Onset of Pion Condensation at the LHC

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in collaboration with

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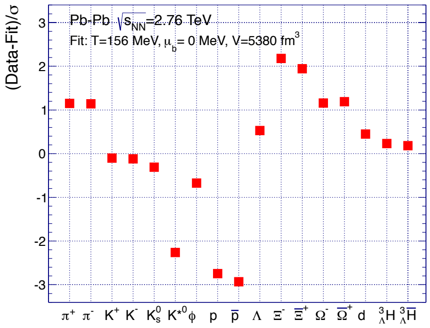
1.1 Problems of thermal models with the proton yield

Statistical models have become one of the cornerstones of our understanding of heavy-ion and elementary (e^+e^-, $p\bar{p}$) collisions. (Becattini, Braun-Munzinger, Broniowski, Cleymans, Gaździcki, Gorenstein, Koch, Rafelski, Redlich, Satz, Stachel, Stock, ...)

The new data from LHC do **not agree** with the most common version of the thermal model for **proton** abundances .

Possible explanations:

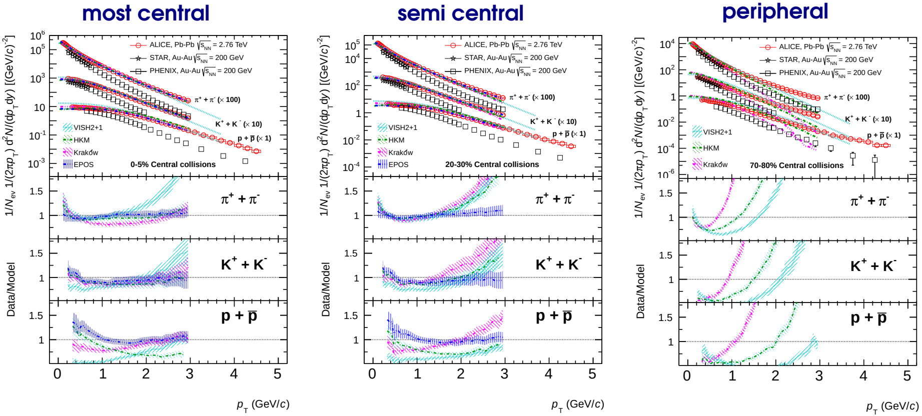
- hadronic rescattering in the final stage (Becattini, Bleicher, Kollegger, Schuster, Steinheimer, Stock, PRL 111 (2013) 082302)
- hadronization and subsequent freeze-out taking place off chemical equilibrium (Petran, Rafelski, PRC 88 (2013) 021901; Petran, Letessier, Petracek, Rafelski, PRC 88 (2013) 034907)
- incomplete list of hadrons (Noronha-Hostler, Greiner, 1405.7298, 1408.0761)
- flavor hierarchy at freeze-out (Chatterjee, Godbole, Gupta, PLB 727 (2013); Melo, Tomasik, QM 2014)



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

1.2 Problems of hydrodynamic models with the pion spectra

Besides the proton anomaly, the same LHC data exhibits another interesting feature:



most central

semi central

peripheral

The low-transverse-momentum **pion** spectra show **enhancement** by about 25%–50% with respect to the predictions of various thermal and hydrodynamic models

(ALICE compares experimental data to various hydro models: PRL 109 (2012) 252301, PRC 88 (2013) 044910)

2. Cracow single-freeze out model

Single-freeze out model (Broniowski, Florkowski, PRL 87 (2001) 272302)
Monte-Carlo implementations, THERMINATOR 1 & 2 (Kisiel, Taluc, Broniowski, Florkowski, Comput. Phys. Commun. 174 (2006) 669; Chojnacki, Kisiel, Florkowski, Broniowski, Comput. Phys. Commun. 183 (2012) 746)

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

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

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

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

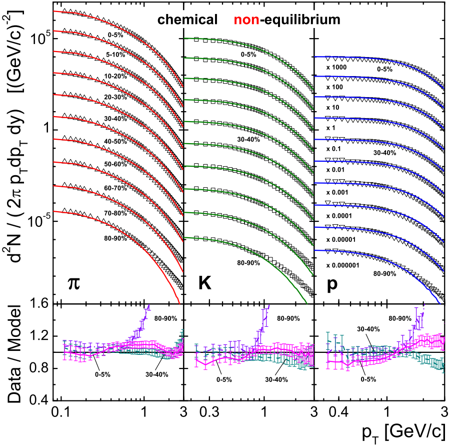
The phase-space distribution includes all well established resonances from PDG. The primordial distribution in the local rest frame has the form:

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

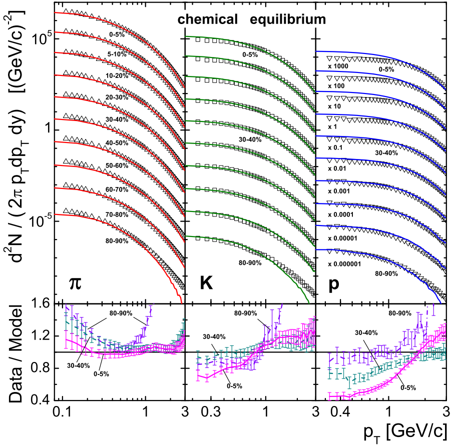
and N_q^i, N_s^i are the numbers of light (u, d) and strange (s) quarks in the ith hadron.

2.1 Spectra of pions, kaons and protons

Chemical non-equilibrium:
V, T, γ_q, γ_s, r_{max}/τ_f



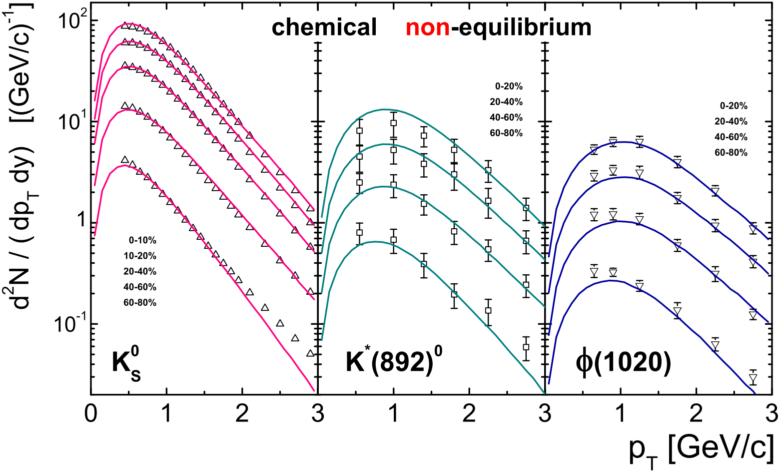
Chemical equilibrium:
V, T, r_{max}/τ_f



One can observe a good agreement for pions and kaons, however, protons in central collisions are described only in non-equilibrium (V.B., Florkowski, Rybczyński, PRC (2014) 054912).

2.2 Spectra of strange particles

Predictions for other hadrons:



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)

3. Pion condensation

There is an upper bound on γ_q because of Bose-Einstein condensation. The fits to the ratios of hadron abundances yield γ_q which is very close to the critical pion chemical potential

$$\mu_\pi = 2T \ln \gamma_q \simeq 134\,\mathrm{MeV} \simeq m_{\pi^0} \simeq 134.98\,\mathrm{MeV}$$

It may suggest that a substantial part of π^0 mesons form the condensate. Therefore we add the estimation for the number of π^0 mesons in the χ^2 fits, and take into account the **ground state** with zero momentum (V.B., Gorenstein, PRC (2008), V.B. arXiv:1412.6532):

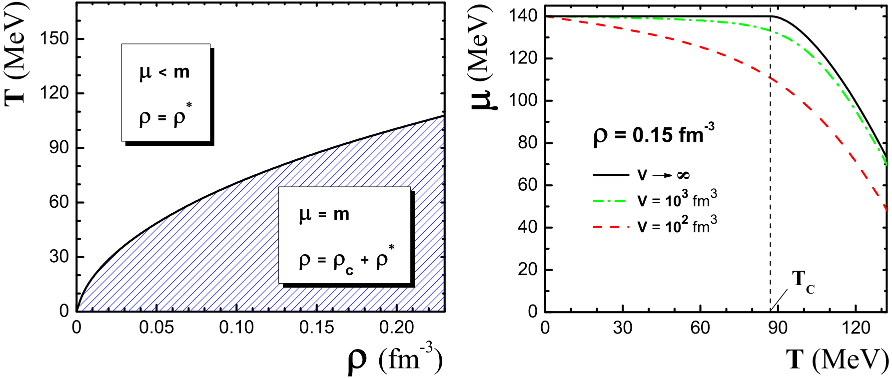
$$N = \sum_i \frac{g_i}{\exp\left(\frac{\sqrt{p_i^2+m^2}-\mu}{T}\right)-1}$$

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

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

3.1 Finite size effects in the pion gas

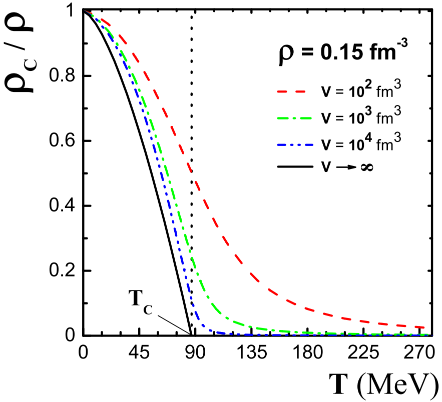
Bose-Einstein condensation is possible at any temperature, if the density is high enough.

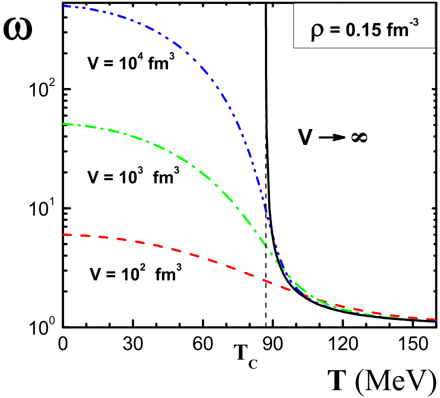


The chemical potential is always smaller than the mass in the system with a finite volume (V.B., Gorenstein, PLB (2007), PRC (2008)).

3.2 Finite size effects in the pion gas

Counterintuitively, the fraction of particles in condensate is bigger for smaller systems.

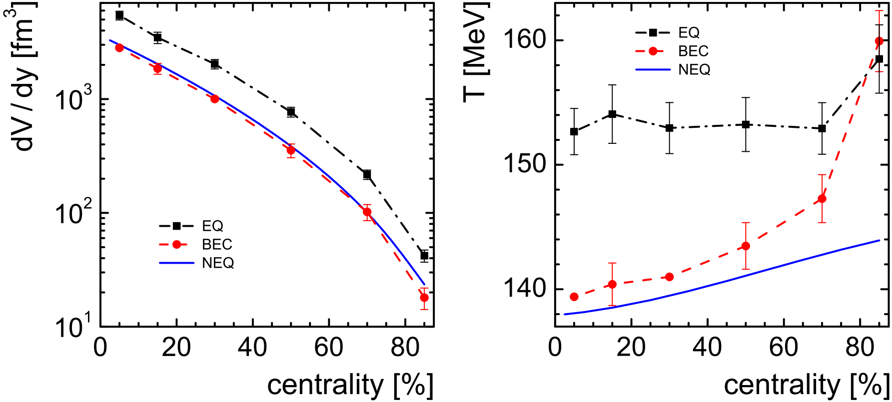




Fluctuations rapidly increase with increasing the fraction of particles in the condensate.
This effect is stronger for bigger volume of the system (V.B., Gorenstein, PRC (2008)).

4.1 Volume and temperature

Inclusion of the ground state into the NEQ model makes temperature closer to the EQ model. The BEC and EQ models give the same temperature at peripheral collisions!



EQ - equilibrium model

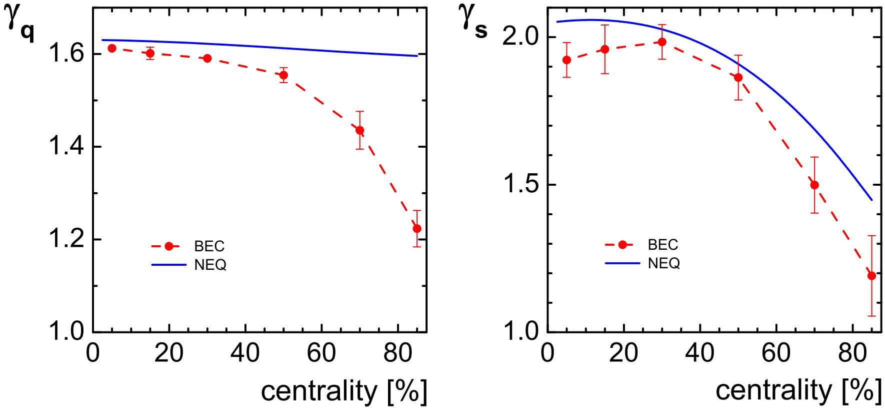
NEQ - non-equilibrium model, previously shown

BEC - non-equilibrium with **condensate** at the zero momentum level - **NEW!**

(V.B. arXiv:1412.6532)

4.2 Non-equilibrium parameters

Inclusion of the ground state into the NEQ model makes γ's closer to the EQ model, especially for very peripheral collisions.



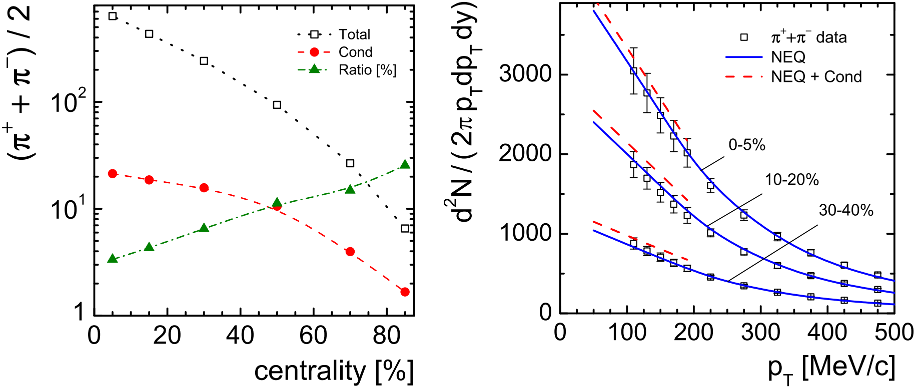
Equilibrium model is not shown, since there $\gamma_q \equiv \gamma_s \equiv 1$ (V.B. arXiv:1412.6532)

NEQ - non-equilibrium model, previously shown

BEC - non-equilibrium with **condensate** at the zero momentum level - **NEW!**

4.3 Ground state contribution

The fraction of pions in the condensate is bigger than 3% and increases with centrality.



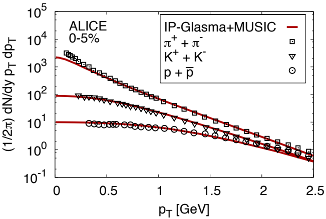
The effect for the spectrum is within the current error bars. However, it is several times stronger for π^0 mesons, which are not measured yet.

5. Conclusions

- The non-equilibrium thermal model combined with the single freeze-out scenario explains very well the spectra of pions, kaons, and protons
- It eliminates the proton anomaly and explains the low-p_T enhancement of pions
- This enhancement may be interpreted as a signature of the onset of pion condensation in heavy-ion collisions at the LHC energies
- The introduction of the ground state makes a link between equilibrium and non-equilibrium thermal models
- It would be interesting to see measurement of the pion spectrum at smaller values of p_T than those available at the moment, especially for π^0 mesons

Problems of hydrodynamic models with the pion spectra

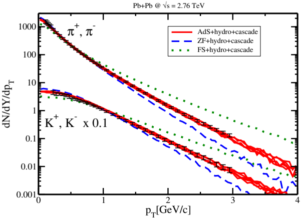
IP - Glasma + MUSIC:



(Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL (2013))

pion enhancement!

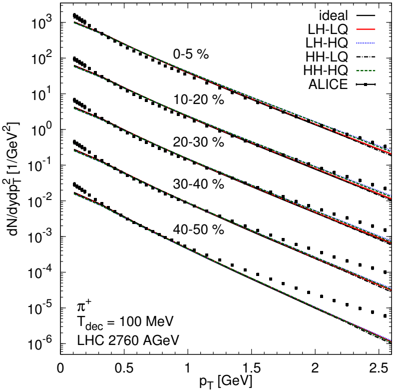
AdS + hydro + cascade:



(Schee, Romatschke, Pratt, PRL (2013))

pions well described, **protons?!**

Hydro with dynamical freeze-out:



(Huovinen et al., arXiv:1407.8152)

again pion enhancement!

Fugacity and chemical potentials

The parameters γ_q and γ_s are equivalent to the chemical potentials $\mu_i/T = \ln \gamma_i$

$$\Upsilon_i \;=\; \exp\left(\frac{\mu_q\left(N_q^i + N_{\bar{q}}^i\right) + \mu_s\left(N_s^i + N_{\bar{s}}^i\right)}{T}\right)$$

They are connected with the conservation of the SUM of the number of quarks and antiquarks during the hadronization process, similarly as μ_B and μ_S are connected with the conservation of the DIFFERENCE of the quark and antiquark numbers. (Rafelski: This must be so, since the entropy is conserved during the hadronization process.) This is valid when the hadronization process is fast and there is no significant volume expansion.

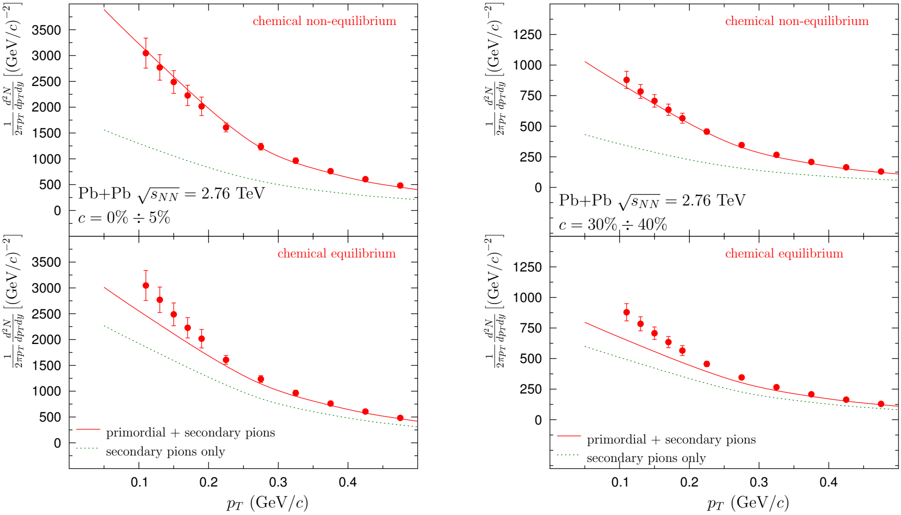
It can be also a result of the interplay between annihilation and recombination processes. For example, a $p\bar{p}$ annihilation to n pions would produce the relation between nucleon and pion chemical potentials:

$$2\,\mu_N \;=\; n\,\mu_\pi$$

Generally, n may depend on energy, however, in our case $n = 3$.

One can also imagine a QCD mechanism like the gluon condensation followed by the formation of low momentum $q\bar{q}$ pairs which fuse into pions which subsequently condense

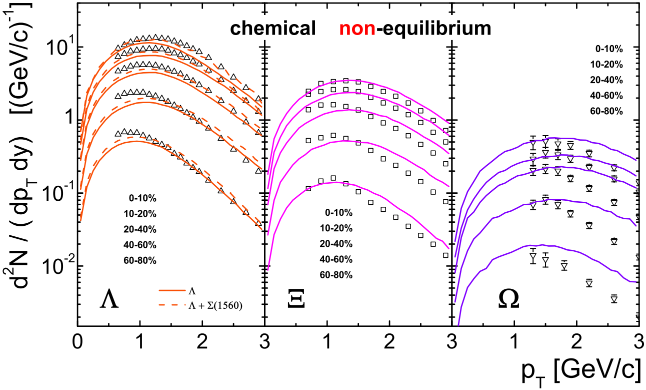
Spectra of pions. Linear scale



most central events

semi central events

Spectra of strange particles. Hyperons

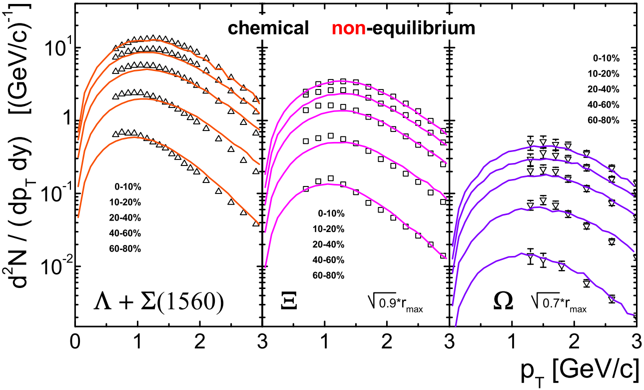


The possible sources of these discrepancies:

- the thermodynamic parameters obtained when the data on multi-strange particles were not available
- unknown decays into Λ
- too much flow for heavy particles which is equivalent to the emission from a smaller volume in our model

Spectra of strange particles. Hyperons

If the $\Sigma(1560)$ decay into Λ is included and the Ξ's and Ω's are emitted from a smaller volume,

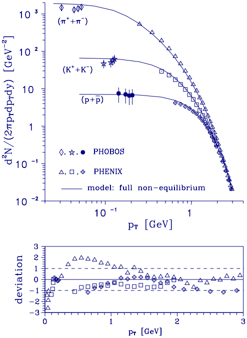


then the agreement is improved. However one should re-fit the new data before making conclusions.

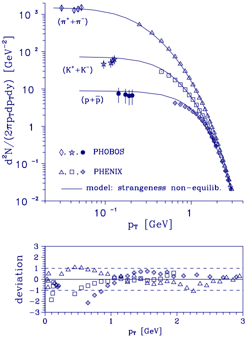
Spectra of pions, kaons and protons at RHIC

Dariusz Prorok, Phys.Rev. C75 (2007) 014903, the same approach but applied for RHIC

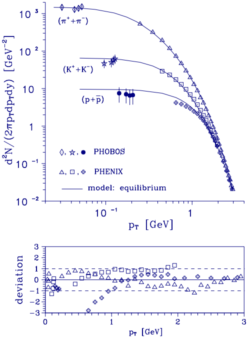
chemical non-equilibrium



strangeness non-equilibrium



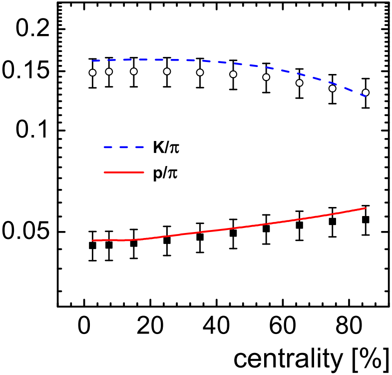
chemical equilibrium



situation opposite to that at the LHC!

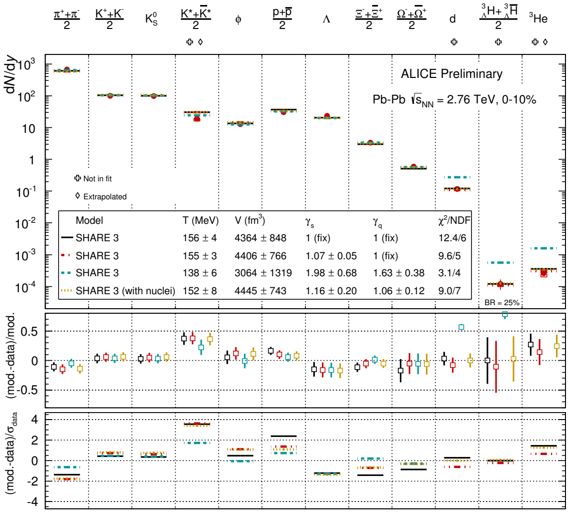
The ratios

Since we describe the spectra – the corresponding ratios are described automatically:



Data analysis in SHARE thermal model

M. Floris, Quark Matter 2014, arXiv:1408.6403



Model	T (MeV)	V (fm^3)	γ_s	γ_q	χ^2/NDF
SHARE 3	156 ± 4	4364 ± 848	1 (fix)	1 (fix)	12.4/6
SHARE 3	155 ± 3	4406 ± 766	1.07 ± 0.05	1 (fix)	9.6/5
SHARE 3	138 ± 6	3064 ± 1319	1.98 ± 0.68	1.63 ± 0.38	3.1/4
SHARE 3 (with nuclei)	152 ± 8	4445 ± 743	1.16 ± 0.20	1.06 ± 0.12	9.0/7

ALI-PREL-74481

Problems with the data

- Different centrality selection for different data:
  $\pi^\pm$, $K^\pm$, p, $\overline{p}$ and $\phi(1020)$ are published in 10 centrality windows,
  K^0_S and Λ are published in 7 centrality windows,
  $\Xi^\pm$ and $\Omega^\pm$ are published in 5 centrality windows,
  $K^*(892)^0$ is published in 4 centrality windows.
- We found that the best way is to merge the data for $\pi^\pm$, $K^\pm$, p, $\overline{p}$ $\phi(1020)$, K^0_S and Λ to the centrality set of $\Xi^\pm$ and $\Omega^\pm$