Evidences of the quark-gluon plasma formation in central nuclear collisions

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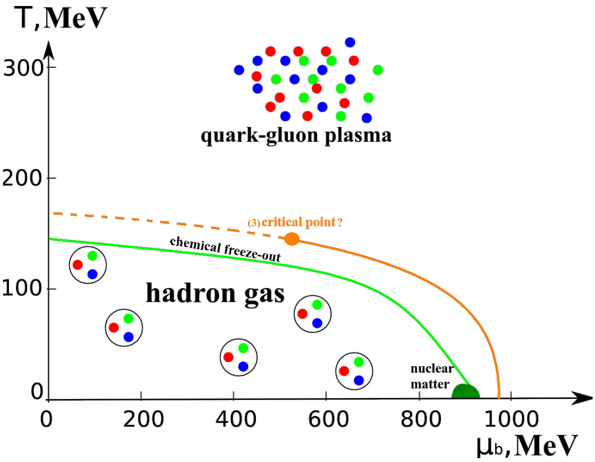
Strongly interacting matter phase diagram



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)

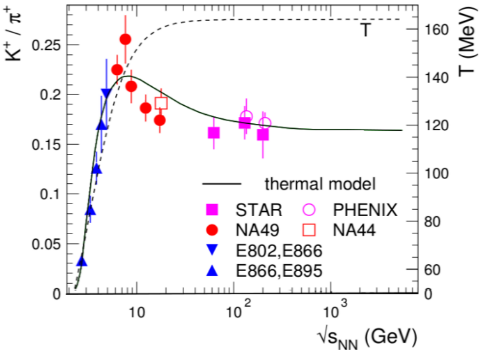
- HRGM accounts for all hadrons from PDG tables with masses up to 3.2 GeV

  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**

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

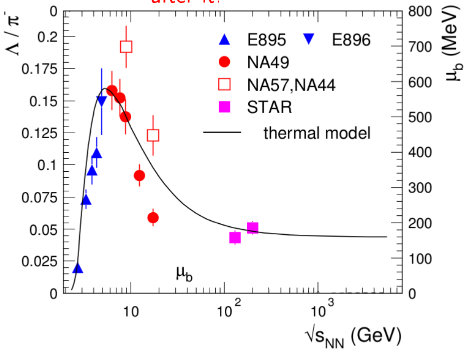
Too slow decrease after maximum!



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

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

Multicomponent case: $p = \sum_i p_i = \sum_i T\phi_i \exp\left[\frac{\mu_i - 2\sum_j p_j V_{ji} + \sum_{jl} p_j V_{jl} p_l / p}{T}\right]$

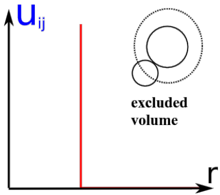
All hadrons are in full chemical equilibrium

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

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

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

R_{pions}, R_{kaons}, R_{mesons}, $R_{baryons}$, R_{lambda} - fixed hard-core radii.
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)

Hadron Resonance Gas Model corrections

- 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:

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

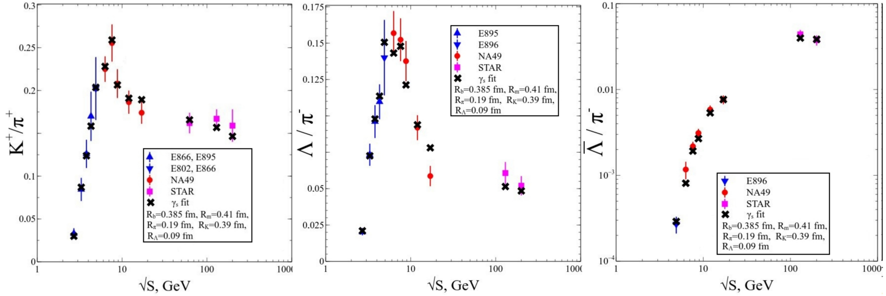
Breit-Wigner distribution having a threshold M_0,
m - resonance mass,
Γ - resonance width.

- Ratios:

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

Strangeness Horn and Λ Horn

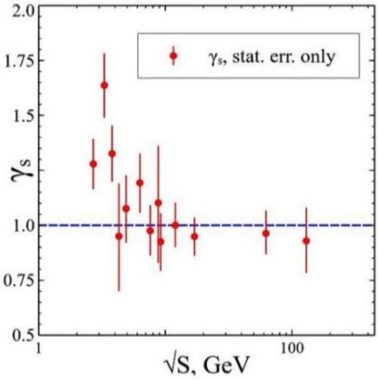
With new radii and γ_s fit

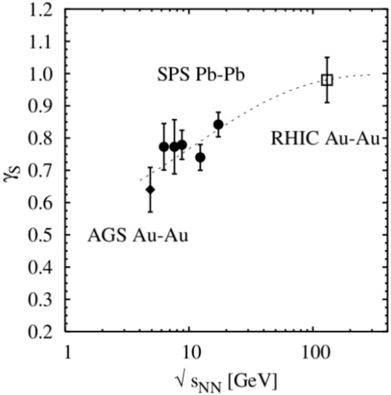


Total fit of 121 hadron ratios is the best of existing!

$$\chi^2/dof = 63.978/65 \approx 0.98$$

Model parameter - γ_s





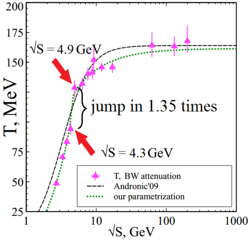
F. Becattini et al., PR C 73 044905 (2006)

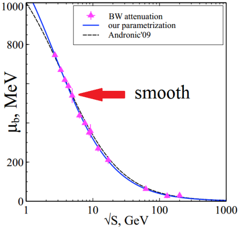
In contrast to F. Becattini et al., PR C **73** 044905 (2006), we find $\gamma_s > 1$ for $\sqrt{s_{NN}} =$ 2.7, 3.3, 3.8, 4.9, 6.3, 9.2 GeV

$\Longrightarrow$ Strangeness enhancement

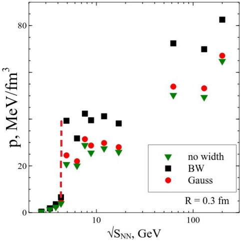
Jump of ChFO Pressure at AGS Energies

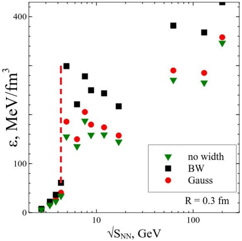
- Temperature T_{CFO} as a function of collision energy $\sqrt{s}$ is rather non smooth





- Significant jump of pressure ($\simeq$ 6 times) and energy density ($\simeq$ 5 times)





K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015) [arXiv:1405.3575];
Ukr. J. Phys. 60 (2015) [arXiv:1312.4367]

Correlated Quasi-Plateaus

Mixed phase has anomalous thermodynamic properties => plateau in collision energy dependence of entropy per baryon!

K.A. Bugaev, M.I. Gorenstein, B. Kampher, V.I. Zhdanov, Phys. Rev. D 40, 9, (1989)
K.A. Bugaev, M.I. Gorenstein, D.H. Rischke, Phys. Lett. B 255, 1, 18 (1991)

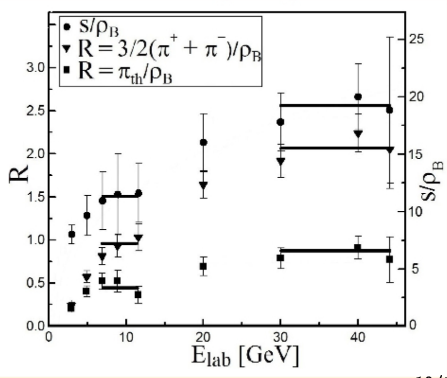
Since the main part of the system entropy is defined by thermal pions =>
thermal pions/baryon should have a plateau too!

Also the total number of **pions per baryons should have a (quasi)plateau!**

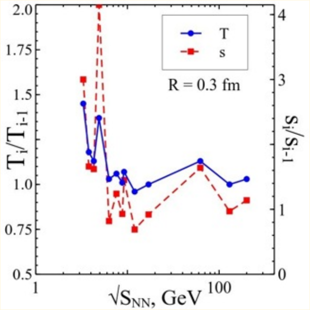
Entropy per baryon has wide plateaus due to large errors

Quasi-plateau in total pions per baryon ?

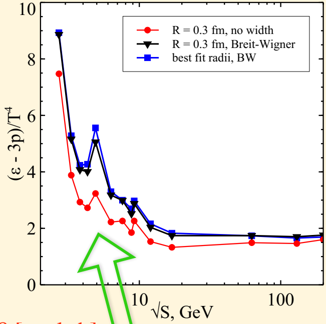
Thermal pions demonstrate 2 plateaus



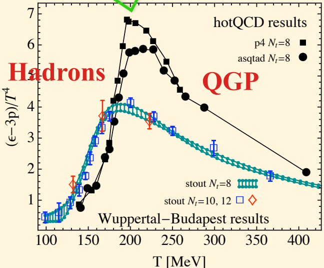
Jump of Entropy Density and Trace Anomaly Peak



These peaks are at same energy



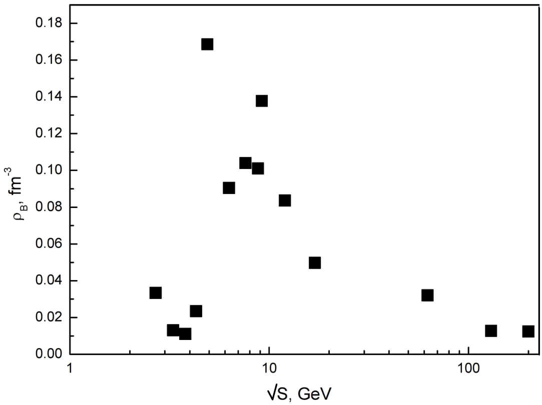
K.A. Bugaev et al., arXiv:1412.0718 [nucl-th]



Are these trace anomaly peaks related to each other?

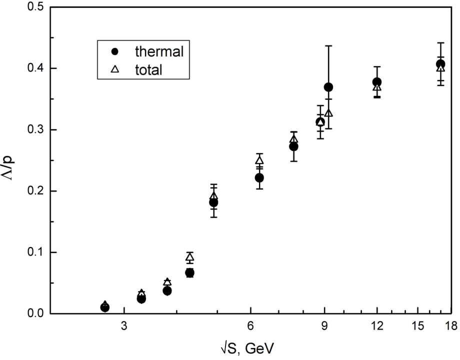
WupBud EOS arxive: lat 1007.2580

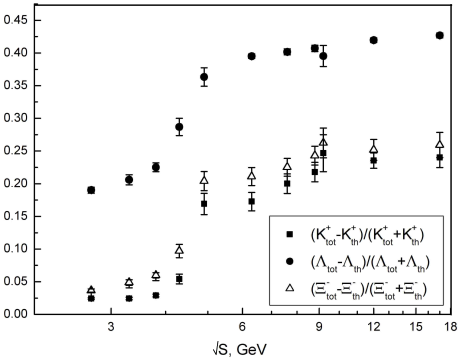
Baryonic density as functions of collision energy at CFO



Sharp peak of the baryonic charge density at $\sqrt{s_{NN}} = 4.9$ GeV

Irregularities in hadron production





In 1982 J. Rafelski and B. Müller predicted that enhancement of strangeness production is a signal of deconfinement

Phys. Rev. Lett. 48(1982)

total to thermal particle yields asymmetry indicating a significant role of the particle decays at CFO

freeze-out

Narrow collision energy range $\sqrt{s_{NN}}$ = 4.3-4.9 GeV

Conclusions

- With our HRGM the high quality fit is achieved for 121 hadron ratios measured at 14 values of the center of mass energy $\sqrt{s_{NN}}$ at the AGS, SPS and RHIC with the accuracy $\chi^2/dof = 63.978/65 \simeq 0.98$;
- high quality description of the chemical FO data allowed us to find few novel irregularities in the collision energy range $\sqrt{s_{NN}} =$ 4.3-4.9 GeV (pressure, energy density jumps and correlated plateaus);
- in addition, we found a sharp peak of the trace anomaly $\delta = \frac{\varepsilon - 3p}{T^4}$ and baryonic charge density at $\sqrt{s_{NN}} = 4.9$ GeV;
- these irregularities are also accompanied by the total to thermal particle yields asymmetry, i.e. $\frac{K^+_{tot} - K^+_{th}}{K^+_{tot} + K^+_{th}}$, $\frac{\Lambda_{tot} - \Lambda_{th}}{\Lambda_{tot} + \Lambda_{th}}$, $\frac{\Xi^-_{tot} - \Xi^-_{th}}{\Xi^-_{tot} + \Xi^-_{th}}$, indicating a significant role of the particle decays at chemical freeze-out;
- we conclude that a dramatic change in the system properties seen in the narrow collision energy range $\sqrt{s_{NN}} = 4.3 - 4.9$ GeV opens entirely new possibilities for experimental studies on FAIR and NICA.

thank you for your attention!