The evidences of missing resonances from THERMINATOR

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in collaboration with

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Excited Hyperons in QCD Thermodynamics at Freeze-Out
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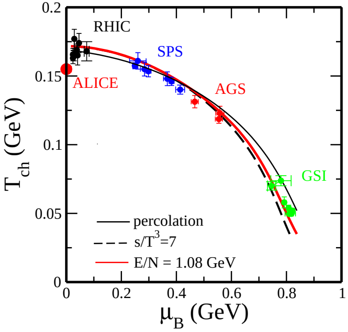
- Thermal model gives particle multiplicities and the freeze-out curve
- The prediction was too high for ratios to **pions**, especially **proton to pion** ratio
- The best fit of the **LHC** data still gives **three standard deviations** for **protons**
- The low-transverse-momentum **pion spectra** 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 et. al., PRC (2006); EPJ (2015)

Possible explanations:

- hadronization and freeze-out in chemical **non-equilibrium** (Rafelski et al., PRC (2013))
- hadronic **rescattering** (not enough for pion spectra?) in the final stage (Becattini, Stock et al., PRL (2013); Ryu, Paquet, Shen et al., PRL (2015))
- **incomplete list** of hadrons (Noronha-Hostler, Greiner, 1405.7298; NPA (2014))

Reasons for the non-equilibrium:

- super(over)cooling of the QGP (Shuryak, 1412.8393; Csorgo, Csernai, PLB (1994))
- gluon condensation in CGC (Blaizot, Gelis, Liao, McLerran, Venugopalan, NPA (2012); Gelis, NPA (2014))

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

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

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

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 the **PDG. Resonances decay** according to their branching ratios.

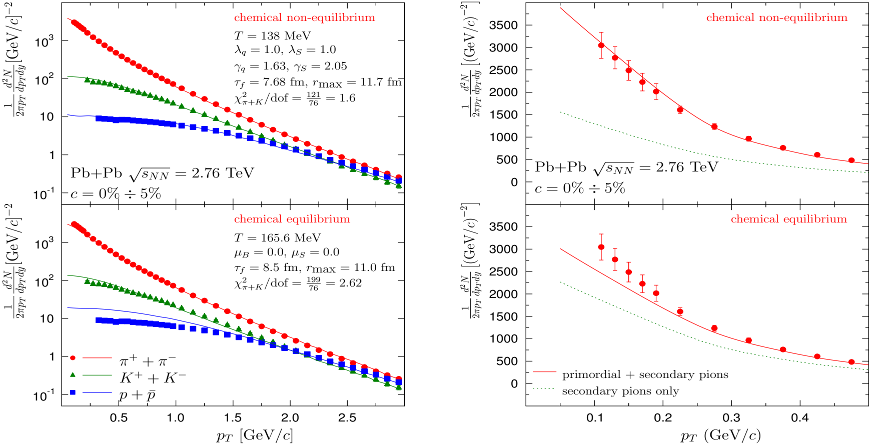
The spectra are calculated from the Cooper-Frye formula at the freeze-out **hyper surface**

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

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.

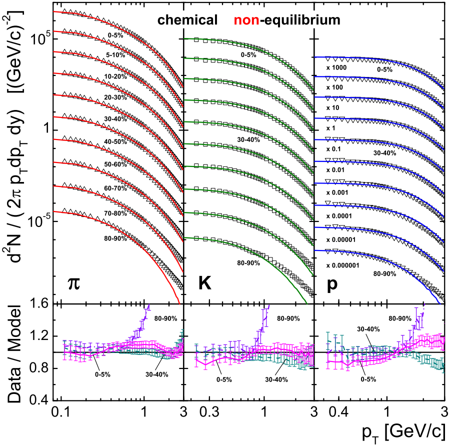
The fits to the ratios of hadron abundances (Rafelski et al., PRC (2013)) yield γ_q which is close to the critical pion chemical potential: $\mu_\pi = \mathbf{2T \ln \gamma_q} \simeq \mathbf{134}$ MeV $\simeq \mathbf{m_{\pi^0}} \simeq \mathbf{134.98}$ MeV



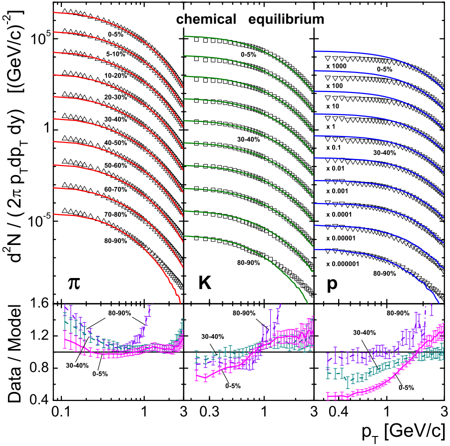
The **spectra** favor the **non-equilibrium** model. It may suggest that a substantial part of π^0 **mesons form** the **condensate** (V.B., Florkowski, Rybczynski, PRC (2014))

Centrality dependence for pions, kaons and protons

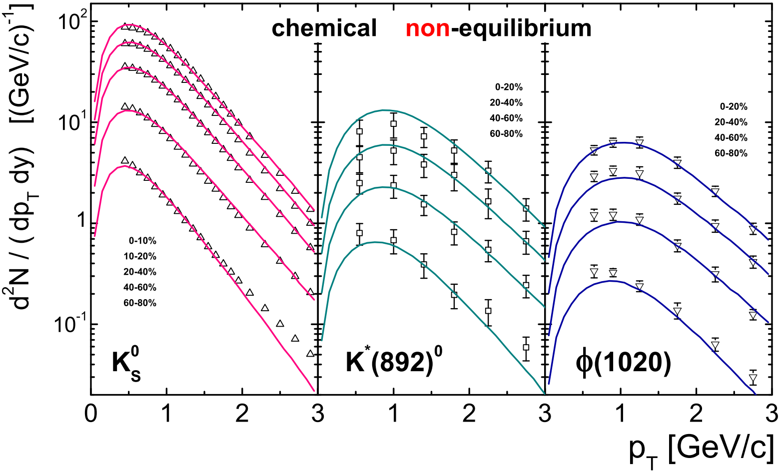
Chemical non-equilibrium:
V, T, γ_q, γ_s, r_{max}/τ_f



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



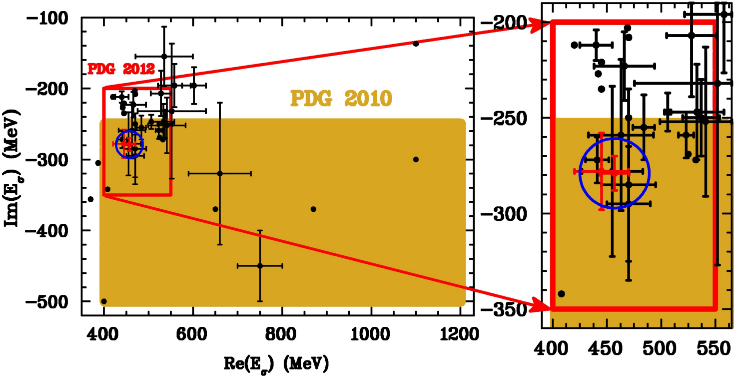
One can observe a good agreement for pions and kaons, however, protons in central collisions are described **only** in **non-equilibrium**. **Protons** were **not fitted!** (V.B., Florkowski, Rybczyński, PRC (2014) 054912).



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

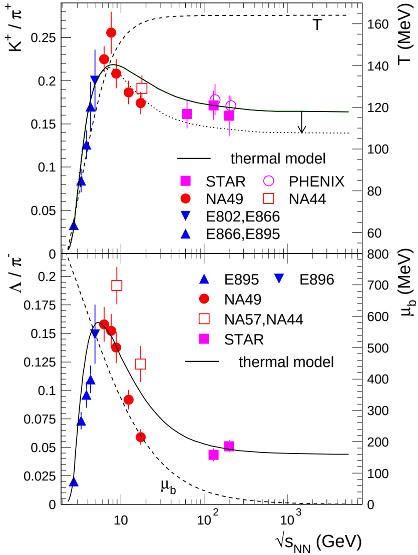
Can the LHC data be explained by the updated sigma?

- 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**

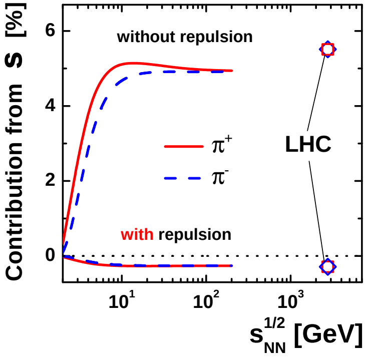


Kaminski, Acta Phys. Polon. Supp. (2015); Garcia-Martin, Kaminski, Pelaez, Ruiz de Elvira, Phys. Rev. Lett. (2011)

No! Sigma should *not* be included in thermal models at all



Andronic, Braun-Munzinger, Stachel, PLB (2009)



V.B., Broniowski, Giacosa, PRC (2015)

- The contribution from σ **cancels** in **all** isospin-averaged **observables** (Pelaez et. al., PRD (2013), Pelaez, Phys.Rept. (2016).)
- The K/π **horn** can **not** be **explained** by the σ
- **All ratios** to **pions**, and therefore the extracted **temperatures** are **affected**.

Finite size effects in a quantum gas

In the thermodynamic limit, $V \to \infty$, the sum over momentum levels is transformed into the integral over momentum $\sum_{\mathbf{p}} \cdots \simeq (V/(2\pi)^3) \int d^3\mathbf{p}$:

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

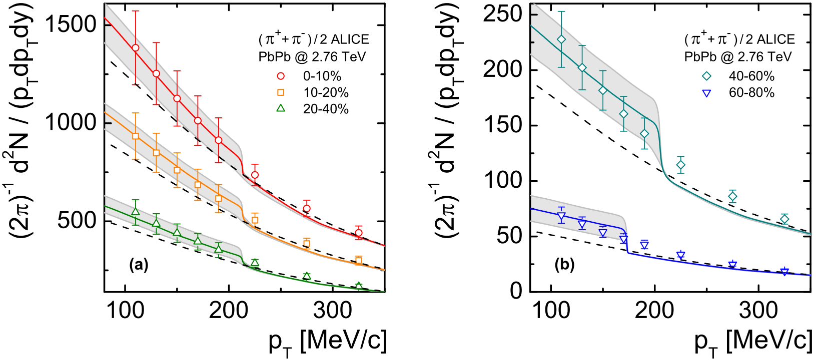
$$= \frac{g_0}{\exp\left(\frac{m-\mu}{T}\right)-1} + \frac{g_1}{\exp\left(\frac{\sqrt{p_1^2+m^2}-\mu}{T}\right)-1} + \ldots + V\int_{p_{\min}}^{\infty} \frac{d^3p}{(2\pi)^3} \frac{g}{\exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right)-1}$$

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))

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

where N_{cond} is the number of particles in Bose condensate and N_{norm} is the number of particles in normal state. For small volumes one should take into account at least the **ground state**.

The p_T distribution is $\frac{dN}{dy d\phi_p\, p_T dp_T} = \frac{N_{cond}}{V} \frac{\tau_f^3}{m^2} \theta\left(r_{max} - p_T \tau_f / m\right)$ (V.B., Florkowski, PRC (2015)):



Condensate rate and p_T spectrum for charged pions. The grey area show the **10%** deviation from the best fit.

- The inclusion of several more levels would lead to finer steps
- The data on multiplicities and spectra are compatible with **5%** of the **condensate**
- If not the condensate, then plenty of **heavy resonances** decaying into **low pT pions**?
- If there is the **condensate**, there must be **large fluctuations** of pions, which should be seen starting from the **fourth moment** of the multiplicity distribution (V.B., PRC (2016), arXiv: 1603.02254.)

- One can **predict** the **multiplicities** of not yet measured particles.
- Many decay channels for heavy resonances are unknown. **Missing branching ratios** lead to the **missing charge**.
- For example, the missing charge for the **p+p** at **158 GeV/c** is $\Delta B/B \simeq 0.15/2 \sim 8\%$, $\Delta Q/Q \simeq 0.11/2 \sim 6\%$ and $\Delta S \simeq -0.01$ (V.B., Vovchenko, Gorenstein, ongoing work. Thanks to H. Stroebele for fruitful discussion!).

TABLE I. The comparison between fitted and measured total 4π multiplicities, and the prediction for the unmeasured yields. The fit is done within the CE formulation of the HRG. Some yields at the lowest energy are omitted from the table, because the energy of the system is not enough for their creation. The mean multiplicities in p+p inelastic interactions are measured by HADES [18] at $\sqrt{s_{NN}} = 3.2$ GeV, and by NA61/SHINE [14] at $\sqrt{s_{NN}} = 6.3$ GeV and 7.7 GeV.

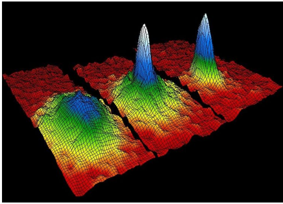
	$\sqrt{s_{NN}} = 3.2$ GeV		$\sqrt{s_{NN}} = 6.3$ GeV		$\sqrt{s_{NN}} = 7.7$ GeV	
	Measurement	Fit	Measurement	Fit	Measurement	Fit
π^+		0.782	1.582 ± 0.232	1.698	1.985 ± 0.288	1.903
π^-		0.238	1.067 ± 0.203	0.9345	1.438 ± 0.288	1.174
K^+		0.00398	0.097 ± 0.015	0.0938	0.157 ± 0.018	0.130
K^-		3.82×10^{-4}	0.024 ± 0.00632	0.0258	0.045 ± 0.005	0.051
p		1.37		1.14		1.1
$\bar{p}$				4.78×10^{-5}	0.0047 ± 0.0008	0.0046
Λ		0.00466		0.0669		0.0785
$\bar{\Lambda}$				1.57×10^{-5}		0.00161
Σ^+		2.20×10^{-4}		0.0226		0.0254
$\bar{\Sigma}^+$				3.11×10^{-6}		3.27×10^{-4}
Σ^-		6.00×10^{-5}		0.011		0.0129
$\bar{\Sigma}^-$				4.78×10^{-6}		4.90×10^{-4}
Ξ^0				9.04×10^{-4}		0.00122
$\bar{\Xi}^0$				7.35×10^{-7}		8.32×10^{-5}
Ξ^-				6.93×10^{-4}		0.00101
$\bar{\Xi}^-$				8.53×10^{-7}		9.36×10^{-5}
Ω				4.06×10^{-6}		1.11×10^{-5}
$\bar{\Omega}$				1.70×10^{-8}		3.28×10^{-6}
π^0	0.39 ± 0.1	0.578		1.54		1.76
K^0_S	0.0013 ± 0.0003	0.000977		0.0501		0.0811
η	0.02 ± 0.007	0.017		0.0846		0.134
ω	0.006 ± 0.002	0.00591		0.0364		0.145
K^{*+}	$(2.0 \pm 0.6) \times 10^{-4}$	0.000218		0.0113		0.0406
K^{*-}		4.62×10^{-5}		0.00273		0.0117
K^{*0}		1.36×10^{-4}		0.00797		0.0302
$\bar{K}^{*0}$		5.86×10^{-5}		0.00347		0.0144
ϕ		7.72×10^{-5}		0.00454		0.0129
$\Lambda(1520)$		3.83×10^{-5}		0.00206		0.00626

Vovchenko, V.B., Gorenstein, PRC (2016)

Conclusions

- The **non-equilibrium** thermal model **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 **enhancement** of the **pion spectra** may be interpreted as a signature of the **onset** of **pion condensation** at the **LHC**
- A similar effect may be produced by many **heavy** ($m > 2.5 GeV$?) **not yet discovered resonances** decaying predominantly into **low momentum**, $p_T < 150$ MeV, **pions**

- 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 (V.B., Gorenstein, PRC (2008))

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

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