The impact of the sigma meson on the freeze-out, pion condensation and proton puzzle at the LHC

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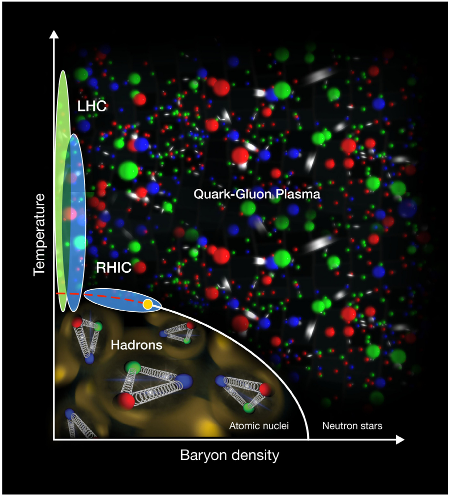
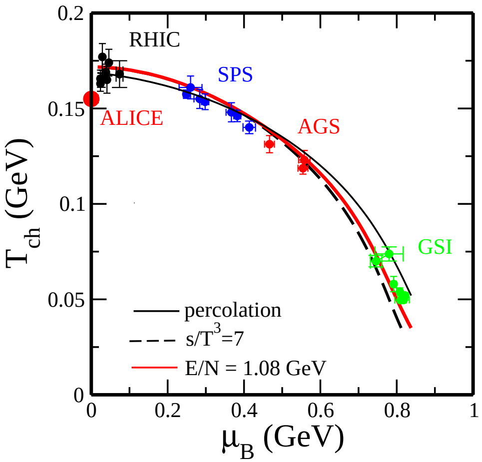
arXiv:1506.01260

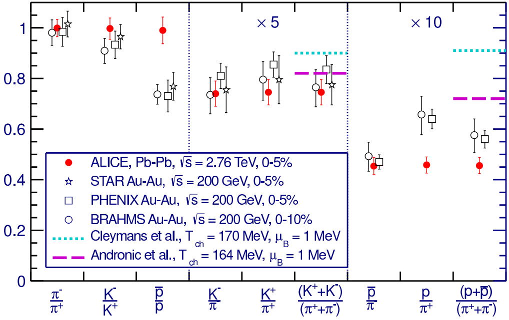


http : //www0.bnl.gov/newsroom/news.php?a = 24281

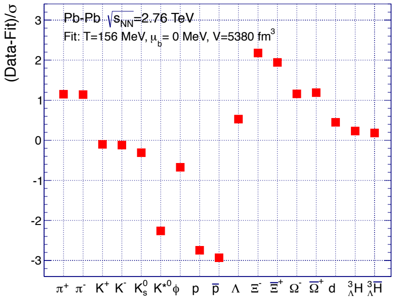


Cleymans, EPJ Web Conf. (2015)

- **Thermal model** gives the **freeze-out** curve
- The fit of the **LHC data** gives the parameters that **fall out** to the "wrong" side



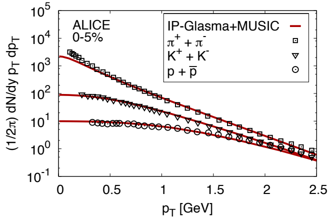
ALICE Collaboration, Phys. Rev. Lett. (2012)



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**

IP - Glasma + MUSIC:

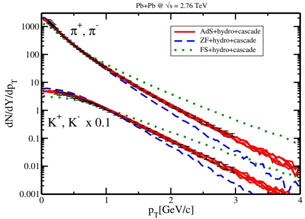


Gale, Jeon, Schenke, Tribedy, Venugopalan,

Phys. Rev. Lett. (2013)

pion enhancement

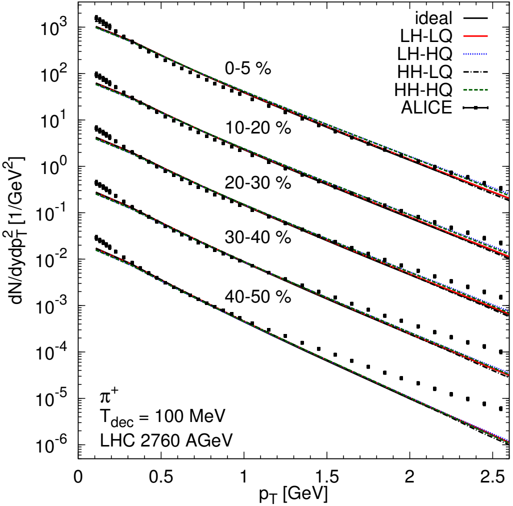
AdS + hydro + cascade:



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

Cracow single freeze-out thermal model

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

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

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, Phys. Rev. Lett. (2001))
Monte-Carlo implementations, **THERMINATOR 1 & 2** (Kisiel, Taluc, Broniowski, Florkowski, Comput. Phys. Commun. (2006); Chojnacki, Kisiel, Florkowski, Broniowski, Comput. Phys. Commun. (2012))

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

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

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.

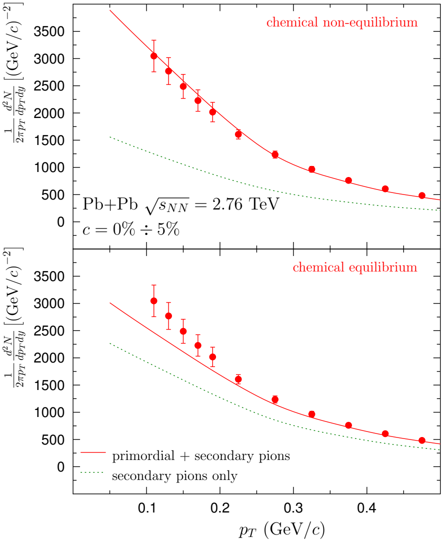
The fits to the ratios of hadron abundances (Petran, Letessier, Petracek, Rafelski, Phys. Rev. C (2013)) yield γ_q which is very close to the critical pion chemical potential

$$\mu_\pi = \mathbf{2T}\ln\gamma_{\mathbf{q}} \simeq \mathbf{134}\ \text{MeV}$$
$$\simeq \mathbf{m_{\pi^0}} \simeq \mathbf{134.98}\ \text{MeV}$$

It may suggest that a substantial part of π^0 **mesons form** the **condensate**.

The calculations of the pion **spectra support** the formation of the **condensate** at the LHC

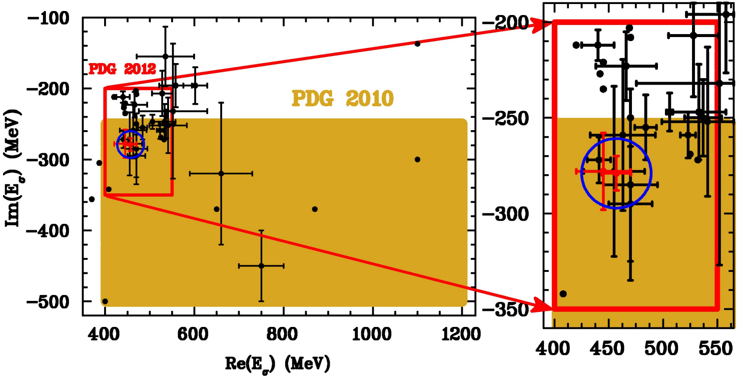
V.B., Florkowski, Phys. Rev. C (2015)



V.B., Florkowski, Rybczynski, Phys. Rev. C (2014)

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)

In thermal models the calculations are performed using the sum of contributions of all (stable and resonance) hadrons to the partition function

$$\ln Z = \sum_k \ln Z_k^{\mathrm{stable}} + \sum_k \ln Z_k^{\mathrm{res}}$$

In practice, one uses the list of existing particles from the PDG.
In the limit where the decay widths of resonances and chemical potentials are neglected, one has

$$\ln Z_k^{\mathrm{stable,res}} = g_k V \int \frac{d^3p}{(2\pi)^3} \ln\left[1 \pm e^{-E_p/T}\right]^{\pm 1}$$

where g_k is the spin-isospin degeneracy, V – volume, $\vec{p}$ – momentum, M_k – the mass of the resonance, $E_p = \sqrt{\vec{p}^2 + M_k^2}$ – the energy, and the $\pm$ corresponds to fermions or bosons.
As a better approximation for the partition function, one can take into account the finite widths of resonances:

$$\ln Z_k^{\mathrm{res}} = g_k V \int_0^\infty d_k(M)\, dM \int \frac{d^3p}{(2\pi)^3} \ln\left[1 - e^{-E_p/T}\right]^{-1}$$

For narrow resonances one can approximate $d_k(M)$ with a (non-relativistic or relativistic) normalized Breit-Wigner function peaked at M_k.

The $2 \to 2$ reactions are incorporated according to the formalism of Dashen, Ma, Bernstein, and Rajaraman. The mass distribution is given by the physical **phase shifts** δ:

$$d_k(M) = \frac{d\delta(M)}{\pi dM}$$

One can get it for the relative radial wave function of a pair of scattered particles with angular momentum l, interacting with a central potential, which has the asymptotic

$$\psi_l(r) \propto \sin[kr - l\pi/2 + \delta]$$

where $k = |\vec{k}|$ is the length of the three-momentum, and δ is the phase shift. If we confine our system into a sphere of radius R, the condition

$$kR - l\pi/2 + \delta = n\pi \;\; \text{with} \;\; n = 0, 1, 2, \ldots$$

must be met, since $\psi_l(r)$ has to vanish at the boundary. Analogously, in a free system

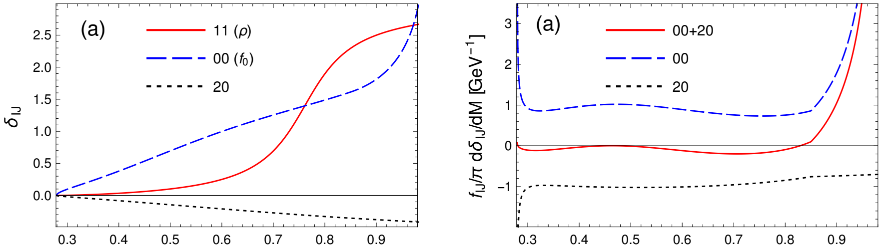
$$kR - l\pi/2 = n_{\mathrm{free}}\pi$$

In the limit $R \to \infty$, upon subtraction,

$$\delta = (n - n_{\mathrm{free}})\pi$$

Differentiation with respect to M yields the distribution $d\delta/(\pi dM)$

The isospin-spin **channel** (0,0) that is responsible for the emergence of the $f_0(500)$ pole is **attractive**, while the **channel** (2,0) is **repulsive**.



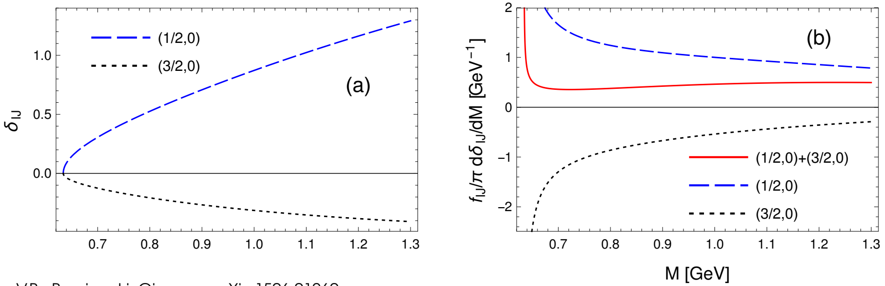
V.B., Broniowski, Giacosa, arXiv:1506.01260

The derivative of the **phase shift** for the resonance (0,0) is almost **cancelled** by the derivative of the (2,0) channel until $f_0(980)$ takes over above $M \sim 0.85$ GeV.

This is achieved with the multiplication of the isotensor channel by the isospin degeneracy factor $(2I+1) = 5$, which occurs for isospin-averaged quantities.

The phase shifts are from Garcia-Martin, Kaminski, Pelaez, Ruiz de Elvira, Phys. Rev. Lett. (2011), Phys.Rev. D (2011)

The attractive πK channel with $I = 1/2$ and $J = 0$ is capable of the generation of a pole corresponding to the $K_0^*(800)$ or the κ resonance. It is not included in the PDG, but is naturally expected to exist.

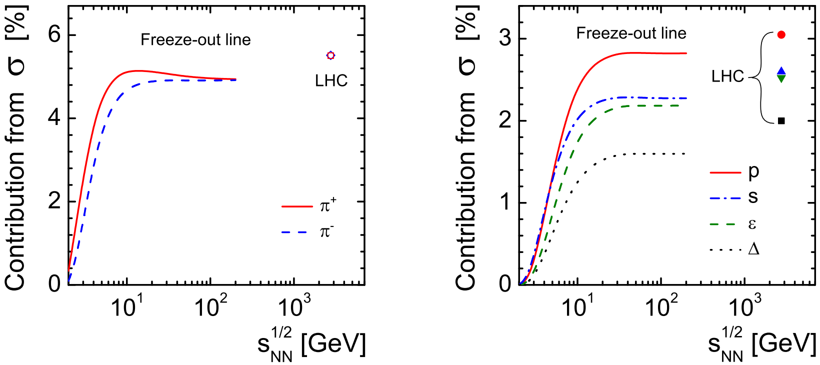


V.B., Broniowski, Giacosa, arXiv:1506.01260

One can see that there is a **partial cancellation** and one can neglect the $K_0^*(800)$.

The phase shifts are from Estabrooks, Martin, Brandenburg, Carnegie, Cashmore, et al., Nucl.Phys. B106, 61 (1976).

The **cancellation occurs** at the level of the distribution functions $d_k(M)$, therefore it persists in all isospin-averaged observables.



Left: the pions coming from the σ decay. Right: the contribution to pressure, entropy, energy density and the "interaction measure" $\Delta = (\varepsilon - 3p)/T^4$.

The σ is implemented as a Breit-Winger pole with $M_\sigma = 484$ and $\Gamma_\sigma/2 = 255$ MeV.

The famous K/π **horn** is **affected**, as well as **all ratios** to **pions**.

V.B., Broniowski, Giacosa, arXiv:1506.01260

Conclusions

- The **contribution of** the resonance $f_0(500)$ or **sigma** meson to isospin-averaged observables like thermodynamic functions, pion yields, etc. **is cancelled** by the **repulsion** from the isotensor-scalar channel
- The cancellation occurs from a "conspiracy" of the isospin degeneracy factor and the derivative of the phase shifts
- There is **no cancellation** mechanism **in correlation** studies of pion pair production
- We thus clearly see the potential importance of the σ in studies of pion correlations
- The **ratios** of particle multiplicities **involving pions** are **affected** up to **6%**
- The **cancellation enhances** the **proton**-pion **puzzle** at the LHC and **opens** even **more space** for possible **novel** interpretations