

# Updates to the chemical freeze-out line from the new data in p+p and A+A collisions

**Viktor Begun**

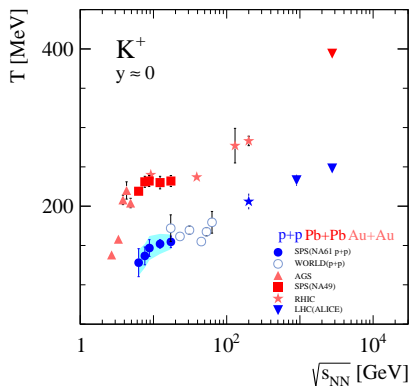
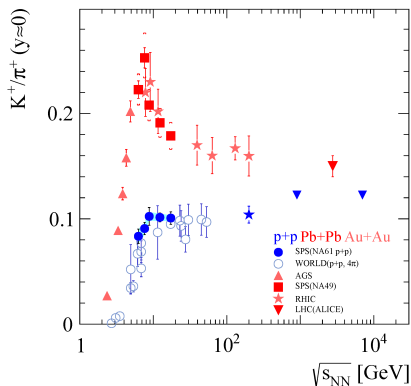
Jan Kochanowski University, Kielce

in collaboration with

**V. Vovchenko** and **M. I. Gorenstein**, arXiv: **1512.08025**, **PRC 2016**

SQM 2016, 27 June 2016 - 1 July 2016

# Motivation: the new p+p and updated A+A data at SPS



NA61/SHINE, arXiv:1510.08239

- The data are consistent with the **onset of deconfinement** close 30A GeV
- It is **important to know** the "**baseline**": the effects of the **non-QGP phenomena**
- The **NA61/SHINE data** are much more precise – **test for the models** (see extra slides)

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

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

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

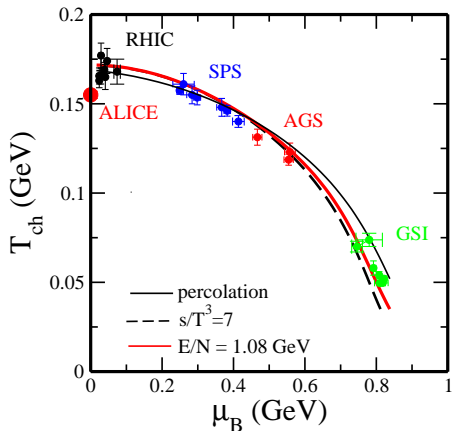
$$\ln Z_k^{\text{stable,res}} = g_k V \int \frac{d^3 p}{(2\pi)^3} \ln [1 \pm e^{(\mu - E_p)/T}]^{\pm 1}$$

where  $g_k$  is the spin-isospin degeneracy,  $V$  - **volume**,  $T$  - **temperature**,  $\mu$  - **chemical potential**,  $\vec{p}$  - 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:

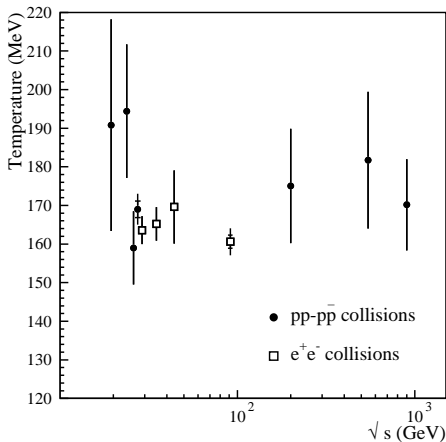
$$\ln Z_k^{\text{res}} = g_k V \int d_k(M) dM \int \frac{d^3 p}{(2\pi)^3} \ln [1 \pm e^{(\mu - E_p)/T}]^{\pm 1}$$

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

# Temperature in A+A (GCE, sCE) and p+p (CE) collisions



Cleymans, Oeschler, Redlich, Wheaton, PRC (2006); EPJ (2015)



Becattini, Heinz ZPC (1997)

- The **temperature** in **A+A** follows the common **freeze-out line**, except for the LHC
- The **temperature** in **p+p** was found **high**, with **unclear** behavior **at the SPS** energies

# Freeze-out phase diagram in A+A (GCE)

The **change** in the parametrization of the chemical **freeze-out line** is a combination of two effects:

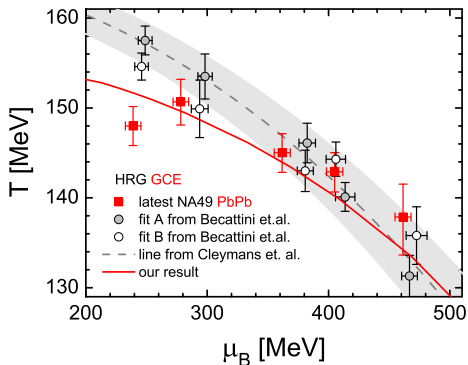
- The extension of the **list of particles**
- The changes in the experimentally **measured particle set**

We have analyzed different cuts for the maximal resonance mass,  $M_{\text{cut}}$ , included in the table of particles.

- Varying the cut in the range  $1.7 < M_{\text{cut}} < 2.4$  GeV, we have found that the inclusion of heavy resonances **may decrease** the temperature **up to 10 MeV**.

The effect is stronger at larger energy.

**A problem** of the **THERMUS 3.0** code **was** found and **corrected**. THERMUS does not take into account the resonance decay contribution to mean multiplicities of particles which are marked as unstable. As a result, yields of  $\phi$ ,  $K^*(892)$ , or  $\Lambda(1520)$  can be **underestimated** by up to **25%**.



Cleymans, Oeschler, Redlich, Wheaton, PRC (2006)

Becattini, Manninen, Gazdzicki, PRC (2006)

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

The grey band is the parametrization  
(Cleymans, Oeschler, Redlich, Wheaton, PRC (2006)):

$$T_{A+A}(\mu_B) = a - b\mu_B^2 - c\mu_B^4$$

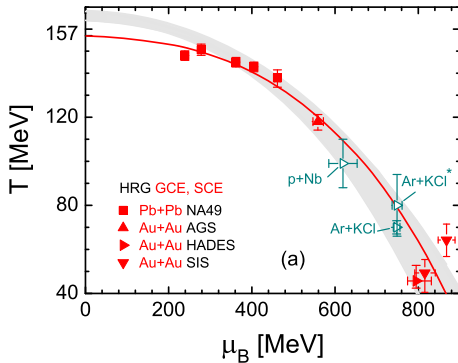
$$\mu_B = \frac{d}{1 + e\sqrt{s_{NN}}}$$

Our **fit** to the **newest** compilation of the **NA49** data yields the red line with the parameters

$$a = 0.157 \text{ GeV}, b = 0.087 \text{ GeV}^{-1},$$

$$c = 0.092 \text{ GeV}^{-3}, d = 1.477 \text{ GeV},$$

$$e = 0.343 \text{ GeV}^{-1}.$$



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

- The new fit gives  $T = 157$  MeV at  $\mu_B = 0$ , which is very close to the latest findings at the **LHC**.

The independent analysis of **p+Nb** and **Ar+KCl** reactions by **HADES** Collaboration (arXiv:1512.07070) shows that temperatures reached in **p+A** and **A+A** reactions of different size nuclei **follow the same  $T(\mu_B)$  line** as for **A+A**.

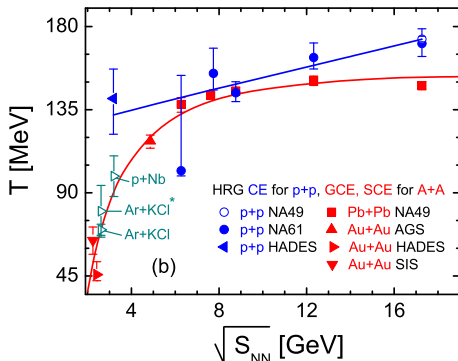
# Temperature in A+A (GCE) and p+p (CE)

The **p+p** data are fitted in the **CE** HRG model.

- The **temperature** in **p+p** is **gradually increasing** with collisions energy from  $T_{p+p} \simeq 130$  MeV to  $T_{p+p} \simeq 170$  MeV.
- The **temperatures** reached by different systems in the **beam energy scan** at the **SPS** might be very **similar**

The sudden drop of the temperature at **20A** GeV is correlated with the increase of the radius  $R_{p+p}$  and the  $\gamma_S$  (see extra slides).

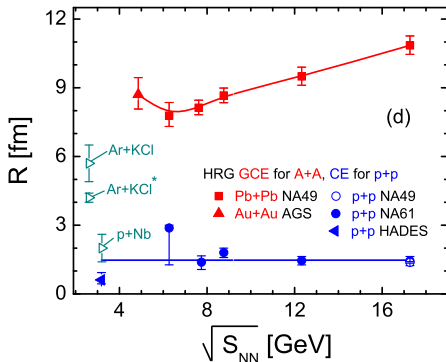
- **Larger error bars** for the p+p **NA61/SHINE** are due to **smaller number** of **measured particles** compared to **NA49 (5 vs 18)**
- The analysis of the **p+p NA49** shows that the **minimal set** of fitted **multiplicities** should include particles possessing **all three conserved charges, B, S, Q**, for both **p+p** and **A+A**. For example, an appropriate set may include  $\pi^\pm$ ,  $K^\pm$ ,  $p$ , and  $\bar{p}$ .
- Therefore, the **additional measurements** of  $\bar{p}$  at the lowest **SPS** and  $p$  mean multiplicities in both **p+p** and intermediate **A+A** reactions **at all SPS energies** are **necessary**.



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

# Radius of the system in A+A (GCE) and p+p (CE)

- The HRG fit of the **latest A+A NA49 data** gives **growing radius** of the system.
- The previous HRG fit of the **old NA49 data** gave the opposite: **constant radius** and **growing temperature**.
- The system **radius** in **p+p**  $R_{p+p} \approx 1.62$  fm is approximately **independent of** the collisions **energy** and corresponds to the volume  $V_{p+p} \approx 17.8 \text{ fm}^3$ .
- The **radius** allows to **distinguish intermediate size reactions** better than temperature.

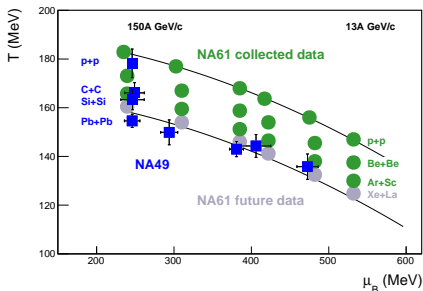


V.B., Vovchenko, Gorenstein, PRC (2016)

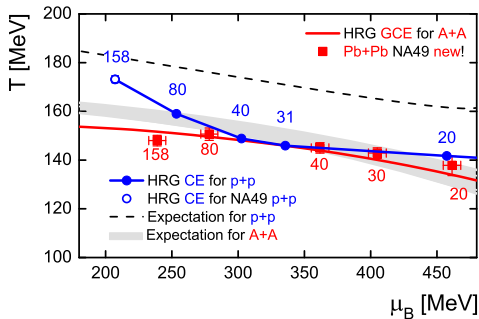
**Excluded volume** corrections can significantly **reduce all densities** (V.B., Gazdzicki, Gorenstein PRC (2013)) and **change the positions** of the characteristic points like **maximum of the net-baryon density**, the **meson/baryon domination transition** point, etc. However, their introduction requires additional assumptions (and new model parameters) about sizes of various hadrons, which are presently rather poorly constrained (see extra slides and the talk by Vovchenko).



# The Surprise



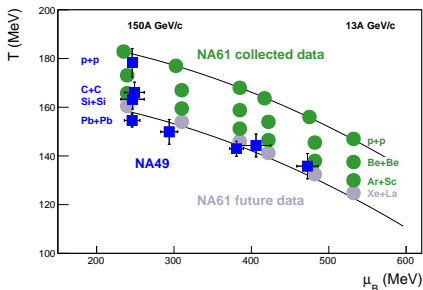
Gazdzicki, Seyboth, arXiv:1506.08141



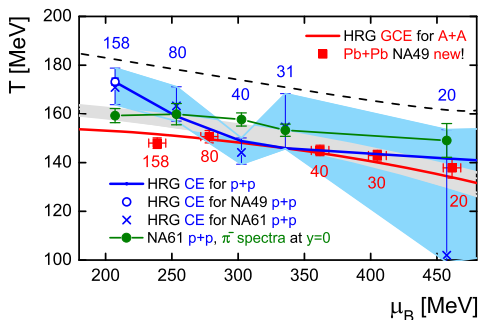
V.B., Vovchenko, Gorenstein, PRC (2016)

- The available **range of parameters** is **squeezed** and **shifted** compared to expectations
- The **p+p** line **touches** the **A+A** line in the **vicinity** of the  **$K^+/\pi^+$  horn**.

# The Surprise



Gazdzicki, Seyboth, arXiv:1506.08141



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

- The best fit of the **p+p cross** the **A+A** line in the **vicinity** of the  **$K^+/\pi^+$  horn**
- There is a **very little flow** in **p+p at SPS** ( $\pi^-$  temperature in p+p from arXiv:1310.2417)
- The **error bars** are too **large** to make final conclusions - **more data** are **needed**

- The **freeze-out temperature** is larger in p+p than in A+A,  $T_{p+p} > T_{A+A}$
- The **temperature** in **p+p** **slowly grows** with energy from **130** to **175** MeV, while the **A+A** **temperature increases** very **fast** from zero and **saturates** at  $T_{A+A} \approx 157$  MeV
- **The largest difference**  $T_{p+p} - T_{A+A} \approx 60$  MeV is **at low energies**. The  $T_{p+p} \approx T_{A+A}$  at  $\sqrt{s_{NN}} = 6.3 - 7.7$  GeV, and then the difference grows again reaching **20** MeV at the highest SPS energy
- The radius  $R_{A+A}$  **increases** with collision energy, while  $R_{p+p}$  is approximately **constant**
- The available **range of parameters** in the **NA61/SHINE** scan is **squeezed** and **shifted** compared to expectations
- The **p+p** line **touches** the **A+A** line in the **vicinity** of the  **$K^+/\pi^+$  horn**.
- **More data** are **needed**. The **minimal set** should include particles possessing all **three conserved charges** **B, S, Q**, for both p+p and A+A. For example,  $\pi^\pm, K^\pm, p, \bar{p}$

# Extra Slides

$$V = \sum_i v_i \cdot N_i$$

**Particle volume**

$$v_i = 4 \cdot \frac{4}{3} \pi r_i^3$$

**Density**

$$n_i = \frac{n_i^{\text{id}}(T, \tilde{\mu}_i)}{1 + \sum_i v_i n_i^{\text{id}}(T, \tilde{\mu}_i)}$$

**Chemical potential**

$$\tilde{\mu}_i = \mu_i - v_i P$$

**Pressure**

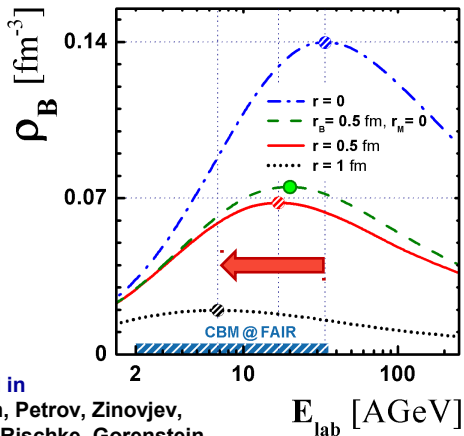
$$P = \sum_i P_i^{\text{id}}(T, \tilde{\mu}_i)$$

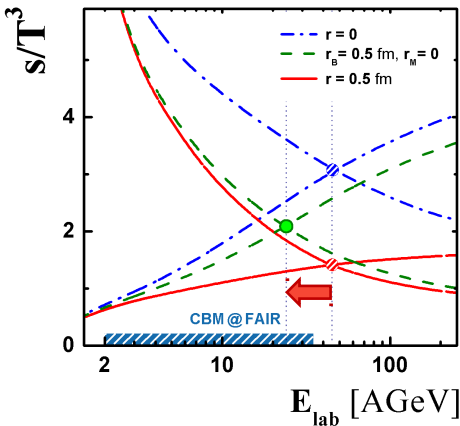
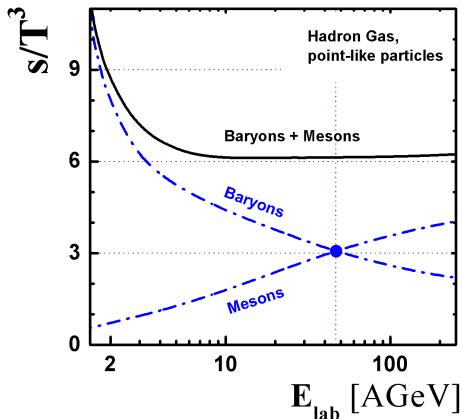
**Introduced in**

Gorenstein, Petrov, Zinovjev,  
PLB 1981; Rischke, Gorenstein,  
Stocker, Greiner, ZPC 1991

**Implemented in THERMUS:** Wheaton, Cleymans,  
Comput. Phys. 2009 [hep-ph/0407174]

**V.B., Gazdzicki, Gorenstein, PRC (2013)**



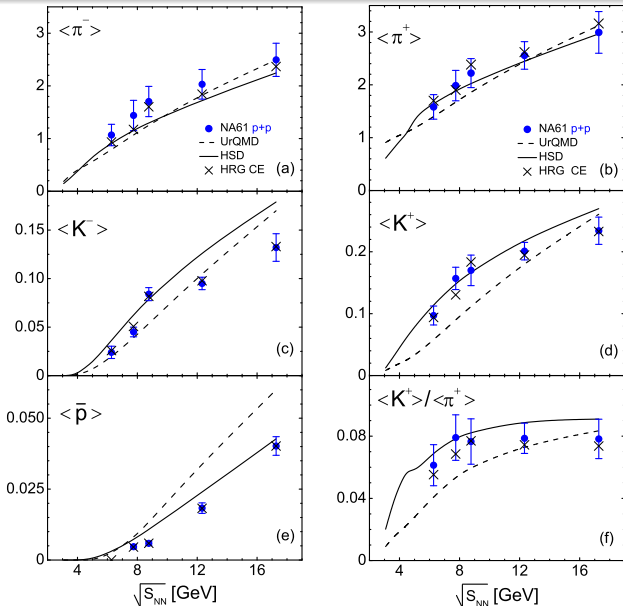


**The transition point of baryon/meson domination moves to lower energies only for different meson and baryon radii**

V.B., Gazdzicki, Gorenstein, PRC (2013)

- **Hadron gas fits the data**
- Both **UrQMD** and **HSD** models **have problems** describing the data
- Properties of **p+p** reactions **is the input** in **UrQMD** and **HSD**, which should be modified

V.B., Vovchenko, Gorenstein,  
arXiv:1512.08025



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

$$d_k(M) = \frac{1}{\pi} \frac{d\delta(M)}{dM}$$

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  $\delta$  is the phase shift. If we confine our system into a **sphere** of radius  $R$ , the condition

$$kR - l\pi/2 + \delta = n \cdot \pi \quad \text{with } n = 0, 1, 2, \dots$$

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

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

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

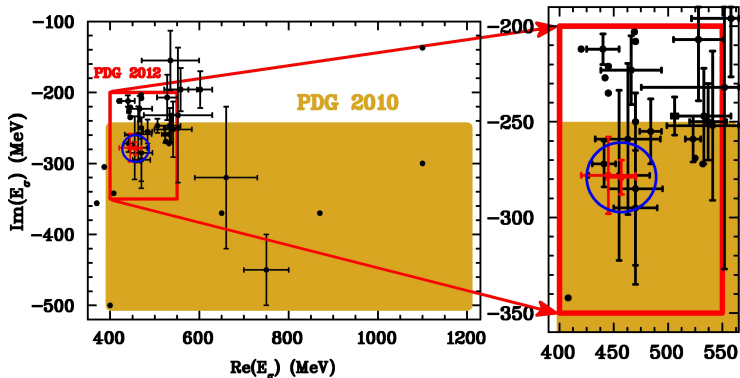
$$\delta = (n - n_{\text{free}}) \cdot \pi$$

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



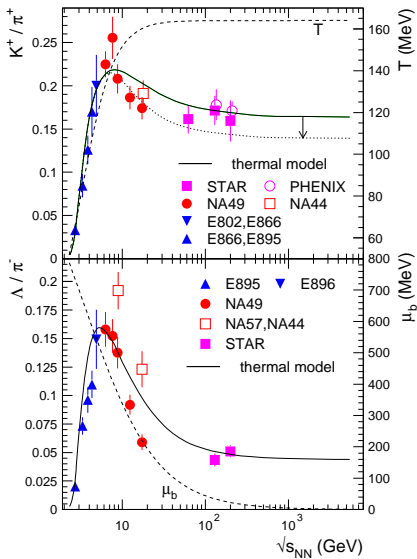
## Can the data be explained by the updated sigma?

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

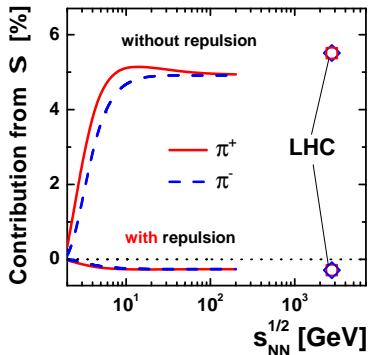


Kaminski, Acta Phys. Polon. Supp. (2015); Garcia-Martin, Kaminski, Pelaez, Ruiz de Elvira, Phys. Rev. Lett. (2011)

# Cancellation of the sigma meson in thermal models



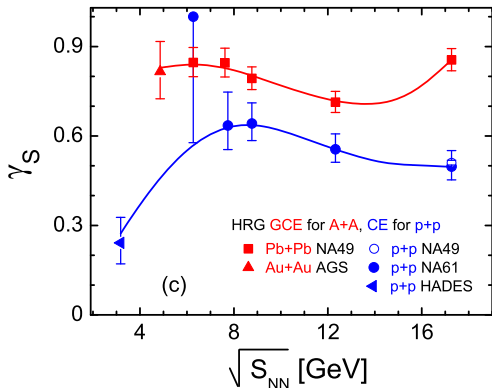
Andronic, Braun-Munzinger, Stachel, PLB (2009)



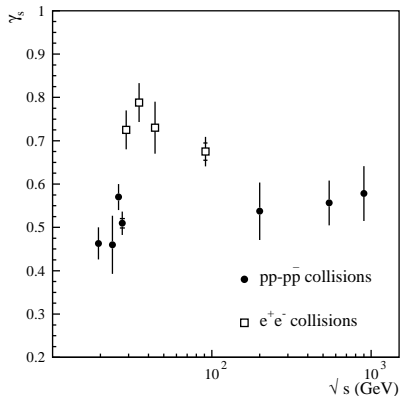
V.B., Broniowski, Giacosa, PRC (2015)

- The contribution from  $\sigma$  **cancels** in **all** isospin-averaged **observables**
- The  $K/\pi$  **horn** can **not** be explained by the  $\sigma$
- **All ratios to pions**, and therefore the extracted **temperatures** are **affected**.

# Strangeness saturation factor in A+A (GCE) and p+p (CE)



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



Becattini, Heinz ZPC (1997)

- The **unexpected** finding is the **decrease** of  $\gamma_s$  parameter with collision energy in p+p collisions in the SPS energy region.
- However, it agrees with the known  $\gamma_s$ , which was calculated starting from the energy  $\sqrt{s_{NN}} = 19.4$  GeV or  $E_{lab} \approx 200A$  GeV.

For a relativistic system in equilibrium consisting of one sort of positively,  $N_+$ , and negatively charged particles  $N_-$ , with total charge equal to  $Q_{c.e.} = N_+ - N_-$ . In the case of the Boltzmann ideal gas in the volume  $V$  and at temperature  $T$  the GCE and CE partition functions read:

$$Z_{GCE}(T, V, \mu_Q) = \sum_{N_+=0}^{\infty} \sum_{N_-=0}^{\infty} \frac{z^{N_+}}{N_+!} \frac{z^{N_-}}{N_-!} e^{\mu_Q(N_+ - N_-)/T} = \exp(2z \cosh[\mu_Q/T]),$$

$$Z_{CE}(T, V, Q) = \sum_{N_+=0}^{\infty} \sum_{N_-=0}^{\infty} \frac{z^{N_+}}{N_+!} \frac{z^{N_-}}{N_-!} \delta(Q - [N_+ - N_-]) = I_Q(2z),$$

where  $z$  is a single particle partition function:

$$z = \frac{gV}{2\pi^2} \int_0^{\infty} p^2 dp e^{-\frac{\sqrt{p^2+m^2}}{T}},$$

$g$  is a degeneracy factor (number of spin states),  $m$  - particle mass. The average values in both the GCE and CE can be calculated as follows:

$$\langle N_{\pm} \rangle \equiv \frac{1}{Z} \sum_{N_+=0}^{\infty} \sum_{N_-=0}^{\infty} N_{\pm} Z_{N_+, N_-}$$

In thermodynamic limit,  $V \rightarrow \infty$ , and for  $Q = 0$  one obtains:

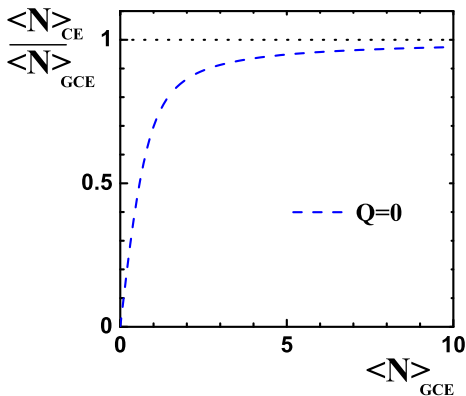
$$\langle N_{\pm} \rangle_{GCE} = z, \quad \langle N_{\pm} \rangle_{CE} \cong z \left( 1 - \frac{1}{4z} \right),$$

The canonical suppression can be compensated by the increase of temperature in CE  $T_{CE} > T_{GCE}$ .

For heavy ( $m \gg T$ ) particles one has

(V.B., Ferroni, Gorenstein, Gazdzicki, Becattini, JPG (2006)):

$$\frac{\langle N_{\pm} \rangle_{CE}}{\langle N_{\pm} \rangle_{GCE}} \sim \exp \left[ m \left( \frac{1}{T_{GCE}} - \frac{1}{T_{CE}} \right) \right]$$

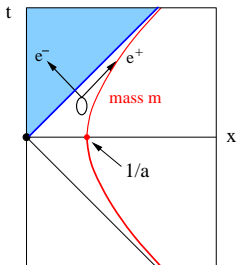


- **Charge conservation** strongly **suppress mean multiplicities**
- The **thermodynamic limit** is reached very quickly at  $\langle N_{\pm} \rangle \simeq 1$
- The **temperature** in **CE** can be much **higher** than in the **GCE**
- One **should use** the **ensemble that** better **suits** the studied **system**. In practice for  $y \simeq 0$  or  $\langle N \rangle \gg 1$  **GCE** is enough, for the values **integrated** over  $y$  and  $\langle N \rangle \ll 1$  **CE** should be used.

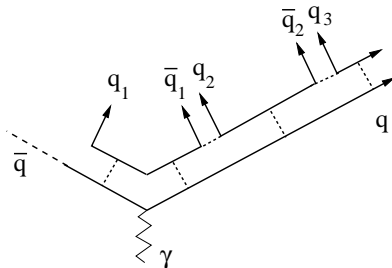
# A possible mechanism of thermal production in p+p and A+A:

## Hadronization due to QCD analog of Hawking radiation by black holes:

A pair creation close to a black hole:



A string breaking through pair production:



Castorina, Kharzeev, Satz, EPJ (2007)

- Due to **confinement**, the vacuum forms an **event horizon** for quarks and gluons, similar to black holes
- The **information** is **not transmitted** and the **radiation** is, therefore, **thermal**
- The **temperature** is defined by the force on the confinement surface, which is given by a **string tension** between  $q\bar{q}$  pair