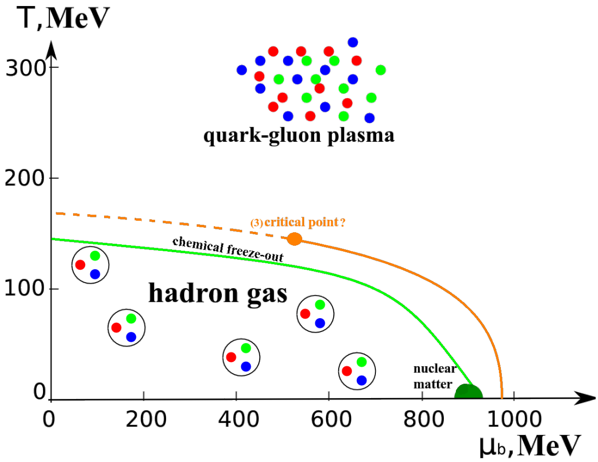
Chemical freeze-out irregularities as an evidence of quark-gluon plasma formation in nucleus-nucleus collisions

V. V. Sagun, K. A. Bugaev, A. I. Ivanytskyi, D. R. Oliinychenko, I.N. Mishustin, D.H. Rischke, L.M. Satarov and G.M. Zinovjev

JINR, October 31 - November 3, 2016

Strongly interacting matter phase diagram



Hadron resonance gas model (HRGM)

- Basic assumption – **thermal/chemical equilibrium** ⇒ 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 2.6 GeV

  K.A. Bugaev et al., Eur. Phys. J. A 49, 30 (2013)

- Hadronic gas – mixture of all **hadron species with hard-core repulsion** ⇒ equation of state of the **Van der Waals type**

HRG: a Multi-component Model

Traditional HRG model: one hard-core radius R=0.25-0.3 fm

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

Overall description of data (mid-rapidity or 4π multiplicities) is good!

But there are problems with K+/pi+ and Λ/pi- ratios at SPS energies!!! => Two component model was suggested

HRG: a Multi-component Model

Traditional HRG model: one hard-core radius R=0.25-0.3 fm

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

Overall description of data (mid-rapidity or 4π multiplicities) is good!

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

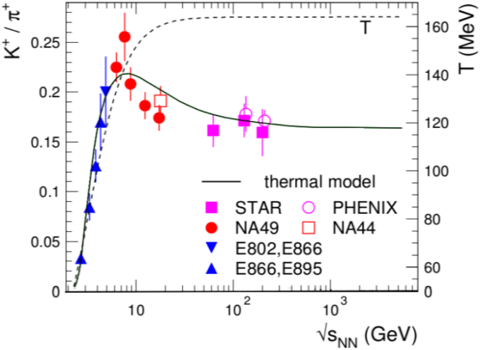
A. Andronic, P.Braun-Munzinger, J. Stachel, NPA (2006) 777 PLB (2009) 673

Two component models do not solve the problems!

Hence we need more sophisticated approach.

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

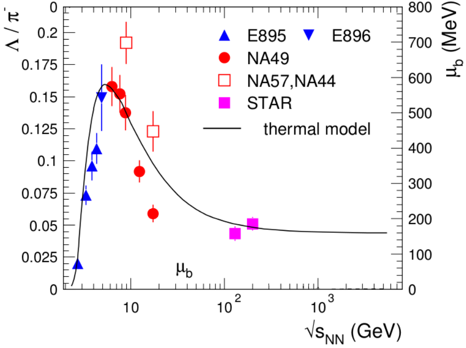
Too slow decrease after maximum!



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

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

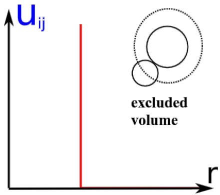
All hadrons are in full chemical equilibrium

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.

Wide Resonances Are Important

The resonance width is taken into account in thermal densities.

In contrast to many other groups we found that
wide resonances are VERY important in a thermal model.
For instance, description of pions cannot be achieved without

σ meson: $m_\sigma = 484 \pm 24$ MeV, width $\Gamma_\sigma = 510 \pm 20$ MeV

R. Garcia-Martin, J. R. Pelaez and F. J. Yndurain, PRD (2007) 76

$$n_X^{tot} = n_X^{thermal} + n_X^{decay} = n_X^{th} + \sum_Y n_Y^{th} Br(Y \to X)$$

$Br(Y \to X)$ is decay branching of Y-th hadron into hadron X

Hadron Resonance Gas Model corrections

- Width correction:

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

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

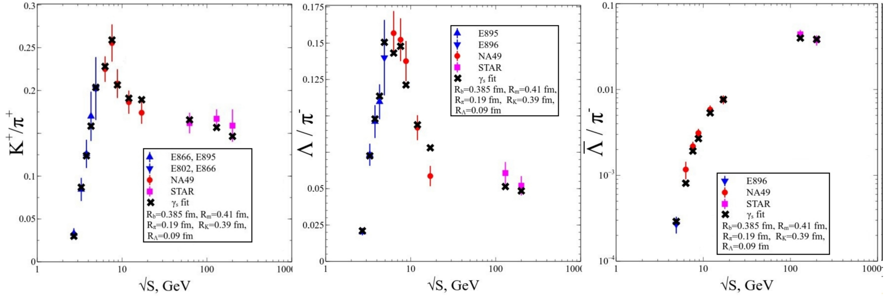
- Ratios:
$R_{ij} = \frac{N_i}{N_j} = \frac{\rho_i}{\rho_j} \quad \Rightarrow$ volume is excluded

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.

Strangeness Horn and Λ Horn

With new radii and γ_s fit



adding radius for Λ-hyperons help to overcome 'Λ-anomaly'
V. Sagun, UJP (2014)

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

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

Strangeness Enhancement as Deconfinement Signal

In 1982 J. Rafelski and B. Müller predicted that enhancement of strangeness production is a signal of deconfinement. **Phys. Rev. Lett. 48(1982)**

In 1991 J. Rafelski introduced strangeness fugacity γ_S **factor** **Phys. Lett. 62(1991)**

which quantifies strange charge chemical oversaturation (>1) or strange charge chemical undersaturation (<1)

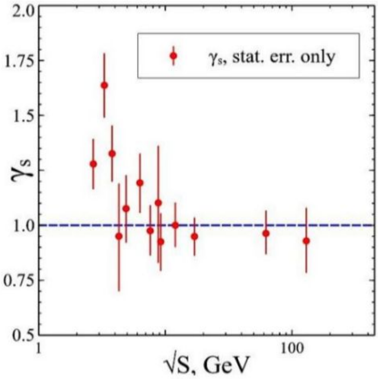
Idea: if s-(anti)quarks are created at QGP stage, then their number should not be changed during further evolution since s-(anti)quarks number is small and since density decreases => there is no chance for their annihilation!
Hence, we should observe chemical enhancement of strangeness with $\gamma_S > 1$

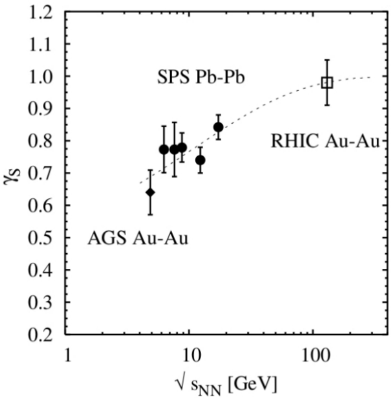
However, until 2013 the situation with strangeness was unclear:

P. Braun-Munzinger & Co found that γ_S factor is about 1

F. Becattini & Co found that γ_S factor is < 1

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

Intermediate Conclusions

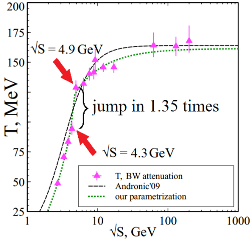
1. The multicomponent HRG model is a precise tool of HIC phenomenology

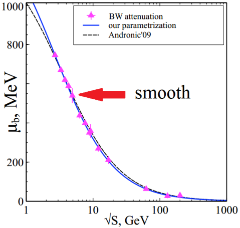
2. With high confidence we conclude that chemical enhancement of strangeness exists at very low energies where we do not expect deconfinement

3. Using multicomponent HRG model we can study thermodynamics at chemical freeze out

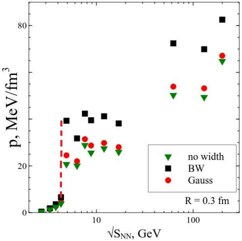
Jump of ChFO Pressure at AGS Energies

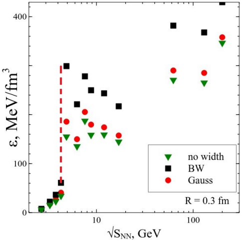
- Temperature T_{CFO} as a function of collision energy $\sqrt{s}$ is rather non smooth





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

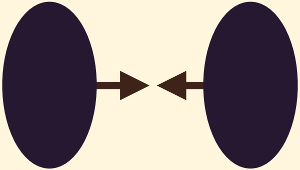




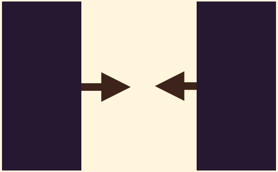
K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015) [arXiv:1405.3575];
Ukr. J. Phys. 60 (2015) [arXiv:1312.4367]

Shock Adiabat Model for A+A Collisions

A+A central collision at 1< Elab<30



Its hydrodynamic model



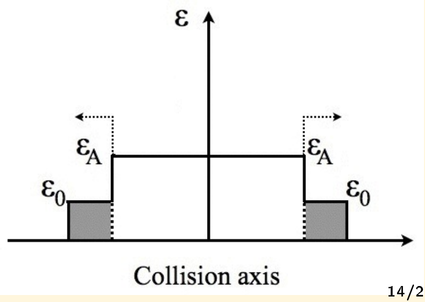
Works reasonably well at these energies.

H. Stoecker and W. Greiner, Phys. Rep. 137 (1986)

Yu.B. Ivanov, V.N. Russkikh, and V.D. Toneev,

Phys. Rev. C 73 (2006)

From hydrodynamic point of view
this is a problem of
arbitrary discontinuity decay:
in normal media there appeared
two shocks moving outwards



Medium with Normal and Anomalous Properties

Normal properties, if $\Sigma \equiv \left(\frac{\partial^2 p}{\partial X^2}\right)^{-1}_{s/\rho_B} > 0$ **= convex down:**

Usually pure phases (Hadron Gas, QGP) have normal properties

$X = \frac{\varepsilon + p}{\rho_B^2}$ – **generalized specific volume**

ε **is energy density,** p **is pressure,**

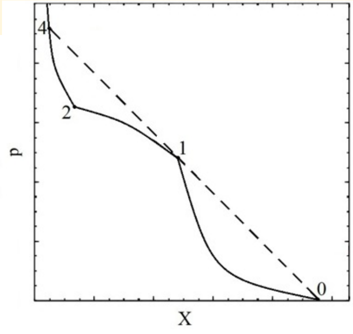
ρ_B **is baryonic charge density**

Anomalous properties otherwise.

Almost in all substances with liquid-gas phase transition the mixed phase has anomalous properties!

Then shock transitions to mixed phase are unstable and more complicated flows are possible.

Shock adiabat example

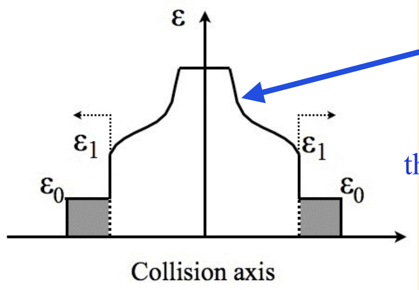


Region 1-2 is mixed phase with **anomalous properties.**

Generalized Shock Adiabat Model

In case of unstable shock transitions more complicated flows appear:

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)



shock 01 + compression simple wave

In each point of simple wave $\frac{s}{\rho_B} = \mathrm{const}$

If during expansion entropy conserves,
then unstable parts lead to entropy plateau!

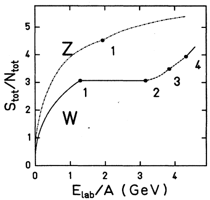


FIG. 9. The entropy per baryon as a function of the bombarding energy per nucleon of the colliding nuclei for models W and Z. The points 1, 2, 3, 4 on curve W correspond to those on the generalized adiabatic as displayed in Fig. 7. The point 1 on curve Z marks the boundary to the mixed phase.

Remarkably

Z model has stable RHT adiabat,
which leads to quasi plateau!

Correlated Quasi-Plateaus

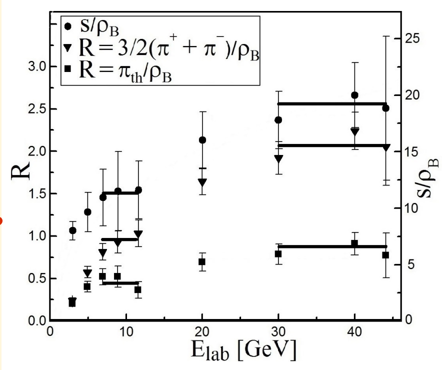
Since the main part of the system entropy is defined by thermal pions =>
thermal pions/baryon should have a plateau!

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

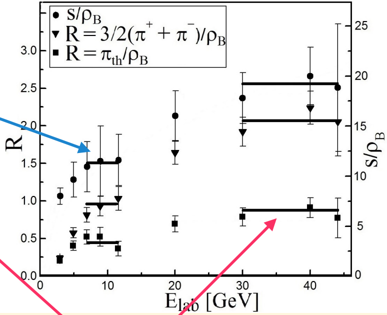


Details on Highly Correlated Quasi-Plateaus

- Common width M – number of points belonging to each plateau
- Common beginning i_0 – first point of each plateau
- For every M, i_0 minimization of χ^2/dof yields $A \in \{s/\rho_B,\ \rho_\pi^{th}/\rho_B,\ \rho_\pi^{tot}/\rho_B\}$:

$$\chi^2/\text{dof} = \frac{1}{3M-3}\sum_{A}\sum_{i=i_0}^{i_0+M-1}\left(\frac{A-A_i}{\delta A_i}\right)^2 \quad \Rightarrow \quad A = \sum_{i=i_0}^{i_0+M-1}\frac{A_i}{(\delta A_i)^2}\Bigg/\sum_{i=i_0}^{i_0+M-1}\frac{1}{(\delta A_i)^2}$$

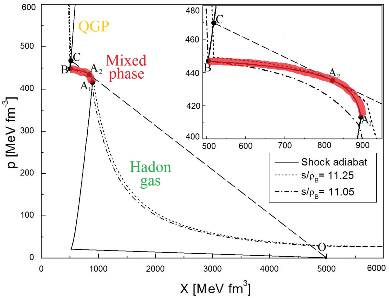
	Low energy plateau				
M	i_0	s/ρ_B	ρ_π^{th}/ρ_B	ρ_π^{tot}/ρ_B	χ^2/dof
2	3	11.12	0.52	0.85	0.17
3	3	11.31	0.46	0.89	0.53
4	2	10.55	0.43	0.72	1.64
5	2	11.53	0.47	0.84	4.45
	High energy plateau				
2	8	19.80	0.88	2.20	0.12
3	7	18.77	0.83	2.05	0.34
4	6	17.82	0.77	1.87	0.87
5	5	16.26	0.64	1.62	3.72



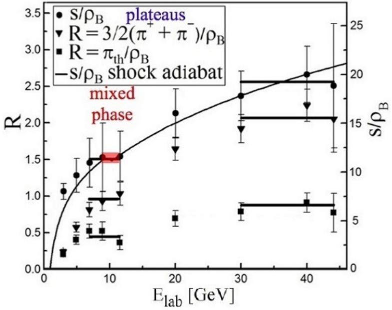
Unstable Transitions to Mixed Phase

$X = \frac{\varepsilon + p}{\rho_B^2}$ – generalized specific volume

other PT ?



K.A. Bugaev et al., arXiv:1405.3575[hep-ph]

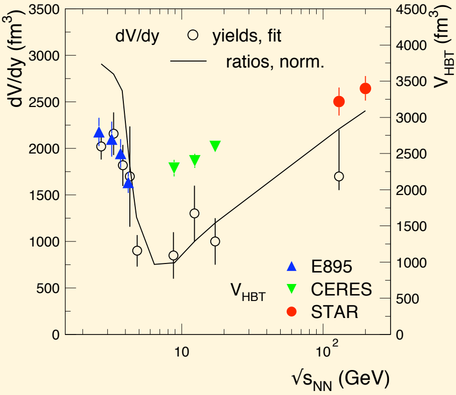


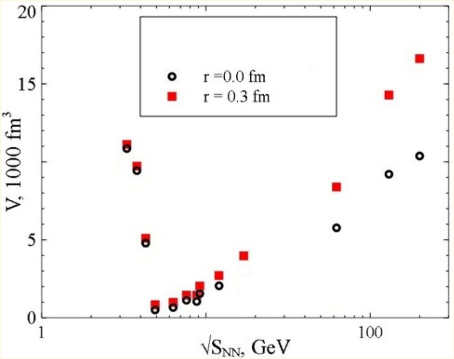
GSA Model explains irregularities at CFO as a signature of mixed phase

QGP EOS is MIT bag model with coefficients been fitted with condition T_c = 150 MeV at vanishing baryonic density!

HadronGas EOS is simplified HRGM discussed above.

Minimum of ChFO Volume at AGS Energies





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

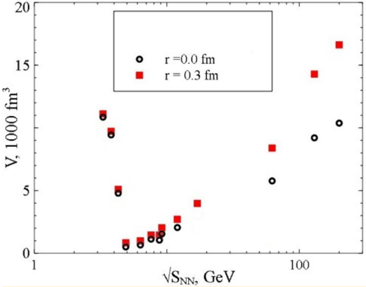
D.R. Oliinychenko, K.A. Bugaev and A.S. Sorin,
Ukr. J. Phys. 58, (2013)

All these irregularities occur at c.m. energies 4.3-4.9 GeV!

Are these minima related to deconfinement?

Other Minima at AGS Energies

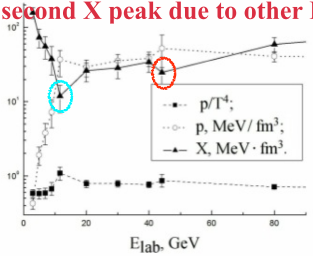
min V at ChFO **SAME energy!** **min X at ChFO**



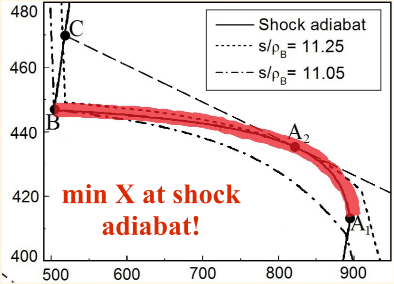
D.R. Oliinychenko, K.A. Bugaev and A.S. Sorin, Ukr. J. Phys. 58, (2013)

X is generalized specific volume

Is second X peak due to other PT ?

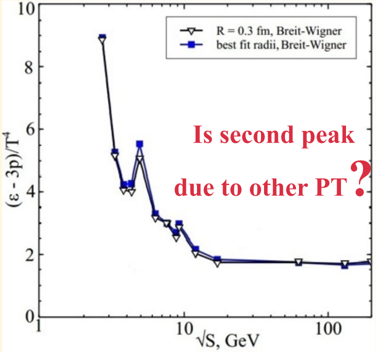


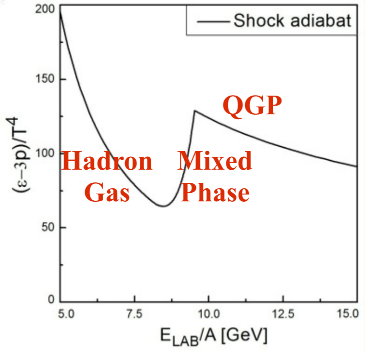
K.A. Bugaev et al., EPJ A (2016)



In this work we gave a proof that min X at boundary between QGP and mixed phase generates min X at ChFO which leads to min V of ChFO!

Trace Anomaly Along Shock Adiabat





K.A. Bugaev et al., EPJ A (2016)

We found one-to-one correspondence between these two peaks.

Thus, sharp peak of trace anomaly at c.m. energy 4.9 GeV evidences for QGP formation.

Strangeness Enhancement as Deconfinement Signal

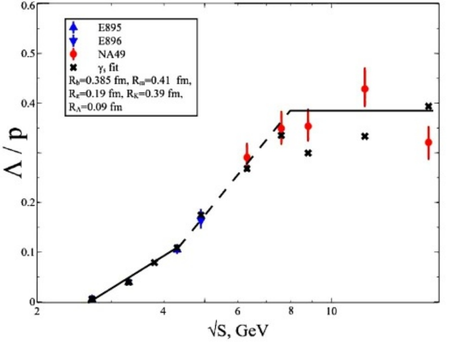
In 1982 J. Rafelski and B. Müller predicted that enhancement of strangeness production is a signal of deconfinement. Phys. Rev. Lett. 48(1982)

We observe 3 regimes: at c.m. energies 4.3 GeV and ~8 GeV slope of experimental data drastically changes!

Combining **Rafelsky & Muller idea with our result** that mixed phase appears at 4.3 GeV we explain this finding:

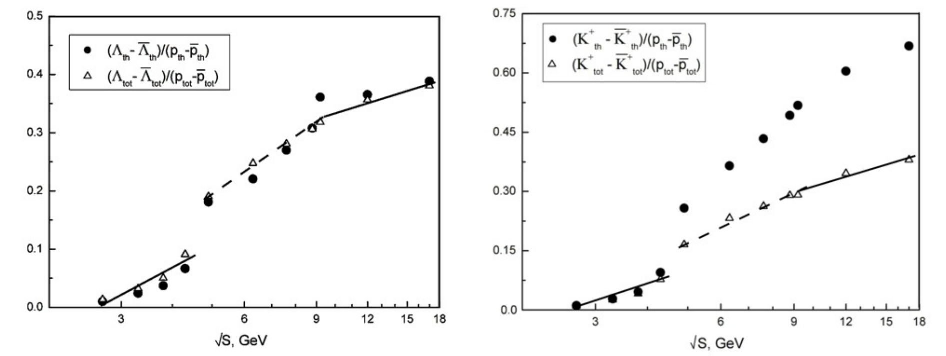
Below 4.3 GeV Lambdas appear in N+N collisions

Above 4.3 GeV and below ~8 GeV formation of QGP produces additional s (anti)s quark pairs



Above ~8 GeV there is saturation due to small baryonic chemical potential

What To Measure at FAIR & NICA ?



We predicted JUMPS of these ratios at 4.3 GeV due to 1-st order PT and

CHANGE OF their SLOPES at ~ 9-12 GeV due to 2-nd order PT (or weak 1-st order PT?)

To locate the energy of SLOPE CHANGE we need MORE data at 7-13 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;
- generalized shock adiabat model allowed us to describe entropy per baryon at chemical FO and determine the parameters of the QGP equation of state from the data.
- 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!

Separate Chemical FO of Strange Hadrons

Parameters

Non-strange hadrons: T_{FO}, $\mu_{B_{FO}}$, $\mu_{I3_{FO}}$

K.A. Bugaev et al., EPL, 104 (2013)

Strange hadrons: T_{SFO}, $\mu_{B_{SFO}}$ and $\mu_{I3_{SFO}}$

Similar idea, but for IDEAL GAS and WITHOUT conservation laws was suggested in S.Chatterjee, R. Godbole and S. Gupta S., arXiv:1306.2006

Conservation laws: + net strangeness =0

Principal difference from other approaches

$$s_{FO} V_{FO} = s_{SFO} V_{SFO} \,,$$
$$n^B_{FO} V_{FO} = n^B_{SFO} V_{SFO} \,,$$
$$n^{I_3}_{FO} V_{FO} = n^{I_3}_{SFO} V_{SFO} \,.$$

Entropy

Baryonic charge

3-rd component of isospin

Getting rid of the effective volumes we obtain

$$\left.\frac{s}{n^B}\right|_{FO} = \left.\frac{s}{n^B}\right|_{SFO} , \quad \left.\frac{n^B}{n^{I_3}}\right|_{FO} = \left.\frac{n^B}{n^{I_3}}\right|_{SFO} .$$

Only T at SFO is independent!

=>

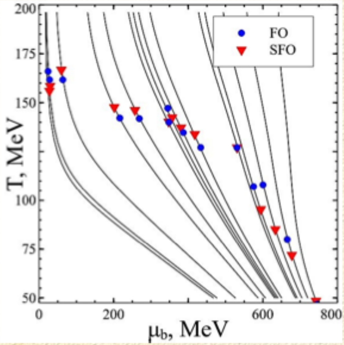
Total number of fitting parameters is same as for strangeness enhancement!

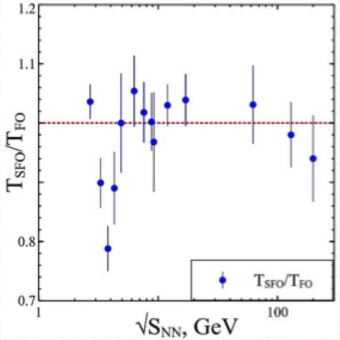
Decays:

Decay branchings $BR(Y \rightarrow X)$ with $BR(X \rightarrow X) = 1$

$$\frac{N^{fin}(X)}{V_{FO}} = \sum_{Y \in FO} BR(Y \rightarrow X) n^{th}(Y) + \sum_{Y \in SFO} BR(Y \rightarrow X) n^{th}(Y) \frac{V_{SFO}}{V_{FO}} .$$

FO versus Strange particle FO





1. SFO temperature differs not more than on 20% =>
there are no problems with decays and entropy conservation!

2. At high energies SFO occurs almost at FO.

3. At low energies there are peculiar irregularities!

4. There are no additional minima as in γ_s fit!