

Surprises for the chemical freeze-out line from the new data in p+p and A+A collisions

Viktor Begun

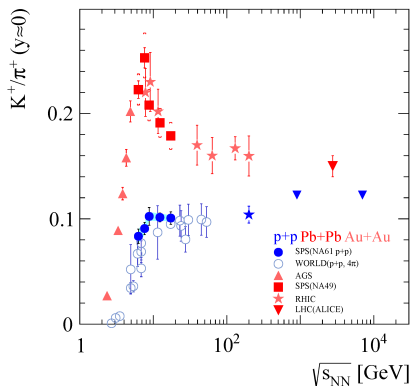
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in collaboration with

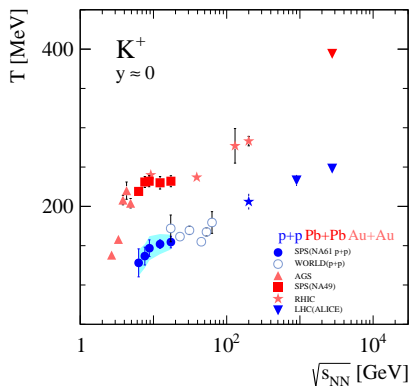
V. Vovchenko and M. I. Gorenstein, arXiv: **1512.08025**

CPOD 2016, May 30th - June 4th, 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 30 A GeV
- It is **important to know** the "**baseline**": the effects of the **non-QGP phenomena**
- The NA49 and **NA61/SHINE data** are much more precise – **test for the models**

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

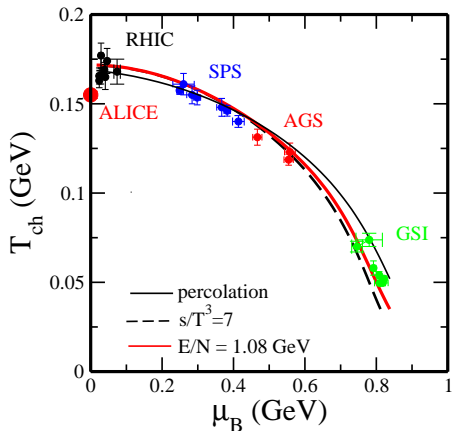
$$\ln Z_k^{\text{stable,res}} = g_k V \int \frac{d^3 p}{(2\pi)^3} \ln [1 \pm e^{(\mu - E_p)/T}]^{\pm 1}$$

where g_k is the spin-isospin degeneracy, V - **volume**, T - **temperature**, μ - **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:

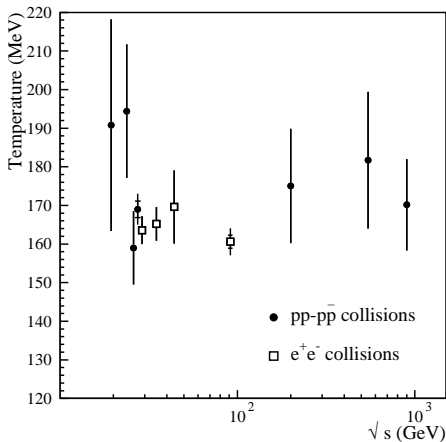
$$\ln Z_k^{\text{res}} = g_k V \int d_k(M) dM \int \frac{d^3 p}{(2\pi)^3} \ln [1 - e^{(\mu - E_p)/T}]^{-1}$$

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:

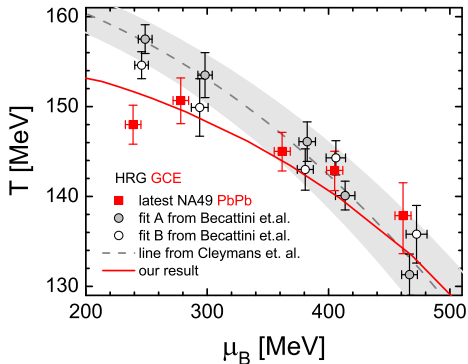
- The extension of the **list of particles**
- The changes in the experimentally **measured particle set**

We have analyzed different cuts for the maximal resonance mass, M_{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 for larger collision 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 ϕ , $K^*(892)$, 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, arXiv:1512.08025

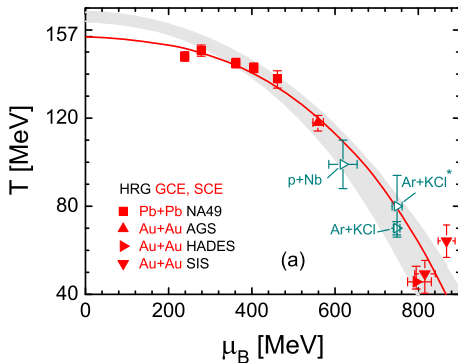
The grey band is the parametrization
(Cleymans, Oeschler, Redlich, Wheaton, PRC (2006)):

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

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

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

a = 0.157 GeV, **b** = 0.087 GeV⁻¹,
c = 0.092 GeV⁻³, **d** = 1.477 GeV,
e = 0.343 GeV⁻¹.



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

- 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 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**.

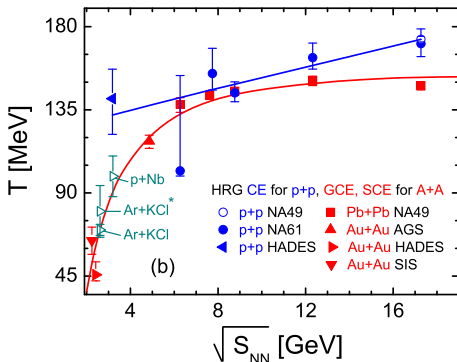
Temperature in A+A (GCE) and p+p (CE)

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 γ_S (next slides).

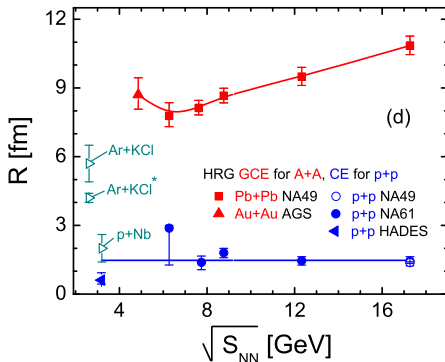
- **Larger error bars** for the p+p **NA61/SHINE** are due to **smaller number** of measured **particles** compared to **NA49** (5 vs 18)
- The analysis of the **p+p NA49** shows that the **minimal set** of fitted **multiplicities** should include particles possessing **all three conserved charges**, **B**, **S**, **Q**, for both **p+p** and **A+A**. For example, an appropriate set may include π^\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, arXiv:1512.08025

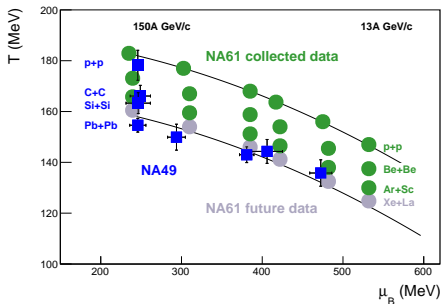
Radius of the system in A+A (GCE) and p+p (CE)

- 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.

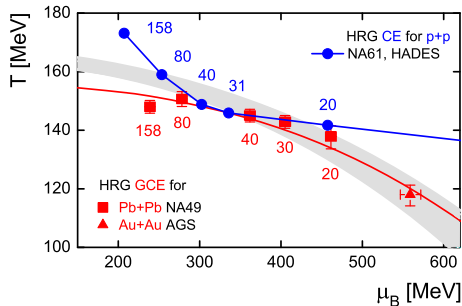


V.B., Vovchenko, Gorenstein, arXiv:1512.08025

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.



Gazdzicki, Seyboth, arXiv:1506.08141



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

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

- 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 crosses** the **A+A** line in the **vicinity** of the **K^+/π^+ 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, π^\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

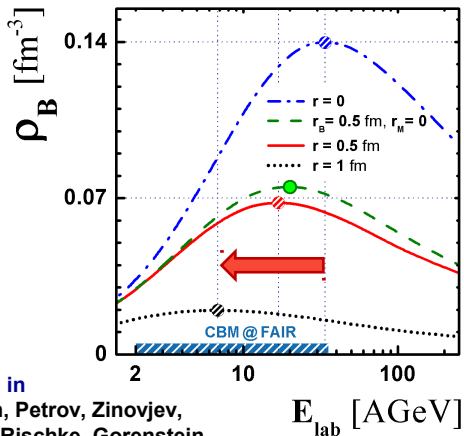
$$P = \sum_i P_i^{\text{id}}(T, \tilde{\mu}_i)$$

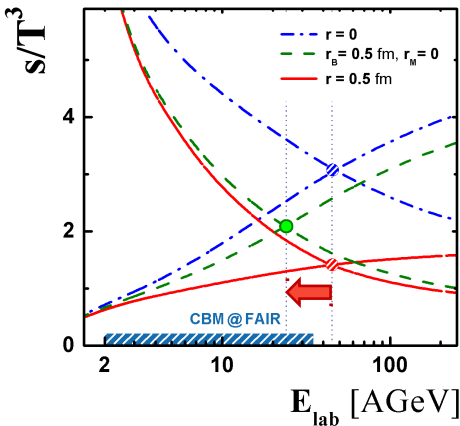
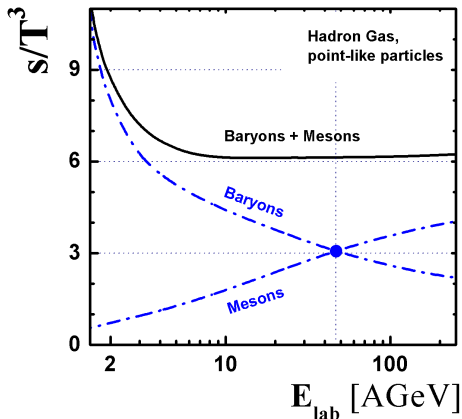
Introduced in

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)



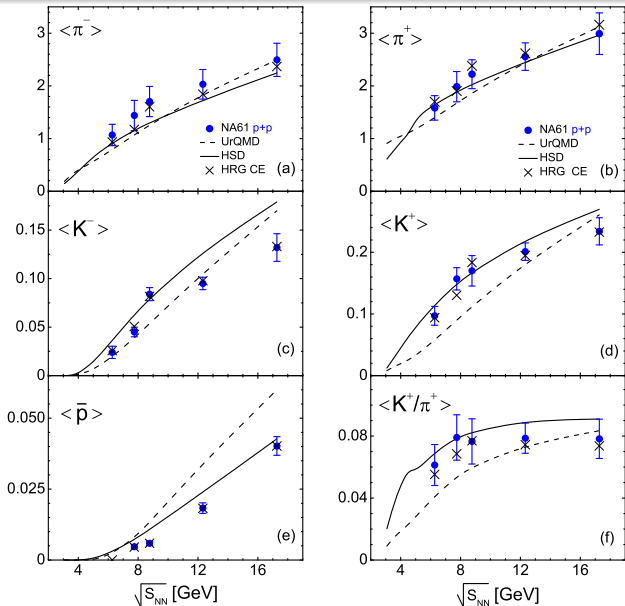


The transition point of baryon/meson domination moves to lower energies only for different meson and baryon radii

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



Interacting hadron gas

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** δ :

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

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

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

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

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

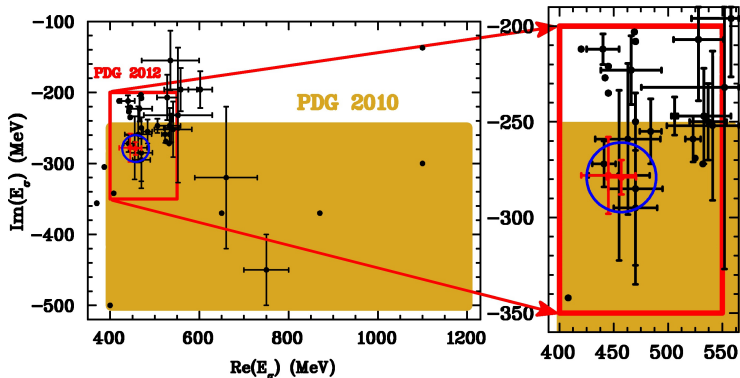
In the limit $R \rightarrow \infty$, upon subtraction,

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

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

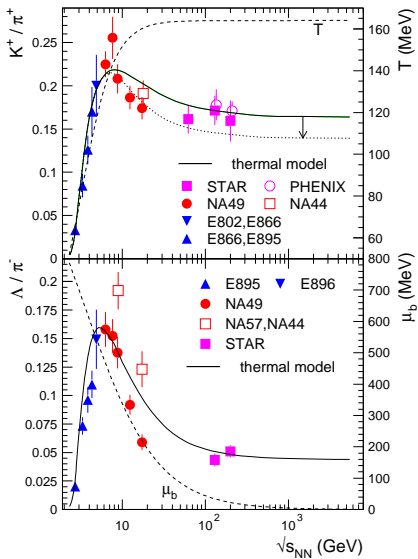
Can the data be explained by the updated sigma?

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

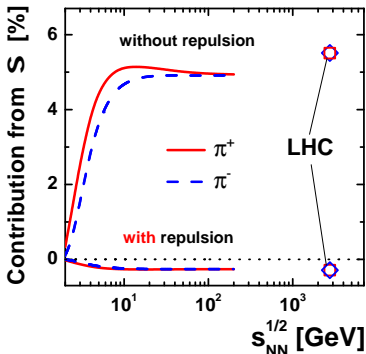


Kaminski, Acta Phys. Polon. Supp. (2015); Garcia-Martin, Kaminski, Pelaez, Ruiz de Elvira, Phys. Rev. Lett. (2011)

Cancellation of the sigma meson in thermal models



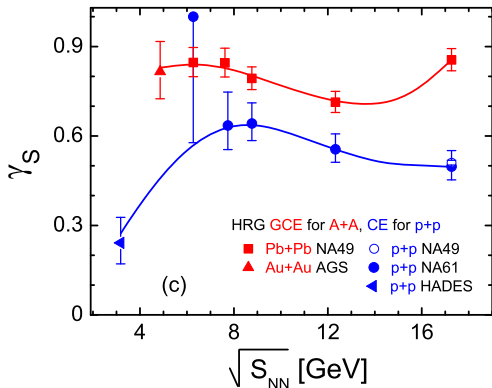
Andronic, Braun-Munzinger, Stachel, PLB (2009)



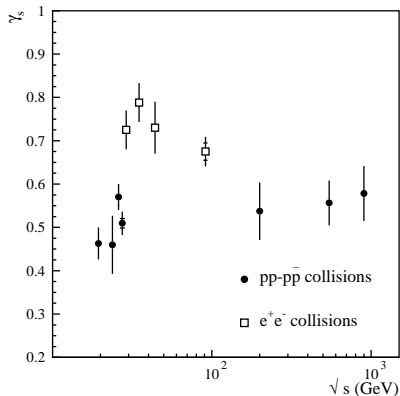
V.B., Broniowski, Giacosa, PRC (2015)

- The contribution from σ **cancels** in **all** isospin-averaged **observables**
- The K/π **horn** can **not** be explained by the σ
- **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, arXiv:1512.08025



Becattini, Heinz ZPC (1997)

- The **unexpected** finding is the **decrease** of γ_S parameter with collision energy in p+p collisions in the SPS energy region.
- However, it agrees with the known γ_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:

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

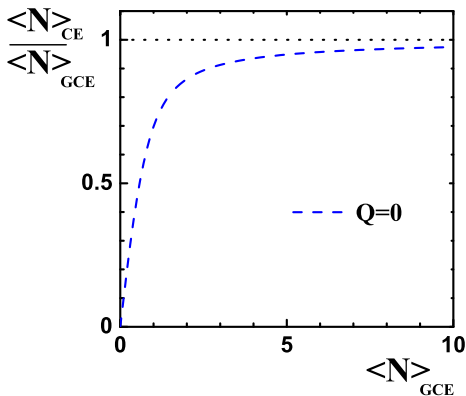
The canonical suppression can be compensated by the increase of temperature in CE $T_{CE} > T_{GCE}$.

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

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

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

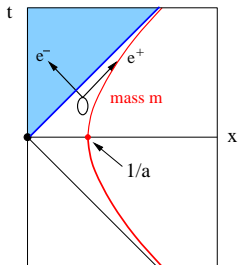
- **Charge conservation** strongly **suppress mean multiplicities**
- The **thermodynamic limit** is reached very quickly at $\langle N_{\pm} \rangle \simeq 5$
- The **temperature** in **CE** can be much **higher** than in the **GCE**
- One **should use** the **ensemble that** better **suits** the studied **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.



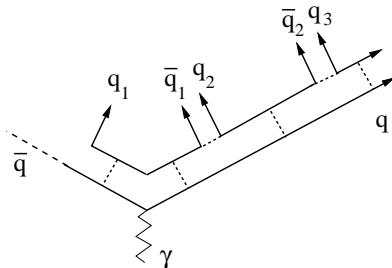
A possible mechanism of thermal production in p+p and A+A:

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