Evidence for the QCD tricritical endpoint existence at NICA-FAIR energies

Kyrill Bugaev, A.Ivanytskyi, D.Oliinychenko, V. Sagun, G. Zinovjev

Bogolyubov ITP, Kiev, Ukraine

E. Nikonov

Laboratory for Information Technologies, JINR, Dubna, Russia

R. Emaus, L.Bravina, E.Zabrodin

University of Oslo, Oslo, Norway

D. Blaschke

University of Wroclaw, Wroclaw, Poland

A.Taranenko

MEPhI, Moscow, Russia

Moscow, Russia, October 5, 2017

Outline

1. Motivation

2. Novel and Old Irregularities at chemical freeze out

3. Shock adiabat model of A+A collisions

4. Newest results and possible evidence for two phase transitions

5. Conclusions

Present Status of A+A Collisions

In 2000 CERN claimed indirect evidence for a creation of new matter

In 2010 RHIC collaborations claimed to have created a quark-gluon plasma/liquid

However, up to now we do not know:

1. **whether deconfinement and chiral symmetry restoration are the same phenomenon or not?**

2. **are they phase transitions (PT) or cross-overs ?**

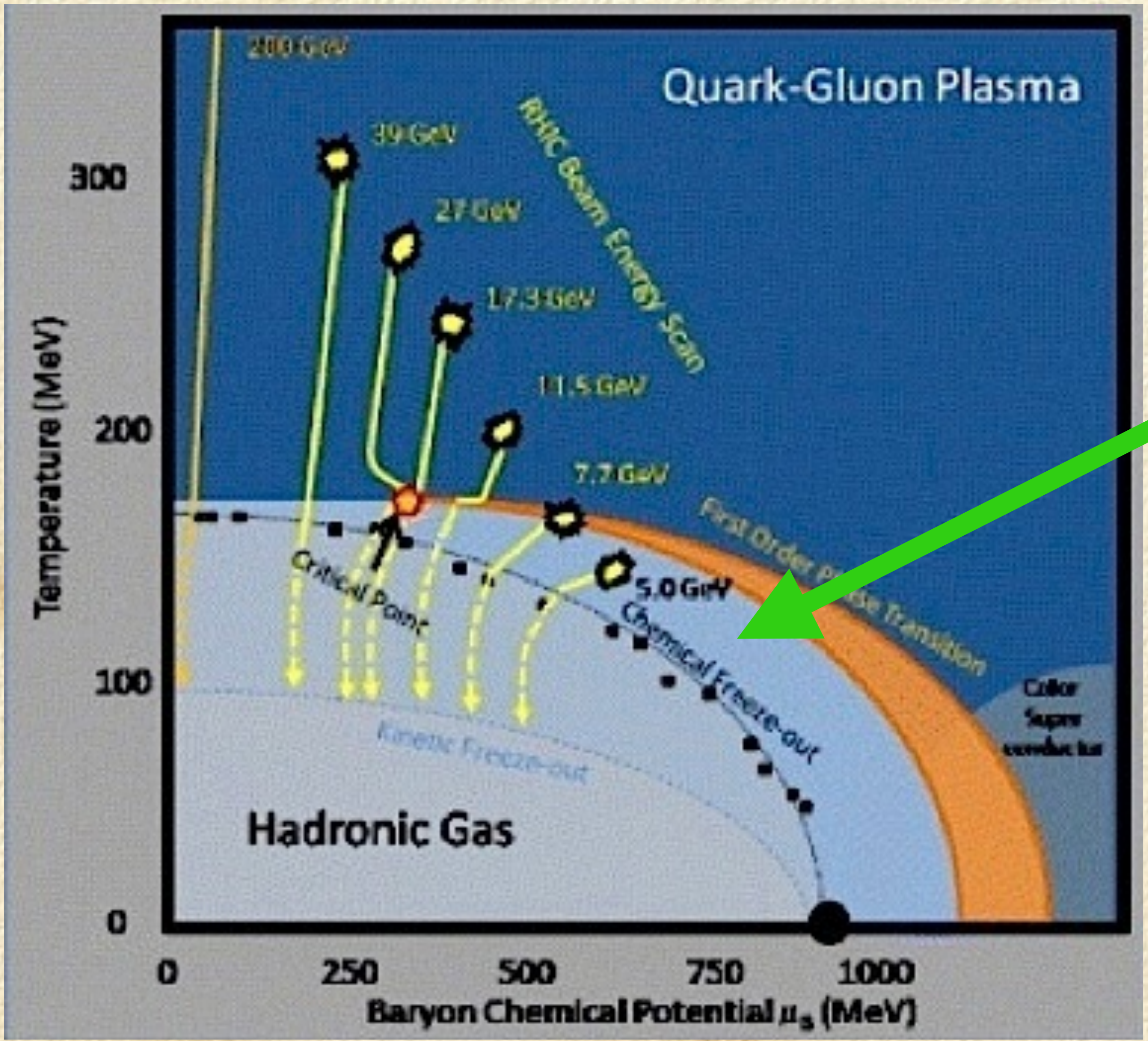
3. **what are the collision energy thresholds of their onset?**

To answer these questions we need a very accurate tool to analyze data

HRG: a Multi-component Model

HRG model is a truncated Statistical Bootstrap Model with the excluded volume correction a la VdWaals for all hadrons and resonances known from Particle Data Group.

For given temperature T, baryonic chem. potential, strange charge chem. potential, chem. potential of isospin 3-rd projection => thermodynamic quantities => all charge densities, to fit data.



Chemical freeze-out - moment after which hadronic composition is fixed and only strong decays are possible. I.e. there are no inelastic reactions.

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.

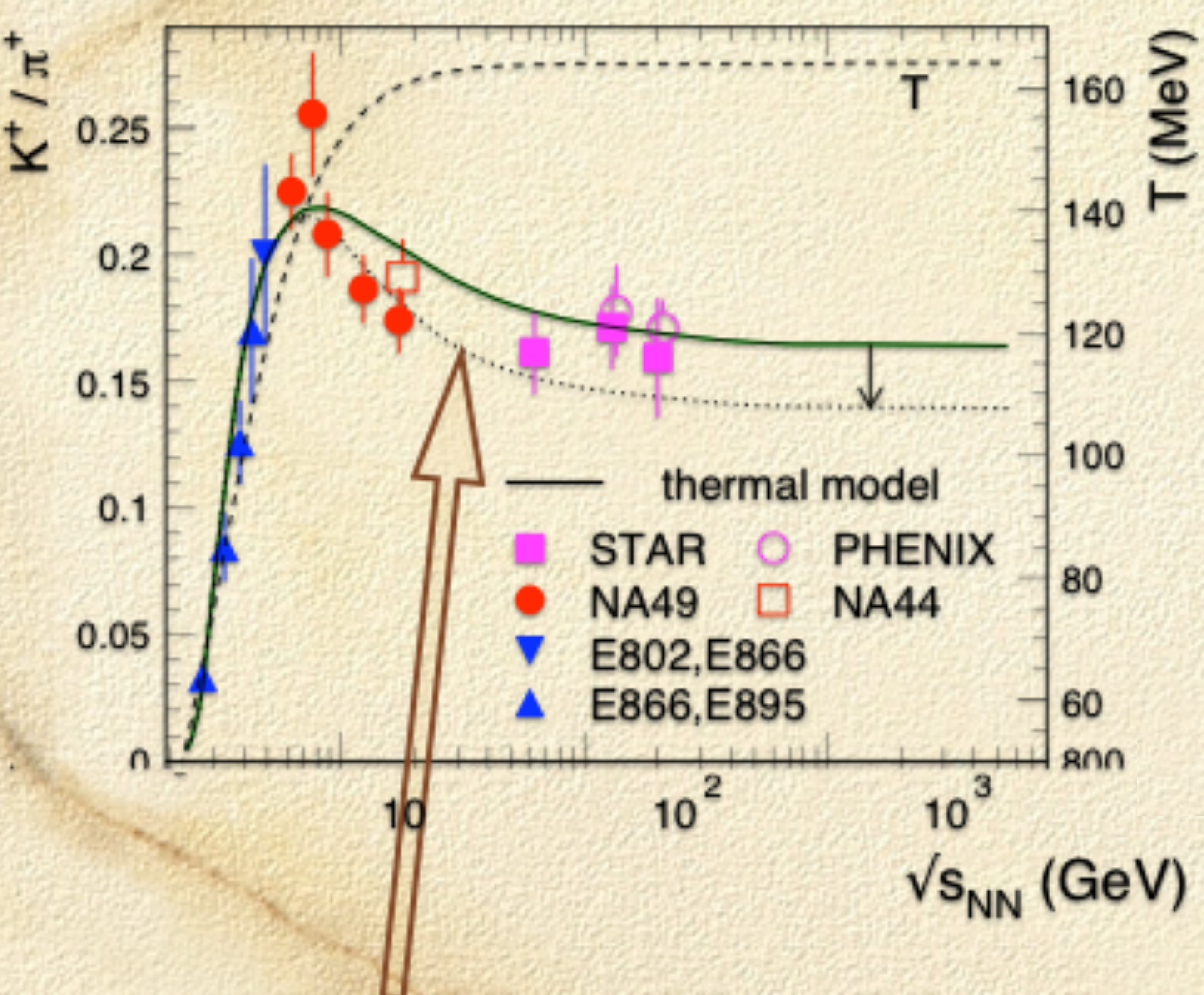
Horns Description in 1-component HRG

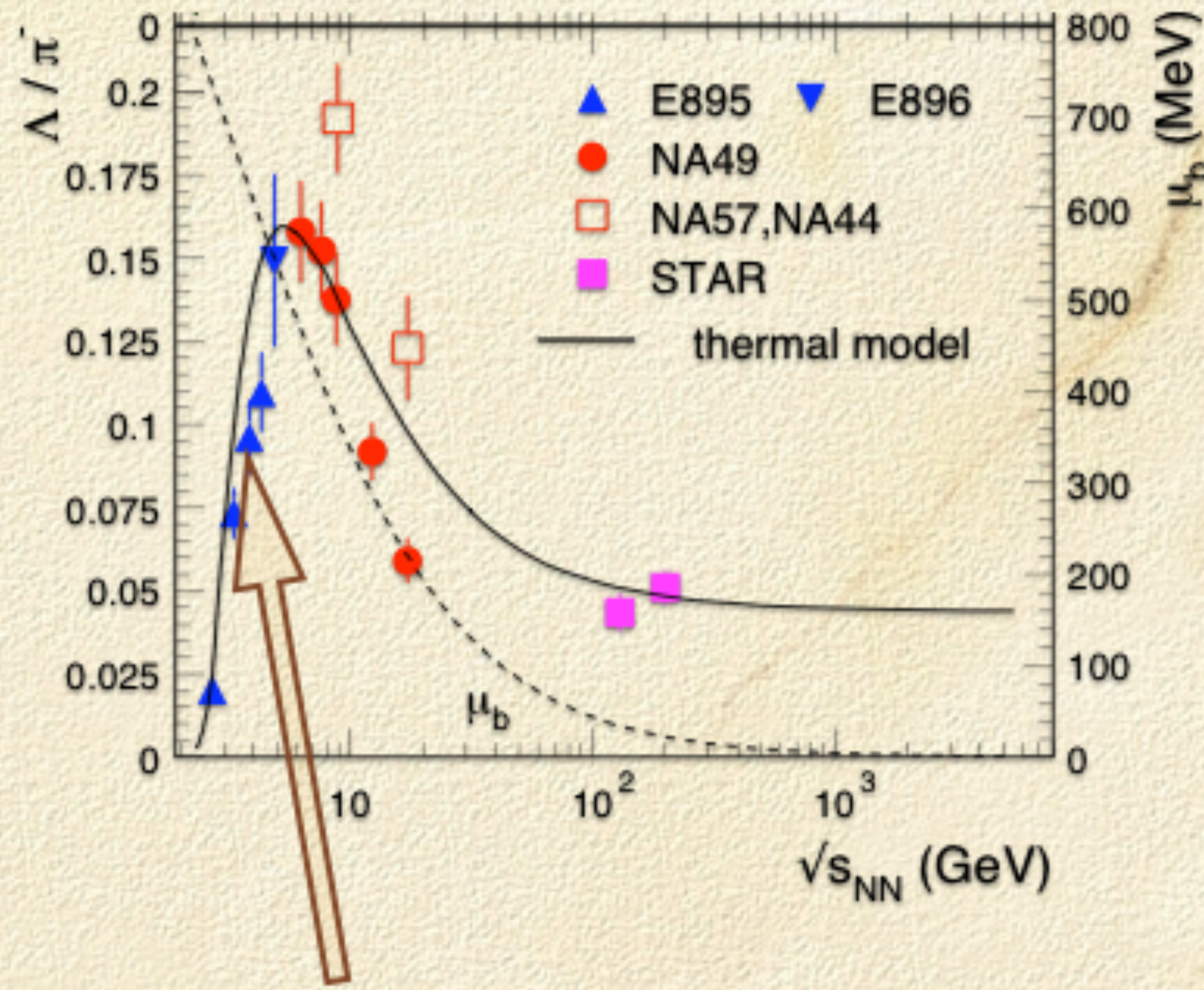
Too slow decrease after maximum!

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

$$\chi^2/dof = 21.8/14$$

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





Short dashed line: a desired result

Anti Lambda problem!

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

Simple Solution to Horn Puzzle

Use four hard-core radii: R_pi, R_K are fitting parameters;
R_mesons = 0.4 fm, R_baryons = 0.2 fm are fixed

G. Zeeb, K.A. Bugaev, P.T. Reuter and H. Stoecker, Ukr. J. Phys. 53, 279 (2008)

D.R. Oliinychenko, K.A. Bugaev and A.S. Sorin, Ukr. J. Phys. 58, (2013), No. 3, 211-227

p is pressure $\quad$ K-th charge density of i-th hadron sort is n_i^K ($K \in \{B, S, I3\}$)

$\mathcal{B}$ the second virial coefficients matrix $b_{ij} \equiv \frac{2\pi}{3}(R_i + R_j)^3$

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

NO strangeness suppression is included!

the variables ξ_i are the solution of the following system:

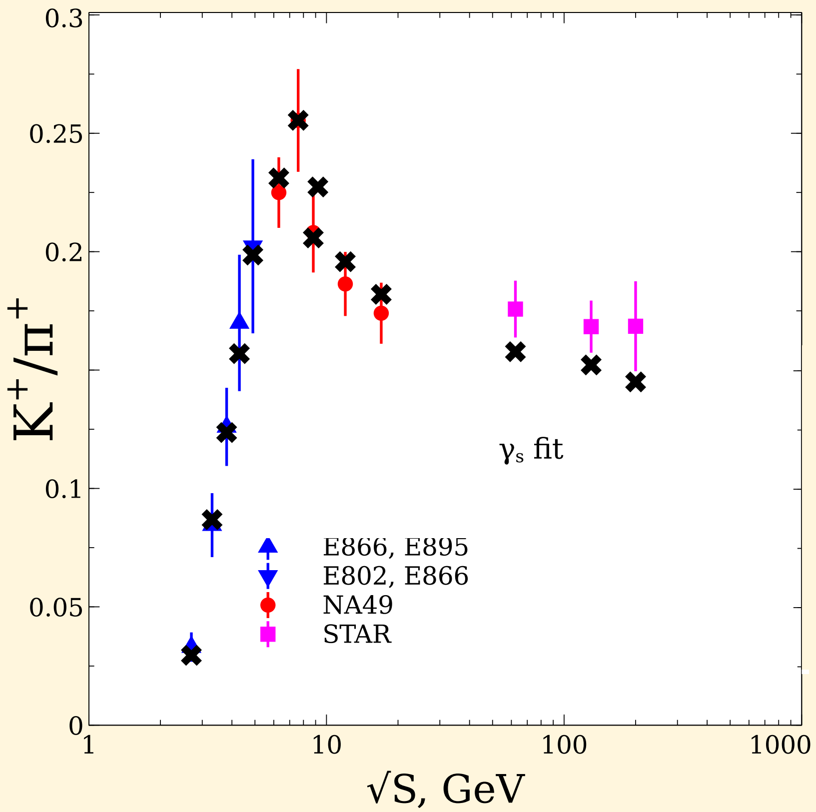
$$\xi_i = \phi_i(T) \exp\left(\frac{\mu_i}{T} - \sum_{j=1}^{N} 2\xi_j b_{ij} + \frac{\xi^T \mathcal{B} \xi}{\sum_{j=1}^{N} \xi_j} \right), \quad \underbrace{\phi_i(T) = \frac{g_i}{(2\pi)^3} \int \exp\left(-\frac{\sqrt{k^2 + m_i^2}}{T} \right) d^3k}_{\text{THERMAL DENSITY}}$$

Chemical potential of i-th hadron sort: $\mu_i \equiv Q_i^B \mu_B + Q_i^S \mu_S + Q_i^{I3} \mu_{I3}$

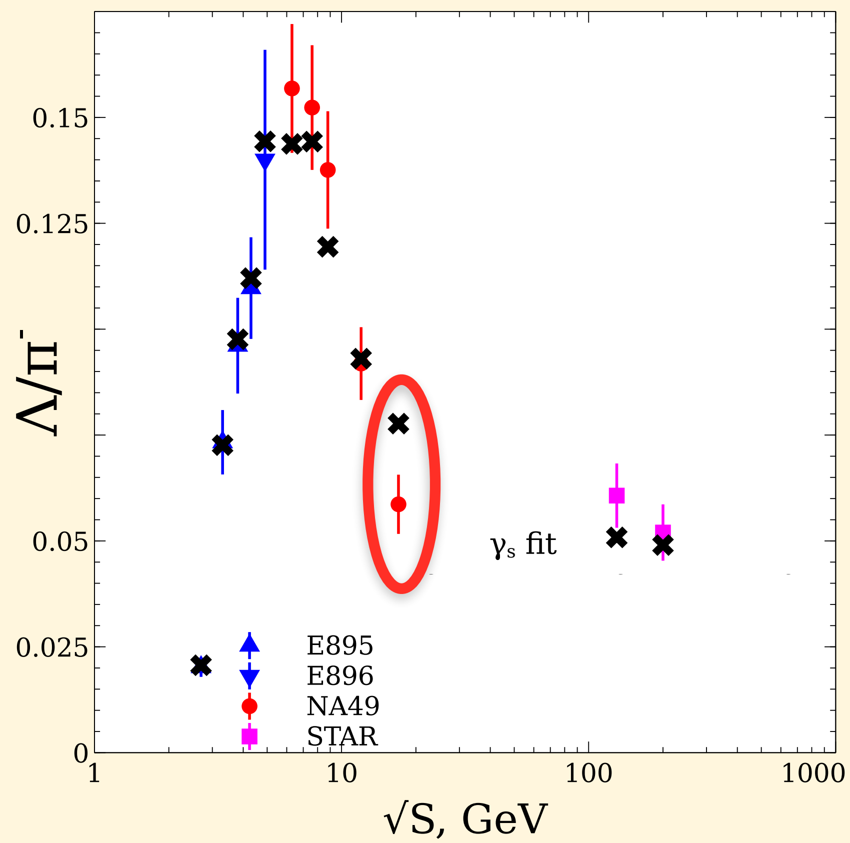
Q_i^K are charges, m_i is mass and g_i is degeneracy of the i-th hadron sort

Strangeness Horn and Λ Horn in 2014

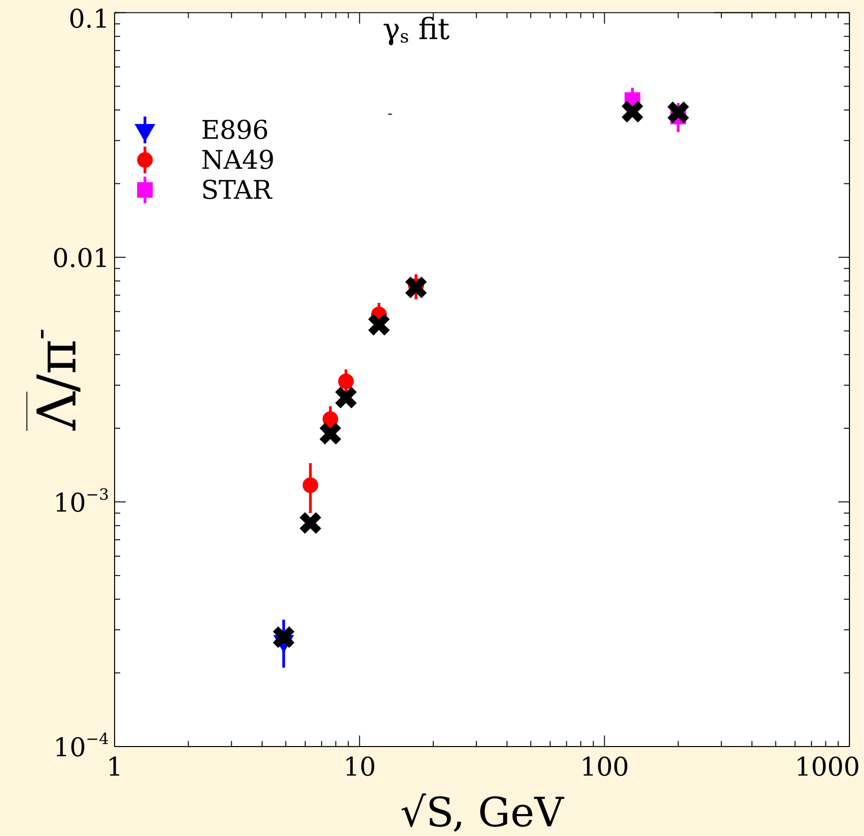
To avoid selective suppression of Λ-hyperons we added their hard-core radius



$\chi^2/dof \simeq 3.29/14$



$\chi^2/dof \simeq 11.62/12$



$\chi^2/dof \simeq 8.89/8$

NEW 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

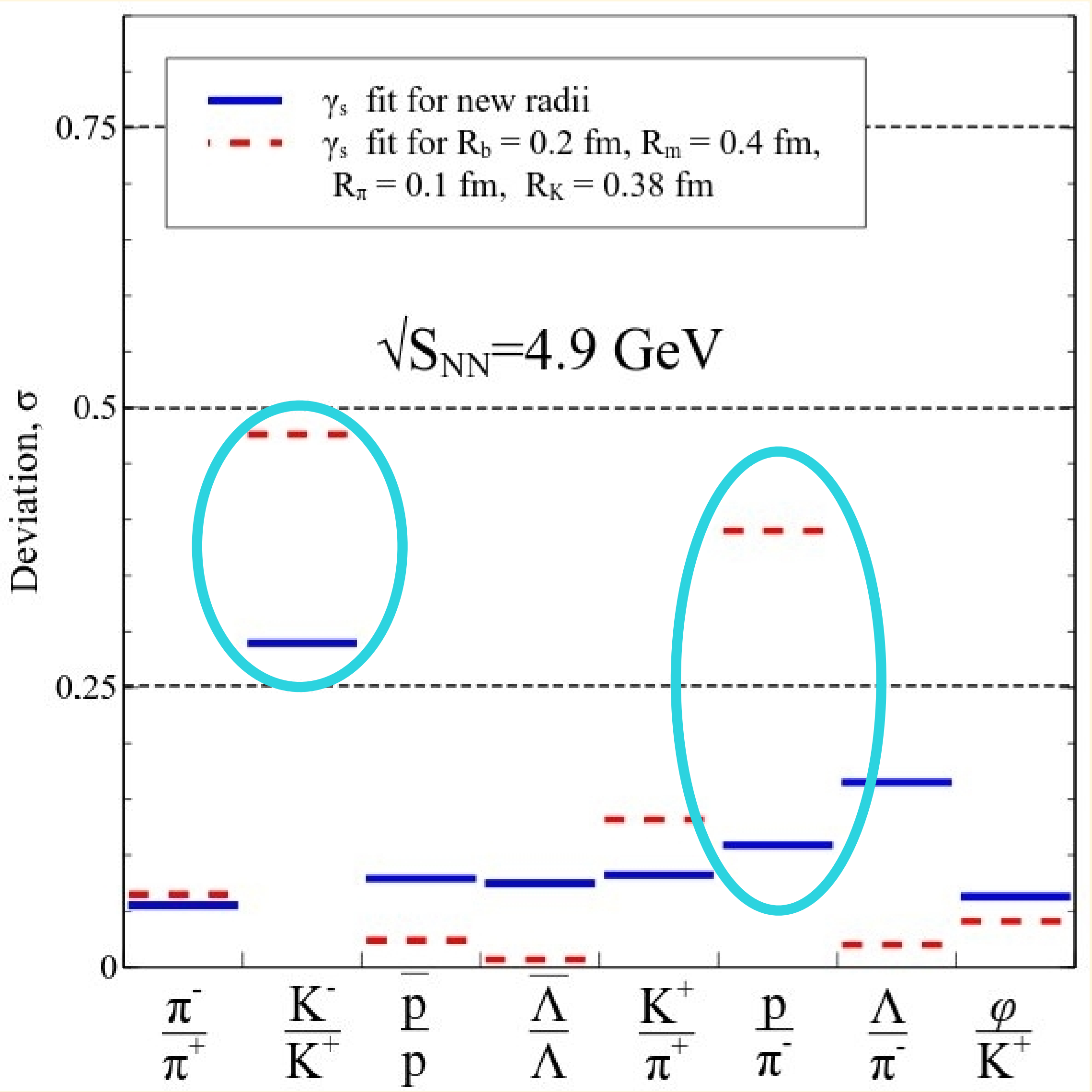
Total fit of 111 independent hadron ratios is the best of existing!

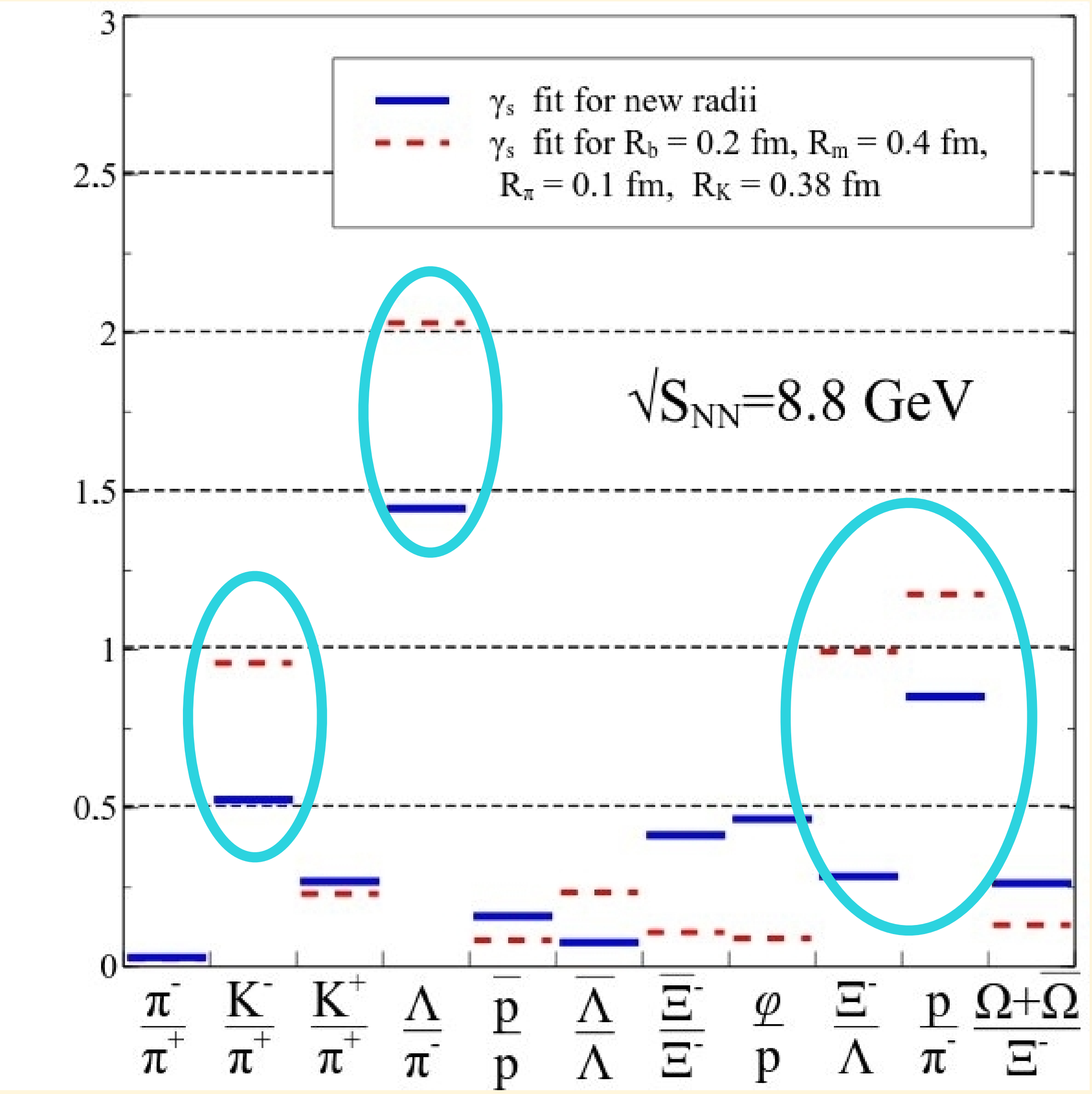
V. V. Sagun, **Ukr. J. Phys.** 59, No 8, 755-763 (2014)

V. V. Sagun et al., **Ukr. J. Phys.** 59, No 11, 1043-1050 (2014)

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

Other Ratios in 2014





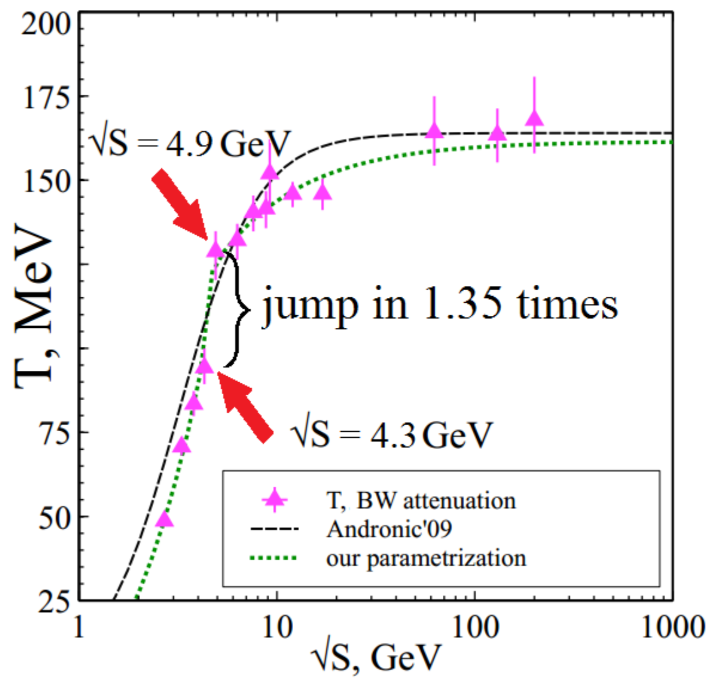
Intermediate Conclusions

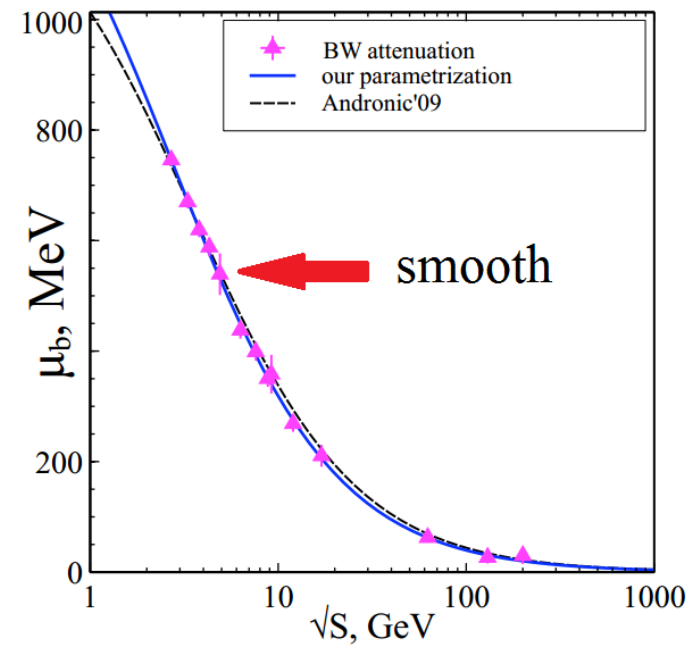
1. The multicomponent HRG model is a precise tool of HIC phenomenology

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

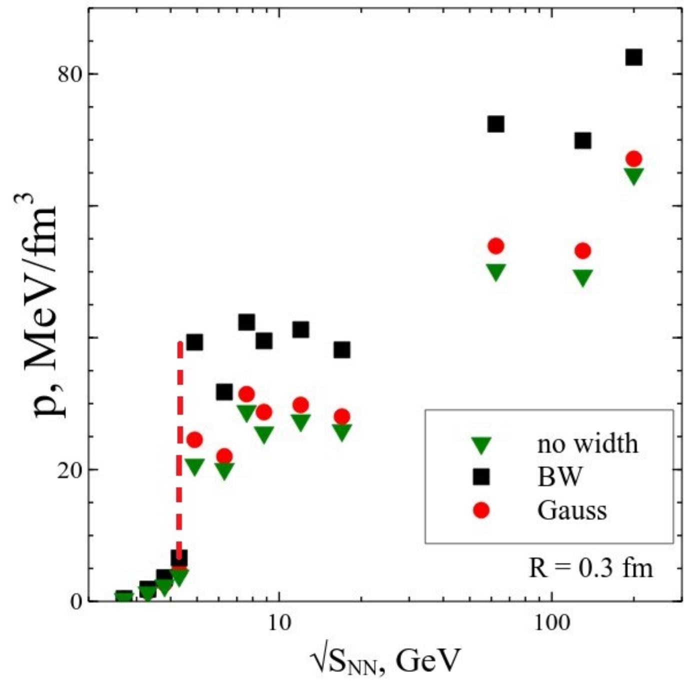
Jump of ChFO Pressure at AGS Energies

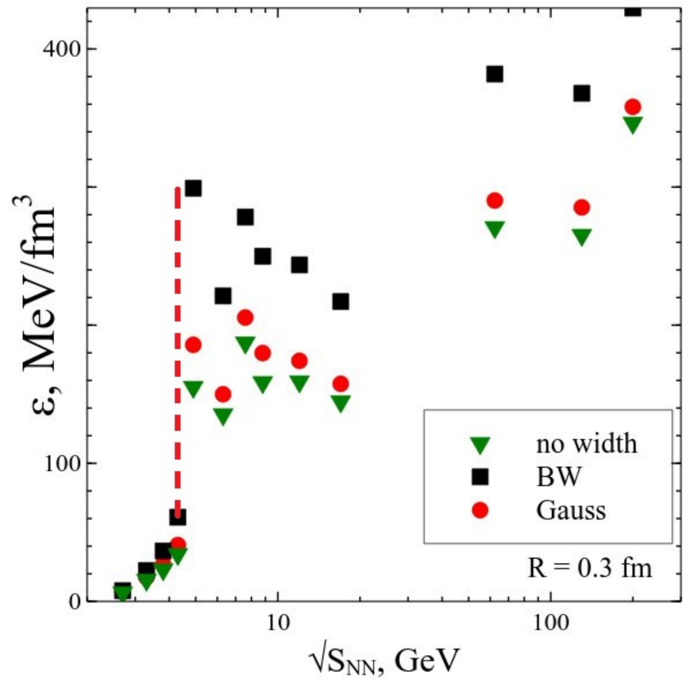
- Temperature T_{CFO} as a function of collision energy $\sqrt{s}$ is rather non smooth





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



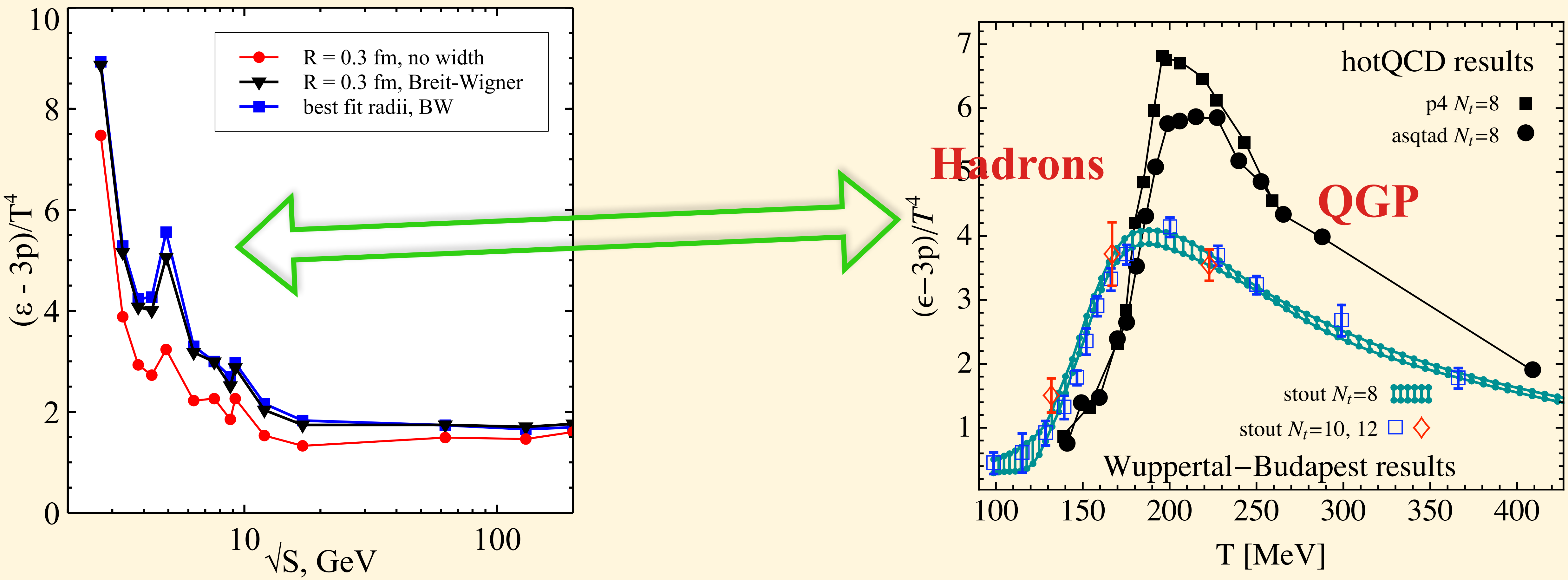


K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015) [arXiv:1405.3575];

Ukr. J. Phys. 60 (2015)

Trace Anomaly Peaks

At chemical FO (large μ) — Lattice QCD (vanishing μ)



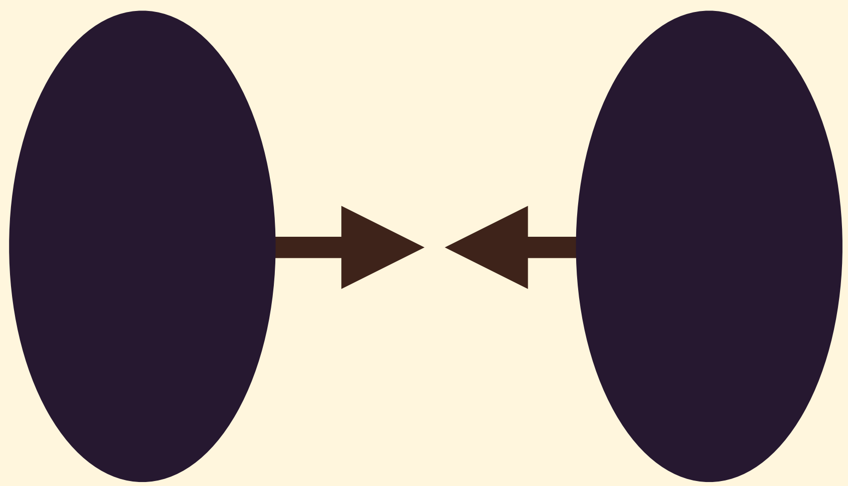
K.A. Bugaev et al., arXiv:1412.0718 [nucl-th]

WupBud EOS arxive: lat 1007.2580

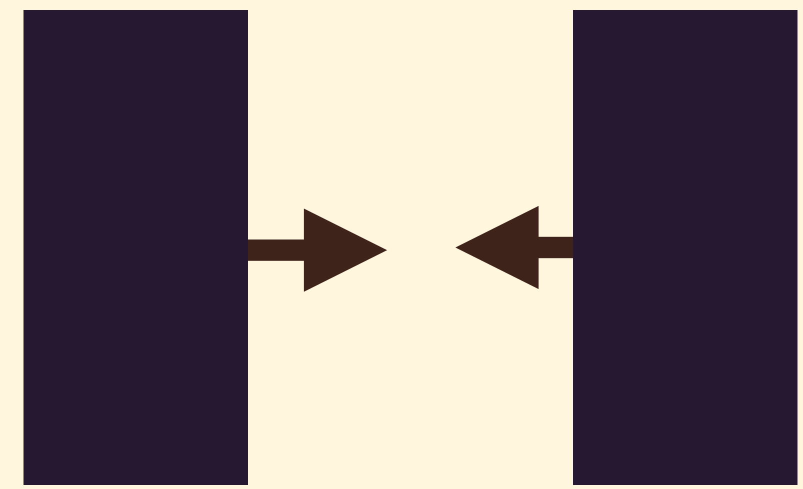
Are these trace anomaly peaks related to each other?

Shock Adiabat Model for A+A Collisions

A+A central collision at 1< Elab<30



Its hydrodynamic model



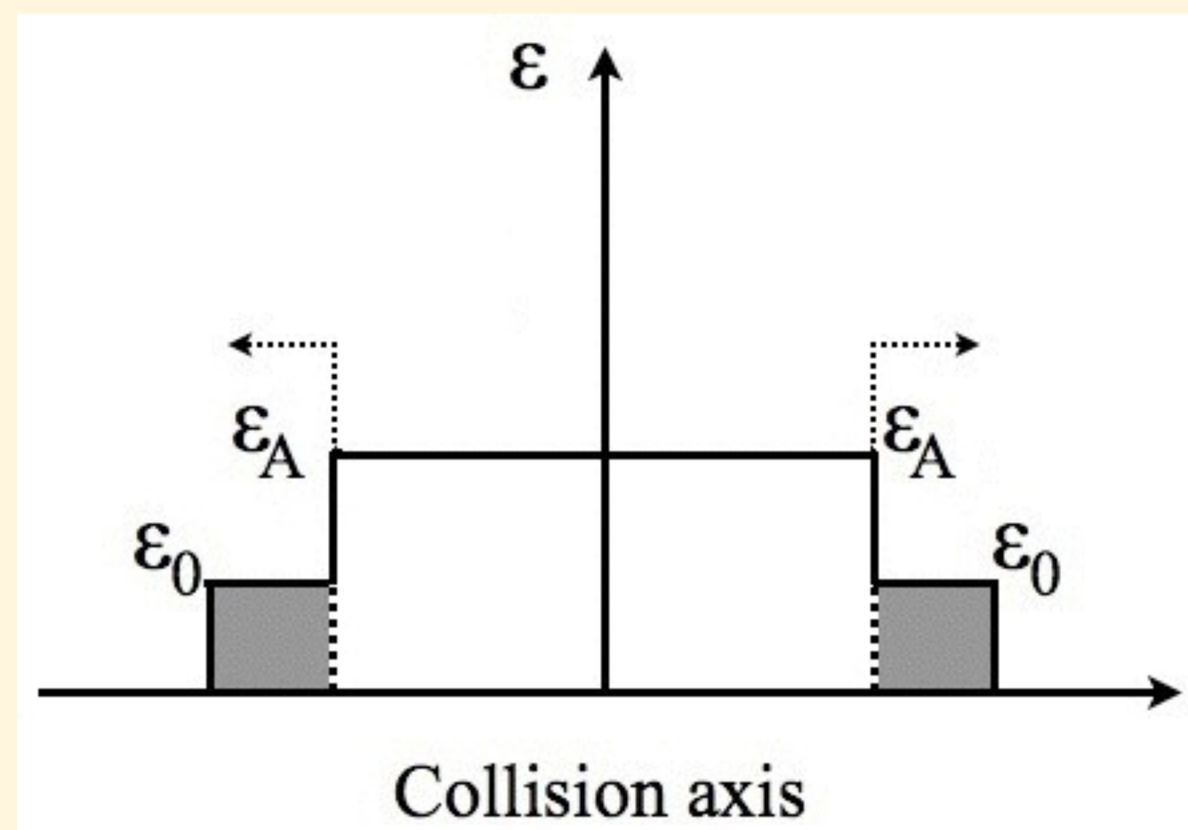
Works reasonably well at these energies.

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 $\boxed{\Sigma \equiv \left(\frac{\partial^2 p}{\partial X^2}\right)^{-1}_{s/\rho_B} > 0} =$ 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,

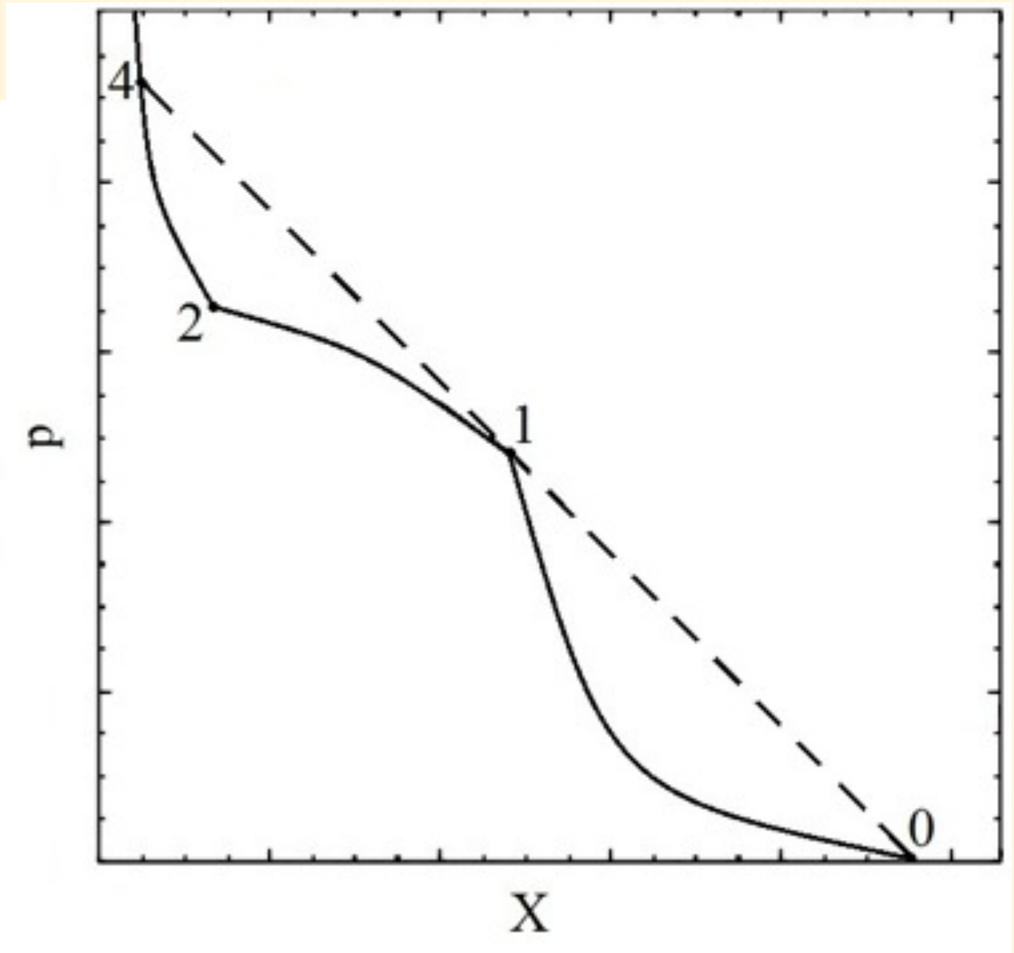
ρ_B is baryonic charge density

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

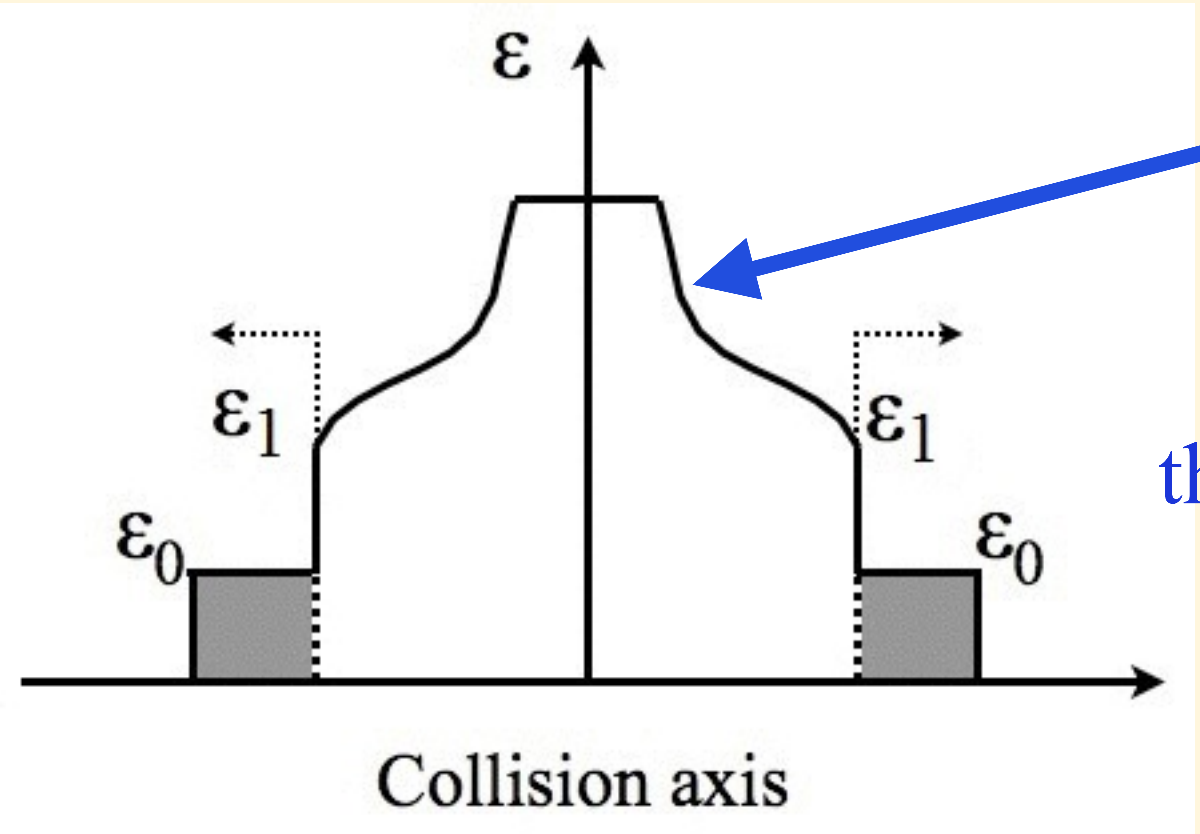


Region 1-2 is mixed phase with **anomalous properties.**

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 $\frac{s}{\rho_B} = \text{const}$

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

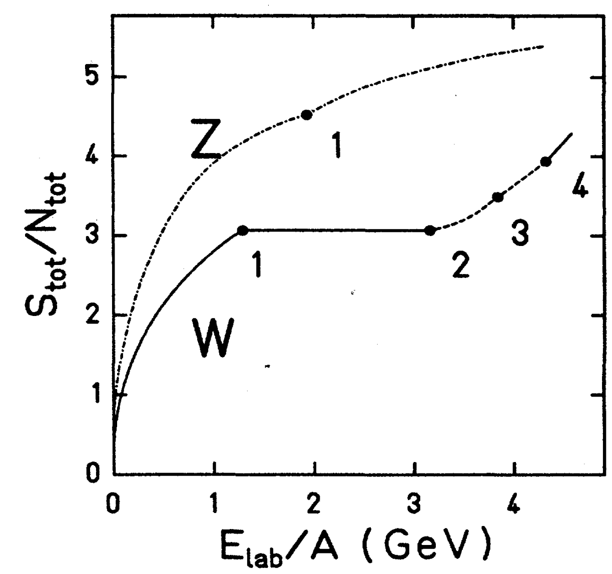


FIG. 9. The entropy per baryon as a function of the bombarding energy per nucleon of the colliding nuclei for models W and Z. The points 1, 2, 3, 4 on curve W correspond to those on the generalized adiabatic as displayed in Fig. 7. The point 1 on curve Z marks the boundary to the mixed phase.

Remarkably

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

Highly Correlated Quasi-Plateaus

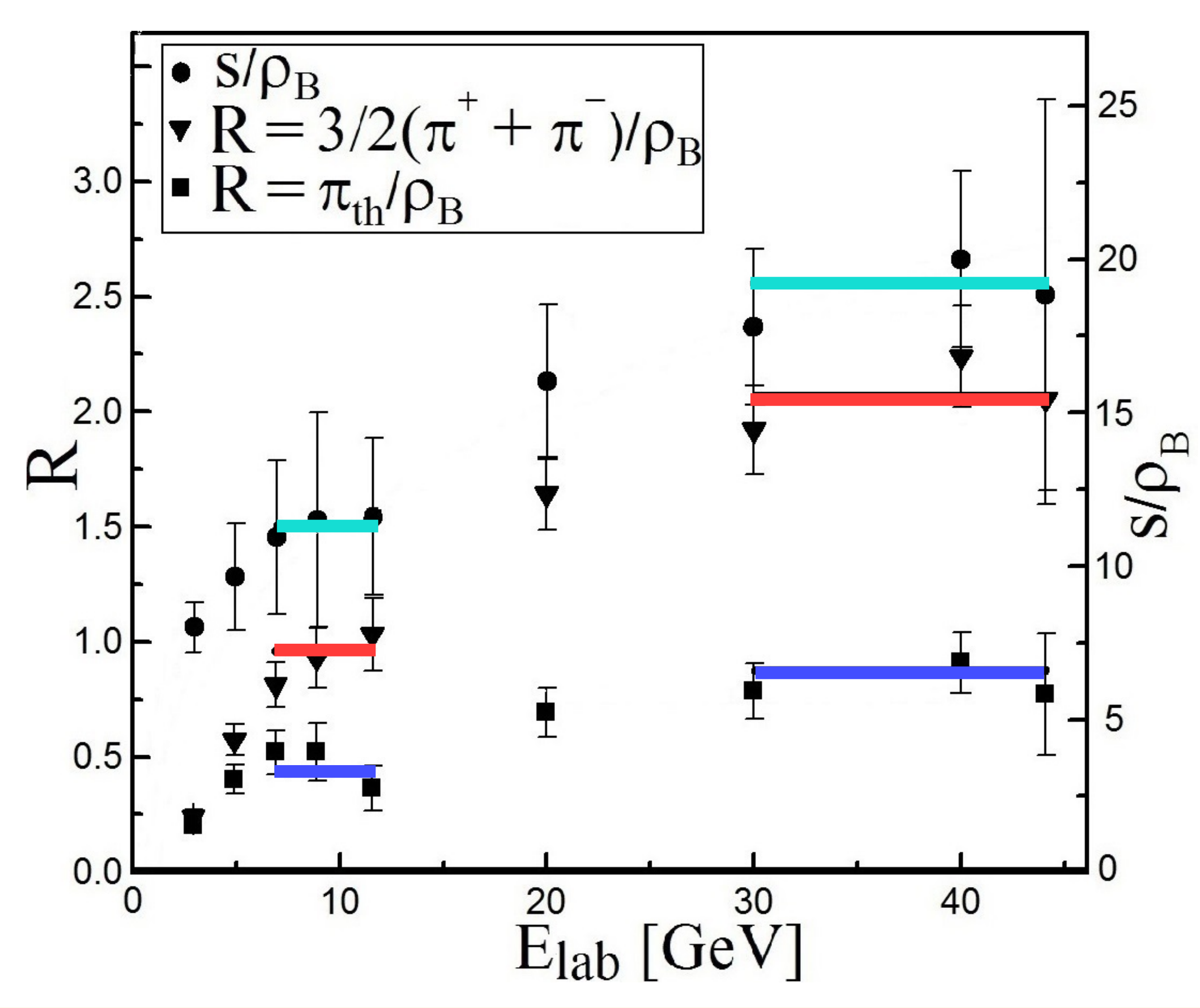
Since the main part of the system entropy is defined by thermal pions =>
thermal pions/baryon should have a plateau!

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

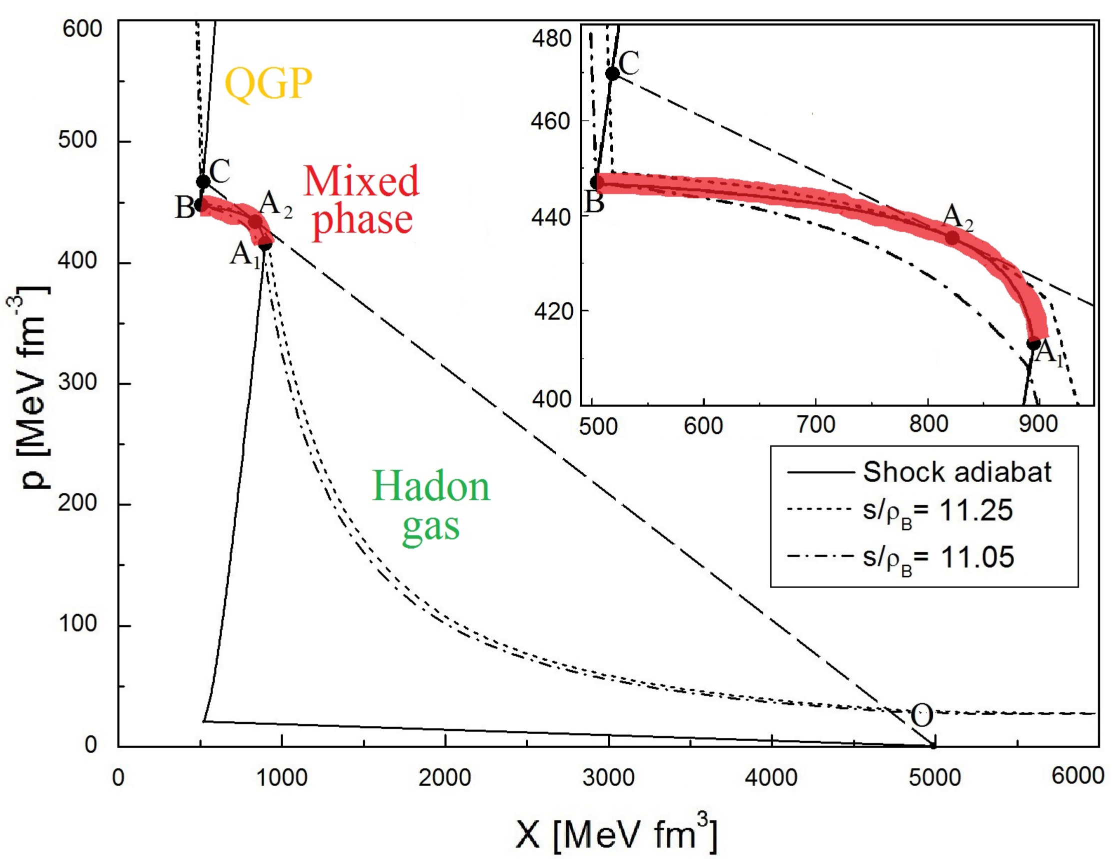


K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015)

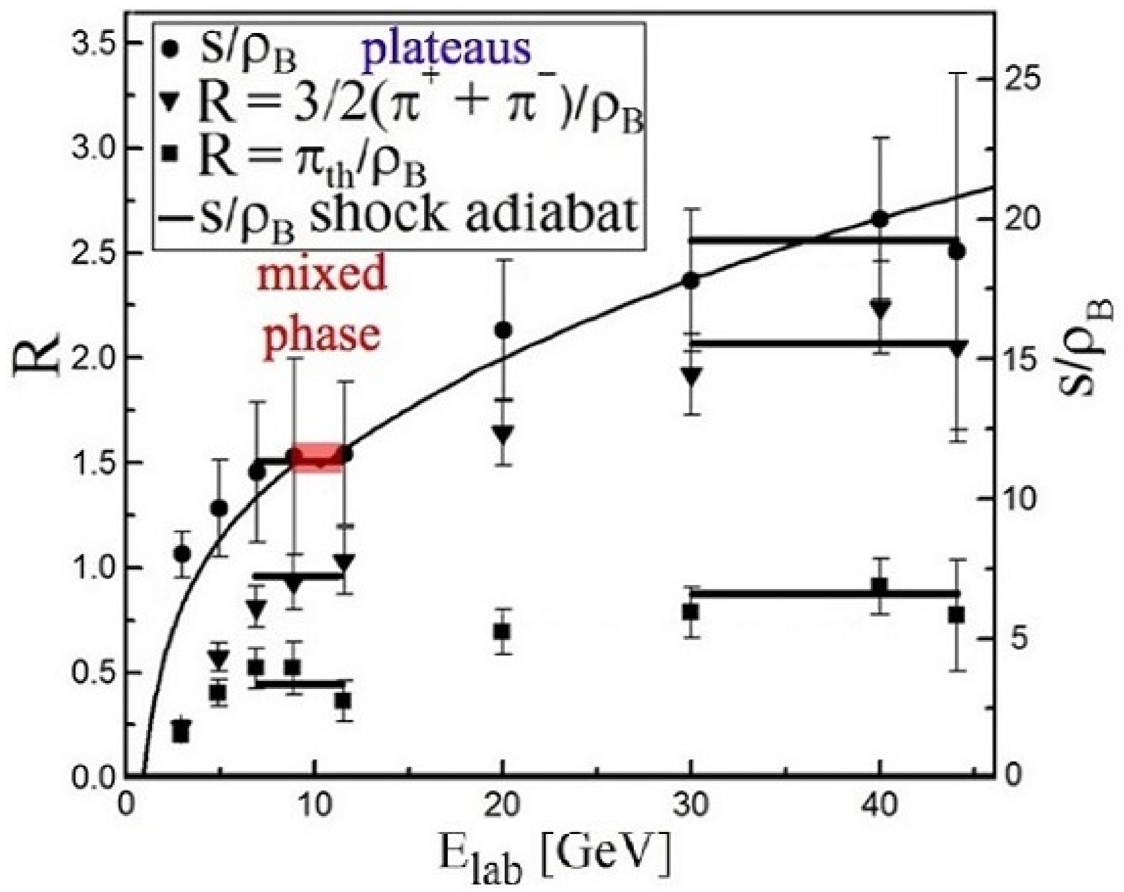
Unstable Transitions to Mixed Phase

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

other PT?



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



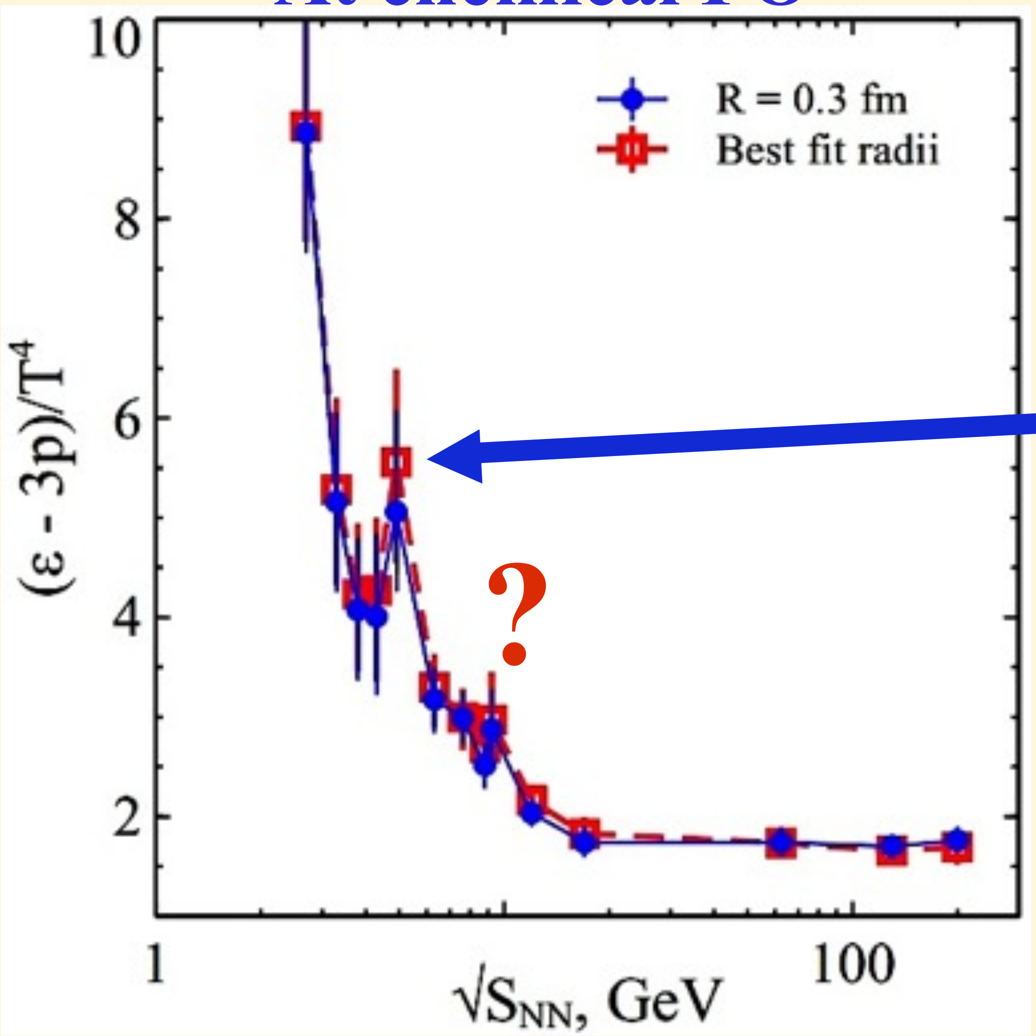
GSA Model explains irregularities at CFO as a signature of mixed phase

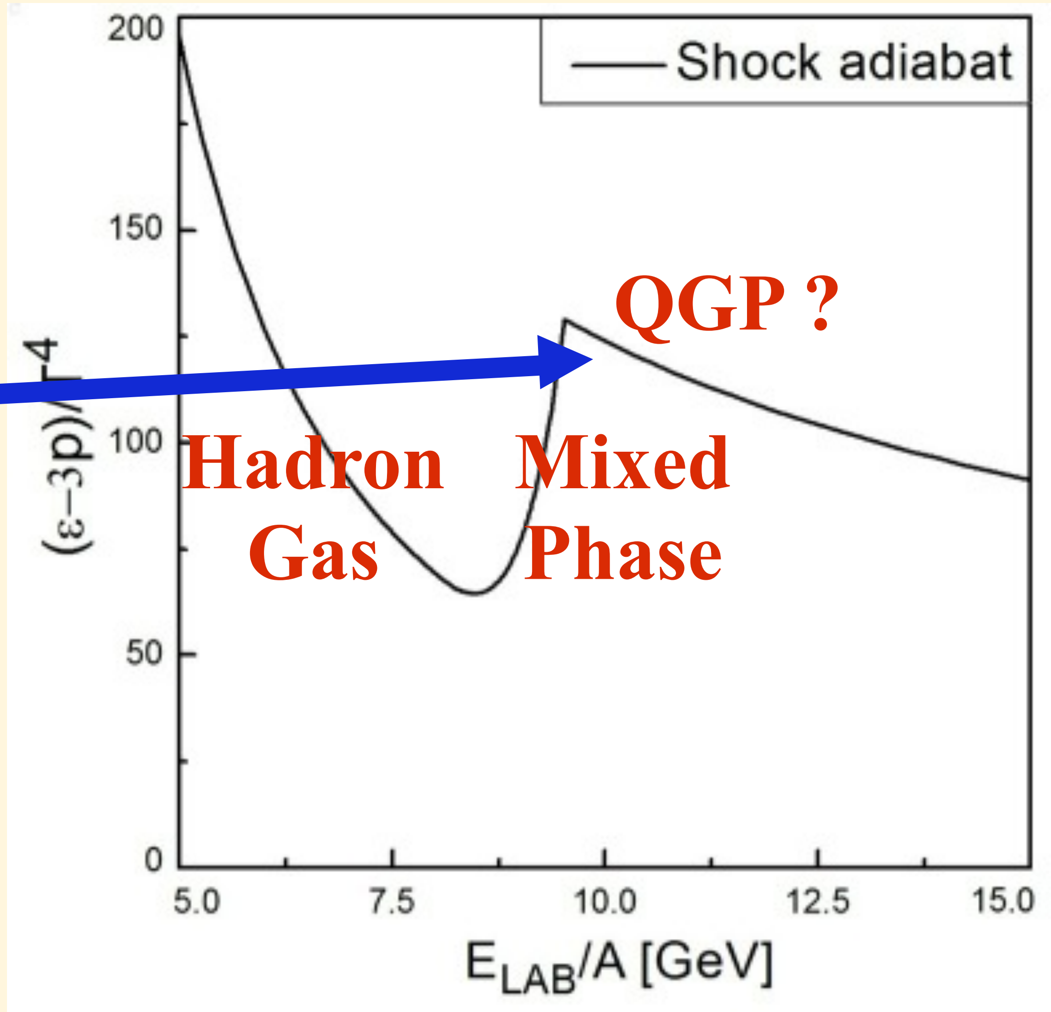
QGP EOS is MIT bag model with coefficients been fitted with condition T_c = 150 MeV at vanishing baryonic density!

HadronGas EOS is simplified HRGM discussed above.

Trace Anomaly Along Shock Adiabat 2016

At chemical FO





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 mixed phase formation. But what is it? QGP?

Is a second peak of trace anomaly (at c.m. energy 9.2 GeV) due to another PT?

Additional Hints for 2 Phase Transitions

Our: **K.A. Bugaev et al., arXiv:1709.05419 [hep-ph]**

Each peak in trace anomaly δ corresponds to a huge peak in baryonic charge density

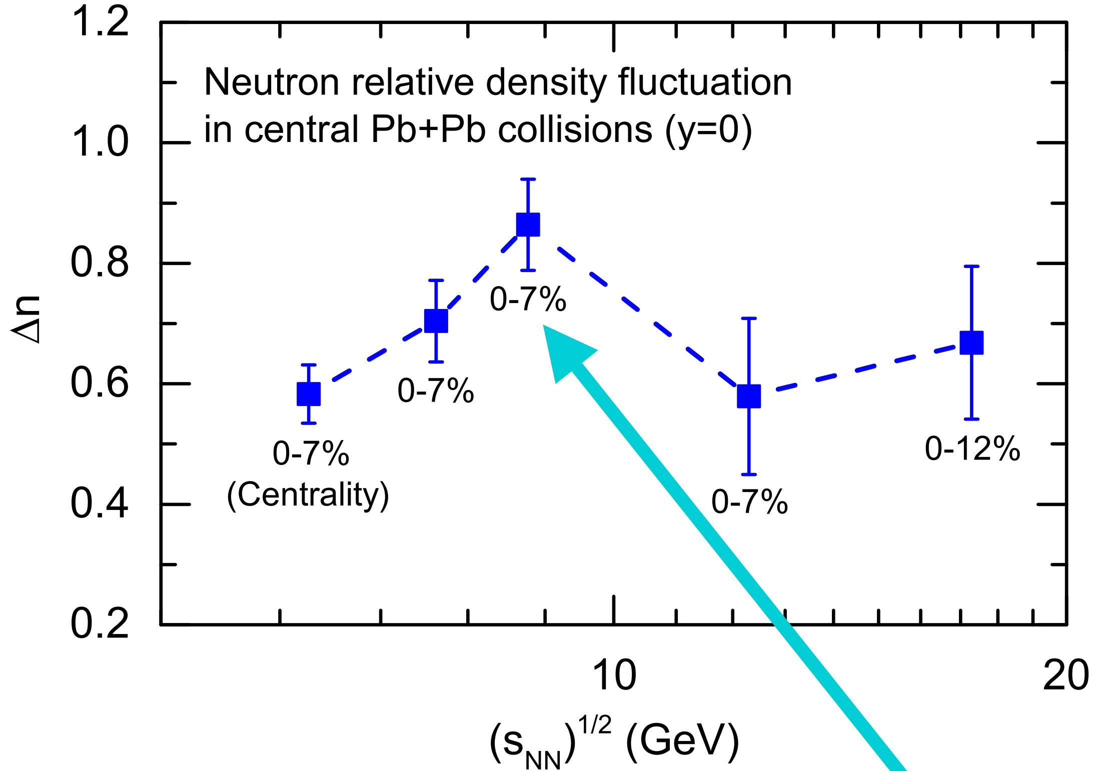
Thermostatic properties of Hagedorn mass spectrum of QGP bags **explain strangeness equilibration at $\sqrt{s} > 9.2$ GeV**

Thermostatic properties **of the 1-st order PT mixed phase explain strangeness equilibration at 4.3 GeV $< \sqrt{s} <$ 4.9 GeV**

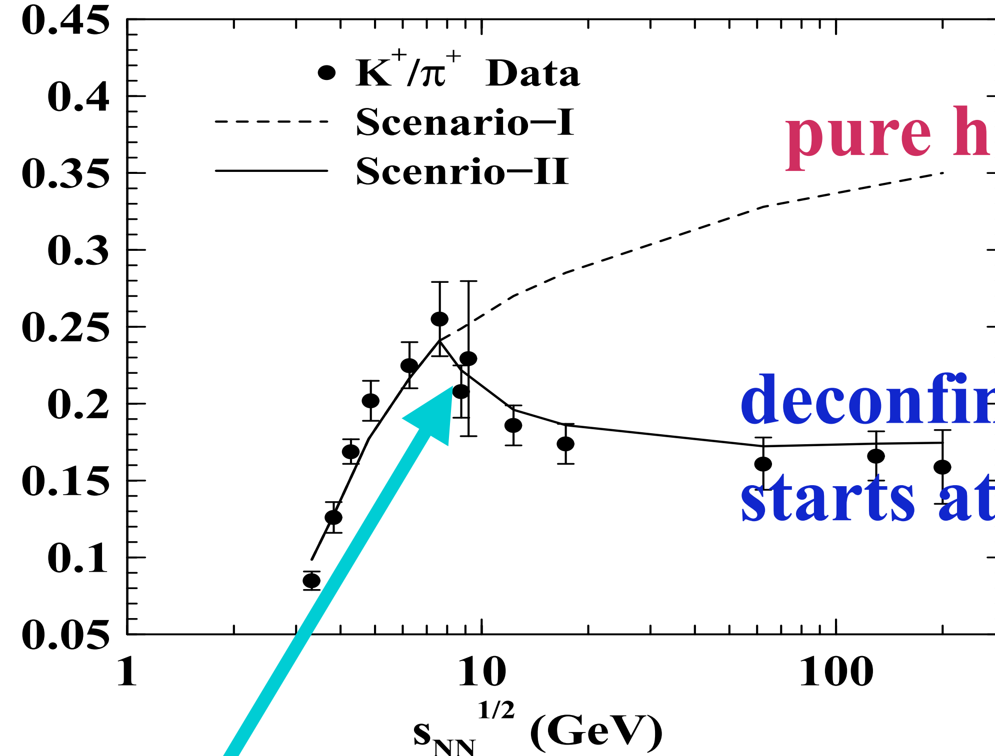
Other models predict deconfinement at $\sqrt{s}$ = 8.7- 9.2 GeV:

Onset of Deconfinement in Other Models

Che Ming Ko et al., arXiv 1702.07620 [nucl-th]]



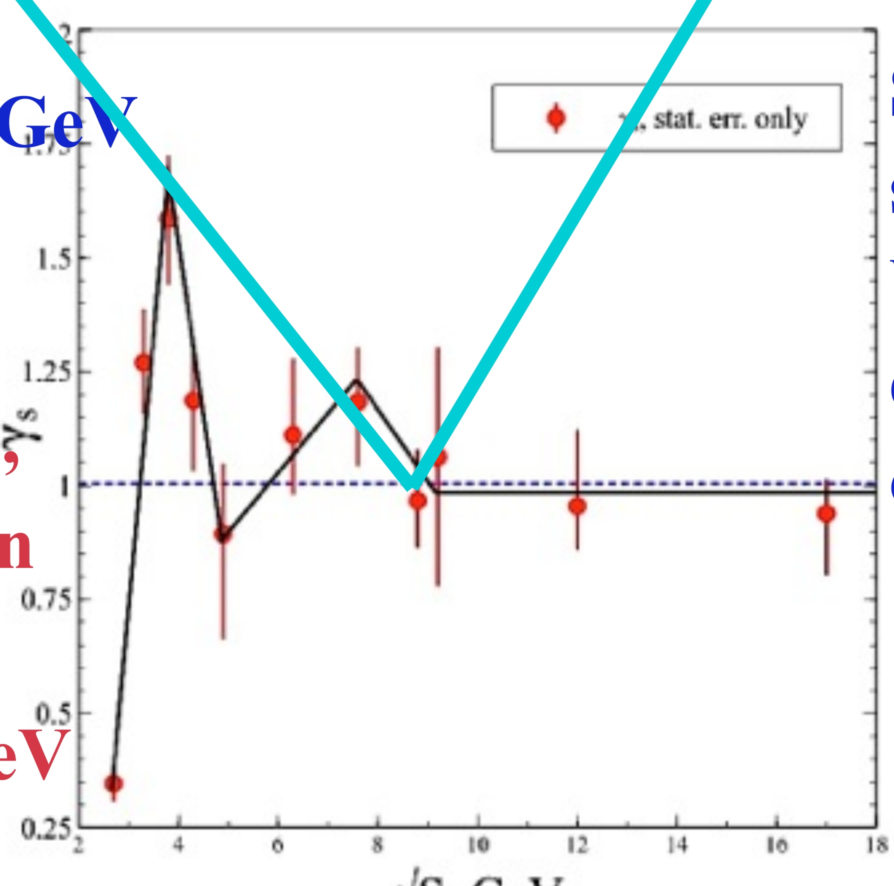
J. K. Nayak, S. Banik, Jan-e Alam, PRC **82**, 024914 (2010)



pure hadronic

deconfinement
starts at 8.7 GeV

Light nuclei fluctuations are enhanced at c.m. energy 8.8 GeV => CEP is located nearby!



Strangeness Horn and other strange particles ratios can be explained, if the onset of deconfinement begins at c.m. energy 8.7 GeV!

Counting for thermodynamic, hydrodynamic and fluctuation signals we conclude that 3CEP may exists at 8.8-9.2 GeV

Recall the talk of
E. Bratkovskaya
on PHSD !

Possible Interpretation

If 1-st order PT exists at 4.3 GeV < $\sqrt{s}$ < 4.9 GeV

and deconfinement exists at $\sqrt{s}$ > 8.7-9.2 GeV

Then what phase does exist at 4.9 GeV < $\sqrt{s}$ < 8.7 GeV?

Can we learn its properties?

Effective Number of Degrees of Freedom

One look at this EoS:

$$p_{QGP} = \underbrace{A_0 T^4 + A_2 T^2 \mu^2 + A_4 \mu^4 - B}_{fitting} = \underbrace{A_0^L T^4 + A_2^L T^2 \mu^2 + A_4^L \mu^4}_{LQCD} - B_{eff}$$

$$B_{eff}(T, \mu_B) = B - (A_0 - A_0^L) T^4 - (A_2 - A_2^L) T^2 \mu^2 - A_4 - A_4^L) \mu^4$$

Another look at this EoS:

$$p_{\text{New phase}} = \underbrace{A_0 T^4 + A_2 T^2 \mu^2 + A_4 \mu^4 - B}_{fitting}$$

It corresponds to massless particles with strong interaction

Then one can find an effective #dof from A_0!

For massless particles

$$A_0 = N_{dof} \frac{\pi^2}{90} \quad \text{with} \quad N_{dof} = N_{dof}^{Bosons} + \frac{7}{8} \times 2 N_{dof}^{Fermions}$$

$$\Rightarrow \quad N_{dof} = A_0 \, \hbar^3 \, \frac{90}{\pi^2} \simeq 1800$$

It`s a huge number for QGP!

K.A. Bugaev et al., arXiv:1709.05419 [hep-ph]

Possible Interpretations

1. The phase emerging at $\sqrt{s}$ = 4.9-9.2 GeV has no Hagedorn mass spectrum, since strange hadrons are not in chemical equilibrium.

2. 1800 of massless dof may evidence either about new phenomena (i.e. unitary/chiral symmetry restoration) in hadronic sector.

3. Or 1800 of massless dof may evidence about tetra-quarks with massive strange quark!?

   see Refs. in R.D. Pisarski, 1606.04111 [hep-ph]

4. Or 1800 of massless dof may evidence about quarkyonic phase!?

   A. Andronic et. al, Nucl. Phys. A 837, 65 (2010)

5. 1800 of massless dof may evidence about something else…

Conclusions

1. High quality description of the chemical FO data allowed us to find **few novel irregularities** at c.m. energies 4.3-4.9 GeV (pressure, entropy density jumps e.t.c.)

2. HRG model with multicomponent repulsion allowed us to find the **correlated (quasi)plateaus** at c.m. energies 3.8-4.9 GeV which were predicted about 27 years ago.

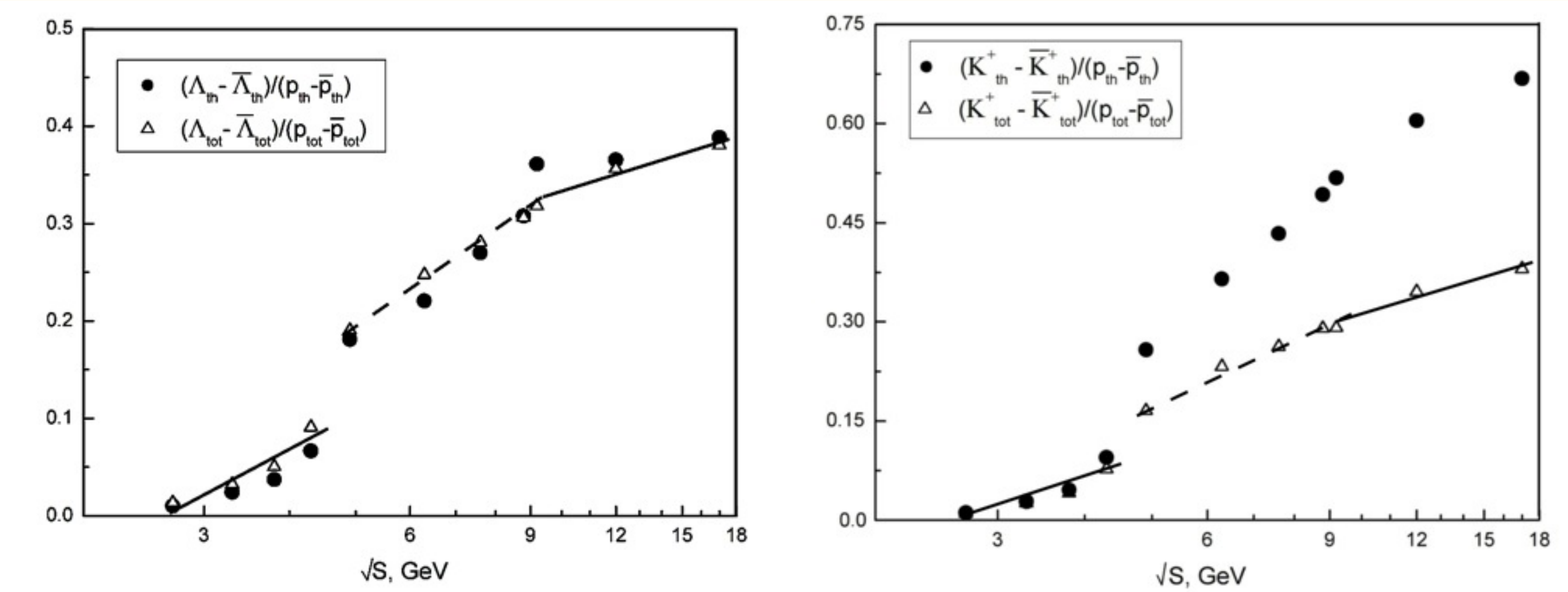
3. The second set of plateaus and irregularities may be a signal of another phase transition! Then the QCD diagram **3CEP may exist at the vicinity of c.m. energies 8.8-9.2 GeV.**

4. Generalized shock adiabat model allowed us to describe entropy per baryon at chemical FO and determine the parameters of the **EOS of new phase from** the data.

5. Hopefully, FAIR, NICA and J-PARC experiments will allow us to make more definite conclusions

Thank You for Your Attention!

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 ~ 8-10 GeV due to 2-nd order PT
(or weak 1-st order PT?)

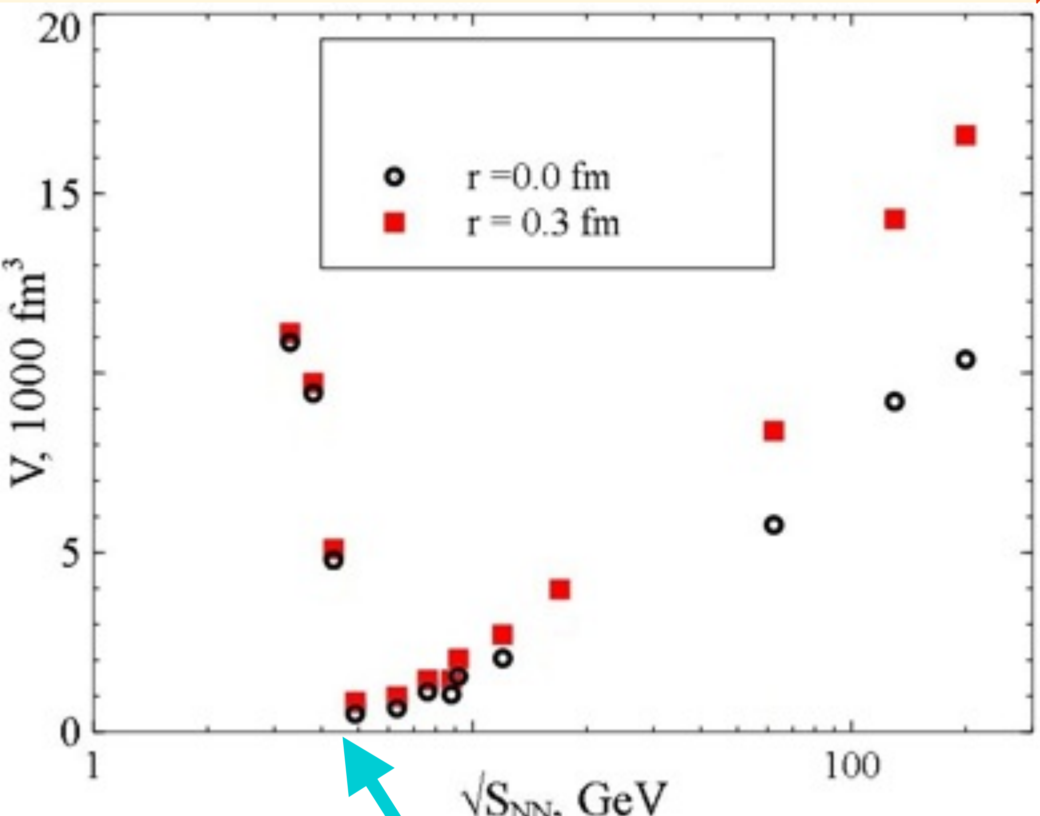
To locate the energy of SLOPE CHANGE we need MORE data at 4-13 GeV

Other Minima at AGS Energies

min V at ChFO

SAME energy!

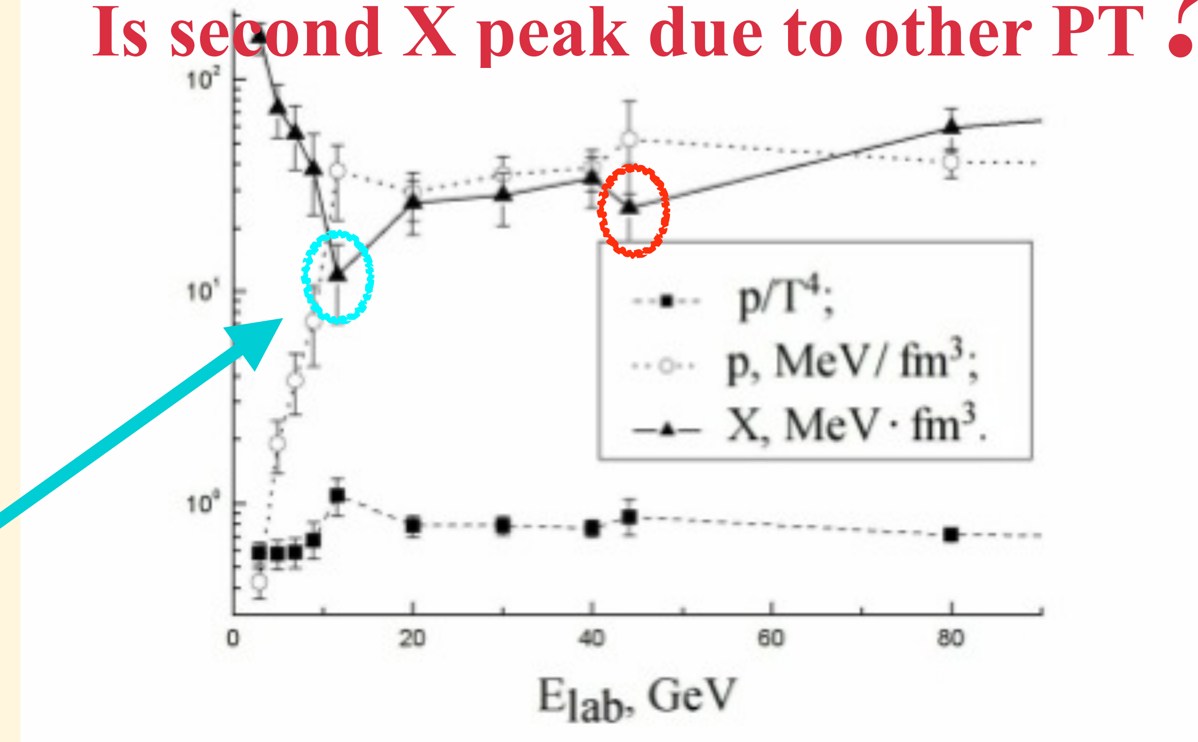
min X at ChFO



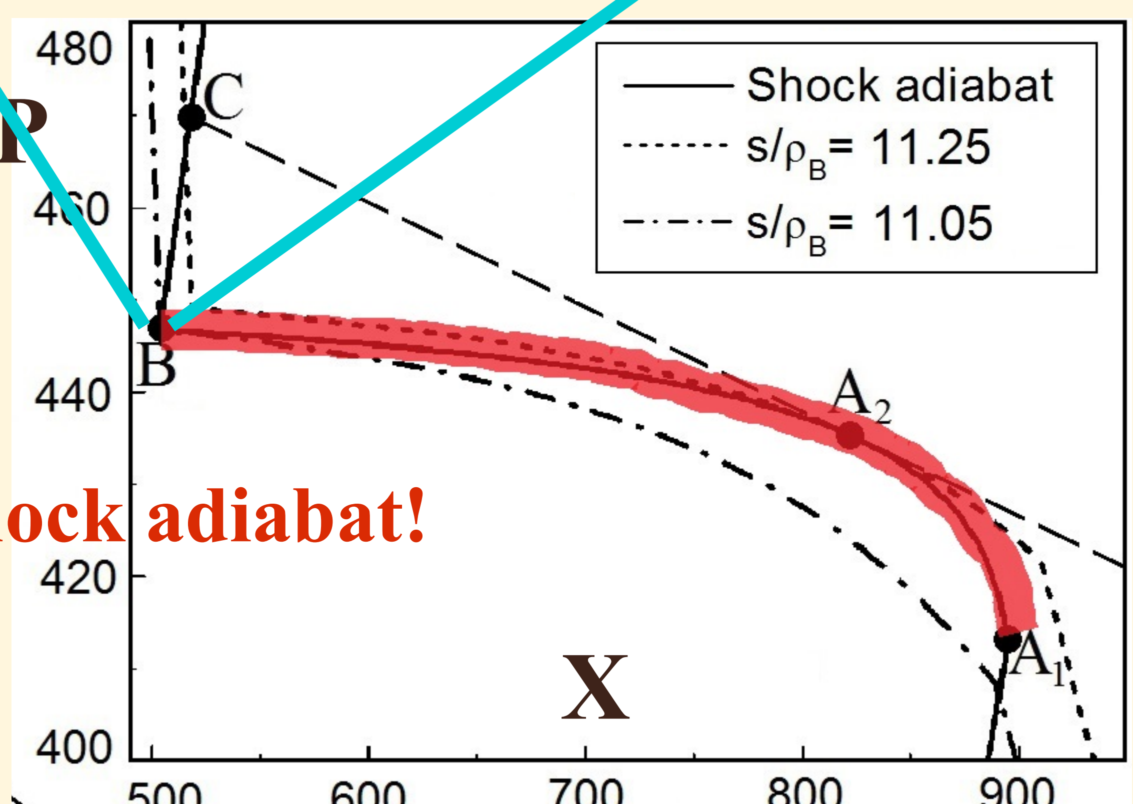
D.R. Oliinychenko, K.A. Bugaev and A.S. Sorin, Ukr. J. Phys. 58, (2013)

X is generalized specific volume

Is second X peak due to other PT?



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



min X at shock adiabat!

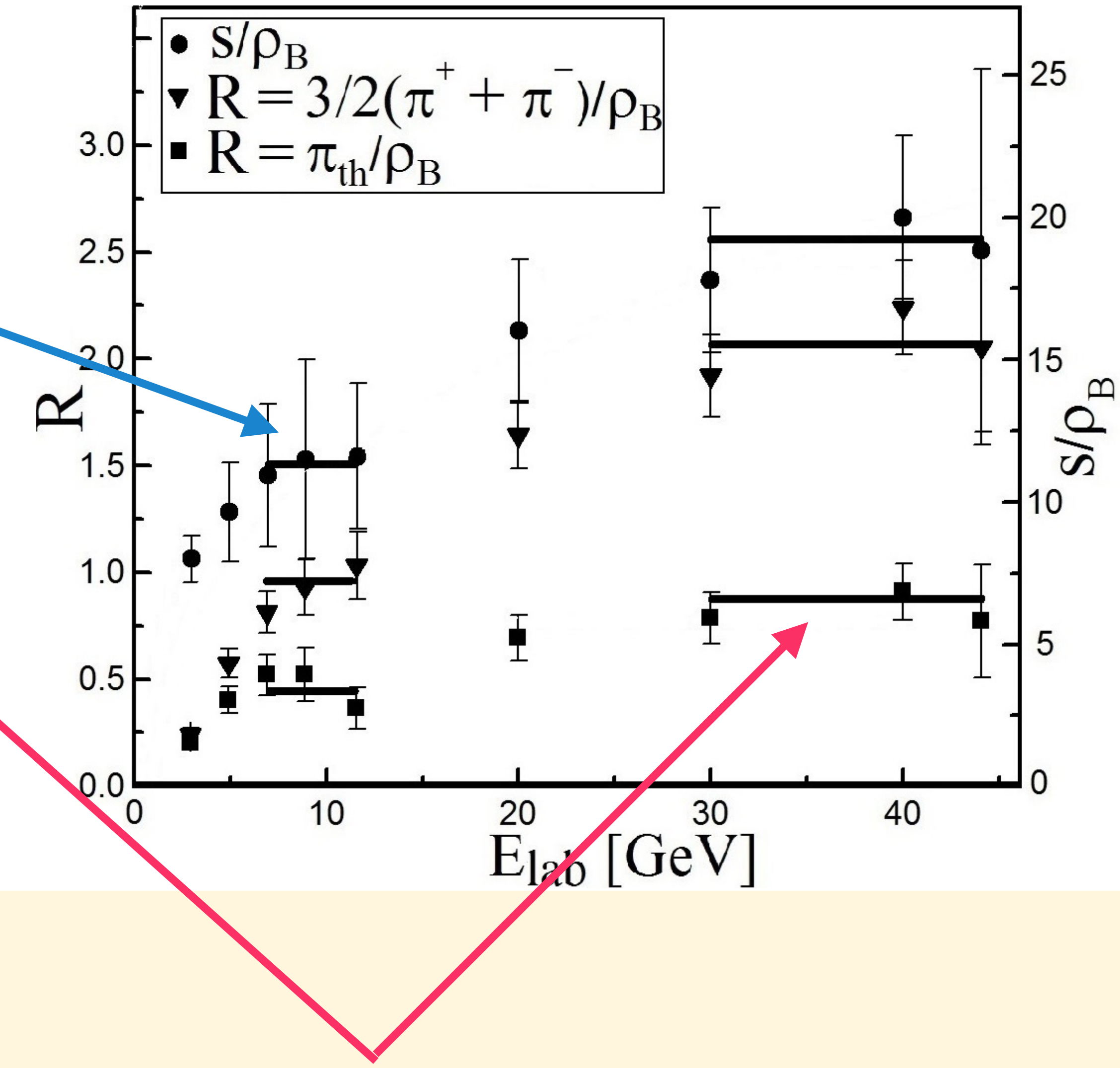
In this work we gave a proof that min X at boundary between QGP? and mixed phase generates min X at ChFO which leads to min V of ChFO!

Details on Highly Correlated Quasi-Plateaus

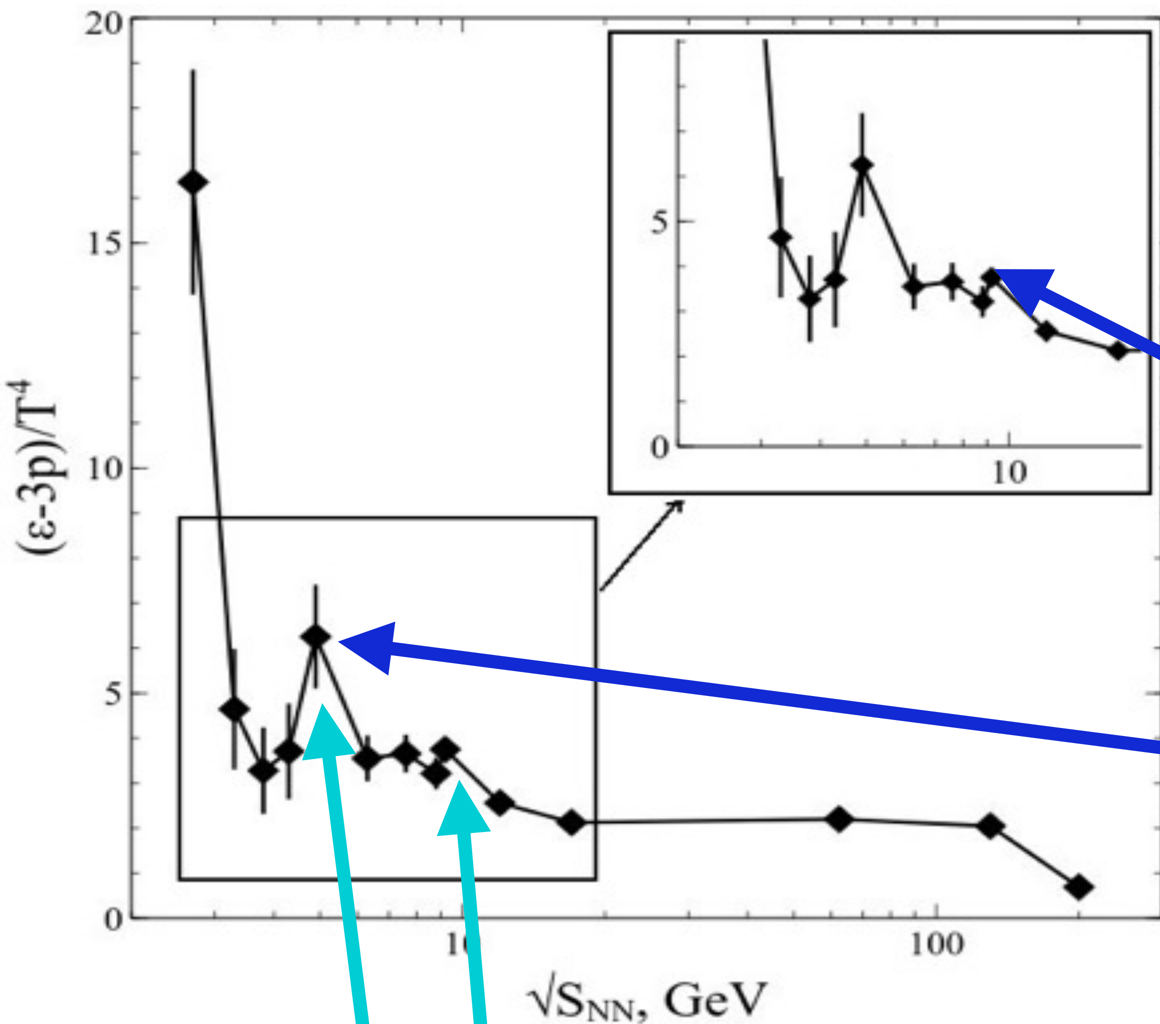
- Common width M – number of points belonging to each plateau
- Common beginning i_0 – first point of each plateau
- For every M, i_0 minimization of χ^2/dof yields $A \in \{s/\rho_B,\ \rho_\pi^{th}/\rho_B,\ \rho_\pi^{tot}/\rho_B\}$:

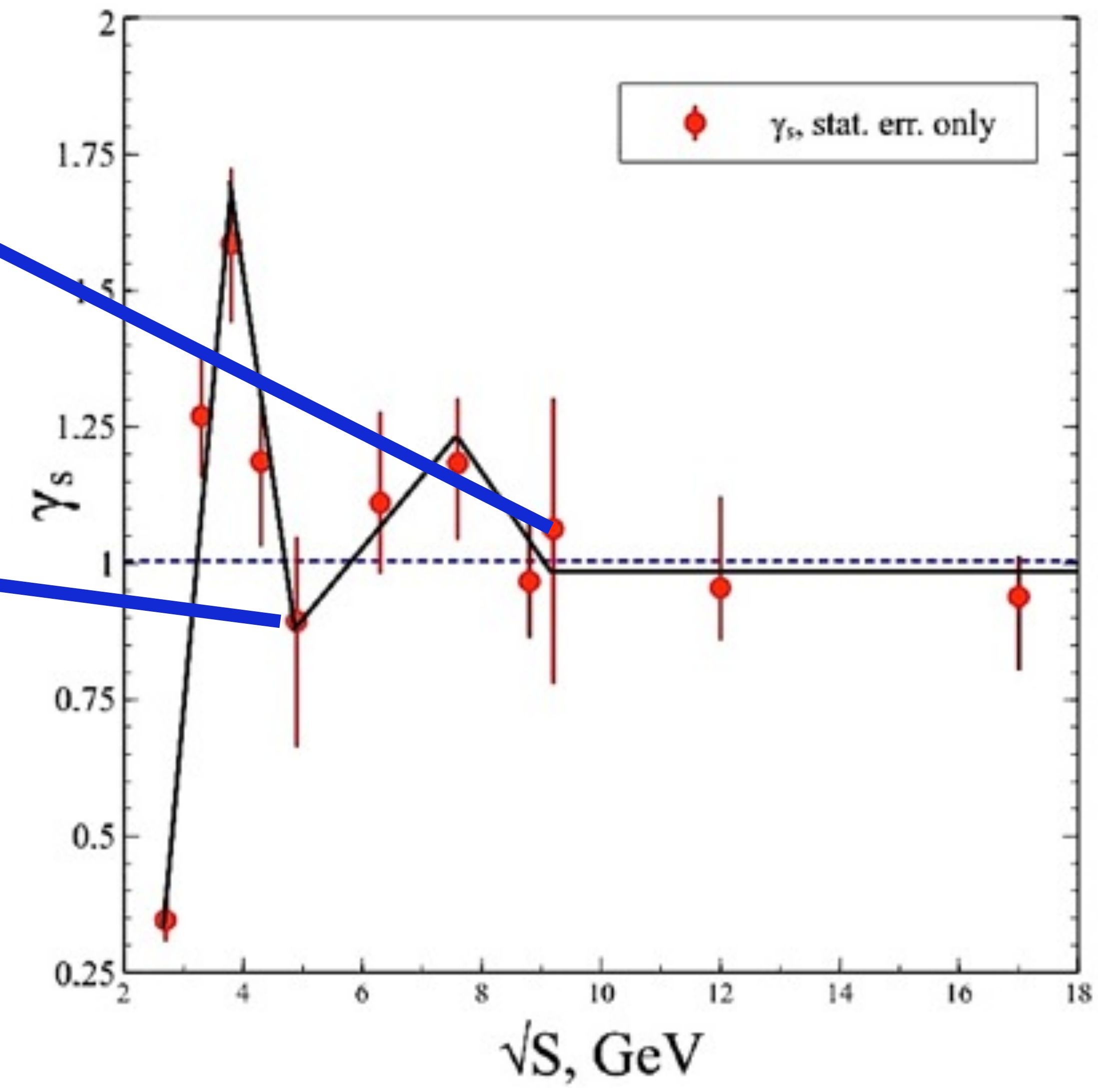
$$\chi^2/\mathrm{dof} = \frac{1}{3M-3} \sum_A \sum_{i=i_0}^{i_0+M-1} \left(\frac{A - A_i}{\delta A_i}\right)^2 \quad \Rightarrow \quad A = \sum_{i=i_0}^{i_0+M-1} \frac{A_i}{(\delta A_i)^2} \Big/ \sum_{i=i_0}^{i_0+M-1} \frac{1}{(\delta A_i)^2}$$

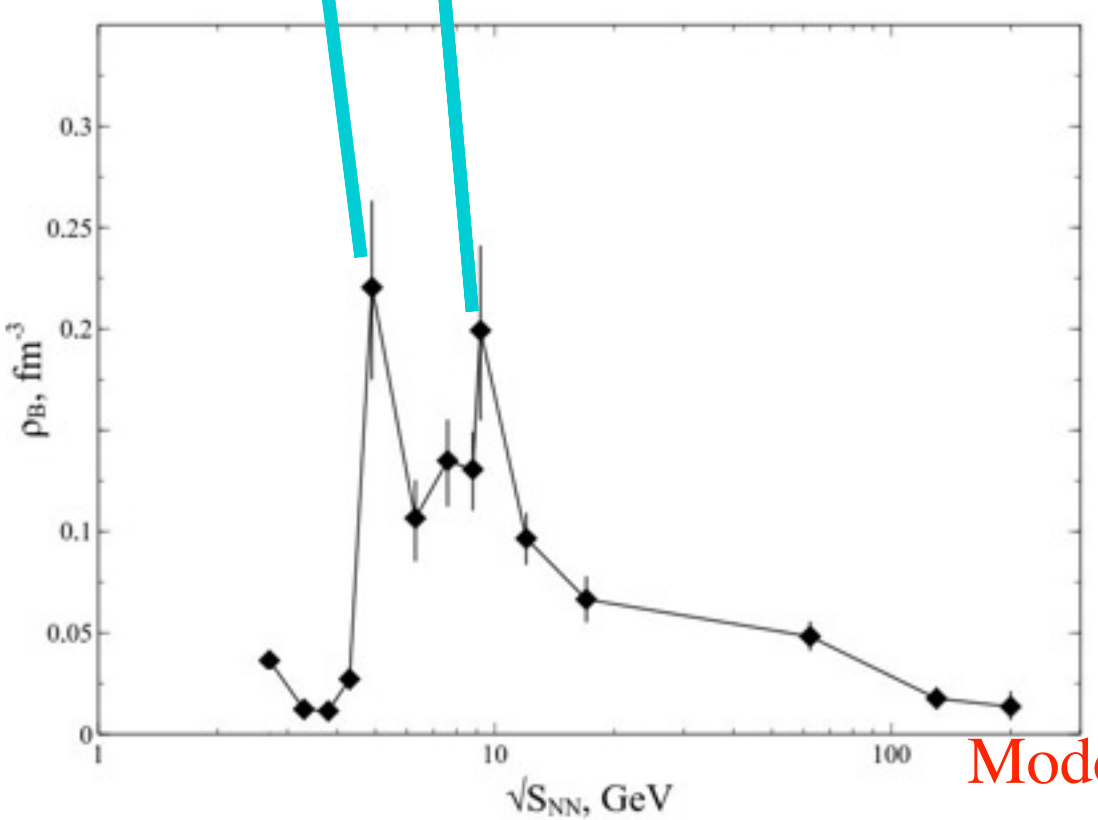
	Low energy plateau				
M	i_0	s/ρ_B	ρ_π^{th}/ρ_B	ρ_π^{tot}/ρ_B	χ^2/dof
2	3	11.12	0.52	0.85	0.17
3	3	11.31	0.46	0.89	0.53
4	2	10.55	0.43	0.72	1.64
5	2	11.53	0.47	0.84	4.45
	High energy plateau				
2	8	19.80	0.88	2.20	0.12
3	7	18.77	0.83	2.05	0.34
4	6	17.82	0.77	1.87	0.87
5	5	16.26	0.64	1.62	3.72



Related Peaks (2017)





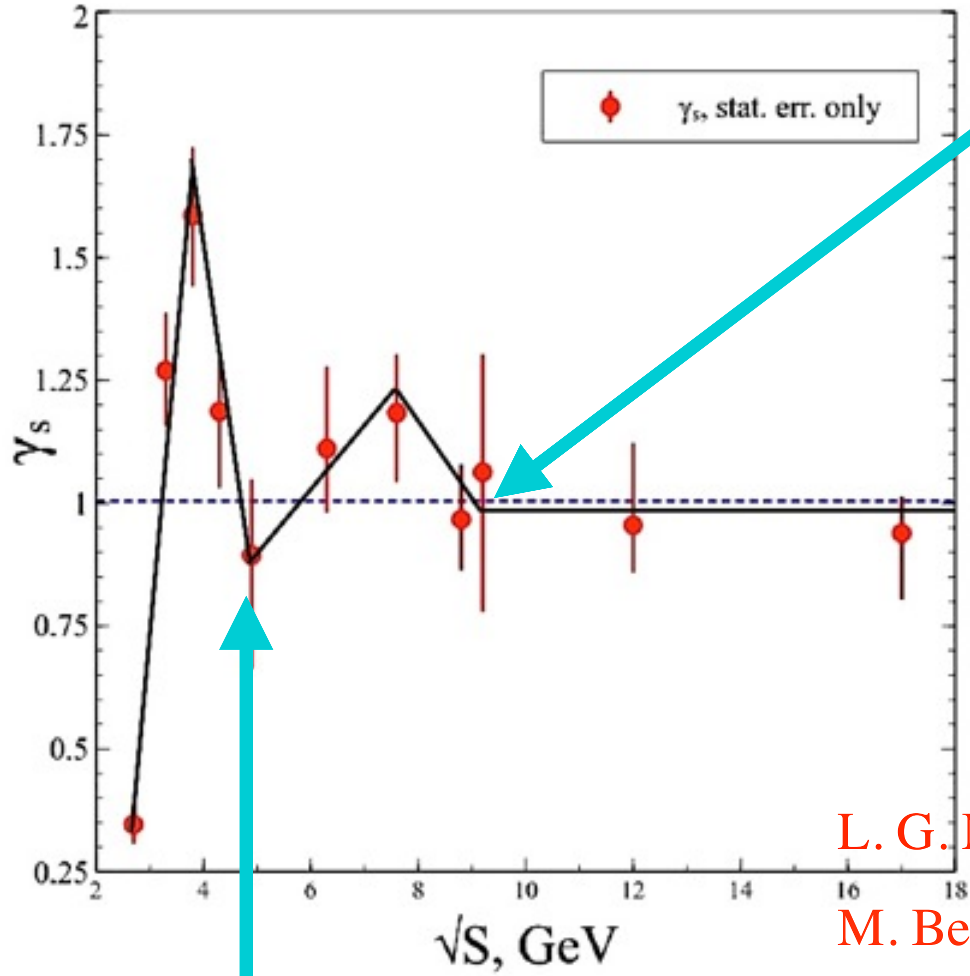


Trace anomaly peaks and baryonic density peaks are related to each other.

Can we relate them to γ_s irregularities?

Model from V.V. Sagun et al., arXiv:1703.00009 [hep-ph]

Strangeness Irregularities



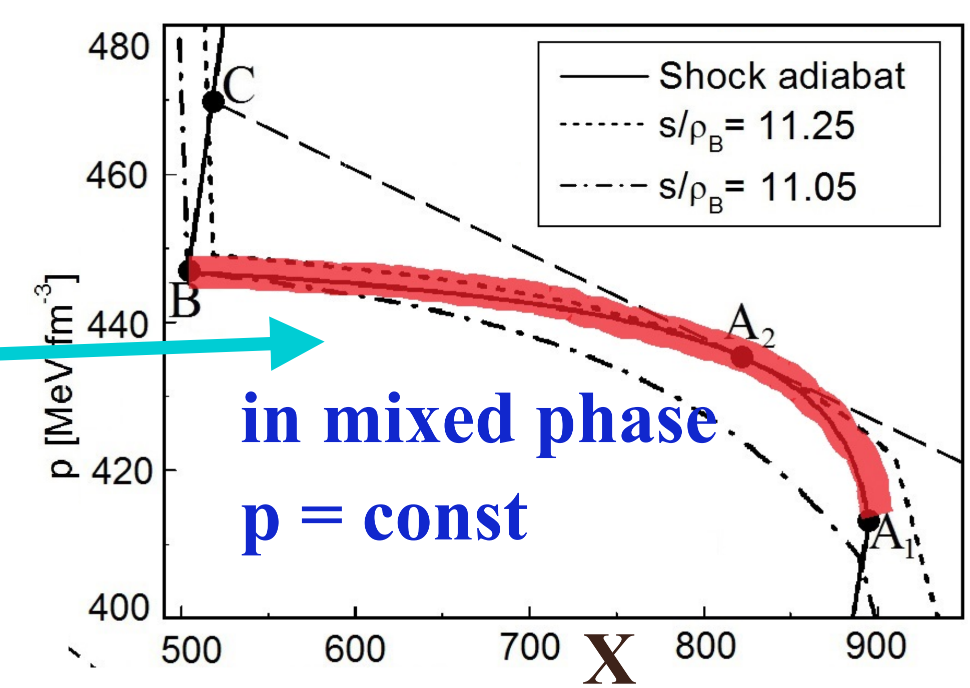
At c.m. energies above 8.8 GeV the strange hadrons are in chemical equilibrium due to formation of QG bags with Hagedorn mass spectrum!

Hagedorn mass spectrum is a perfect thermostat and a perfect particle reservoir! => Hadrons born from such bags will be in a full equilibrium!

L. G. Moretto, K. A. B., J. B. Elliott and L. Phair, Europhys. Lett. 76, 402 (2006)

M. Beitel, K. Gallmeister and C. Greiner, Phys. Rev. C 90, 045203 (2014)

At c.m. energy GeV strange particles are in chemical equilibrium due to formation of mixed phase, since under CONSTANT PRESSURE condition the mixed phase of 1-st order PT is explicit thermostat and explicit particle reservoir!



Explicit Thermostats

1. **At limiting temperature the Hagedorn mass spectrum is a perfect thermostat and a perfect particle reservoir since it is a kind of mixed phase!**

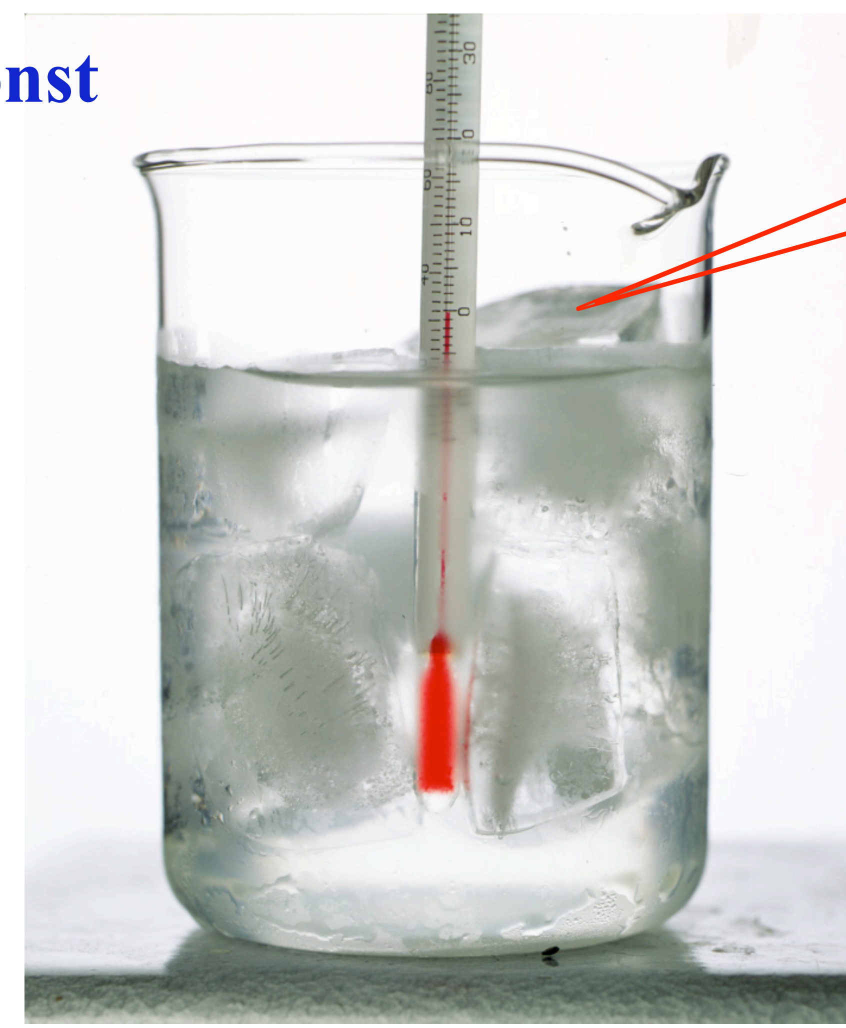
L. G. Moretto, K. A. B., J. B. Elliott, L. Phair, Europhys. Lett. 76, 402 (2006)

2. **Under a constant external pressure ANY MIXED PHASE is a perfect thermostat and a perfect particle reservoir!**

As long as two phases coexist

- Export/import of heat does not change T!

Pressure = const



$T = T_c = 273$K
or
$0 \le T \le 273$K **?**

- First take heat dQ=E from system with temperature T:
- Then give it to thermostat

=> T = const, μ = const

- Export/import of **finite amount of phases => T = const, μ = const**

Induced Surface Tension EOS for HRGM

This EoS allows one to go beyond the Van der Waals approximation!

pressure $$\frac{p}{T} = \sum_i \phi_i \exp\left(\frac{\mu_i - pV_i - \Sigma S_i}{T}\right)$$

induced surface tension $$\frac{\Sigma}{T} = \sum_i R_i \phi_i \exp\left(\frac{\mu_i - pV_i - \Sigma S_i}{T}\right) \cdot \overbrace{\exp\left(\frac{(1-\alpha) S_i \Sigma}{T}\right)}^{\text{new term}}$$

V_k and S_k are eigenvolume and eigensurface of hadron of sort k

α switches excluded and eigen volume regimes

high order virial coefficients

Advantages

1. Allows to go beyond the Van der Waals approximation

2. Number of equations is 2 and it does not depend on the number different hard-core radii!

see V.V. Sagun et al., arXiv:1703.00009 [hep-ph]

Consequent Problem and Its Possible Solution

If 1800 of massless dof exist then at high T and same μ_B the QGP cannot exist, since its pressure is too low to dominate!

$\Longrightarrow$ Contradiction with Lattice QCD!

The only possibility to avoid the contradiction with LQCD is to assume hard-core repulsion for 1800 of massless dof !

Since they are almost massless (m << T), then the hard-core repulsion should be formulated for ultra-relativistic particles and include the effect of Lorentz contraction.

see K. A. Bugaev, Nucl. Phys. A 807, 251 (2008).

In the limit μ_B /T << 1 and mass/T <<1 the pressure of such system is

$p \simeq \frac{T^2}{V_0^{\frac{2}{3}}} N_{dof}^{\frac{1}{3}} C$ with $C = Const \sim 1$ here V_0 is eigenvolume of hadron

No mass dependence and very weak dependences on T and on #dof: $N_{dof}^{\frac{1}{3}} \simeq 12$