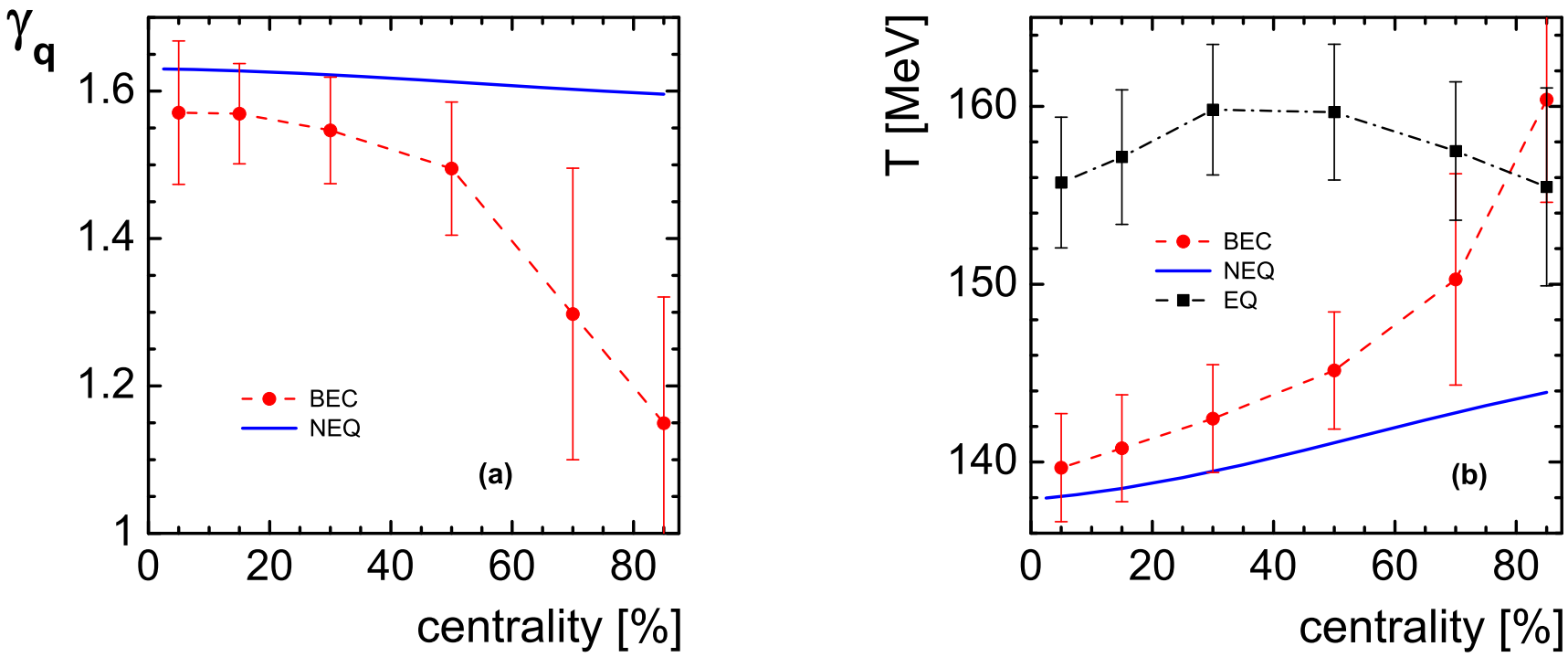


The **fit done** initially **for** $\pi^+ + \pi^-$ **and** $K^+ + K^-$ only appears also very **good for** $p + \bar{p}$, K^0_S, $K^*(892)^0$ **and** $\phi(1020)$**!** (V.B., Florkowski, Rybczyński, PRC (2014) 054912)

Explicit treatment of hadronic ground states

If chemical potential approaches the mass of a particle, $\mu \to m$, the zero momentum level, $\mathbf{p_0 = 0}$ becomes important (V.B., Gorenstein, PRC (2008), V.B. EPJ (2015)):

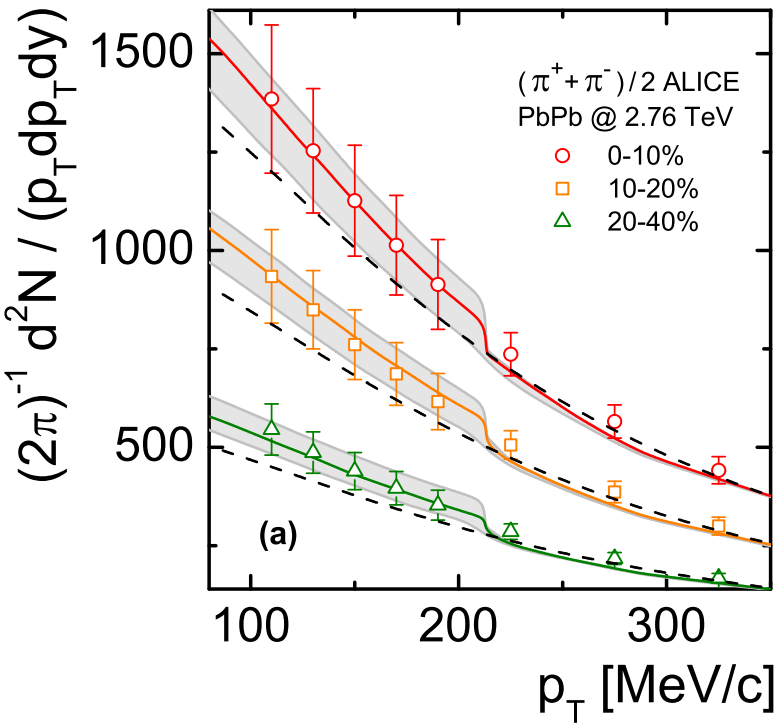
$$\sum_i \frac{1}{\exp[(\sqrt{p_i^2+m^2}-\mu)/T]-1} \simeq \frac{1}{\exp[(m-\mu)/T]-1} + V\int_0^\infty \frac{d^3p}{(2\pi)^3}\frac{1}{\exp[(\sqrt{p^2+m^2}-\mu)/T]-1}$$

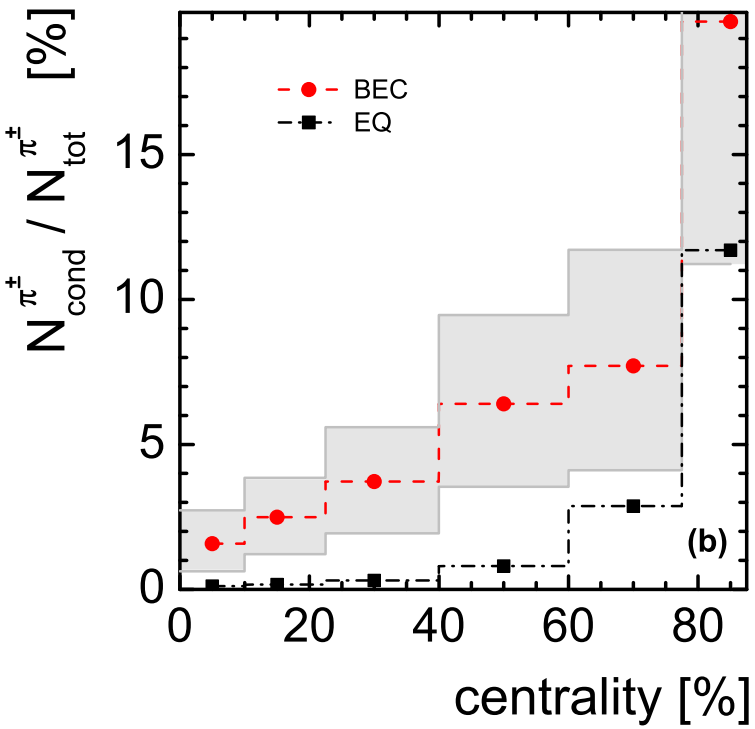


Inclusion of the **ground state** makes equilibrium and non-equilibrium **models closer**.

Pion spectra with the condensate

The momentum distribution is given by $\frac{dN}{dy d\phi_p p_T dp_T} = \frac{N_{\rm cond}}{V} \frac{\tau_f^3}{m^2} \theta\left(r_{\rm max} - p_T \tau_f / m\right)$

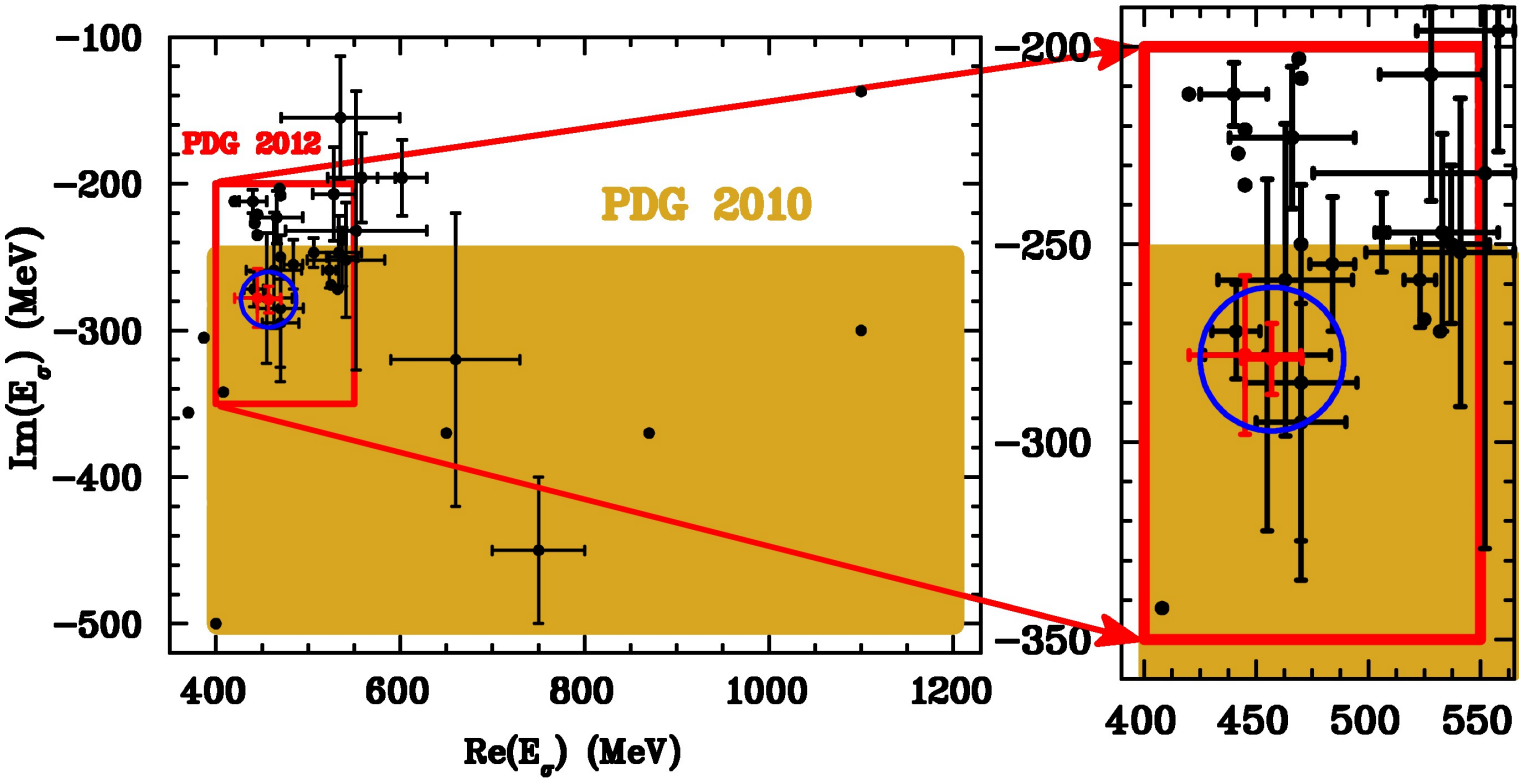




- The inclusion of several more levels would lead to finer steps
- The gray area show the 10% deviation from the best fit
- The EQ fit for pions over-predicts protons at low p_T (V.B., EPJ (2015)).
- The combined data on multiplicities and spectra are compatible with **5%** of **pions** in the **condensate** (V.B., Florkowski, PRC (2015))

Can the LHC data be explained by the updated sigma?

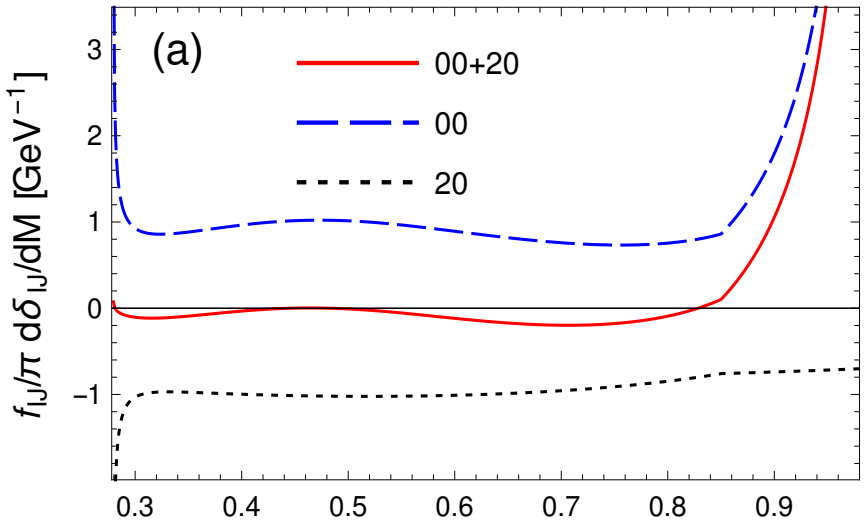
- The recent PDG reviews report much **lower mass** and width of the $f_0(500)$ or the **sigma** meson
- The lower mass of the σ would result in it's **higher multiplicity**. It decays into pions, therefore it **could add** some of the **missing pions**

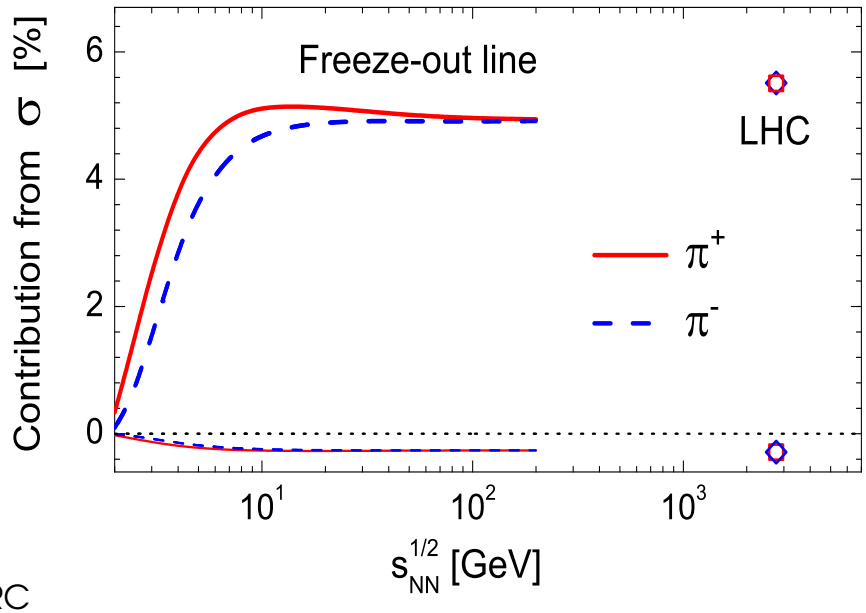


Kaminski, Acta Phys. Polon. Supp. (2015); Garcia-Martin, Kaminski, Pelaez, Ruiz de Elvira, Phys. Rev. Lett. (2011)

Cancellation of the sigma meson in thermal models

The derivative of the experimental $\pi\pi$ phase shift has **attractive** isospin-spin **channel** (0,0) that is responsible for the emergence of the $f_0(500)$. However, the channel (2,0) is **repulsive** and **cancels** $f_0(500)$ until $f_0(980)$ takes over above $M \sim 0.85$ GeV.





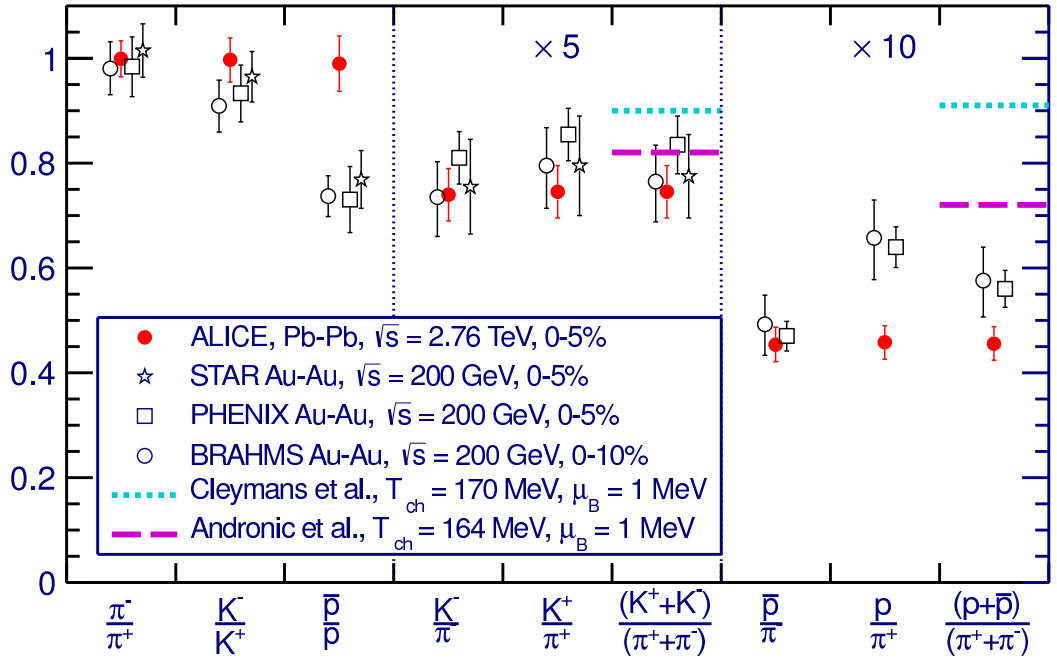
V.B., Broniowski, Giacosa, arXiv:1506.01260, accepted in PRC

The **cancellation** occurs at the level of the distribution functions, therefore it persists in **all** isospin-averaged **observables**. The σ implemented as a Breit-Winger pole with $M_\sigma = 484$ and $\Gamma_\sigma/2 = 255$ MeV produces up to **5%** of pions, while the truth contribution is **−0.3%**. The famous **K/π horn** is **affected**, as well as **all ratios** to **pions**.

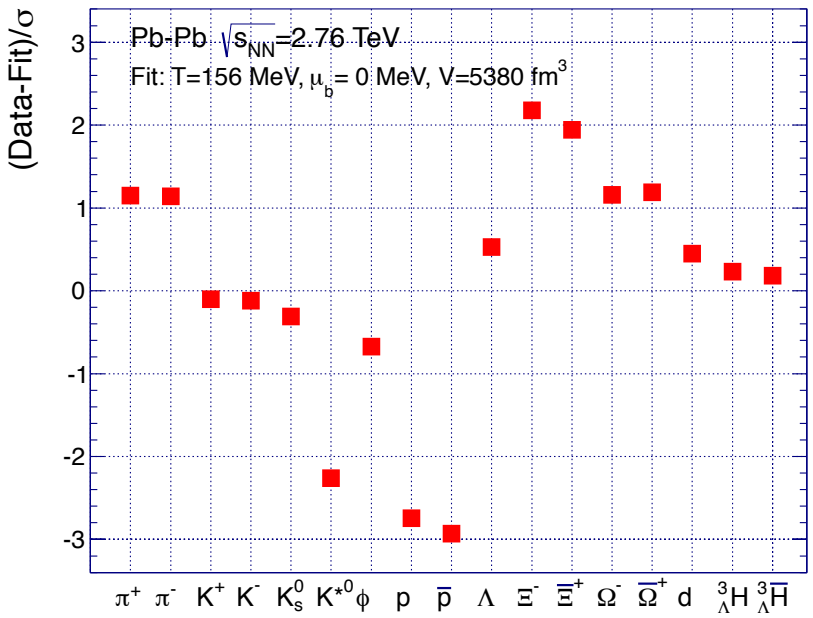
Conclusions

- The contribution of the **sigma** meson ($f_0(500)$ resonance) to isospin-averaged observables **is cancelled** by the repulsion from the isotensor-scalar channel
- The cancellation **enhances** the **K**$/\pi$ **horn** at the **SPS** and the **proton**-pion **puzzle** at the **LHC**
- The **non-equilibrium** thermal model combined with the single freeze-out scenario **explains** very well the **spectra** of $\pi, \mathbf{K}, \mathbf{p}, \mathbf{K^0_S}, \mathbf{K^*(892)^0}$ and $\phi(\mathbf{1020})$ particles at the **LHC**
- The introduction of the **ground state** makes a **link** between equilibrium and non-equilibrium thermal models
- The **enhancement** of the **pion spectra** may be interpreted as a signature of the **onset** of **pion condensation** at the **LHC**

Problems of thermal models with the mean multiplicities at the LHC



ALICE Collaboration, Phys. Rev. Lett. (2012)

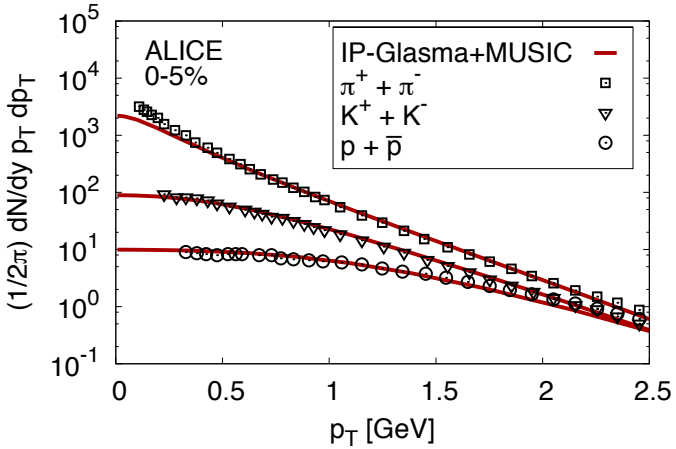


Stachel, Andronic, Braun-Munzinger, Redlich, J. Phys. Conf. Ser. (2014)

- The prediction of thermal models gave **too high ratios** to **pions**, especially proton to pion ratio
- The best fit of the LHC data gives **three standard deviations** for **protons**

Problems of hydrodynamic models with the pion spectra at the LHC

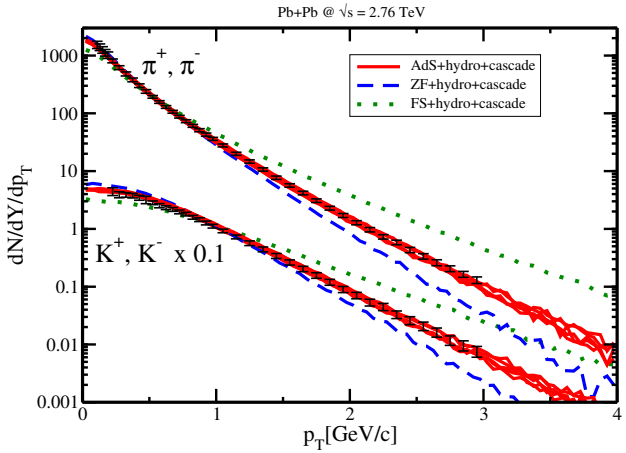
IP - Glasma + MUSIC:



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

pion enhancement

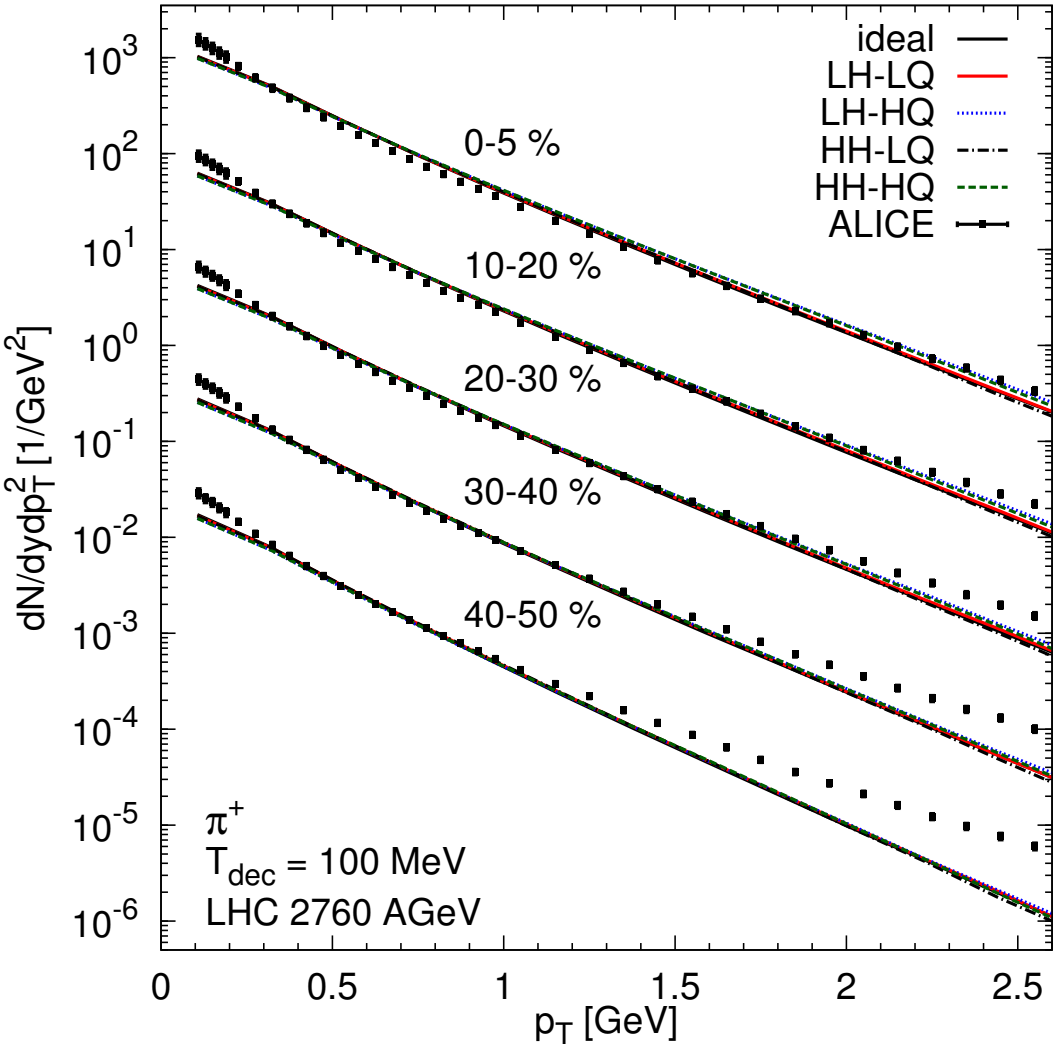
AdS + hydro + cascade:



Schee, Romatschke, Pratt, Phys. Rev. Lett. (2013)

pions well described, **protons?**

Hydro with dynamical freeze-out:



Molnar, Holopainen, Huovinen, Niemi, Phys. Rev. C (2014)

pion enhancement