Heavy ion collisions at NICA-FAIR energies and possible signals of two QCD phase transitions

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Dubna, September 17, 2019

Outline

1. Motivation and introduction

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

Experiments on A+A Collisions

Are aimed to study the QCD phase diagram

$\left.\begin{array}{lll} \text{AGS (BNL)} & \text{up to} & \text{4.9 GeV} \\ \text{SPS (CERN)} & & \text{6.1 - 17.1 GeV} \\ \text{RHIC (BNL)} & & \text{62, 130, 200 GeV} \end{array}\right\}$ Completed

Ongoing HIC experiments
LHC (CERN) > 1 TeV (high energy)
RHIC (BNL) low energy
SPS (CERN) low energy

Future HIC experiments
NICA(JINR, Dubna)
SIS300 = FAIR (GSI)
J-PARC

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?**

In order to answer these questions we need a very good tool to analyze the data!

Recently Suggested Signals of QCD Phase Transitions 2014-2018

During 2013-2017 our group developed a very accurate tool to analyze data

D. Oliinychenko, KAB, A. Sorin, Ukr. J. Phys. 58 (2013)

KAB, D. Oliinychenko, A. Sorin, G.Zinovjev, EPJ A 49 (2013)

KAB et al., Europhys. Lett. 104 (2013)

KAB et al., Nucl. Phys. A 970 (2018)

KAB et al., Universe 5, (2019)

Most successful version of the Hadron Resonance Gas Model (HRGM)

The high quality description of data allowed us to elucidate new irregularities at CFO from data and to formulate new signals of two QCD phase transitions

D. Oliinychenko et al., Ukr. J Phys. 59 (2014)

KAB et al., Phys. Part. Nucl. Lett. 12 (2015)

KAB et al., EPJ A 52 (2016) No 6

KAB et al., EPJ A 52 (2016) No 8

KAB et al., Phys. Part. Nucl. Lett. 15 (2018)

First work on evidence of two QCD phase transitions

Recently Suggested Signals of QCD Phase Transitions 2016

Our results

1-st order PT of Chiral Symmetry Restoration in hadronic phase occurs at about $\sqrt{s} \sim 4.3$-4.9 GeV

and 2-nd order deconfinement PT exists at $\sqrt{s} \sim 9$ GeV

Giessen group results (recall E. Bratkovskaya talk at this meeting!)

W. Cassing et al.,, Phys. Rev. C 93, 014902 (2016);
Phys. Rev. C 94, 044912 (2016).

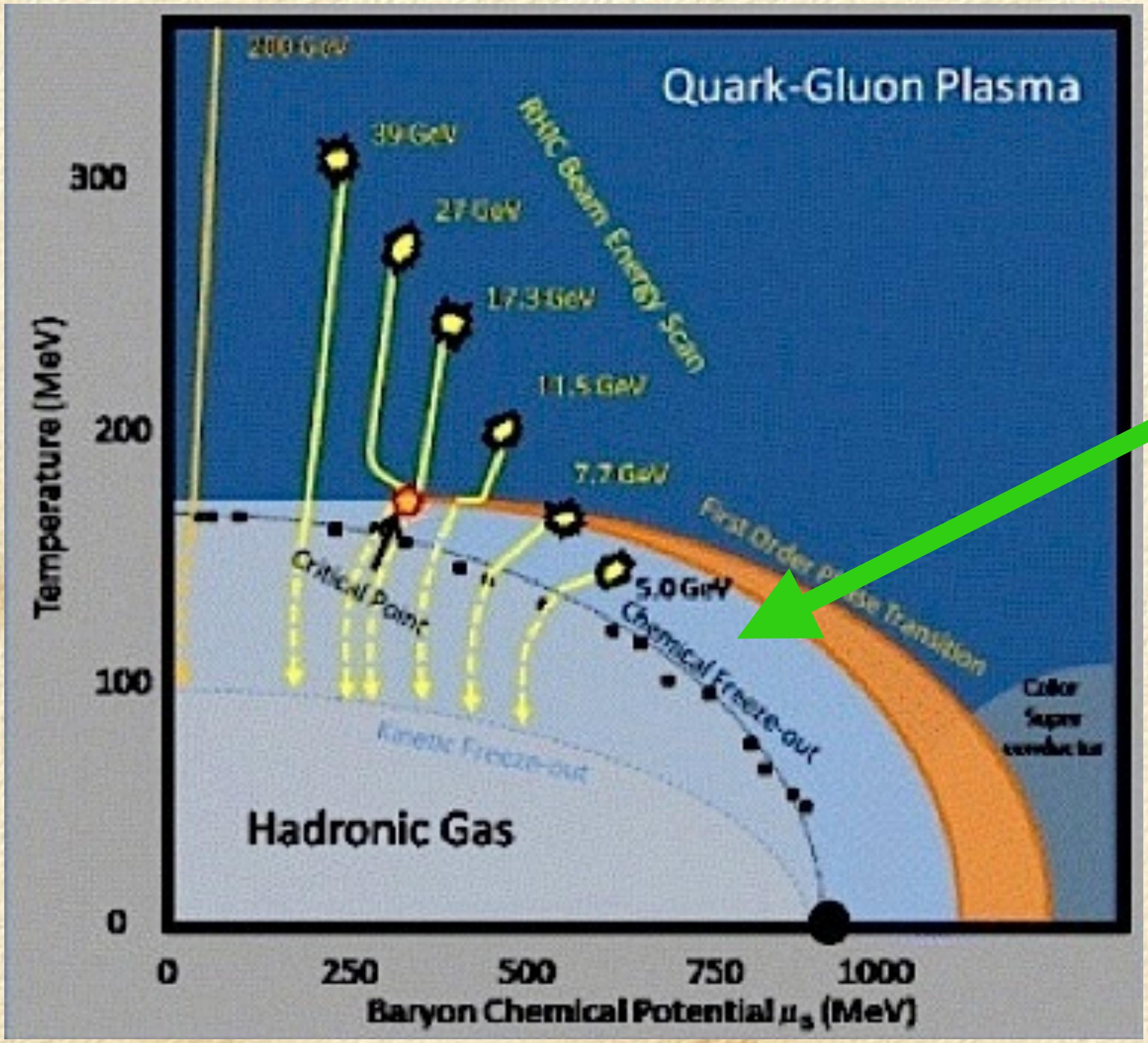
1-st order PT of ChSR in hadronic phase occurs at about $\sqrt{s} \sim 4.$ GeV
and 2-nd order deconfinement PT exists at $\sqrt{s} \sim 10$ GeV

Hard to locate them due to cross-over in Parton-Hadron-String-Dynamics model!

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.

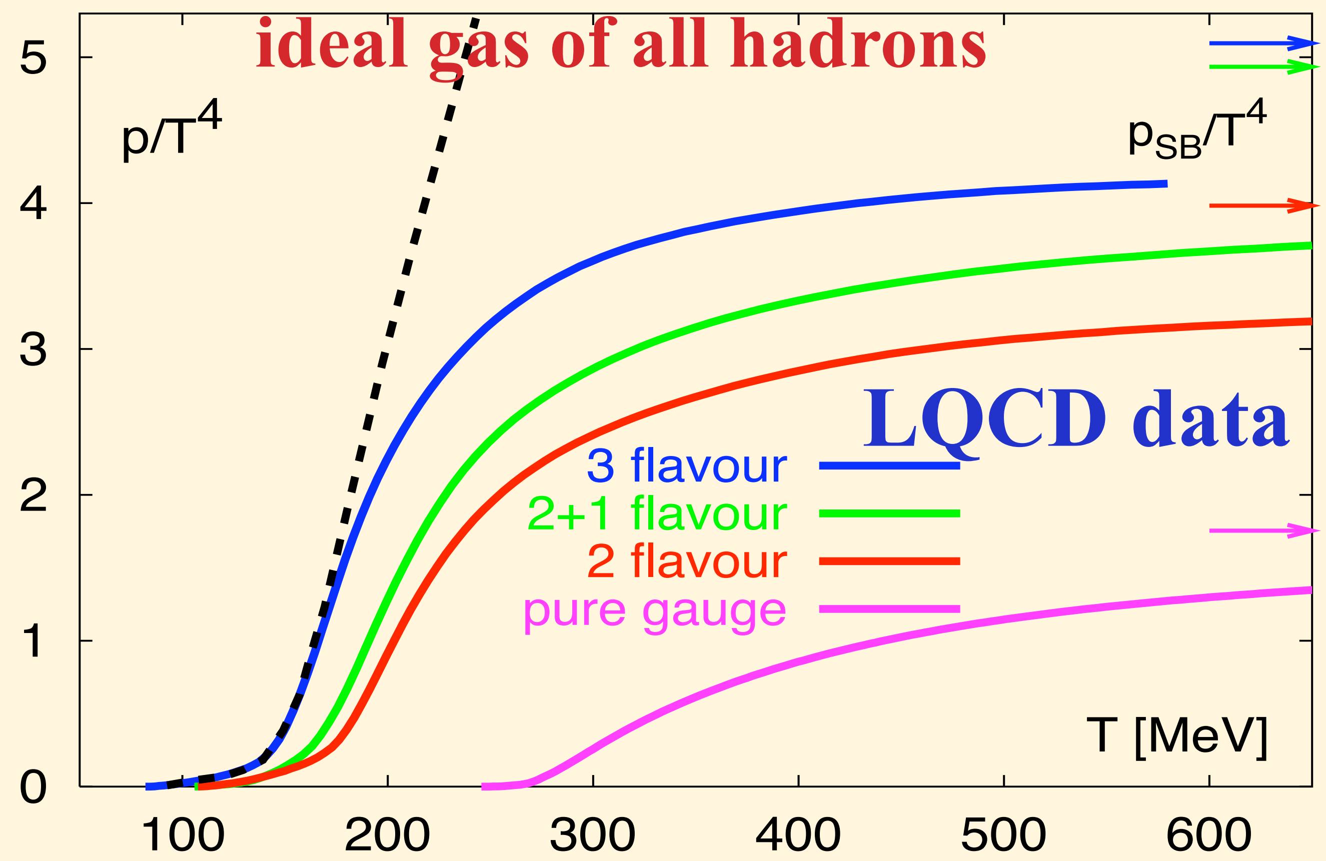
Thanks to Jean Cleymans for great introduction to HRGM!

Why Van der Waals or Hard-core Repulsion EoS?

1. Hard-core repulsion EoS (= VdWaals without attraction) has the same energy per particle as an ideal gas => there is no problems to convert its energy into ideal gas energy

Proof: if particles stay apart, they do not interact, if particles touch each other, potential energy is infinite and => such configurations do not contribute into partition

2. Hard-core repulsion does not create problems with QGP existence, since such repulsion suppresses pressure compared to ideal gas EoS



Why Van der Waals or Hard-core Repulsion EoS?

3. Almost in the whole hadronic phase the mixture of stable hadrons and resonances behaves as a mixture of ideal gases with small hard-core radii

due to approximate cancellation of attraction and repulsion terms

among the quantum second virial coefficients of hadrons

R. Venugopalan and M. Prakash, Thermal properties of interacting hadrons.

***Nucl. Phys. A* 1992, *546*, 718**

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.

Induced Surface Tension EOS

pressure

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

induced surface tension

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

R_k, V_k and S_k are hard-core radius, eigenvolume and eigensurface of hadron of sort k

Advantages

1. It allows one to go beyond the Van der Waals approximation, since it reproduces 2-nd, 3-rd and 4-th virial coefficients of the gas of hard spheres for $\alpha = 1.245$.

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

V.V. Sagun, K.A.Bugaev, A.I. Ivanytskyi, D.R. Oliinychenko, EPJ Web Conf 137 (2017);

K.A.Bugaev, V.V. Sagun, A.I. Ivanytskyi, E. G. Nikonov, G.M. Zinovjev et. al., Nucl. Phys. A 970 (2018) 133-155

V.V. Sagun, K.A.Bugaev, A.I. Ivanytskyi, et al., Eur. Phys. J. A 54, 100 (2018).

Other Features of multicomponent HRGM

The resonance width is taken into account in thermal densities.

Decays of hadronic resonances should be taken into account

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

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

From our experience =>

It is more instructive to fit the ratios of yields since the systematic uncertainties cancel!

Data and Fitting Parameters

111 independent hadronic ratios measured at AGS, SPS and RHIC energies

# of published ratios measured at mid-rapidity depends on energy =>

$\sqrt{s_{NN}}$ (GeV)	N_{rat} FO
2.7	4
3.3	5
3.8	5
4.3	5
4.9	8
6.3	9
7.6	10
8.8	11
9.2	5
12	10
17	13
62.4	5
130	11
200	10
Sum	111

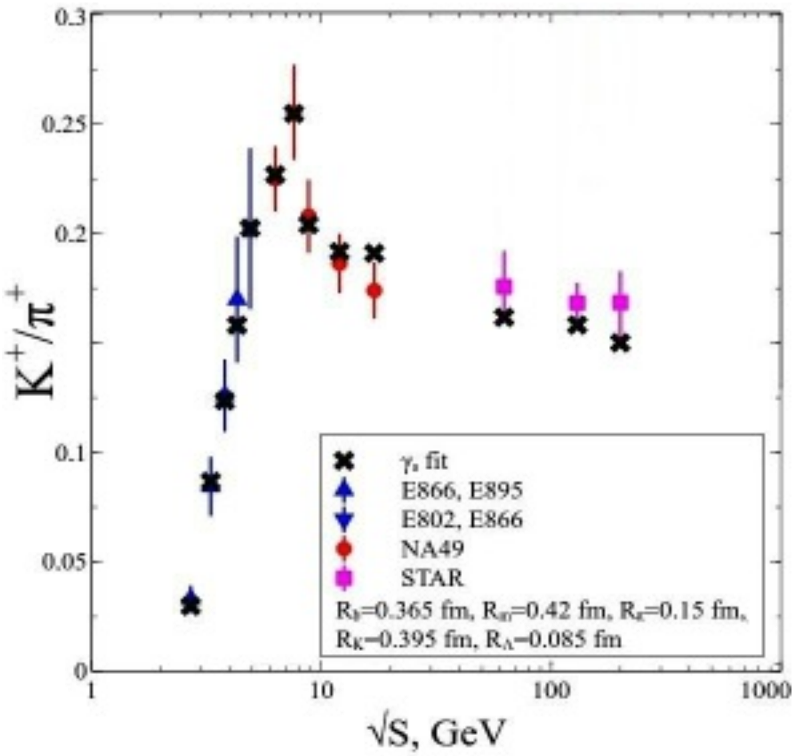
# of local fit parameters cannot be larger than 4 (for all energies) or larger than 5 (for energies above 2.7 GeV)

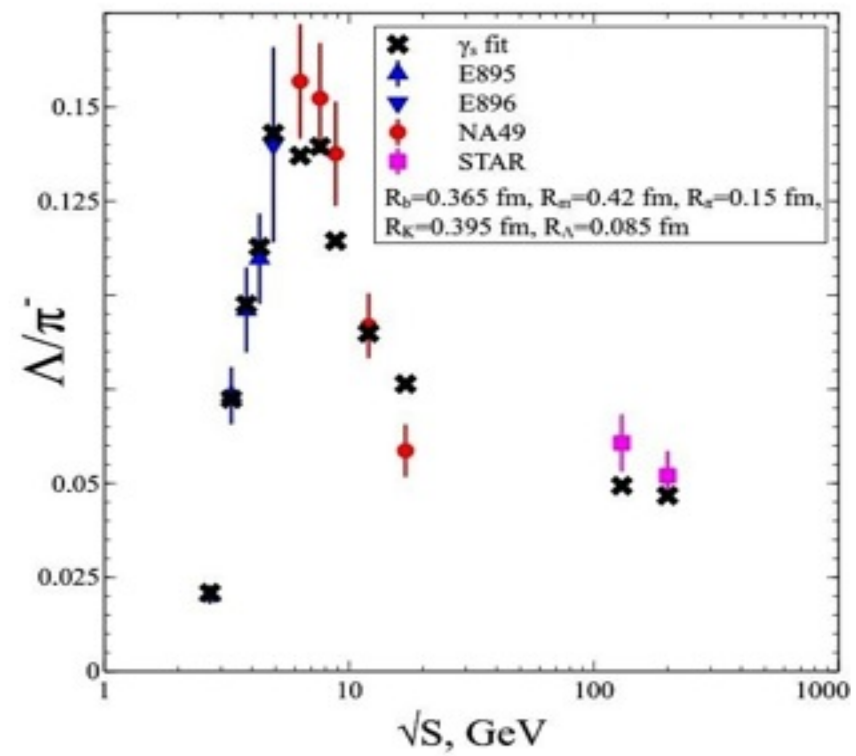
# of local fit parameters for each collision energy = 3 (no γ_S factor)
T, mu_B, mu_I3
Total # for 14 energies = 42

# of fit parameters with γ_S factor is 4
Total # for 14 energies = 56

# of global fit parameters = 4
R_pi, R_K, R_mesons, R_baryons

Most Problematic ratios at AGS, SPS, RHIC energies within Induced Surface Tension EoS



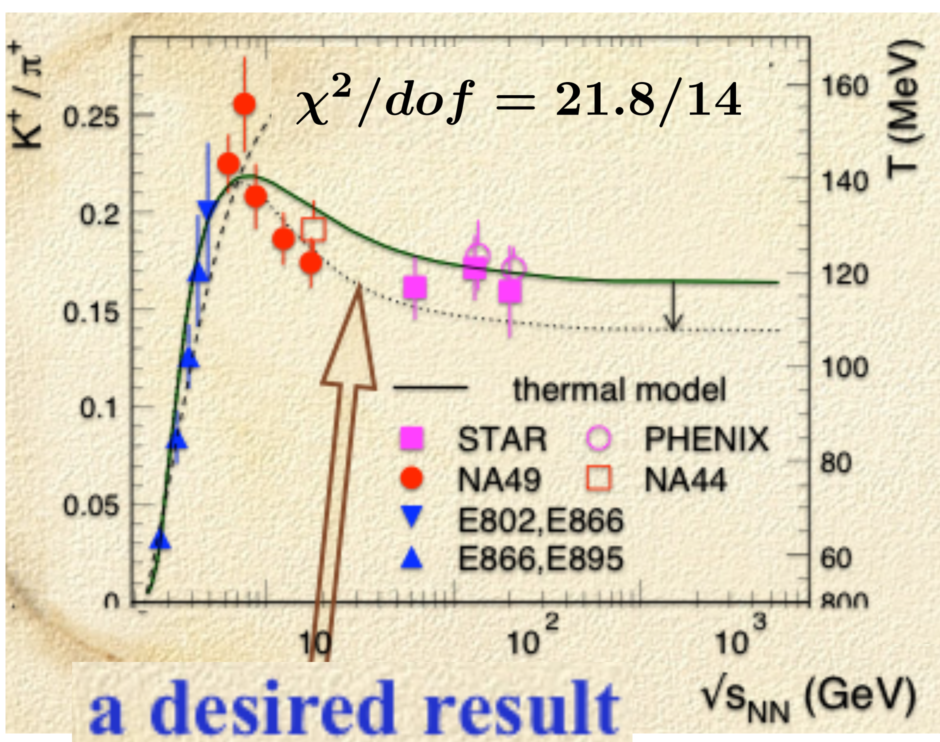


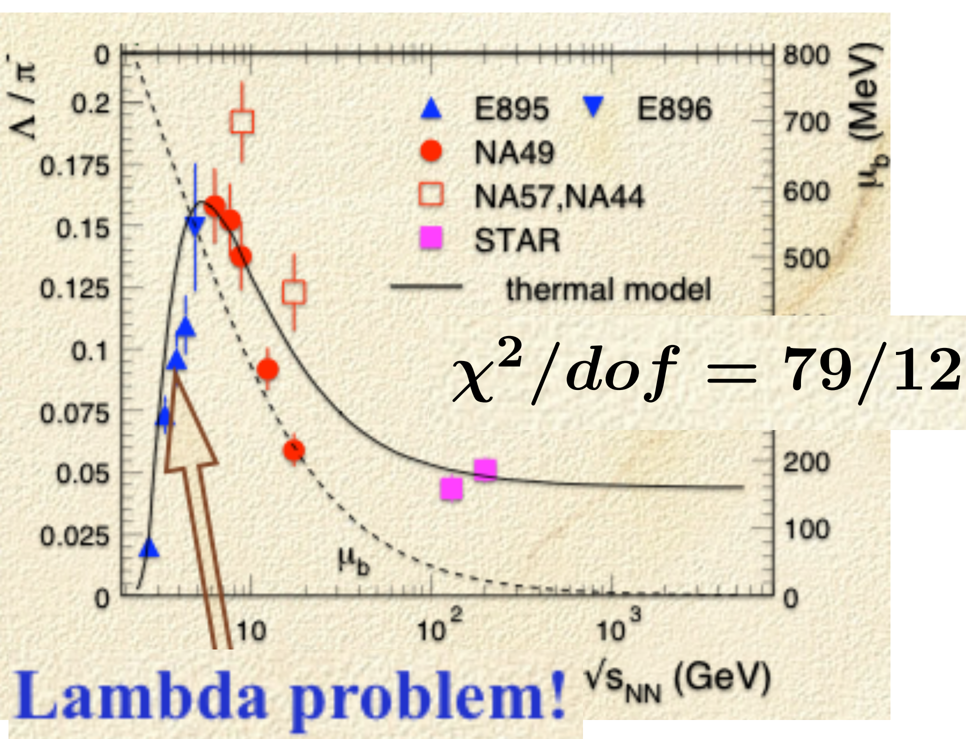
IST EOS: $\chi^2/dof \simeq 3.29/14$ $\chi^2/dof \simeq 11.62/12$

KAB et al., Nucl. Phys. A 970 (2018)

Note: RHIC BES I data have very large error bars and hence, are not analyzed!

Our IST EOS has 3 or 4 more fitting parameters compared to usual HRGM!



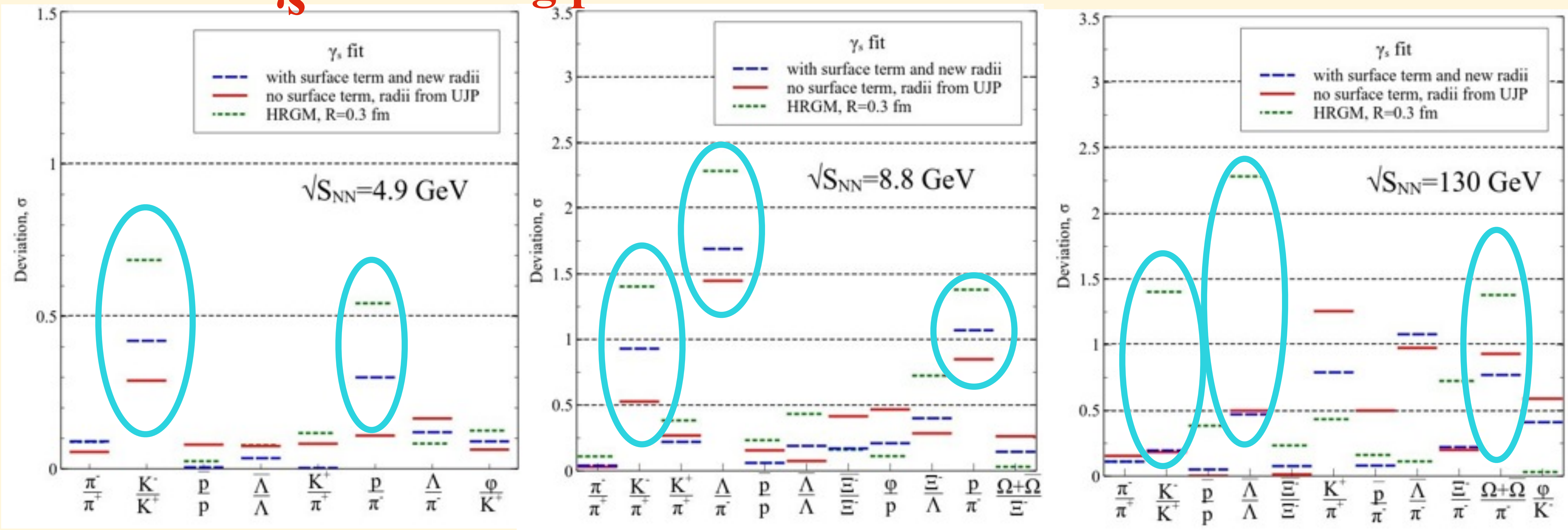


Conventional one component HRGM by PBM and Co:
A. Andronic, PBM, J. Stachel NPA (2006), PLB (2009) [most cited paper on HRGM!?]

Examples of Hadron Multiplicity Ratios for IST EoS, Multicomponent and One-component Van der Waals EoS (2018)

V.V. Sagun et al., Eur. Phys. J. A (2018) 54: 100

All EoS use γ_s as a fitting parameter!



Blue bars **IST EoS (will be presented in a moment)**

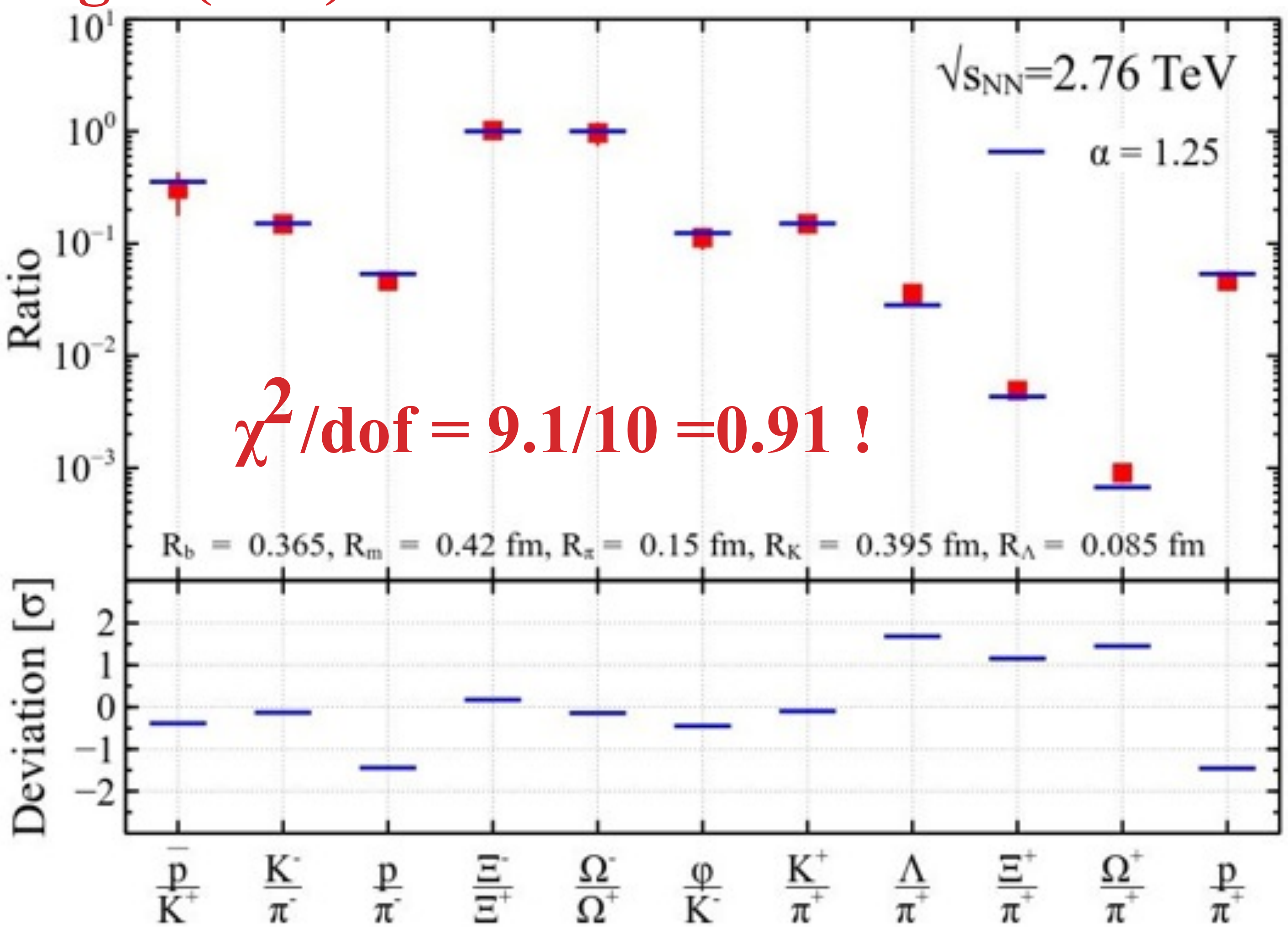
Red bars **Multicomponent Van der Waals EoS**

Green bars **One-component Van der Waals EoS (a la P. Braun-Munzinger et al),**

One-component Van der Waals EoS always gives the worst results!

IST EOS Results for LHC energy

Light (anti)nuclei are NOT included into fit V.V. Sagun et al., Eur. Phys. J. A (2018) 54: 100



Radii are taken from the fit of AGS, SPS and RHIC data => single parameter Tcfo=150+-7MeV

In all our fits (anti)protons and (anti)Ξ-s do not show any anomaly compared to J. Stachel et.al. fit, since we have right physics!

=> There is no proton yield puzzle in a realistic HRGM!

In contrast to J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, J. Phys. Conf. Ser. 509, 012019 (2014) (anti)nuclei are NOT included into the fit!

Combined fit of AGS, SPS, RHIC and LHC data $\chi^2_{tot}/dof \simeq 64.8/60 \simeq 1.08$

Compare with J. Stachel et al. fit quality for Tcfo = 156 MeV χ^2/dof = 2.4 with our one!

Possible solution of (anti)nuclei puzzle was presented in my talk on Crete on 28.08.2019

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

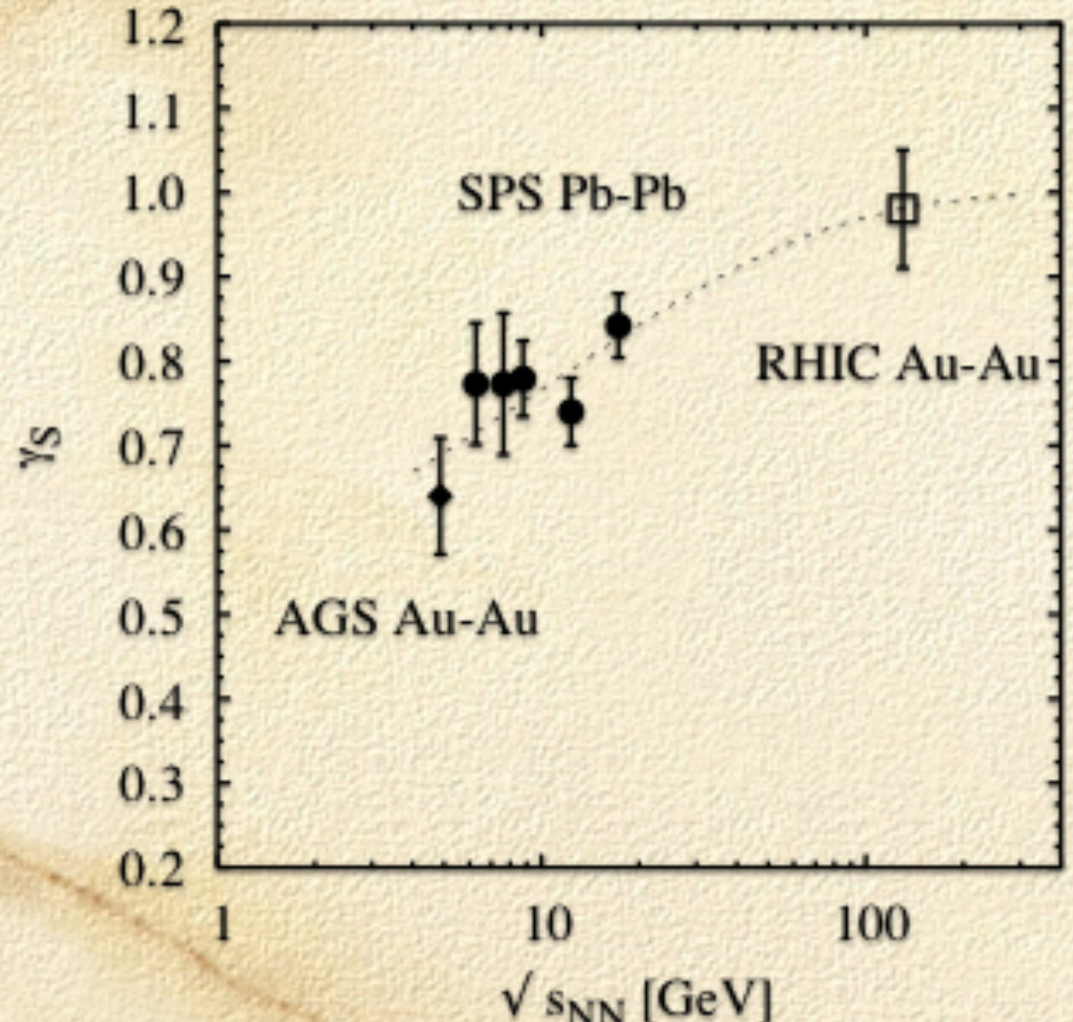
F. Becattini & Co found that γ_S factor is < 1

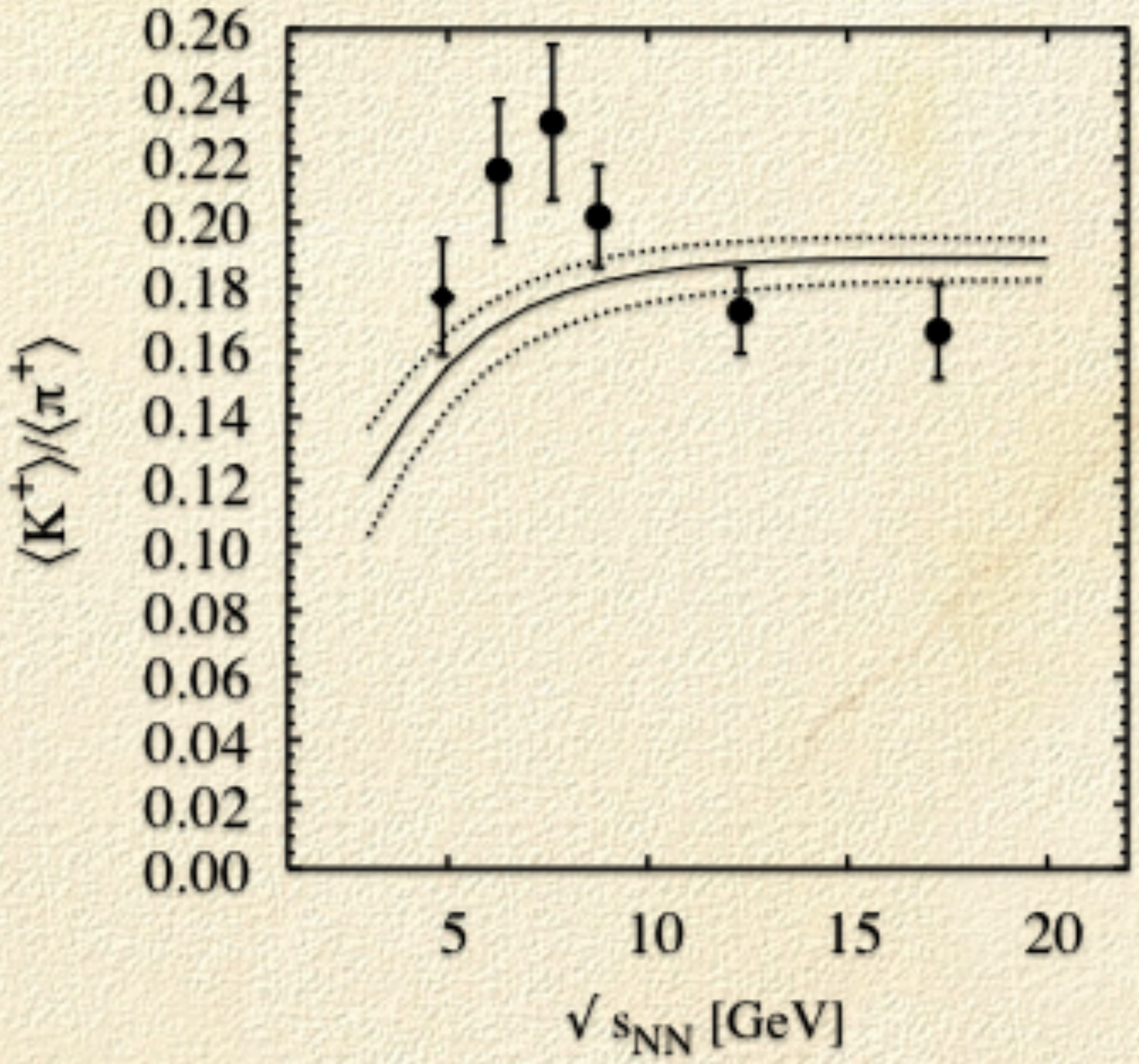
Systematics of Strangeness Suppression

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

where s_i is number of strange valence quarks plus number of strange valence anti-quarks.

Thus, it is a strangeness fugacity **which accounts for 2-nd conservation law**

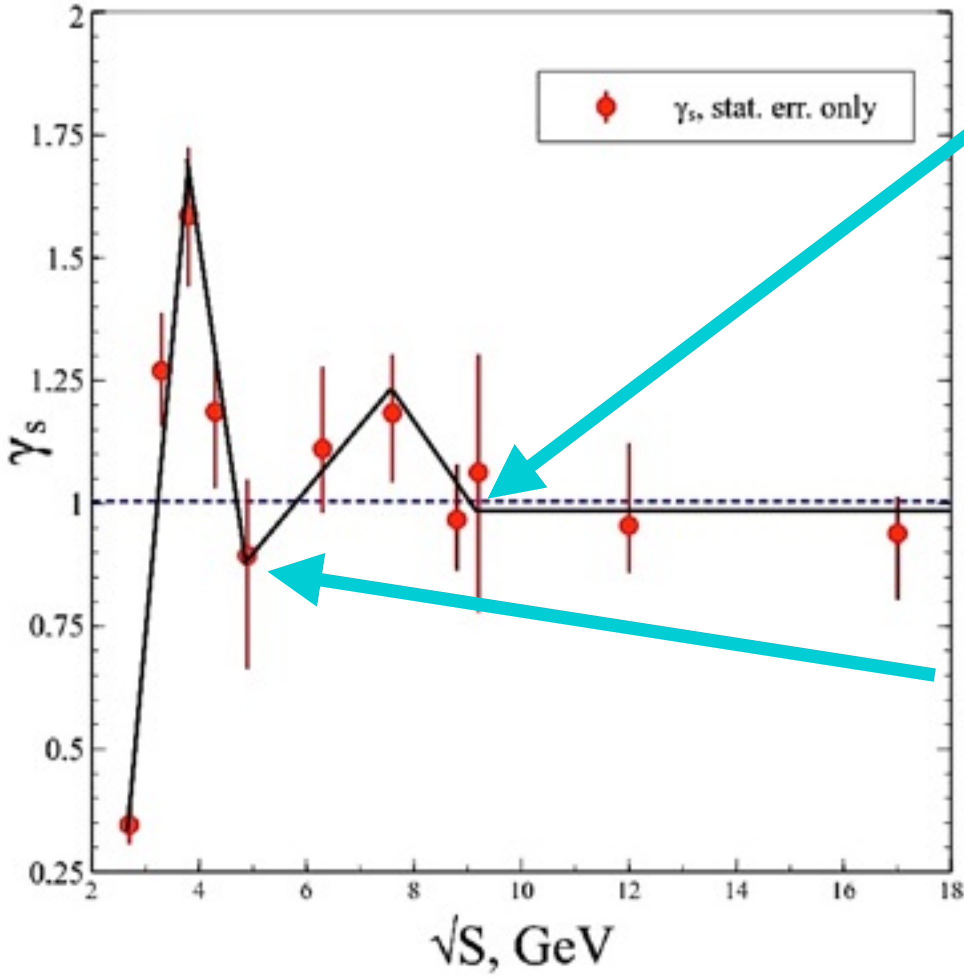




Single component model F. Becattini, J. Manninen and M. Gazdzicki, PRC 73 (2006) 044905

Typical values of χ^2/dof >2 at given energy!

Strangeness Irregularities



At c.m. energies above 8.8 GeV the strange hadrons are in chemical equilibrium! Why?

At c.m. energy 4.3 - 4.9 GeV strange particles are also in chemical equilibrium, while at lower and higher energies of collision there is strangeness enhancement. Why?

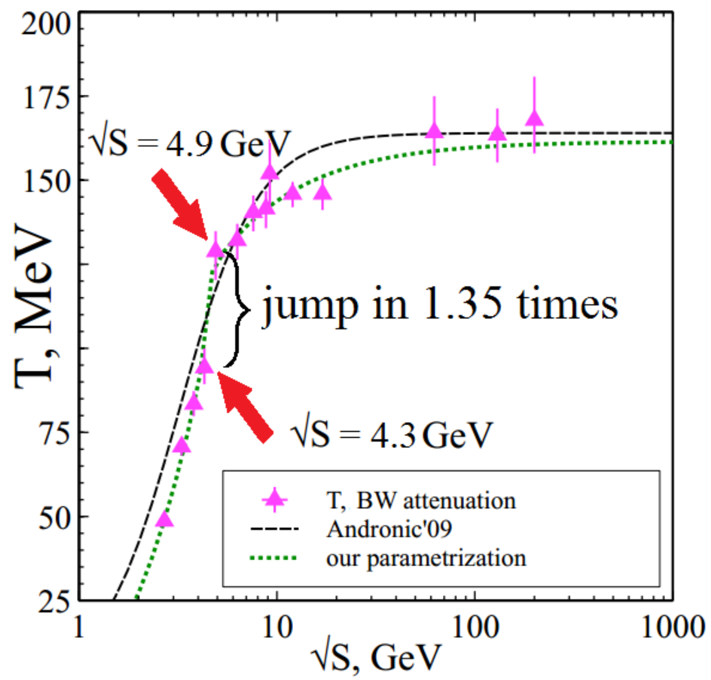
Explanation of such peculiar behavior was found in 2017. See

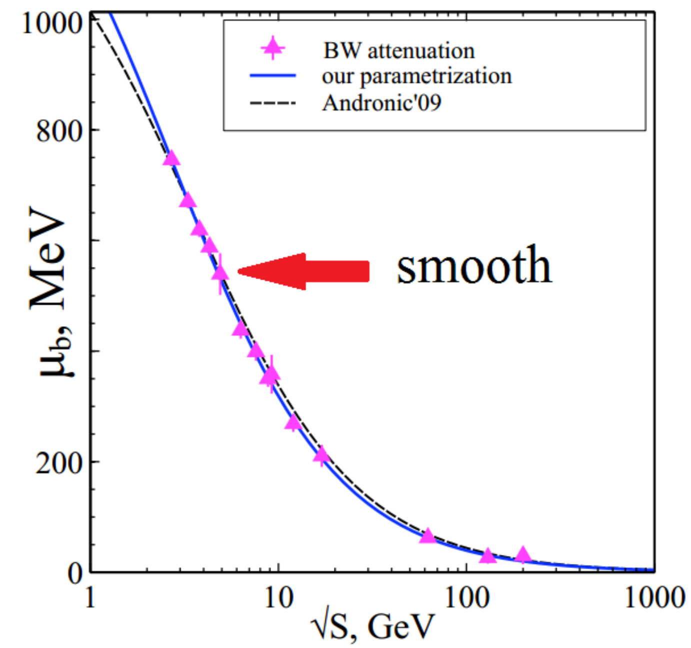
KAB et al., Phys. Part. Nucl. Lett. 15 (2018)

The fact that in A+A collisions $\gamma_s > 1$ is responsible for the difference with LQCD and FRG results on phase diagram! Hence in A+A collisions the (3)CEP can be displaced!

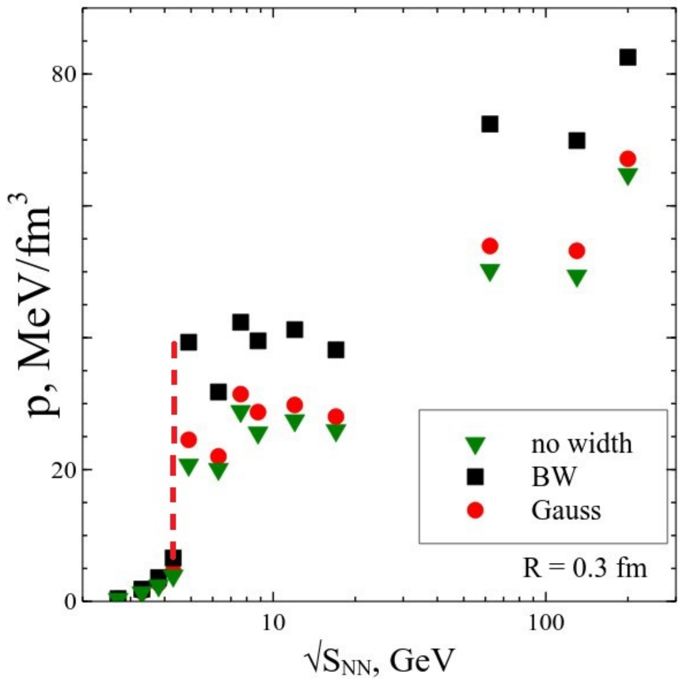
Jump of CFO Pressure at AGS Energies

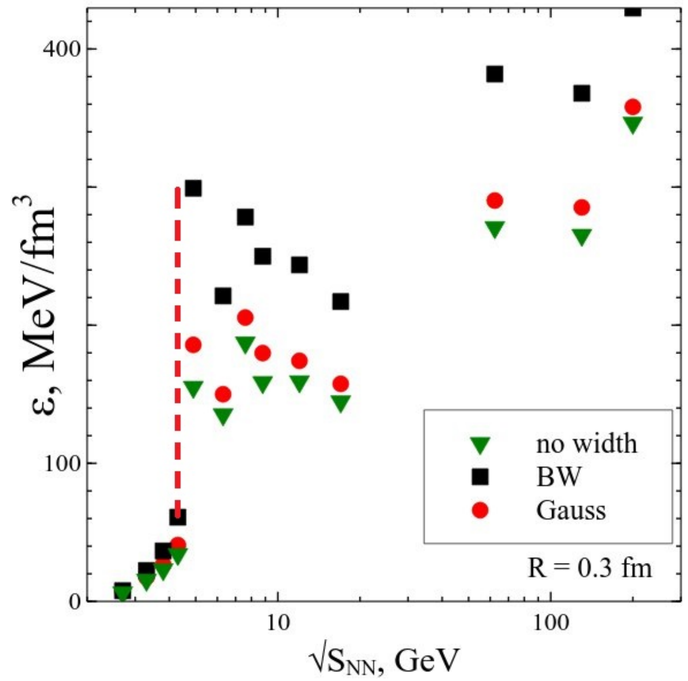
- Temperature T_{CFO} as a function of collision energy $\sqrt{s}$ is rather non smooth





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



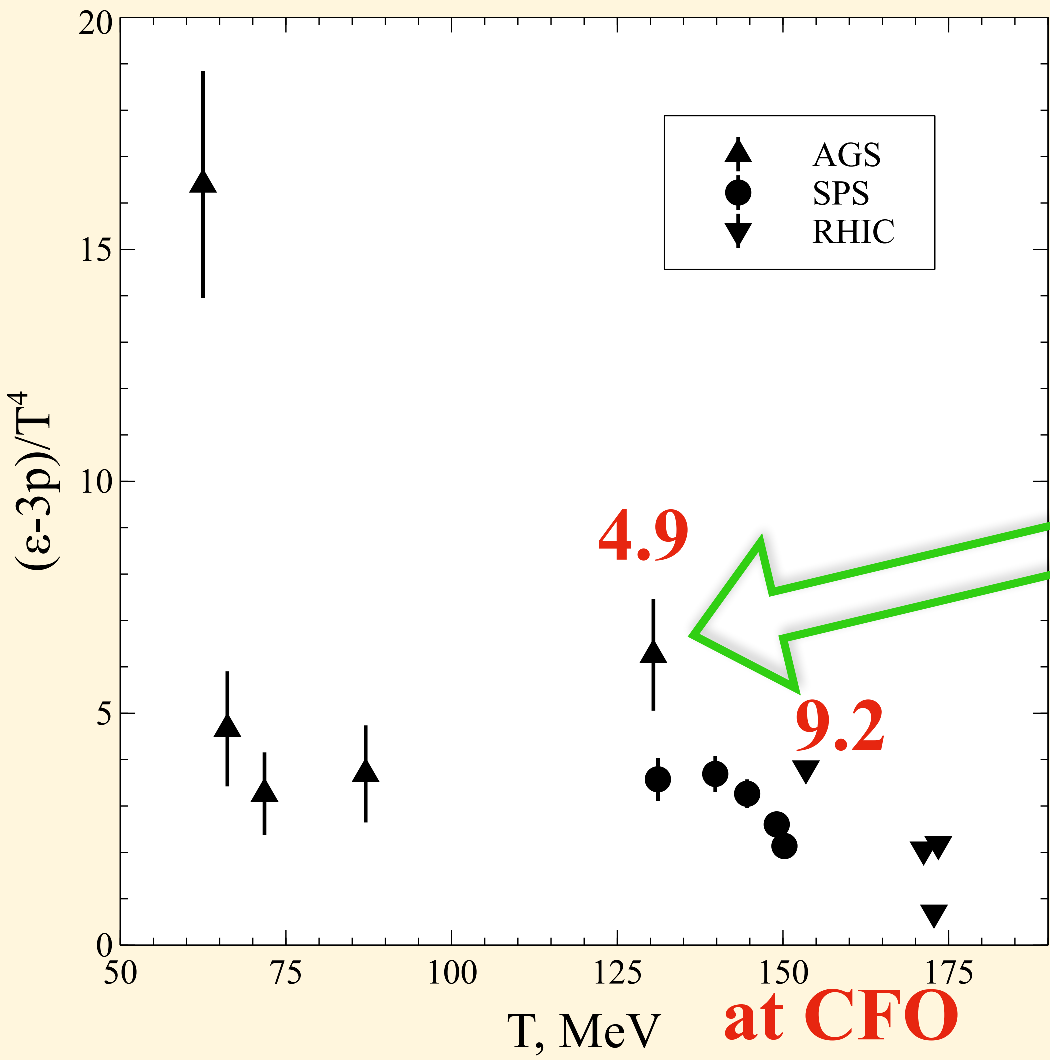


K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015) [arXiv:1405.3575];

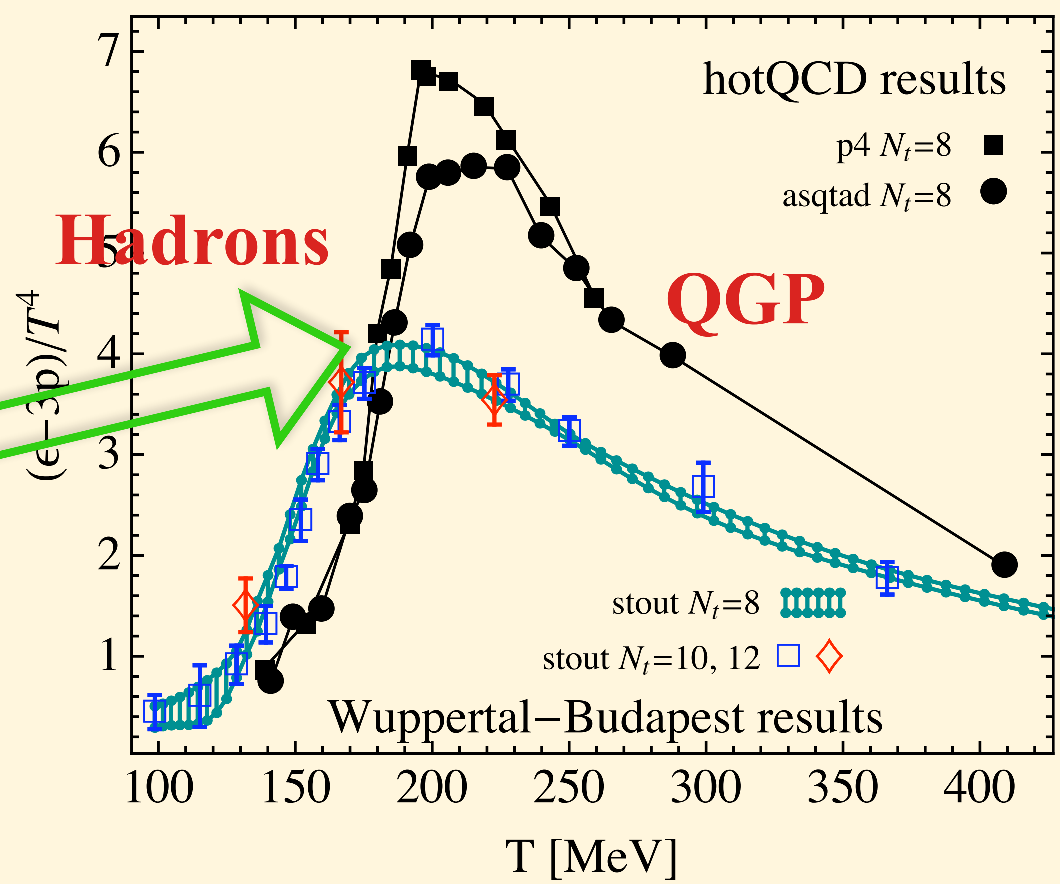
Ukr. J. Phys. 60 (2015)

Trace Anomaly Peaks (Most Recent)

At chemical FO (large μ)



Lattice QCD (vanishing μ)



WupBud EOS arXiv: lat 1007.2580

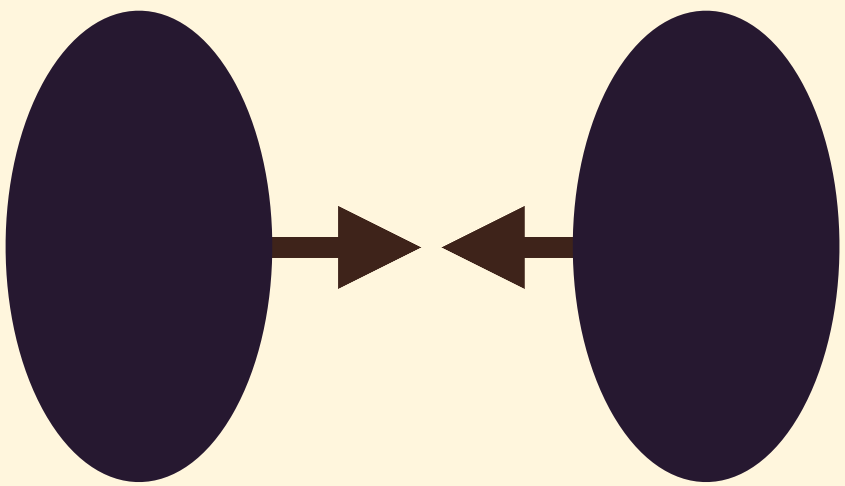
Model from V.V. Sagun et al., Eur. Phys. J. A (2018) 54: 100,

arXiv:1703.00009 [hep-ph]

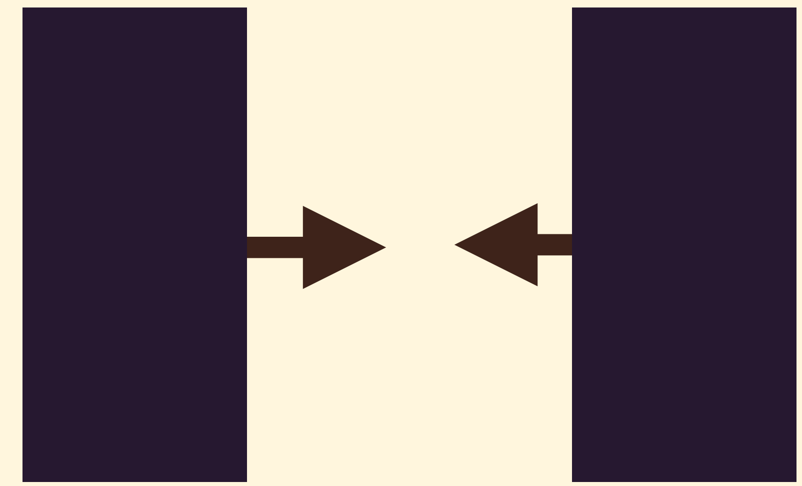
Are these trace anomaly peaks related to each other?

Shock Adiabat Model for A+A Collisions

A+A central collision at 1< Elab<30 GeV



Its hydrodynamic model

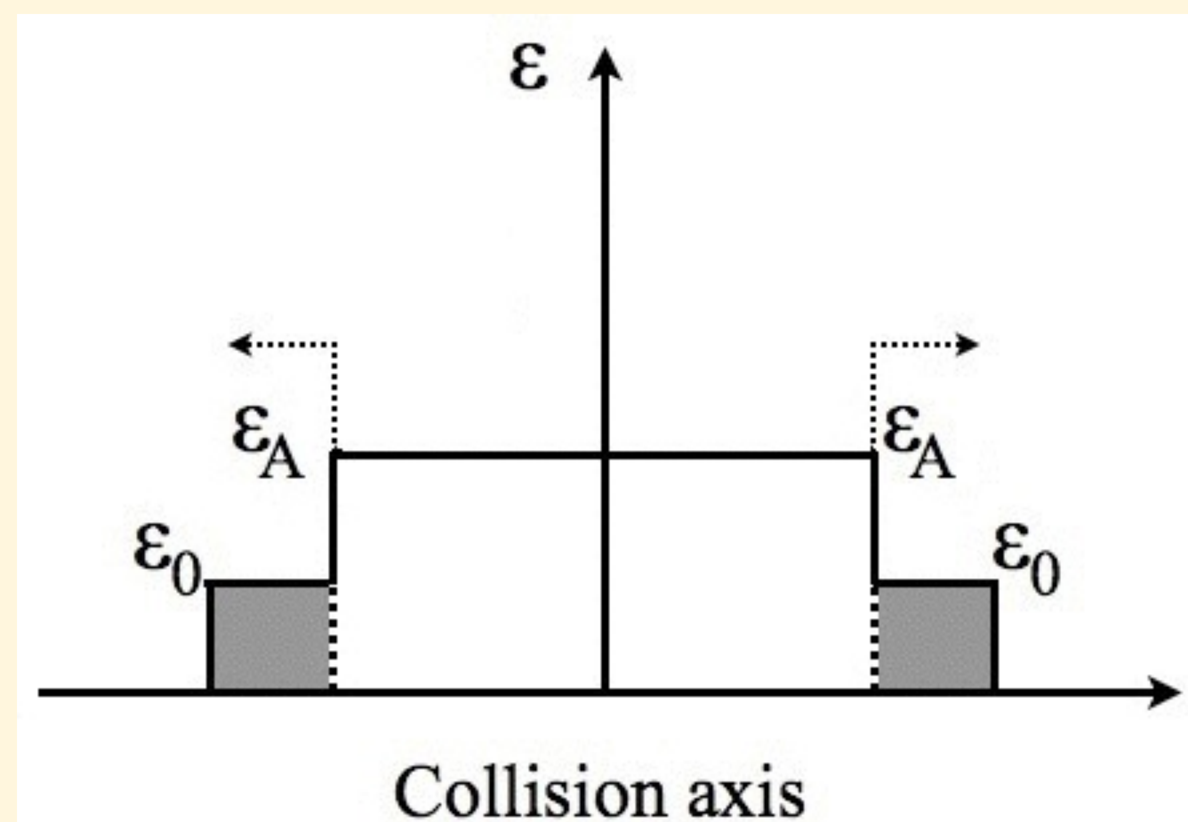


Works reasonably well at these energies.

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

Yu.B. Ivanov, V.N. Russkikh, and V.D. Toneev, Phys. Rev. C 73 (2006)

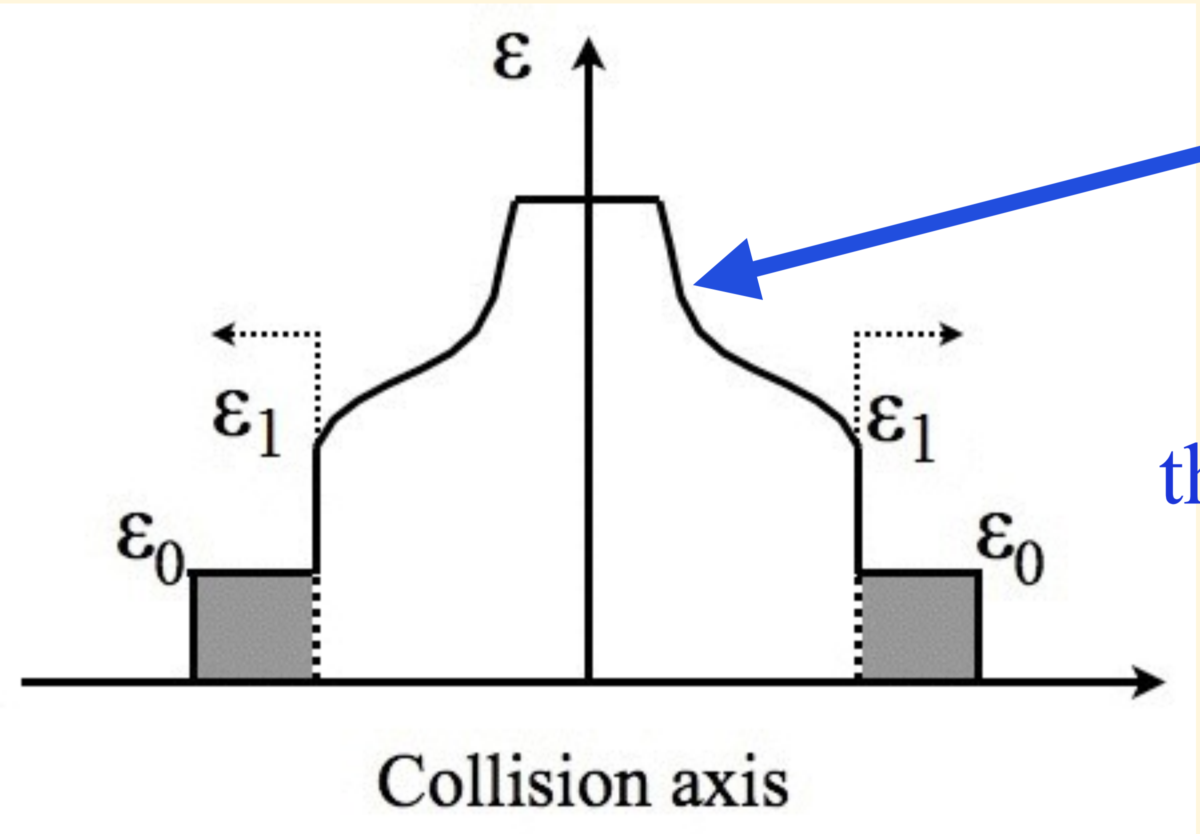
From hydrodynamic point of view
this is a problem of
arbitrary discontinuity decay:
in normal media there appeared
two shocks moving outwards



Generalized Shock Adiabat Model

In case of unstable shock transitions which appear at the 1-sf order PT 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!

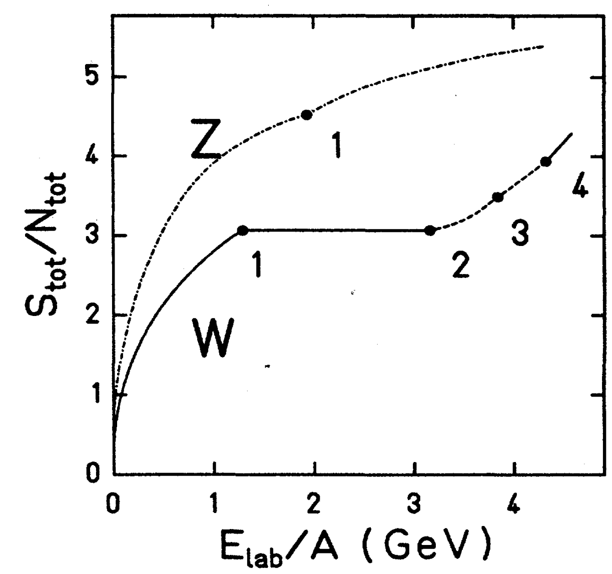


FIG. 9. The entropy per baryon as a function of the bombarding energy per nucleon of the colliding nuclei for models W and Z. The points 1, 2, 3, 4 on curve W correspond to those on the generalized adiabatic as displayed in Fig. 7. The point 1 on curve Z marks the boundary to the mixed phase.

Remarkably

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

Highly Correlated Quasi-Plateaus

For realistic EoS at mixed phase entropy per baryon should have a plateau!

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

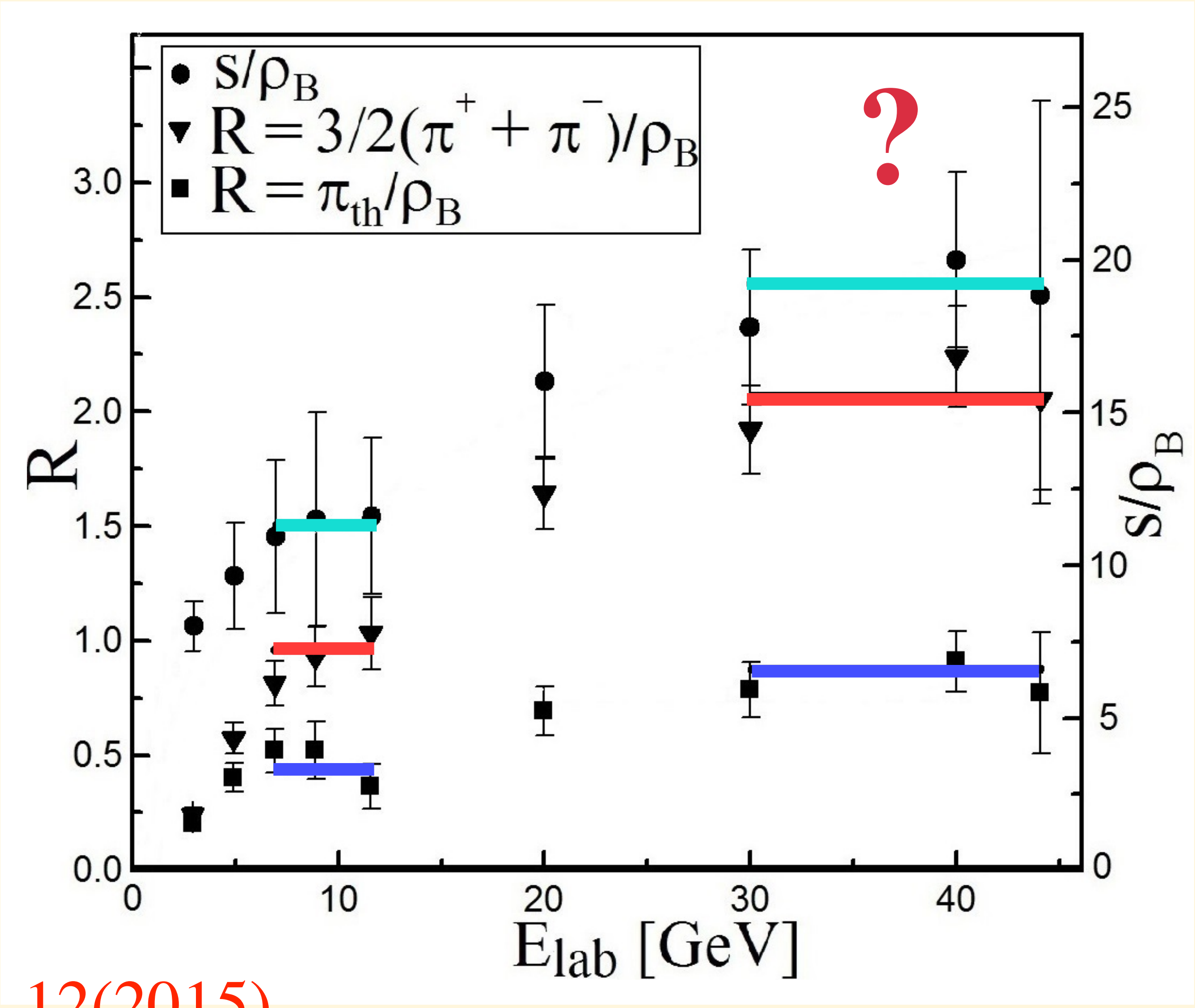
Also the total number of **pions per baryons should have a (quasi)plateau!**

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)

Entropy per baryon has wide plateaus due to large errors

Quasi-plateau in total number of pions per baryon ?

Thermal pions demonstrate 2 plateaus



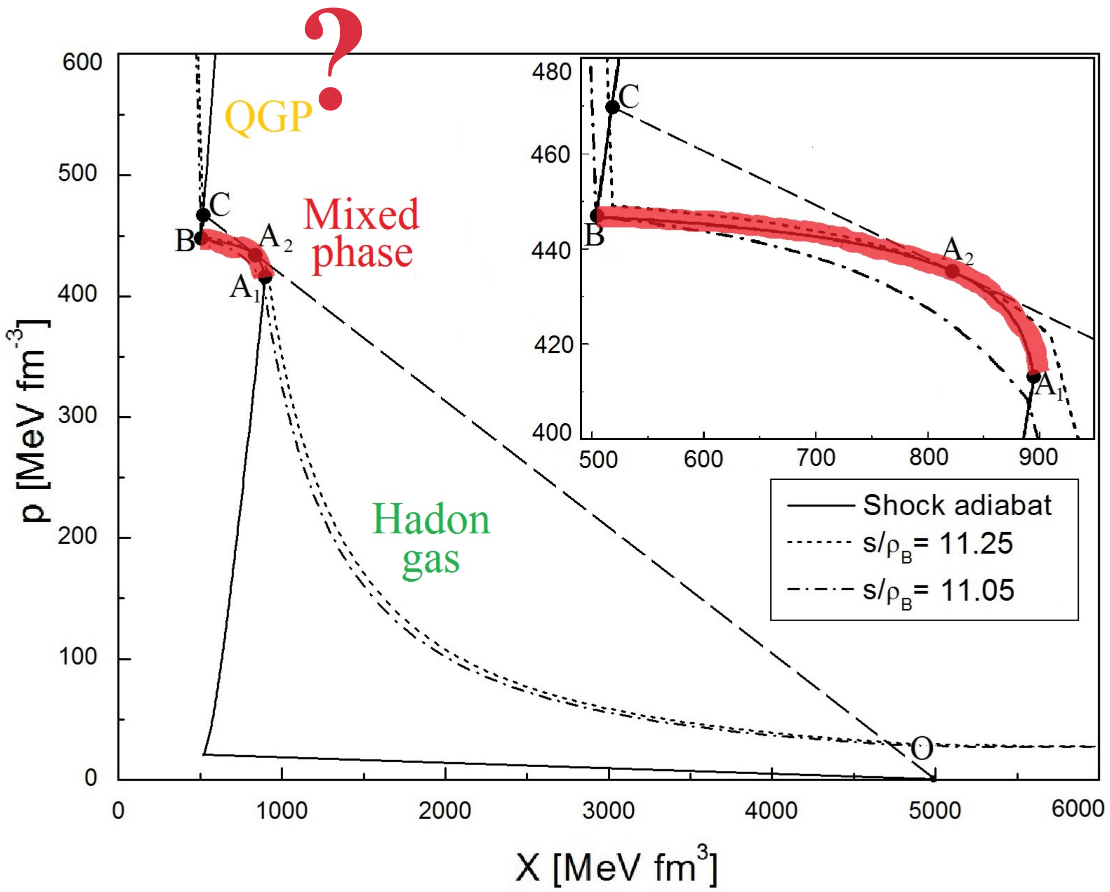
K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015)

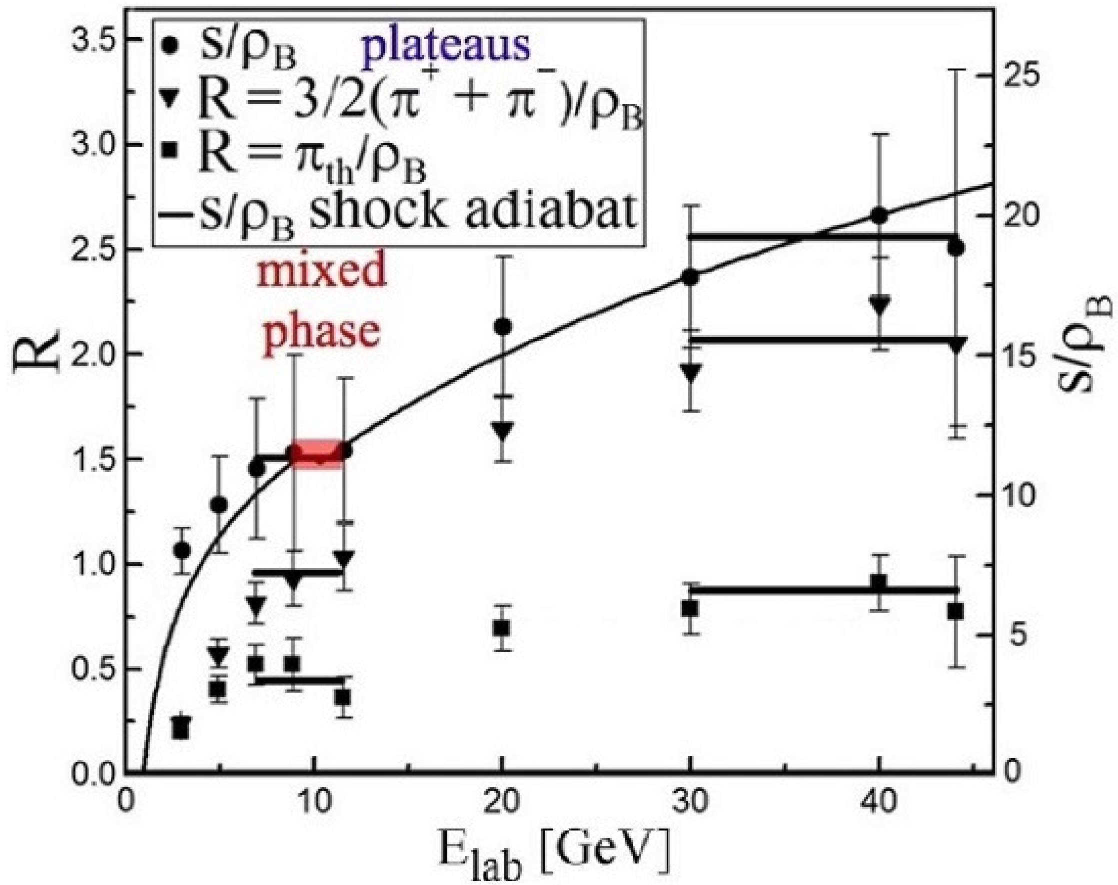
Transitions to Mixed Phase

Main results:constant pressure inside mixed phase+2 sets of plateaux!

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

other PT ?





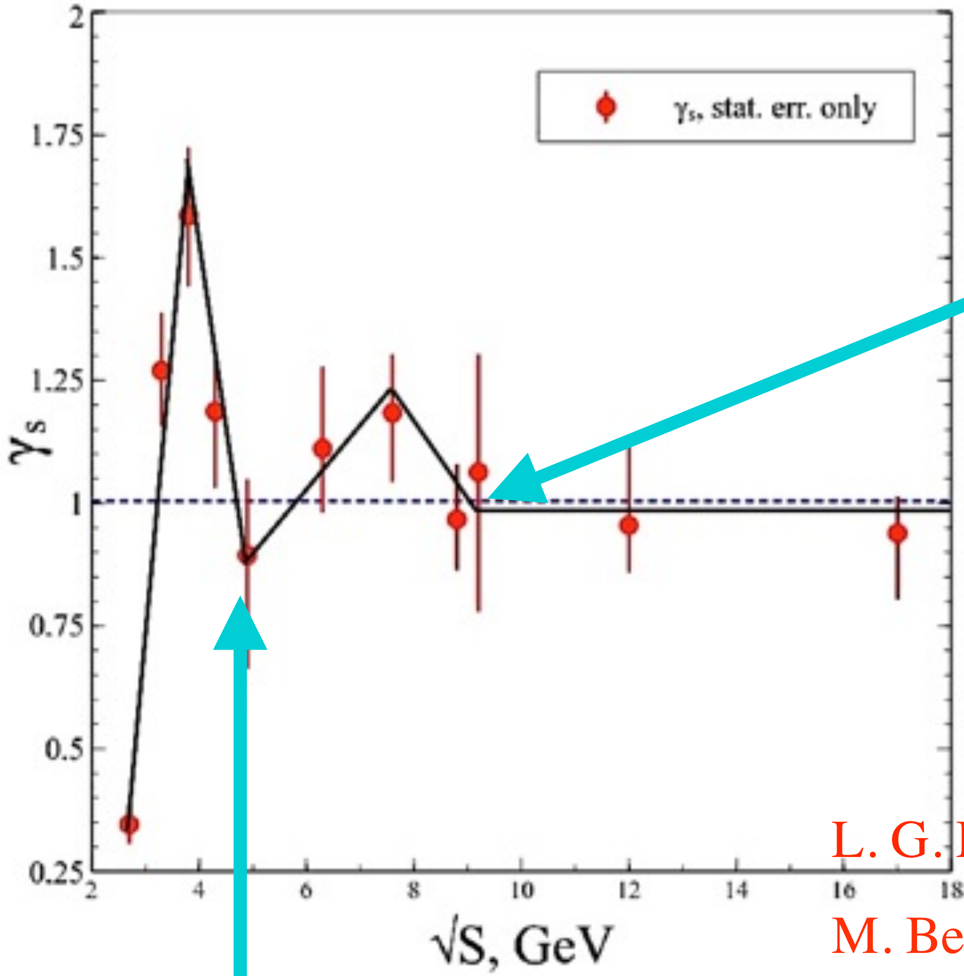
K.A. Bugaev et al., arXiv:1405.3575[hep-ph]

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 a simplified HRGM discussed above.

Strangeness Irregularities



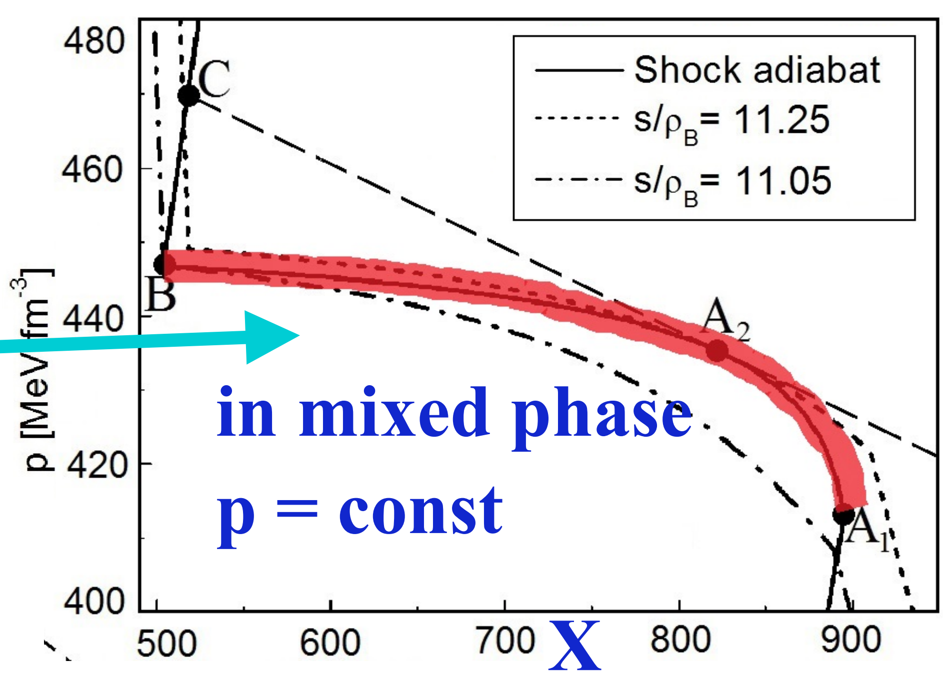
At c.m. energies above 8.8 GeV the strange hadrons are in chemical equilibrium due to formation of QG bags with Hagedorn mass spectrum!

Hagedorn mass spectrum $\frac{dN}{dM} \sim \exp\left[+M/T_H\right]$ 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 4.3-4.9 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!**

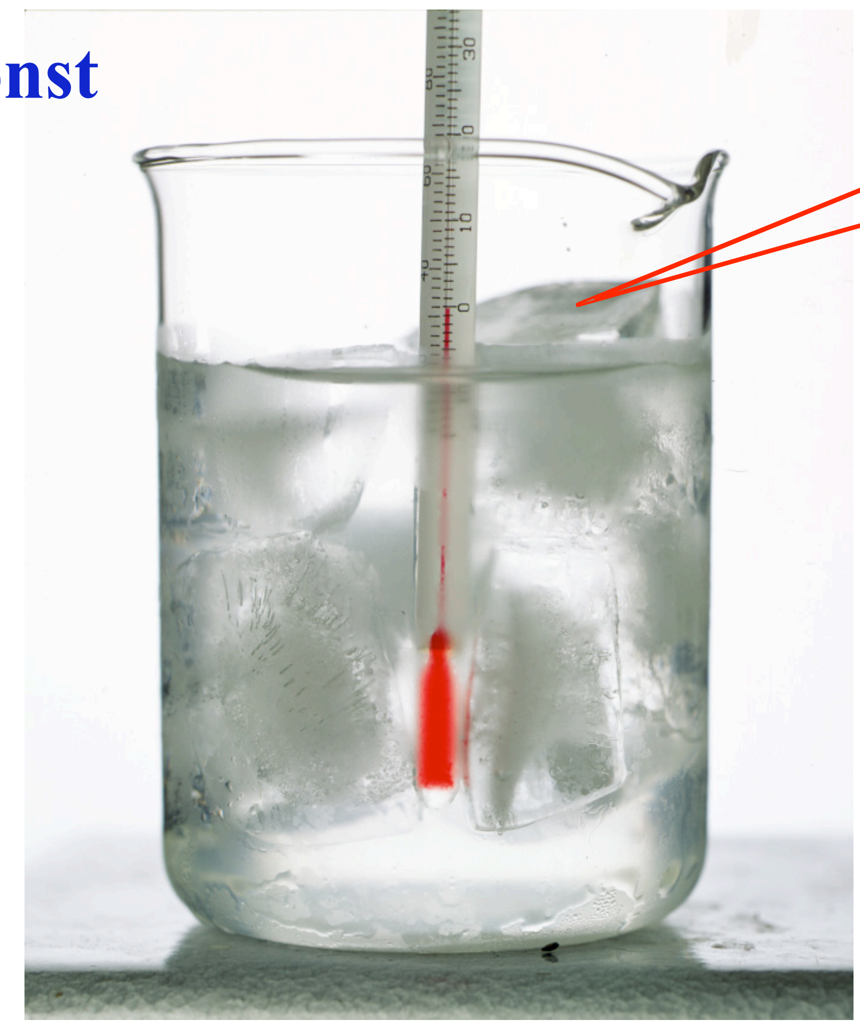
L. G. Moretto, K. A. B., J. B. Elliott, L. Phair, Europhys. Lett. 76, 402 (2006)

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



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

- 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**

If There Are 2 Phase Transitions, then

1. What kind of phase exists at $\sqrt{s}$ = 4.9-9.2 GeV?

2. Can we get any info about its properties?

Effective Number of Degrees of Freedom

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

$A_0 \simeq 2.53 \cdot 10^{-5}\ \mathrm{MeV}^{-3}\mathrm{fm}^{-3}$

$A_2 \simeq 1.51 \cdot 10^{-6}\ \mathrm{MeV}^{-3}\mathrm{fm}^{-3}$

$A_4 \simeq 1.001 \cdot 10^{-9}\ \mathrm{MeV}^{-3}\mathrm{fm}^{-3}$

$B \simeq 9488\ \mathrm{MeV\ fm}^{-3}$

It corresponds to massless particles with strong attraction generated by the vacuum pressure B

(B was not fitted, but was chosen to correspond to lattice QCD!)

Then one can find an effective #dof from A_0!

For massless particles

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

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

It`s a huge number for QGP!

K.A. Bugaev et al., Phys. Part. Nucl. Lett. 15, 210 (2018), 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 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 the gluonic quasiparticles with small masses (10-20 MeV) V. Voronin and S.N. Nedelko, EPJ A (2015)

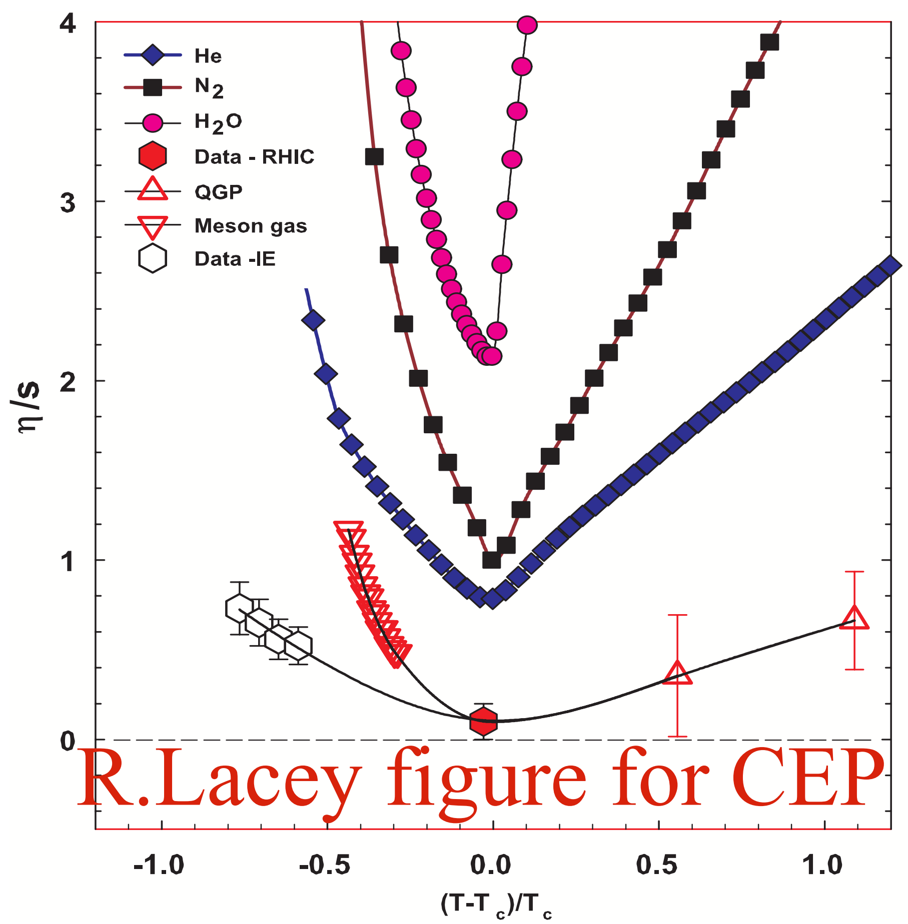
5. Or 1800 of massless dof may evidence about quarkyonic phase!?
   A. Andronic et. al, Nucl. Phys. A 837, 65 (2010)

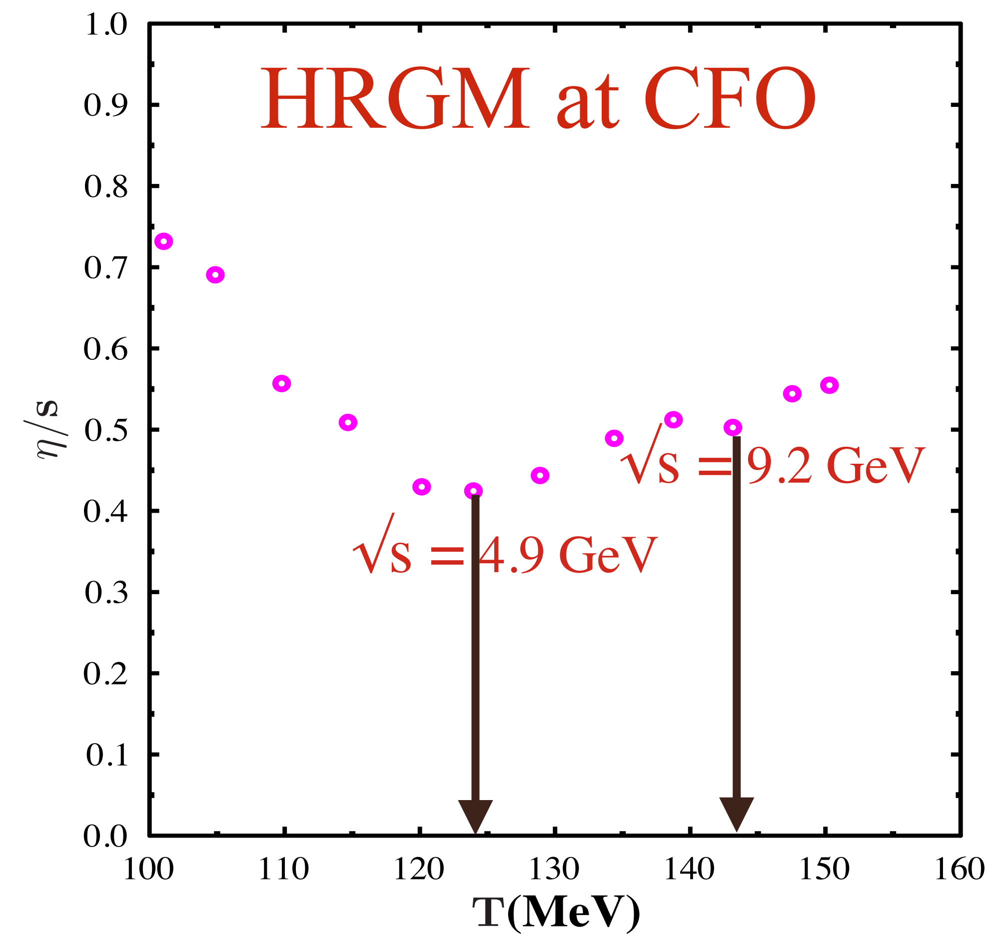
6. 1800 of massless dof may evidence about something else…

Minima of Shear Viscosity over Entropy at CFO

Minimum of shear viscosity η over entropy density s corresponds to a phase transition

L.P. Csernai, J.I. Kapusta & L.D.McLerran PRL 97 (2006)





G. Kadam and S. Pawar, Adv.High Energy Phys (2019) 6795041

Used parameterizations T(√s) and μ(√s) from

KAB et al,, Ukr. J. Phys. 60, 181 (2015)

Evidence for Chiral Symmetry Restoration?

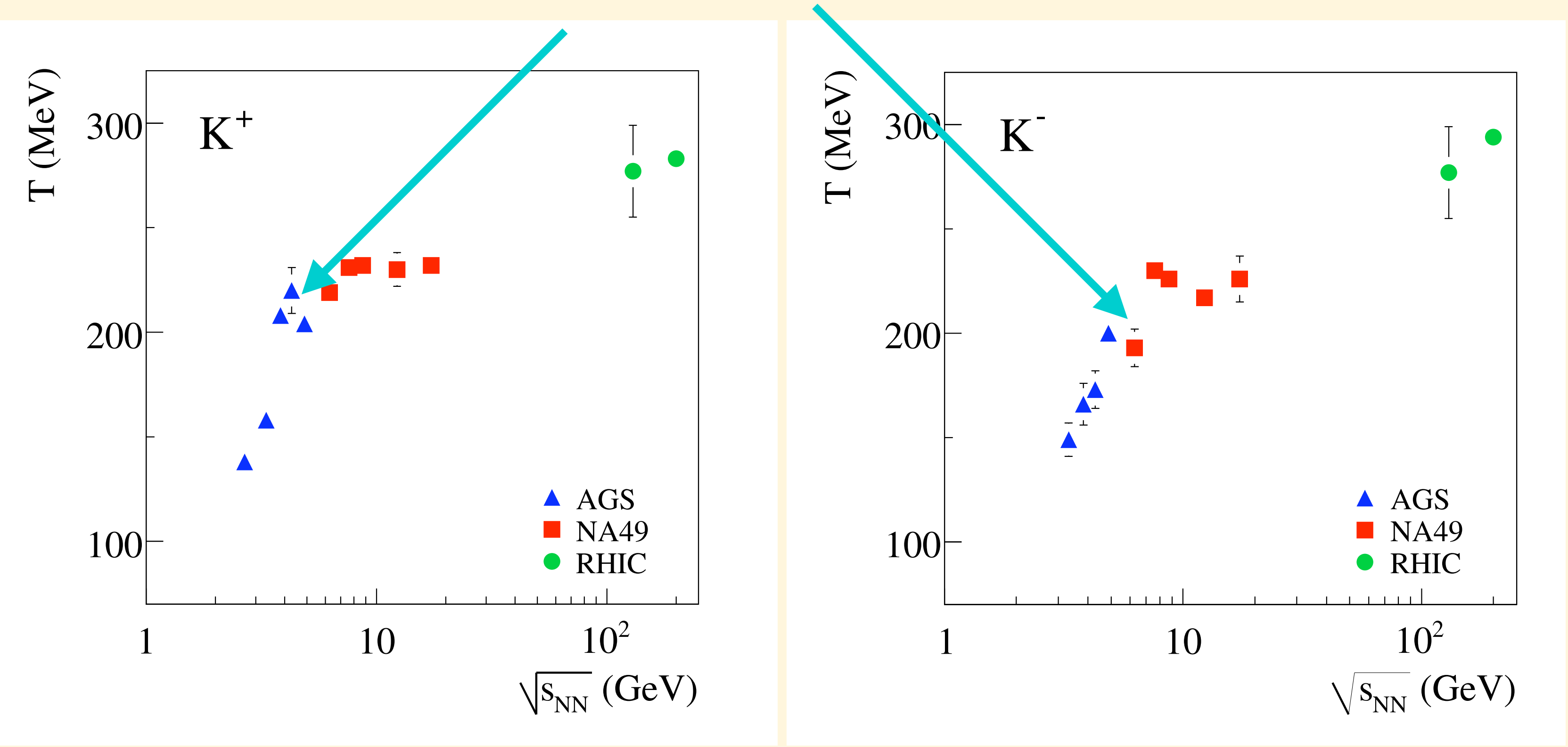
There are KINKs in apparent temperature of K+ and K- at 4.3-6.3 GeV

K.A. Bugaev et al., arXiv:1801.08605 [nucl-th]

$$T_k^*(p_T \to 0) = \frac{T_{fo}}{1 - \frac{1}{2}\,\bar{v}_T^2\,(m_k/T_{fo} - 1)} \approx T_{fo} + \frac{1}{2}\,m_k\,\bar{v}_T^2$$

apparent temperature=
inverse slope of p_T spectra
at p_T —> 0:
depends on FO temperature
and mean transversal velocity

KINKs due to ChSR?



M. Gazdzicki, M.I. Gorenstein and K.A. Bugaev, Phys. Lett. B 567 (2003)

Simple (naive?) explanation:
1. FO temperature cannot decrease, if √s increases.
2. mean transversal velocity cannot decrease, if √s increases.

=> mass of Kaons gets lower due to ChSRestoration!?

Suggestions for RHIC BESII, NICA and FAIR:
measure p_T spectra and apparent temperature of Kaons and (anti)Λ hyperons at 4.3-6.3 GeV with high accuracy and small collision energy steps!

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 many 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, RHIC, FAIR, NICA and J-PARC experiments will allow us to make more definite conclusions

Thank You for Your Attention!

For a summary of two QCD PT signals see

K.A. Bugaev et al., EPJ Web of Conf. 182, 02057 (2018)

or

arXiv:1801.08605 [nucl-th]

and references therein

Table 1. The summary of possible PT signals. The column II gives short description of the signal, while the columns III and IV indicate its location, status and references.

No and Type	Signal	C.-m. energy $\sqrt{s}$ (GeV) Status	C.-m. energy $\sqrt{s}$ (GeV) Status
1. Hydrodynamic	Highly correlated quasi-plateaus in entropy/baryon, thermal pion number/baryon and total pion number/baryon. Suggested in [11, 12].	Seen at **3.8-4.9 GeV** [4, 5]. Explained by the shock adiabat model [4, 5].	Seen at **7.6-9.2 GeV** [4, 5]. Require an explanation.
2. Thermodynamic	Minimum of the chemical freeze-out volume V_{CFO}.	In the one component HRGM it is seen at **4.3-4.9 GeV** [13]. In the multicomponent HRGM it is seen at **4.9 GeV** [14]. Explained by the shock adiabat model [4, 5].	Not seen.
3. Hydrodynamic	Minimum of the generalized specific volume $X = \frac{\epsilon+p}{\rho_b^2}$ at chemical freeze-out.	Seen at **4.9 GeV** [4]. Explained by the shock adiabat model [4, 5].	Seen at **9.2 GeV** [4]. Require an explanation
4. Thermodynamic	Peak of the trace anomaly $\delta = \frac{\epsilon-3p}{T^4}$.	Strong peak is seen at **4.9 GeV** [5]. Is generated by the δ peak on the shock adiabat at high density end of the mixed phase [5].	Small peak is seen at **9.2 GeV** [5]. Require an explanation
5. Thermodynamic	Peak of the baryonic density ρ_b.	Strong peak is seen at **4.9 GeV** [10]. Is explained by min$\{V_{CFO}\}$ [14].	Strong peak is seen at **9.2 GeV** [10]. Require an explanation
6. Thermodynamic	Apparent chemical equilibrium of strange charge.	$\gamma_s = 1$ is seen at **4.9 GeV** [10]. Explained by thermostatic properties of mixed phase at $p = const$ [10].	$\gamma_s = 1$ is seen at $\sqrt{s}$ $\geq$ **8.8 GeV** [10, 13]. Explained by thermostatic properties of QG bags with Hagedorn mass spectrum [10].
7. Fluctuational (statistical mechanics)	Enhancement of fluctuations	N/A	Seen at **8.8 GeV** [9]. Can be explained by CEP [9] or 3CEP formation [10].
8. Microscopic	Strangeness Horn (K^+/π^+ ratio)	N/A	Seen at **7.6 GeV**. Can be explained by the onset of deconfinement at [15]/above [8] **8.7 GeV**.

Thank You for Your Attention!

Main Properties of IST EOS

pressure

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

induced surface tension

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

R_k, V_k and S_k are hard-core radius, eigenvolume and eigensurface of hadron of sort k

- One component case with $\alpha > 1$

$$\Sigma = pR \exp\left(\frac{(1-\alpha)S\Sigma}{T}\right)$$

$$p = T\phi \exp\left(\frac{\mu - pV_eff}{T}\right)$$

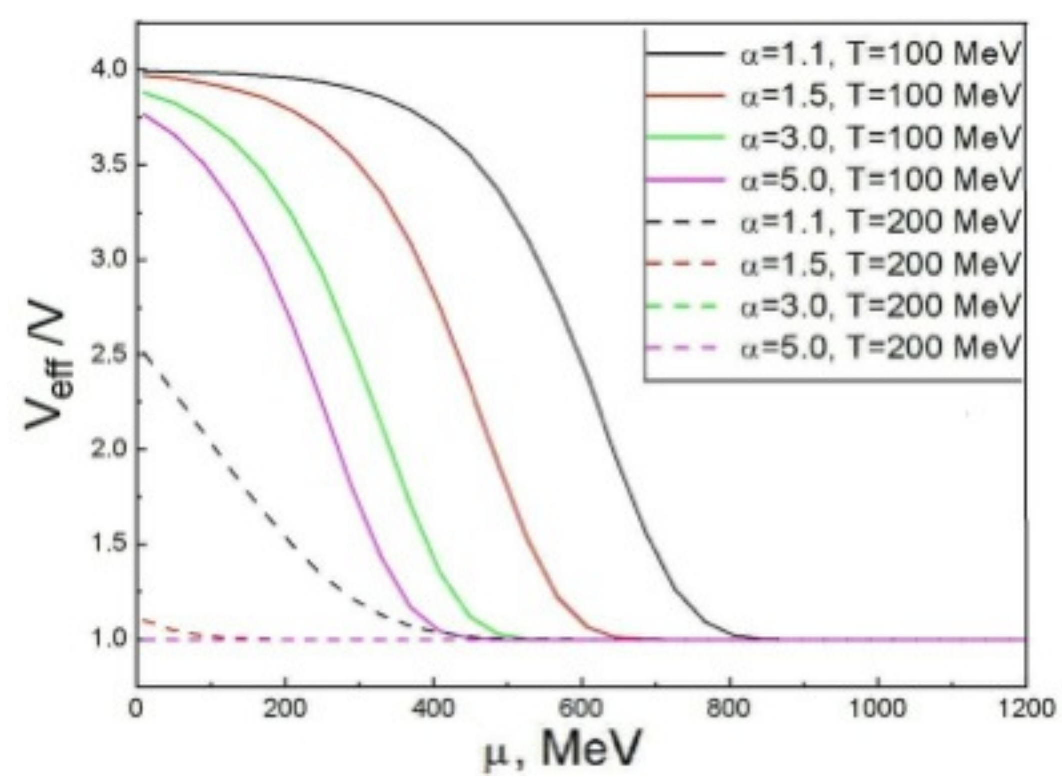
$$V_{eff} = V_o\left[1 + 3\exp\left(\frac{(1-\alpha)S_i\Sigma}{T}\right)\right] \Rightarrow$$

α switches excluded and eigen volume regimes

high order virial coefficients?

low densities $(\Sigma \to 0)$: $V_{eff} = 4V_o$

high densities $(\Sigma \to \infty)$: $V_{eff} = V_o$



Advantages

1. Allows to go beyond the Van der Waals approximation

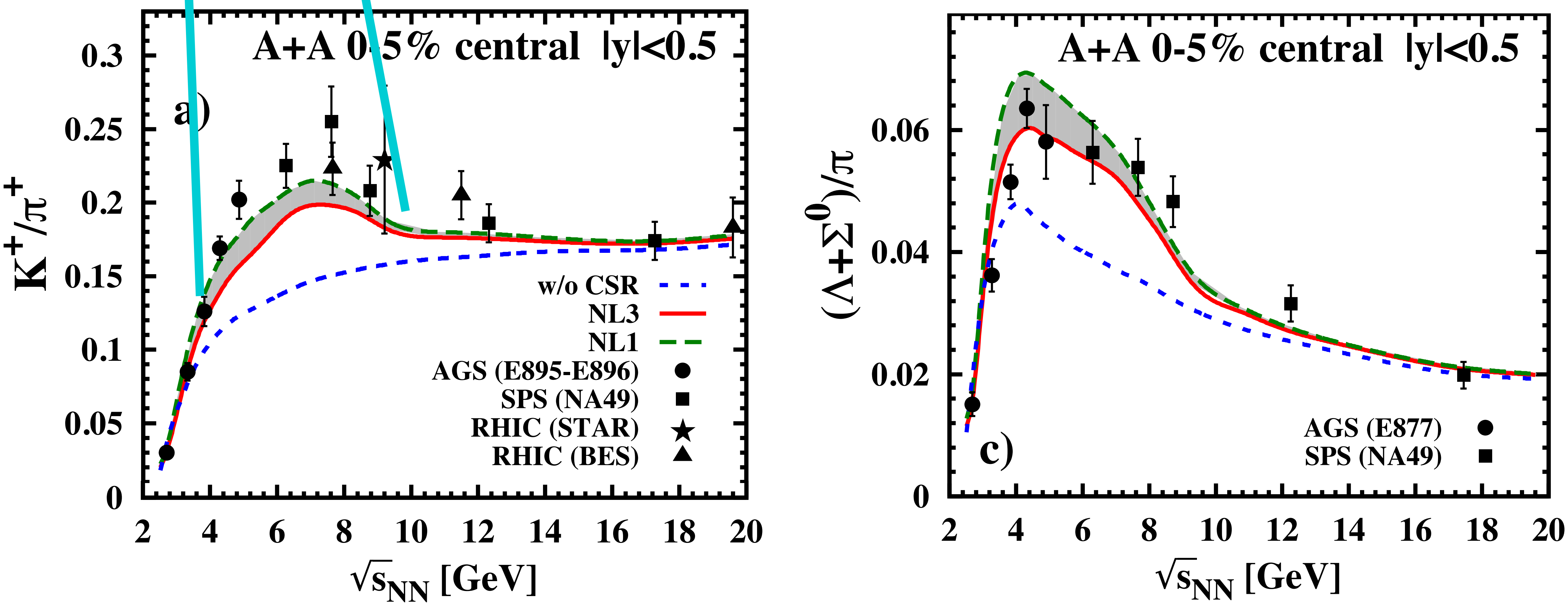
2. Number of equations is 2 and it does not depend on the number different hard-core radii!

Parton-Hadron-String-Dynamics Model

1-st order PT of Chiral Symmetry Restoration in hadronic phase occurs at about √s ~ 4. GeV

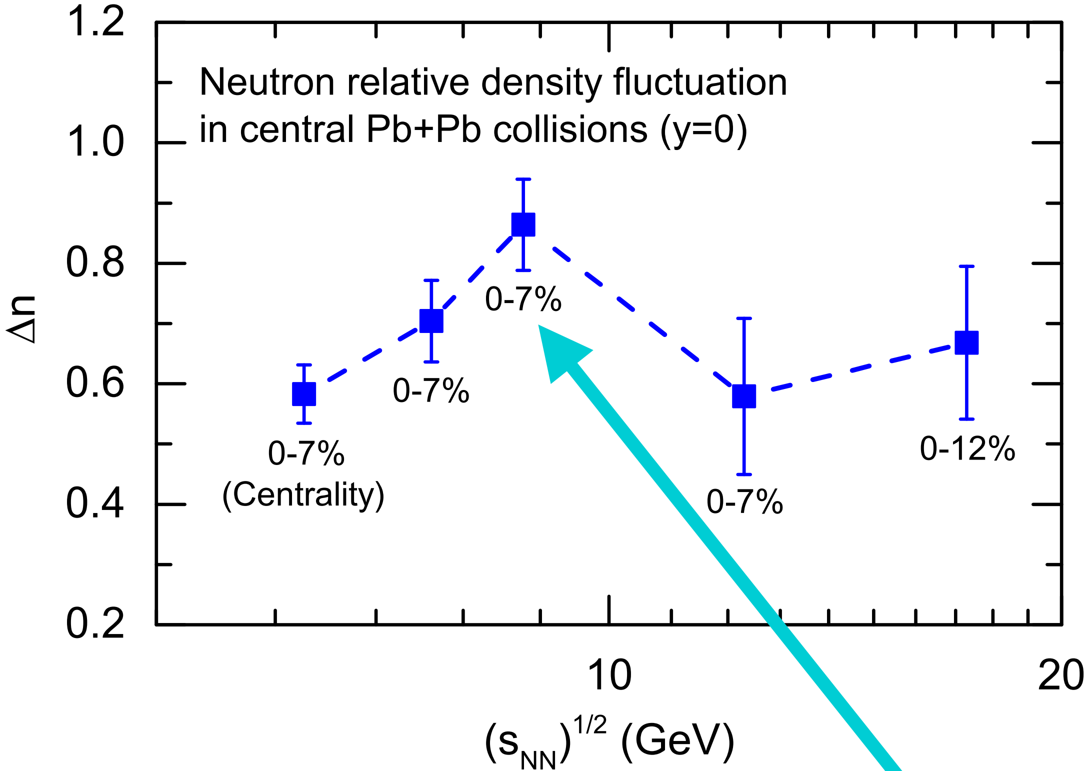
and 2-nd order deconfinement PT exists at √s ~ 9 GeV
Hard to locate them due to cross-over in A+A!

W. Cassing et al.,, Phys. Rev. C 93, 014902 (2016);
Phys. Rev. C 94, 044912 (2016).

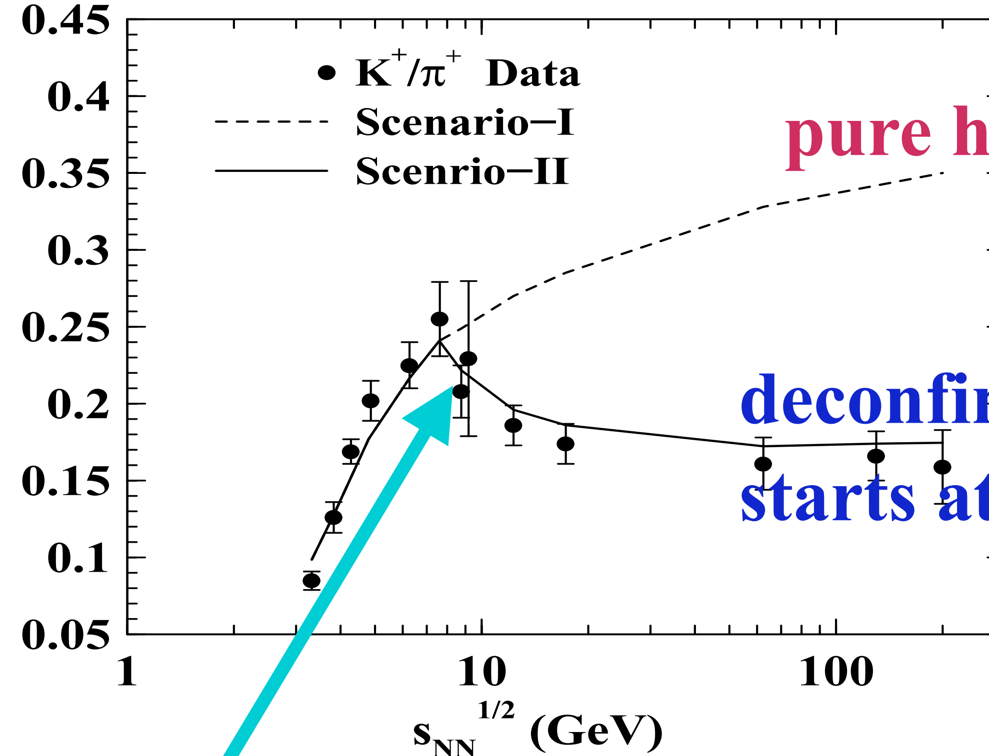


Onset of Deconfinement in Other Models

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



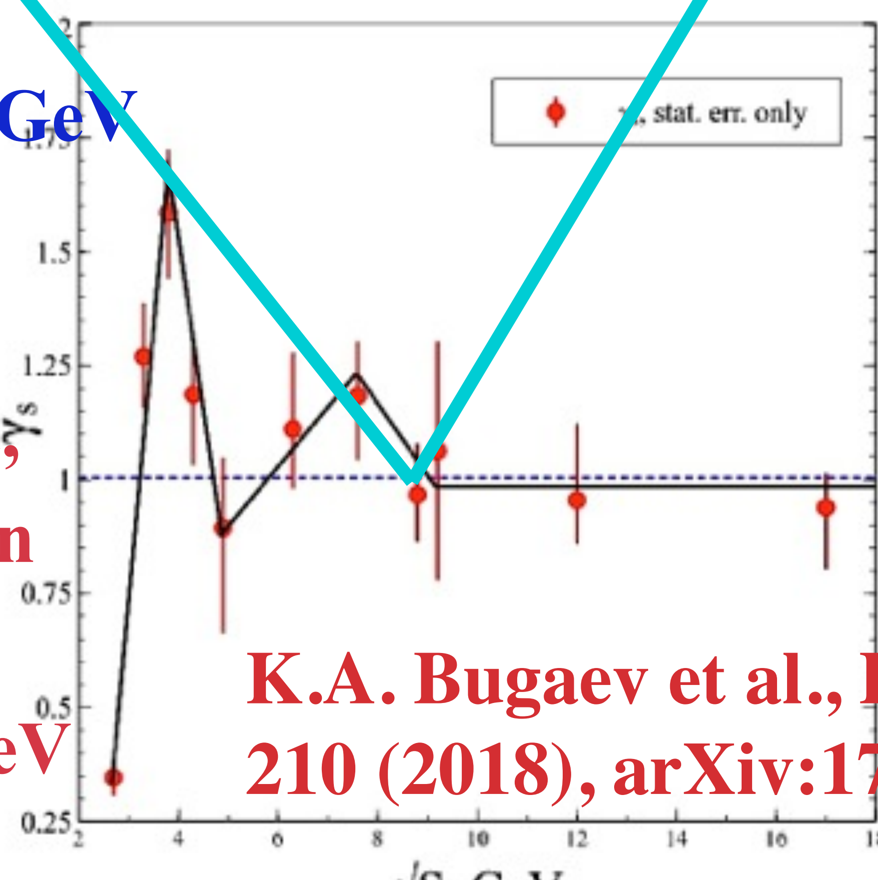
J. K. Nayak, S. Banik, Jan-e Alam, PRC **82**, 024914 (2010)



pure hadronic

deconfinement starts at 8.7 GeV

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

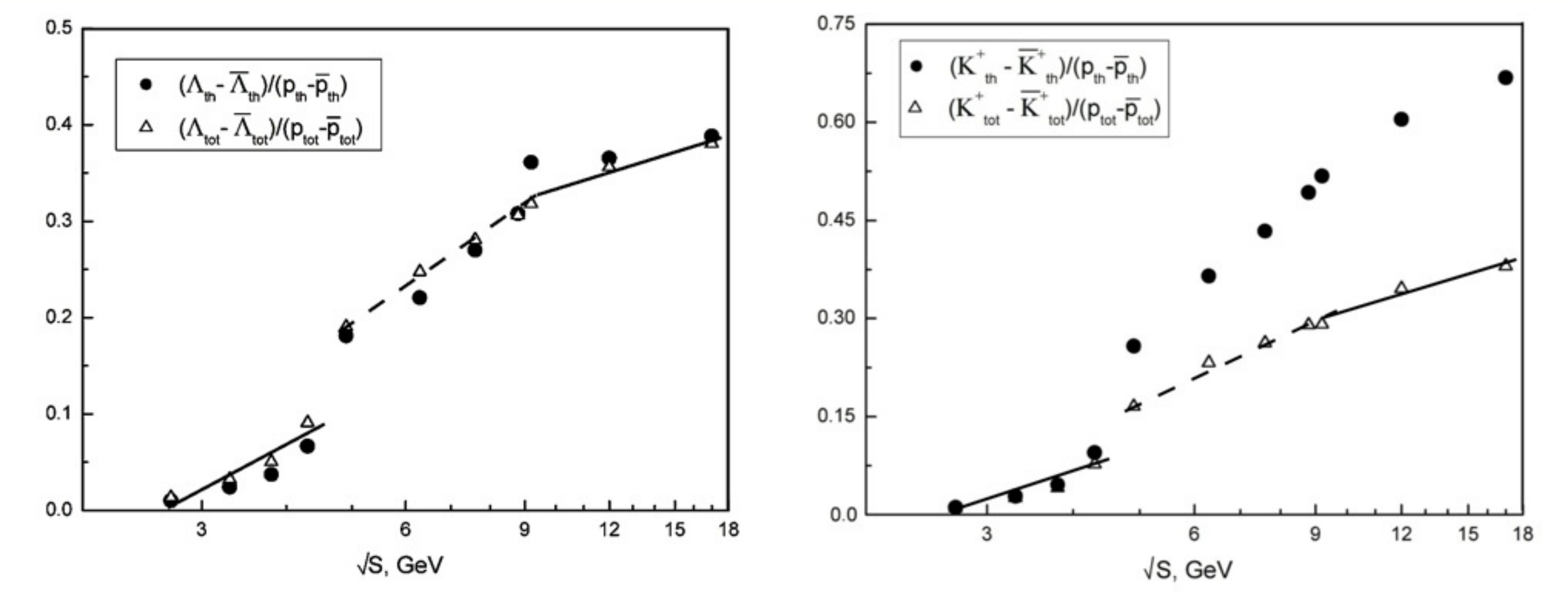


Strangeness Horn and other strange particles ratios can be explained, if the onset of deconfinement begins at c.m. energy 8.7 GeV!

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

K.A. Bugaev et al., Phys. Part. Nucl. Lett. 15, 210 (2018), arXiv:1709.05419 [hep-ph]

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

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,

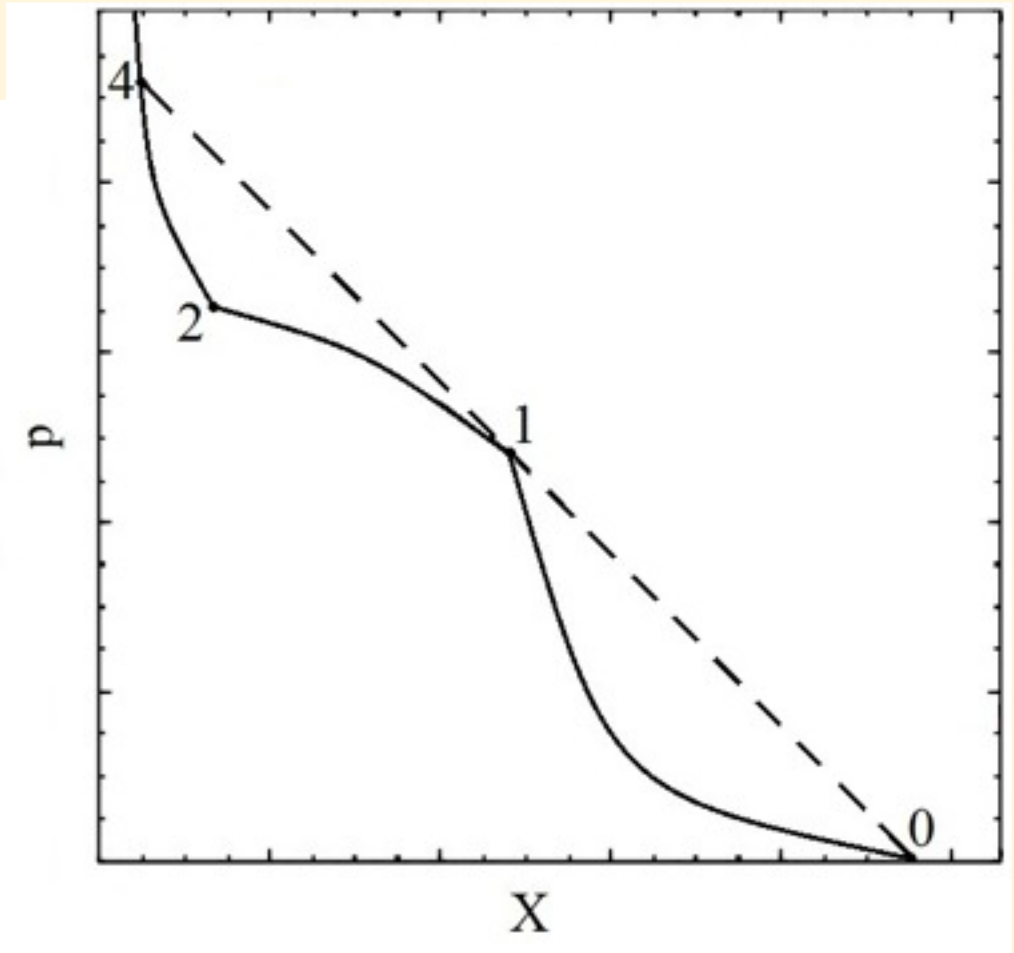
ρ_B is baryonic charge density

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



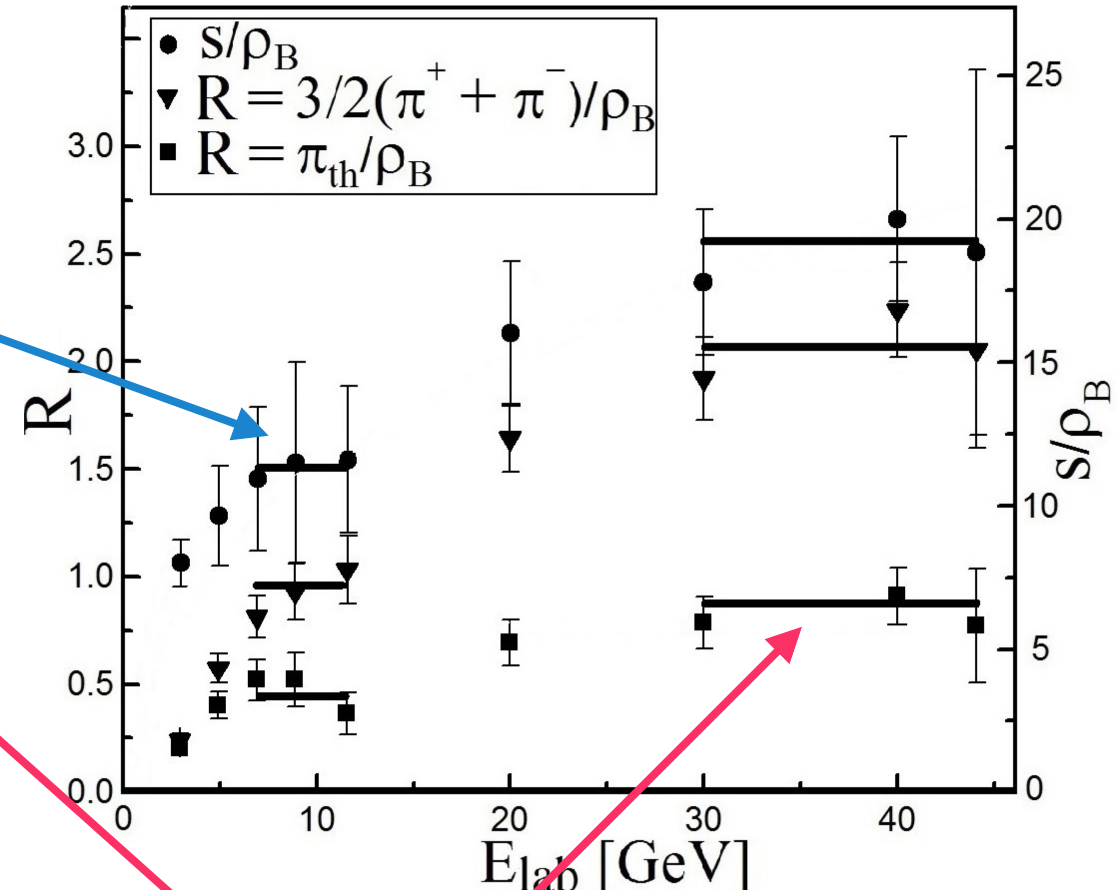
Region 1-2 is mixed phase with **anomalous properties.**

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

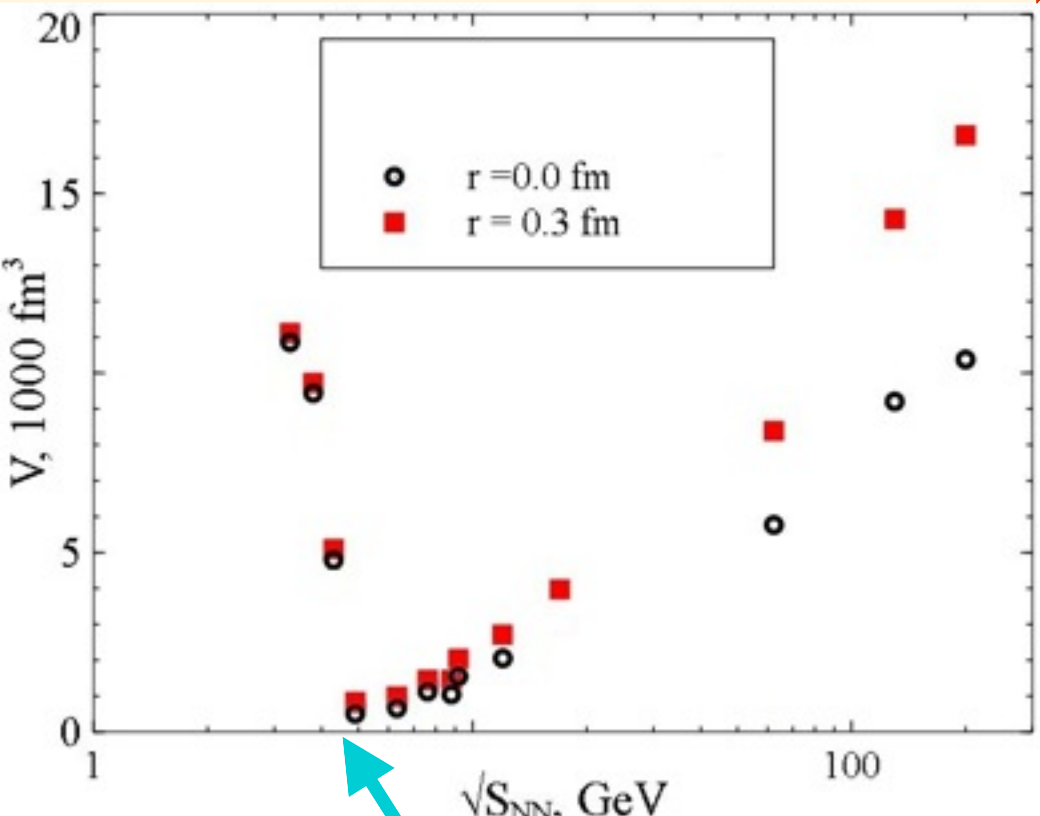


Other Minima at AGS Energies

min V at ChFO

SAME energy!

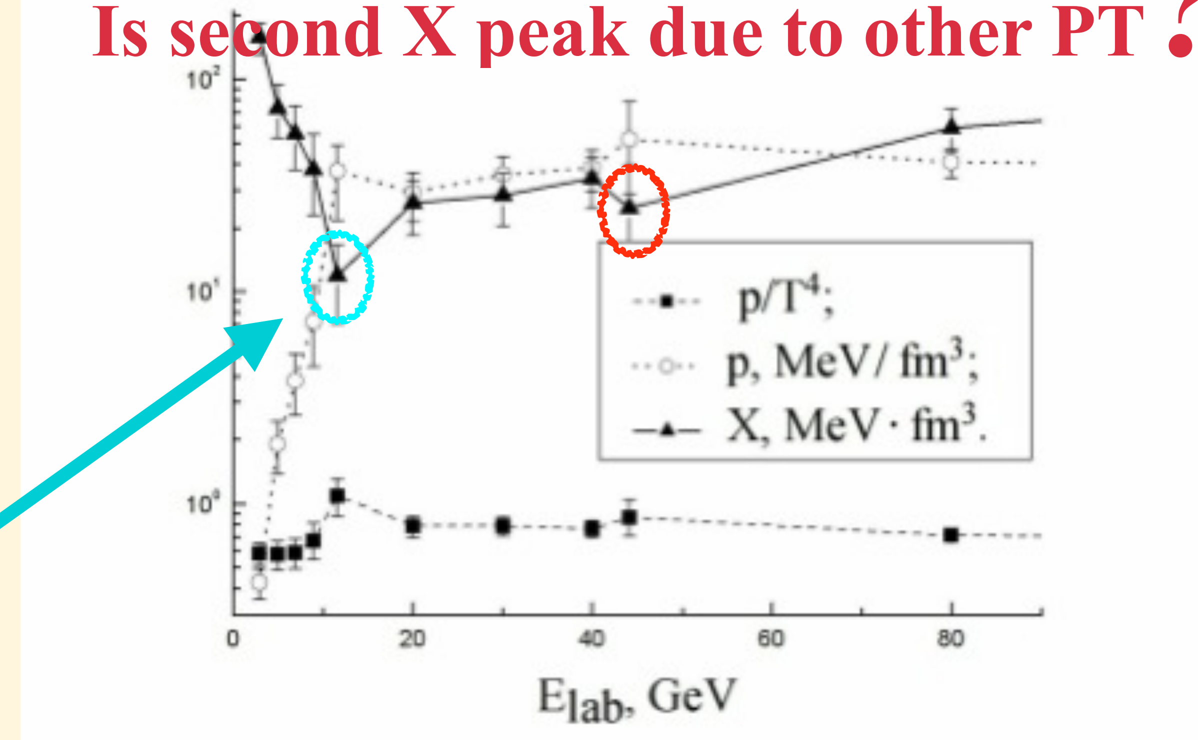
min X at ChFO



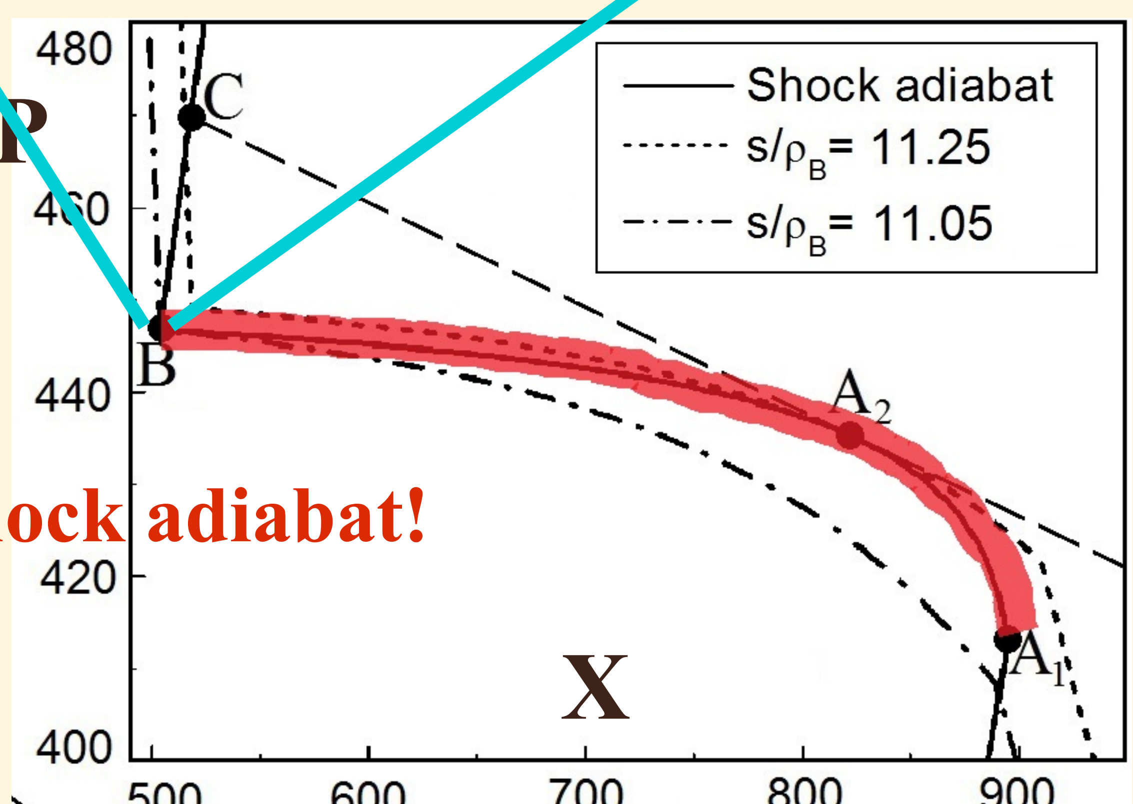
D.R. Oliinychenko, K.A. Bugaev and A.S. Sorin, Ukr. J. Phys. 58, (2013)

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!