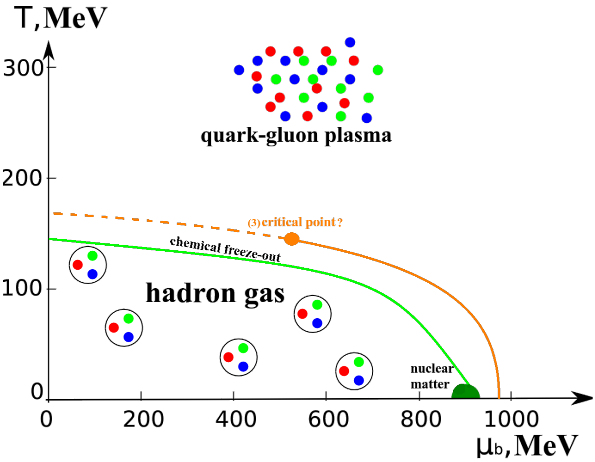
On chemical (non)equilibrium of strange hadrons at freeze-out stage of nuclear-nuclear collisions

V. V. Sagun[1], K. A. Bugaev[1], D. R. Oliinychenko[1,2], J. Cleymans[3]
A. I. Ivanytskyi[1], I. N. Mishustin[2,4], E. G. Nikonov[5] and G.M. Zinovjev[1]

[1] *Bogolyubov Institute for Theoretical Physics, Metrologichna str. 14^B, Kiev 03680, Ukraine*
[2] *FIAS, Ruth-Moufang Str. 1, 60438 Frankfurt upon Main, Germany*
[3] *Department of Physics, University of Cape Town, Rondebosch 7701, South Africa*
[4] *Kurchatov Institute, Russian Research Center, Kurchatov Sqr., Moscow, 123182, Russia*
[5] *Laboratory for Information Technologies, JINR, Joliot-Curie str. 6, 141980 Dubna, Russia*

Erice, 2015

Strongly interacting matter phase diagram



Hadron resonance gas model (HRGM)

- Basic assumption – **thermal/chemical equilibrium** $\Rightarrow$ parameters: T, μ_B, μ_{I3}
  P. Braun-Munzinger et al., Phys. Lett. B 344, 43, (1995)
  J. Cleymans et al., Z. Phys. C 74, 319 (1997)

- HRGM accounts for all hadrons from PDG tables with masses up to 3.2 GeV
  K.A. Bugaev et al., Eur. Phys. J. A 49, 30 (2013)

- Hadronic gas – mixture with **multicomponent hard-core repulsion** $\Rightarrow$ equation of state of the **Van der Wals type**

Hadron Resonance Gas Model (HRGM)

- Traditional HRGM: one hard-core radius $R = 0.25 - 0.3$ fm

  A. Andronic, P.Braun-Munzinger, J. Stachel, NPA (2006)777

- two hard-core radii: $R_{\pi} = 0.62$ fm, $R_{other} = 0.8$ fm

  G. D.Yen. M. Gorenstein, W. Greiner, S.N. Yang, PRC (1997)56

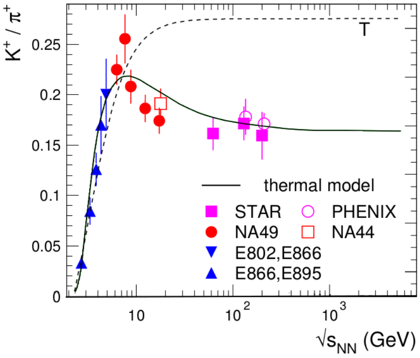
  or: $R_{mesons} = 0.25$ fm, $R_{baryons} = 0.3$ fm

  A. Andronic, P.Braun-Munzinger, J. Stachel, NPA (2006) 777, PLB (2009) 673

There is still a problem with strange particle description!

Problems with description K^+/π^+ and Λ/π^- ratios

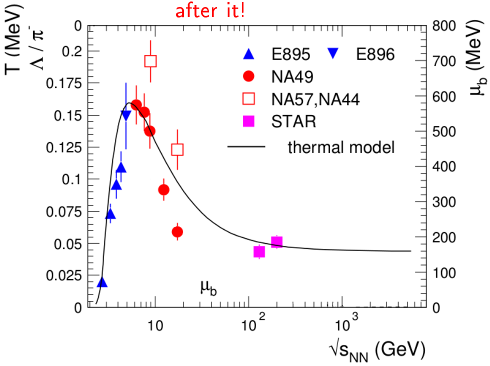
Too slow decrease after maximum!



$\chi^2/dof = 21/12$

A. Andronic, P.Braun-Munzinger, J. Stachel, PLB (2009) 673

Too steep increase before maximum and too slow decrease after it!



$\chi^2/dof = 79/12$

$\gamma_S \simeq 0.85 - 1.05$

"Anti-lambda problem"

These authors FORGOT about the second virial coefficient between different sorts of hadrons

Hadron Resonance Gas Model

One component gas: $p = p^{id.gas} \cdot exp\left(-\frac{pV^{exc}}{T}\right)$

Multicomponent case: $p = \sum_{i=1}^{\infty} p_i^{id.gas}(\mu_i) \sum_{j=1}^{\infty} exp\left(-\frac{p_i V_{ij}^{exc}}{T}\right)$

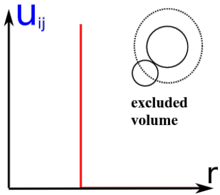
All hadrons are in full chemical equilibrium

The number of particles of i-th sort:

$$N_i = \phi_i(T, m_i, g_i) e^{\frac{\mu_i}{T}} \equiv \frac{g_i V}{(2\pi)^3} \int exp\left(\frac{-\sqrt{k^2 + m_i^2} + \mu_i}{T}\right) d^3k$$

hard-core repulsion of the Van der Waals type

$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3_i}, \; i = 1..s$



g_i - degeneracy factor

ϕ_i -thermal particle density

$V_{ij}^{exc} = \frac{2\pi}{3}(R_i + R_j)^3$ - excluded volume

Bugaev K. A., Oliinychenko D. R., Sorin A. S. and Zinovjev G. M.,Eur. Phys. J. A 49 (2013) 30–1-8.

Hadron Resonance Gas Model

K-th charge density of the i-th hadron sort n_i^k (K $\in$ [B, S, I_3])
$\mathcal{B}$ - symmetric matrix of the second virial coefficients with the elements $V_{ij} \equiv \frac{2\pi}{3}(R_i + R_j)^3$

$$p = T\sum_{i=1}^{N}\xi_i, \quad \xi = \begin{pmatrix}\xi_1\\ \xi_2\\ \ldots\\ \xi_s\end{pmatrix}, \quad n_i^K = Q_i^K \xi_i \left[1 + \frac{\xi^T \mathcal{B}\xi}{\sum_{j=1}^{N}\xi_j}\right]^{-1}, \qquad (1)$$

ξ_i are the solutions of the following system:

$$\xi_i = \phi_i(T)\exp\left(\frac{\mu_i}{T} - \sum_{j=1}^{N}2\xi_j V_{ij} + \frac{\xi^T\mathcal{B}\xi}{\sum_{j=1}^{N}\xi_j}\right), \quad \phi_i(T) = \frac{g_i}{(2\pi)^3}\int \exp\left(-\frac{\sqrt{k^2+m_i^2}}{T}\right)d^3k$$

$\phi_i(T)$– thermal particle density
$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3_i}$ – chemical potential of the i-th hadron sort

Q_K – charge, m_i – mass, g_i – degeneracy

Strange particles non equilibrium

$$\phi_i(T) \to \phi_i(T)\gamma_s^{s_i}$$

s_i — number of strange valence quarks and anti-quarks.
Thus, it is a strangeness fugacity

J. Rafelski, Phys. Lett. B 62, 333 (1991);

$\gamma_s > 1 \Longrightarrow$ strangeness enhancement $\to$ quark-gluon plasma formation ???

J. Rafelski, B. Muller, PRL 48, p. 1066 - 1069 (1982)

$\gamma_s < 1 \Longrightarrow$ strangeness suppression

Fit parameters: $T, \mu_B, \mu_{I_3}, \gamma_s$

μ_S – is found from the net zero strangeness condition.

K. A. Bugaev et al., EPJ A 49, 30–1-8 (2013);
K. A. Bugaev et al., EPL 104, 22002, p.1 - 6 (2013)

- Resonance decay:

$$n^{fin}(X) = \sum_{Y} BR(Y \to X) n^{th}(Y),$$

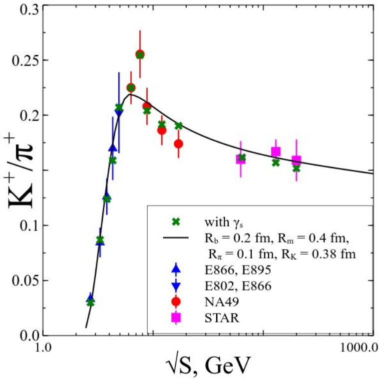
where $BR(X \to X) = 1$,
BR=BRANCHING RATIO (taken from PDG);

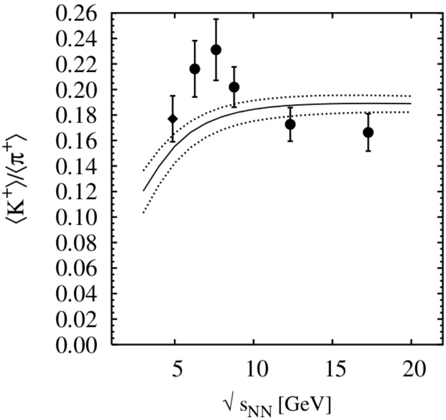
- Width correction:

$$\int exp\left(\frac{-\sqrt{k^2+m_i^2}}{T}\right) d^3k \to \frac{\int_{M_0}^{\infty} \frac{dx_i}{(x-m_i)^2+\Gamma^2/4} \int exp\left(\frac{-\sqrt{k^2+x^2}}{T}\right) d^3k}{\int_{M_0}^{\infty} \frac{dx_i}{(x-m_i)^2+\Gamma^2/4}},$$

Breit-Wigner distribution having a threshold M_0,
m - resonance mass,
Γ - resonance width.

- Ratios:
$R_{ij} = \frac{N_i}{N_j} = \frac{\rho_i}{\rho_j}$ $\Rightarrow$ volume is excluded





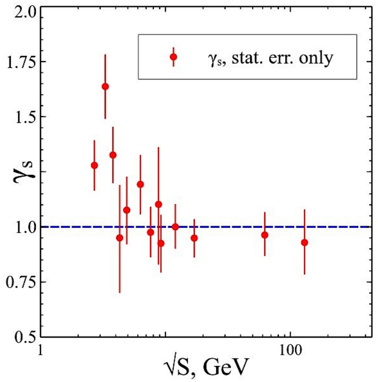
Description of K^+/π^+ ratio with $\chi^2/dof = 3.3/14$.

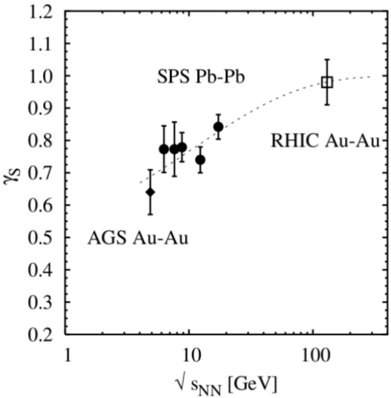
F. Becattini et al., PR C 73 044905 (2006)

We fitted 111 hadron yield ratios measured for 14 $\sqrt{s_{NN}}$ values

$R_{pions} = 0.1$ fm, $R_{kaons} = 0.38$ fm, $R_{mesons} = 0.4$ fm, $R_{baryons} = 0.2$ fm.

Model parameter - γ_s





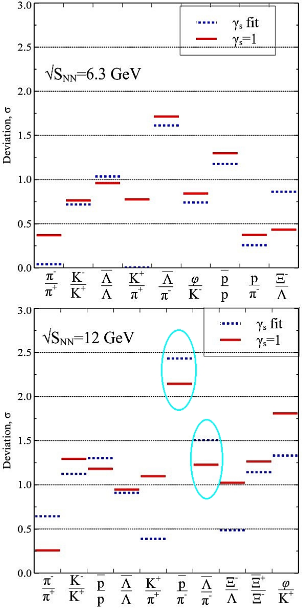
F. Becattini et al., PR C 73 044905 (2006)

In contrast to F. Becattini et al., PR C **73** 044905 (2006), we find $\gamma_s > 1$ for $\sqrt{s_{NN}} =$ 2.7, 3.3, 3.8, 4.9, 6.3, 9.2 GeV

$\Longrightarrow$ Strangeness enhancement

Strangeness enhancement exists where we do not expect deconfinement!

Hadron Resonance Gas Model fit



γ_s fit $\chi^2/dof = 63.4/55 \simeq 1.15$.

$$\sigma = \frac{|r^{theor} - r^{exp}|}{\sigma^{exp}}$$ – relative deviation

$$\chi^2 = \sum_i \frac{(r_i^{theor} - r_i^{exp})^2}{\sigma_i^2},$$

r_i^{exp} - experimental value of i-th particle ratio,
r_i^{theor} - theoretical value of i-th particle ratio
σ_i - total error of experimental value.

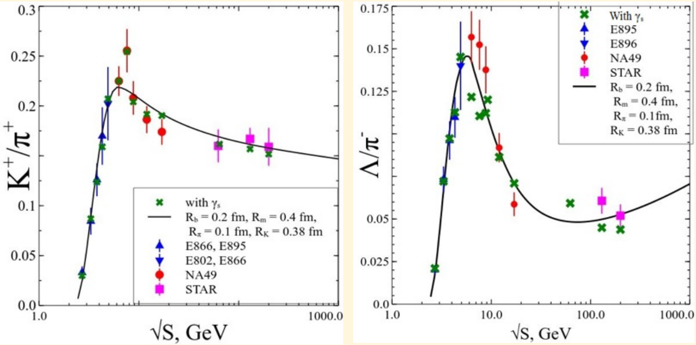
K.A. Bugaev, D.R.Oliinychenko, J. Cleymans, A.I. Ivanytskyi, I.N. Mishustin, E.G. Nikonov, VVS, Europhys. Lett. **104** (2013) 22002.

Strangeness Horn and Λ Horn in 2013

High quality description of hadron multiplicities requires T, μ_B, μ_{I3}

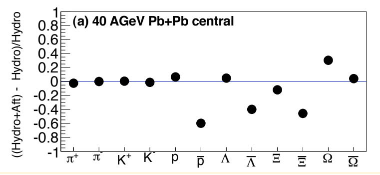
Include γ_s factor $\phi_i(T) \to \phi_i(T)\gamma_s^{s_i}$, **into thermal density**

γ_S factor is a strangeness fugacity



Solving problem with Kaons lead to (anti)Λ selective suppression!

Solutions of (anti)Λ selective Suppression



F. Becattini et al., Phys.Rev. C85 (2012) 044921

Use these deviations from UrQMD as new suppression factor!

Our solution:

1. Introduce Hard core radius for (anti)Λ hyperons

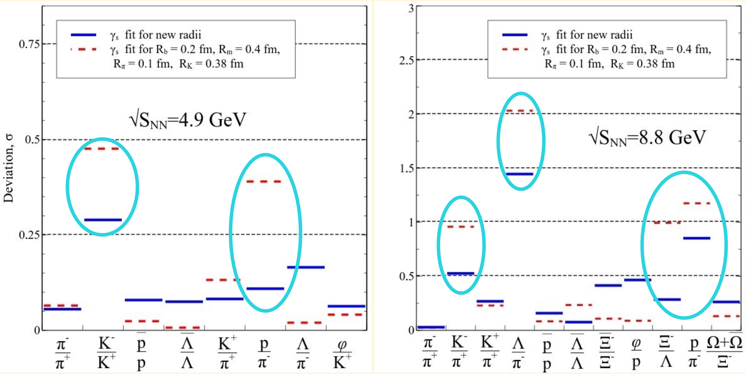
2. Refit globally all hard core radii:

=> R_pi =0.1 fm, R_Λ =0.1 fm, R_b =0.36 fm, R_K=0.38 fm, R_m =0.4 fm

V. V. Sagun, **Ukr. J. Phys.** 59, No 8, 755-763 (2014)

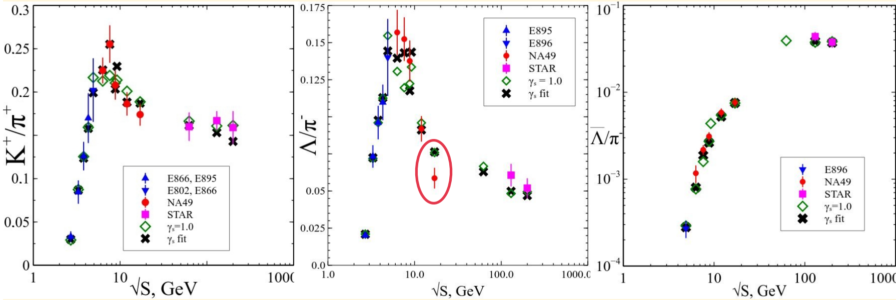
V. V. Sagun, D. R. Oliinychenko, K. A. Bugaev, J. Cleymans, A. I. Ivanytskyi, I. N. Mishustin and E. G. Nikonov, **Ukr. J. Phys.** 59, No 11, 1043-1050 (2014)

Strangeness Horn and Λ Horn in 2014



Strangeness Horn and Λ Horn in 2014

With new radii and γ_s fit



$\chi^2/12 = 10.22/12$

$\chi^2/8 = 6.49/8$

Total fit of 111 independent hadron ratios is the best of existing!

$$\chi^2/dof = 52/55 \simeq 0.95.$$

Conclusions

- We suggested a new way to overcome the Λ hyperon selective suppression, which is known as the Λ-anomaly;
- with our HRGM the high quality fit is achieved for 111 independent hadron ratios measured at 14 values of the center of mass energy $\sqrt{s_{NN}}$ at the AGS, SPS and RHIC with the accuracy $\chi^2/dof = 52/55 \simeq 0.95$;
- with high confidence we conclude that the apparent chemical non-equilibration of strange particles has nothing to do with the formation of quark-gluon plasma in nuclear-nuclear collisions;
- using the multicomponent HRGM we can study thermodynamics at chemical freeze-out.

thank you for your attention!