On Possible signals of two QCD phase transitions at NICA-FAIR energies

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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

AGS (BNL) up to	4.9 GeV	Completed
SPS (CERN)	6.1 - 17.1 GeV	Completed
RHIC (BNL)	62, 130, 200 GeV	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

A+A collisions: Hydro at Work

Full stoping regime of A+A collision: made from «collision» of two water droplets

Hydro at Work in Ordinary Life

Made in Oslo with
photo camera , August 2018

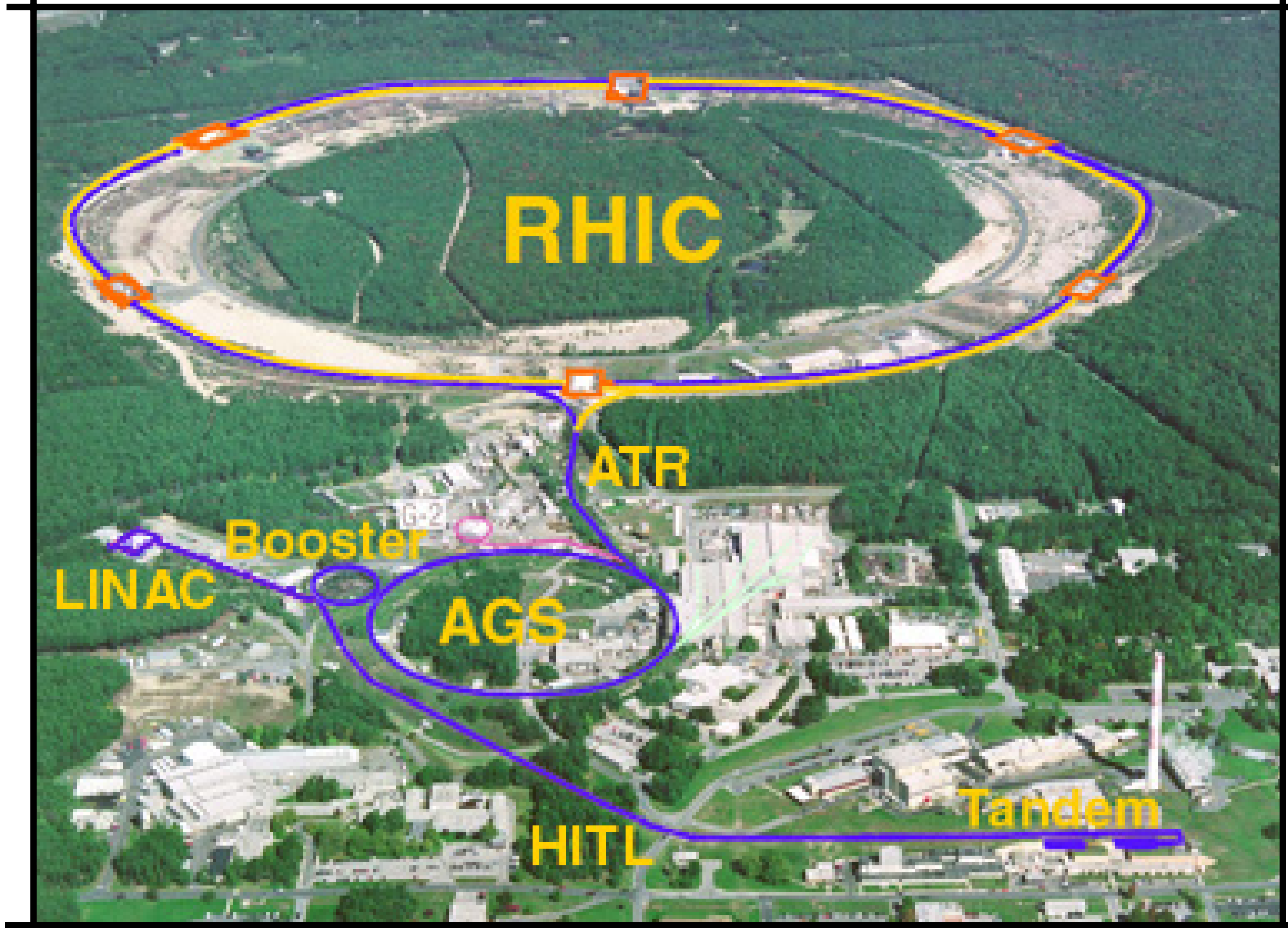
Modern Accelerators: RHIC

RHIC:
[Brookhaven National Lab.]

Relativistic Heavy
Ion Collider

Experiments:

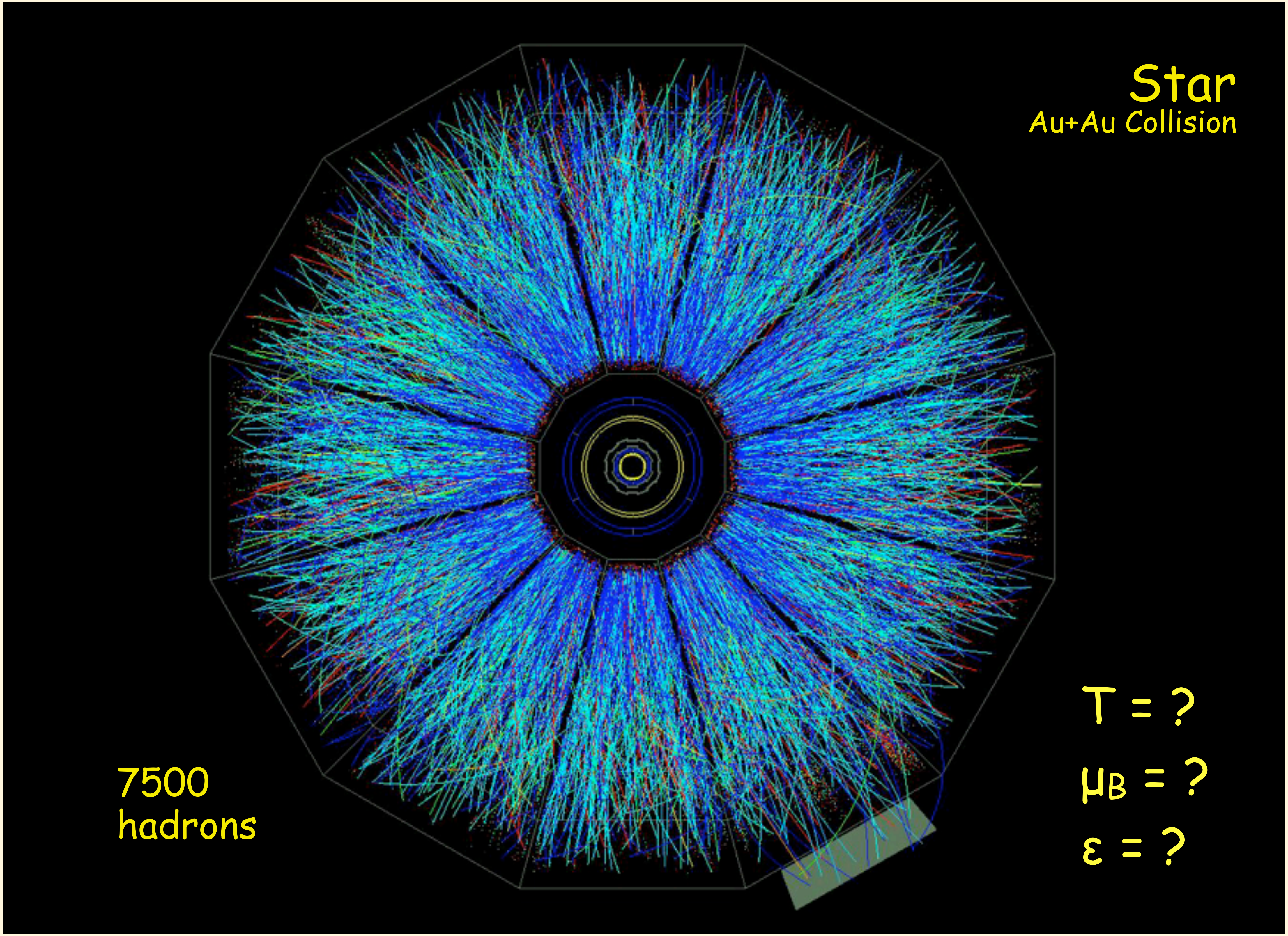
Star, Phenix,
Phobos, Brahms



Facility	Location	Ions	Energy
AGS ('86 - 2000)	BNL	Au + Au	2.6 - 4.3 GeV
SPS ('86 - 2003)	CERN	Pb + Pb	8.6 -17.2 GeV
RHIC (2000 - ?)	BNL	Au + Au	200 GeV
LHC (2009 - ?)	CERN	Pb + Pb	5.5 TeV

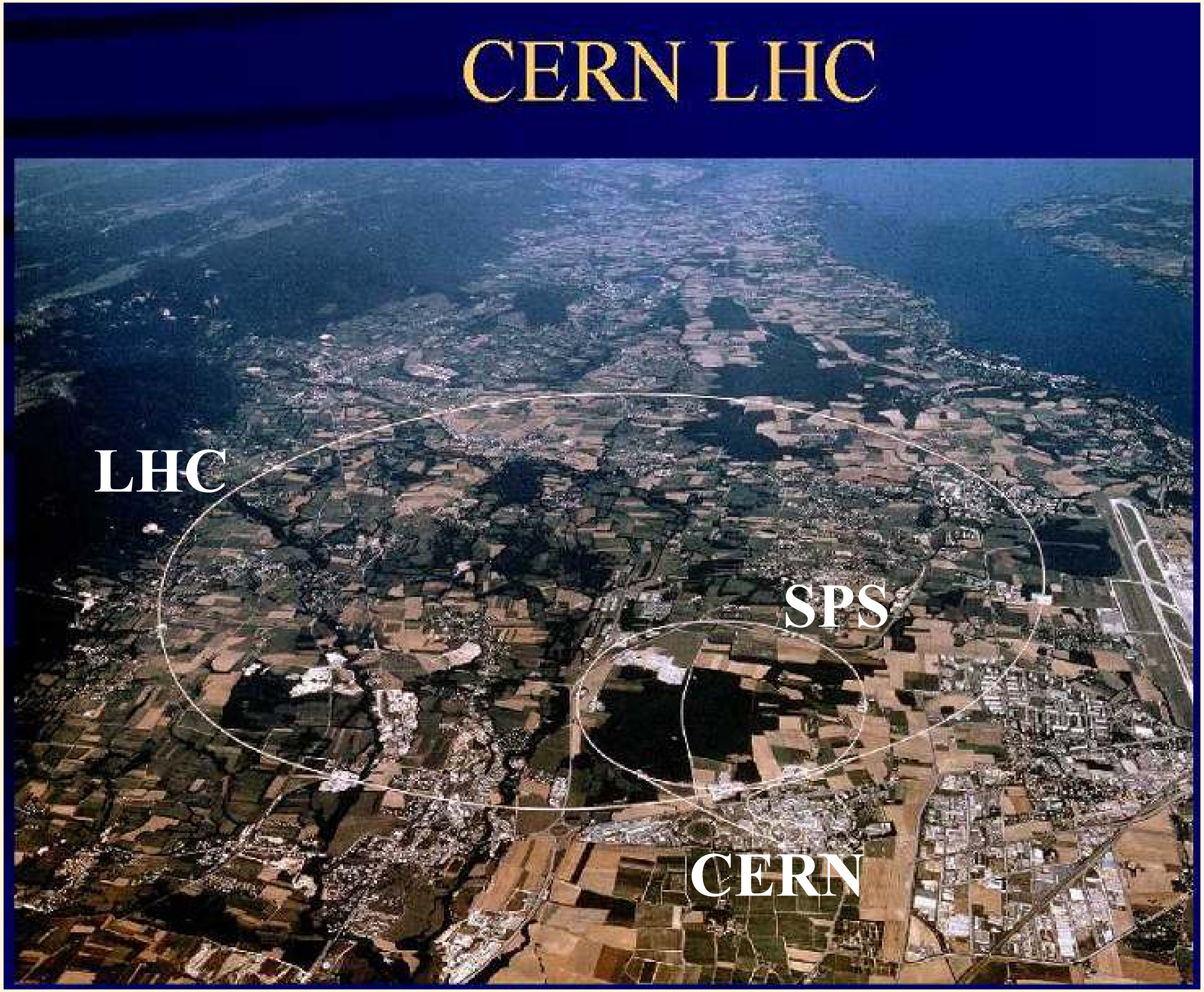
Start '09 → (LHC)

Single Collision at RHIC



It is reconstructed in about 1/1 000 000 000 sec!

Modern Accelerators: LHC



Construction of Large Hadronic Collider was more complicated than sending human to Moon

ALICE at LHC

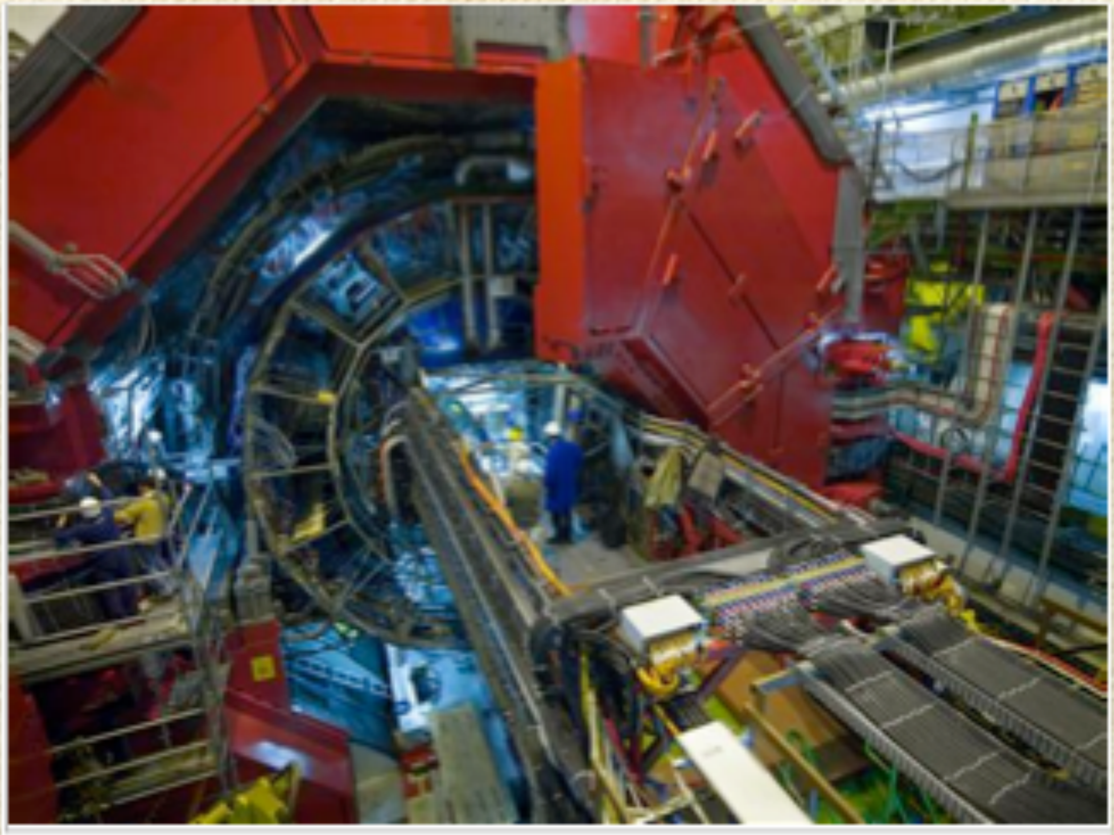


Photo of the Alice Detector in early 2008.

Aerial view of the ALICE site in the territory of Sergy, (France, Ain), 2 km from CERN and the Swiss border (access from St-Genis-Pouilly, Point 2 LHC).

To get a better impression please watch the beginning of the movie «Angels and Demons»! It shows the ATLAS detector

Major Aims of Experiments on A+A Collisions

Study the QCD phase diagram:

1. **detect signals of colour deconfinement;**
2. **detect signals of (partial) chiral symmetry restoration;**
3. **locate (tri)critical endpoint(s) of QCD phase diagram.**

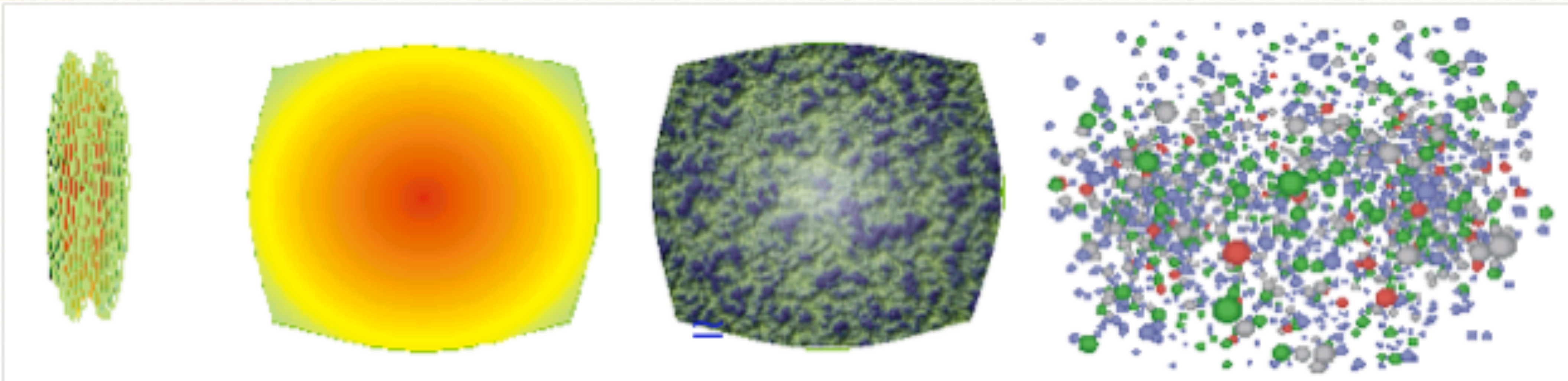
However, these are incredibly complicated tasks even for such an advanced experimental machines!

RHIC Stages

Probe QGP – a new form of matter predicted by Quantum Chromodynamics (QCD)

1 fm ≃ 10^{-15} m

[1 fm/c = 3.3 × 10^{-24} s]



Temperature of $O(10^{12})$

Internal T of Sun is 20 000 000

	Initial singularity	Glasma	sQGP	Hadron gas
	quantum fluctuations	local thermalization	strongly interacting QGP	expansion and decay of resonances
proper time:	$\tau \simeq 0\text{-}0.1$ fm/c	$\tau \simeq 0.1\text{-}1.$ fm/c	$\tau \simeq 1.\text{-}10.$ fm/c	$\tau > 10.$ fm/c

Specific and Principal Theoretical Difficulties

1. Tremendous complexity of A+A collisions

2. Deconfinement phase transition has no well defined order parameter in presence of quarks

3. Lattice QCD cannot guide us at high baryonic densities due to sign problem

Up to now we do not know:

1. What are the analogs of phases in finite volumes

2. What are the analogs of (tri)critical endpoint in finite volumes

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?**

Most promising signals of the onset of deconfinement phase transitions =>

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)

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 √s ~ 4.3-4.9 GeV

and 2-nd order deconfinement PT exists at √s ~ 9 GeV

Giessen group results

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

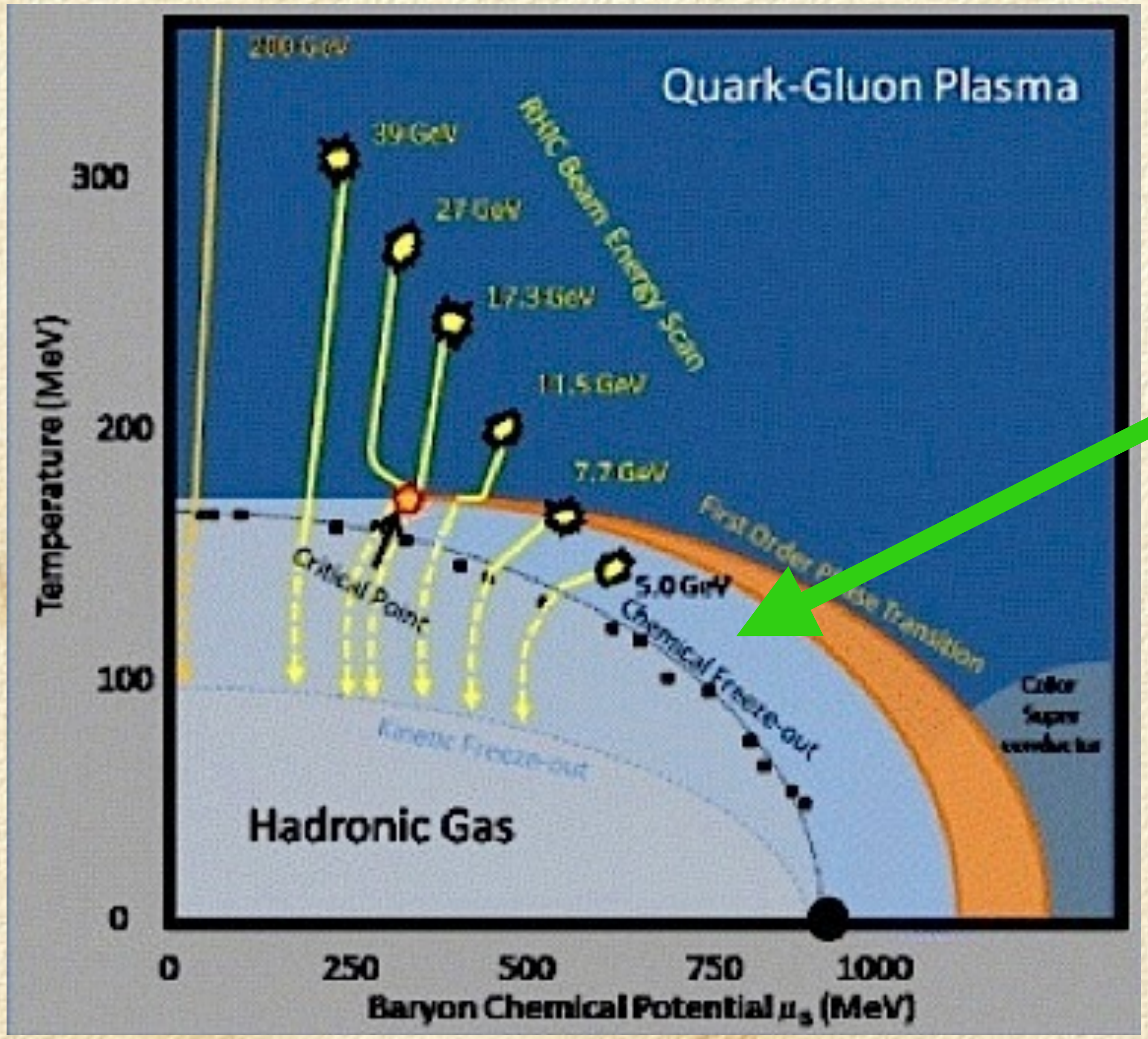
1-st order PT of ChSR in hadronic phase occurs at about √s ~ 4. GeV
and 2-nd order deconfinement PT exists at √s ~ 10 GeV

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.



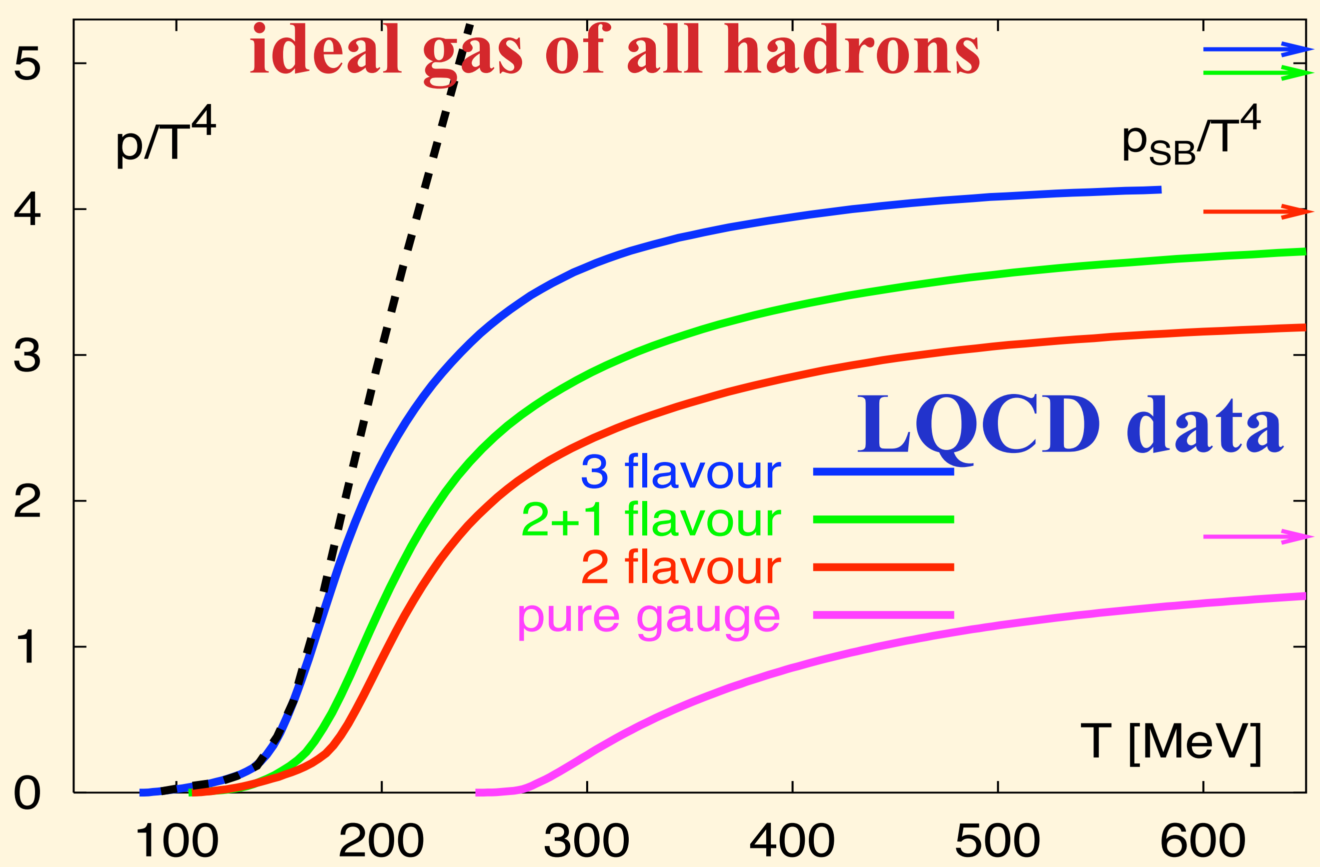
Chemical freeze-out - moment after which hadronic composition is fixed and only strong decays are possible. I.e. there are no inelastic reactions.

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



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.

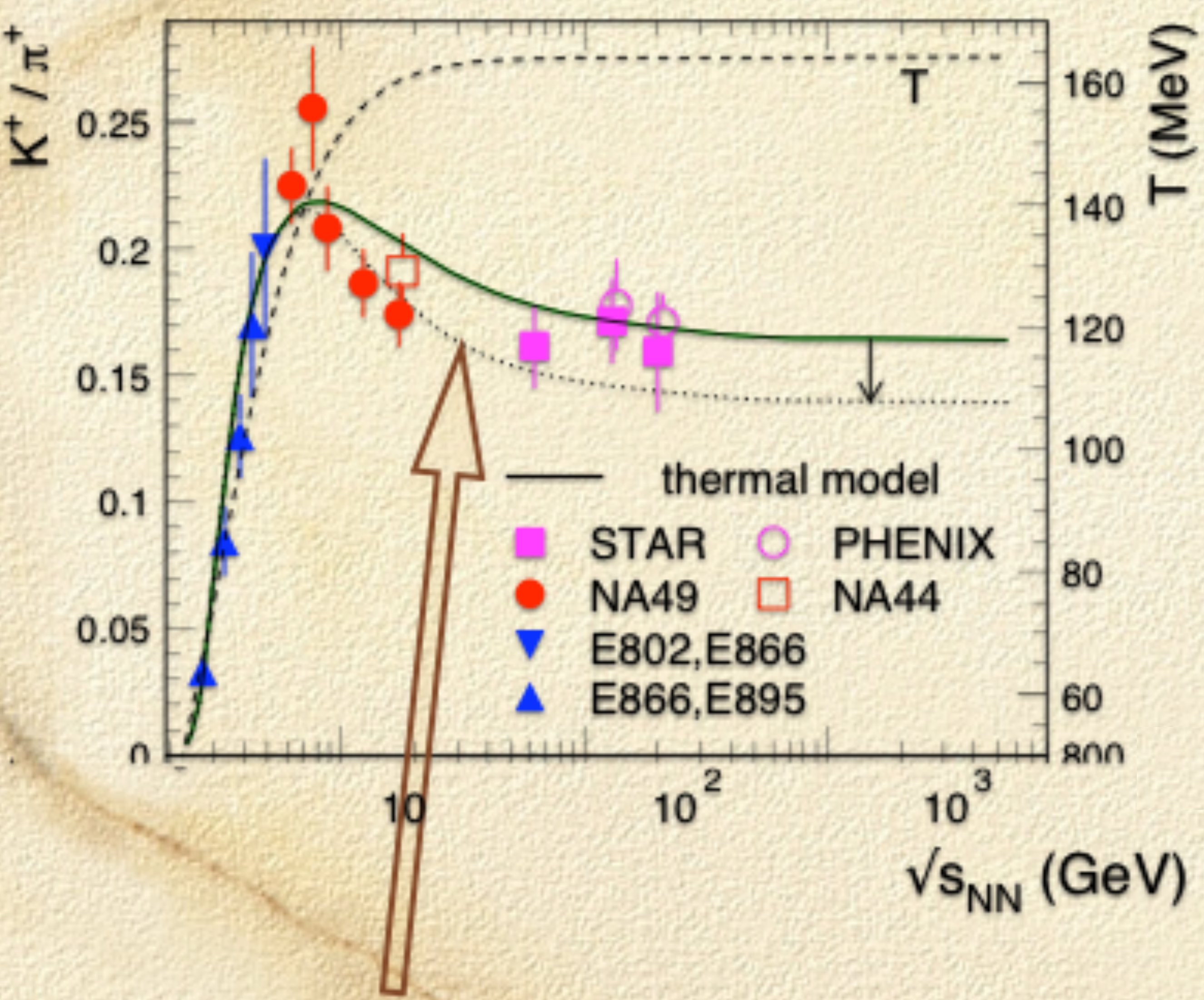
Horns Description in 1-component HRG

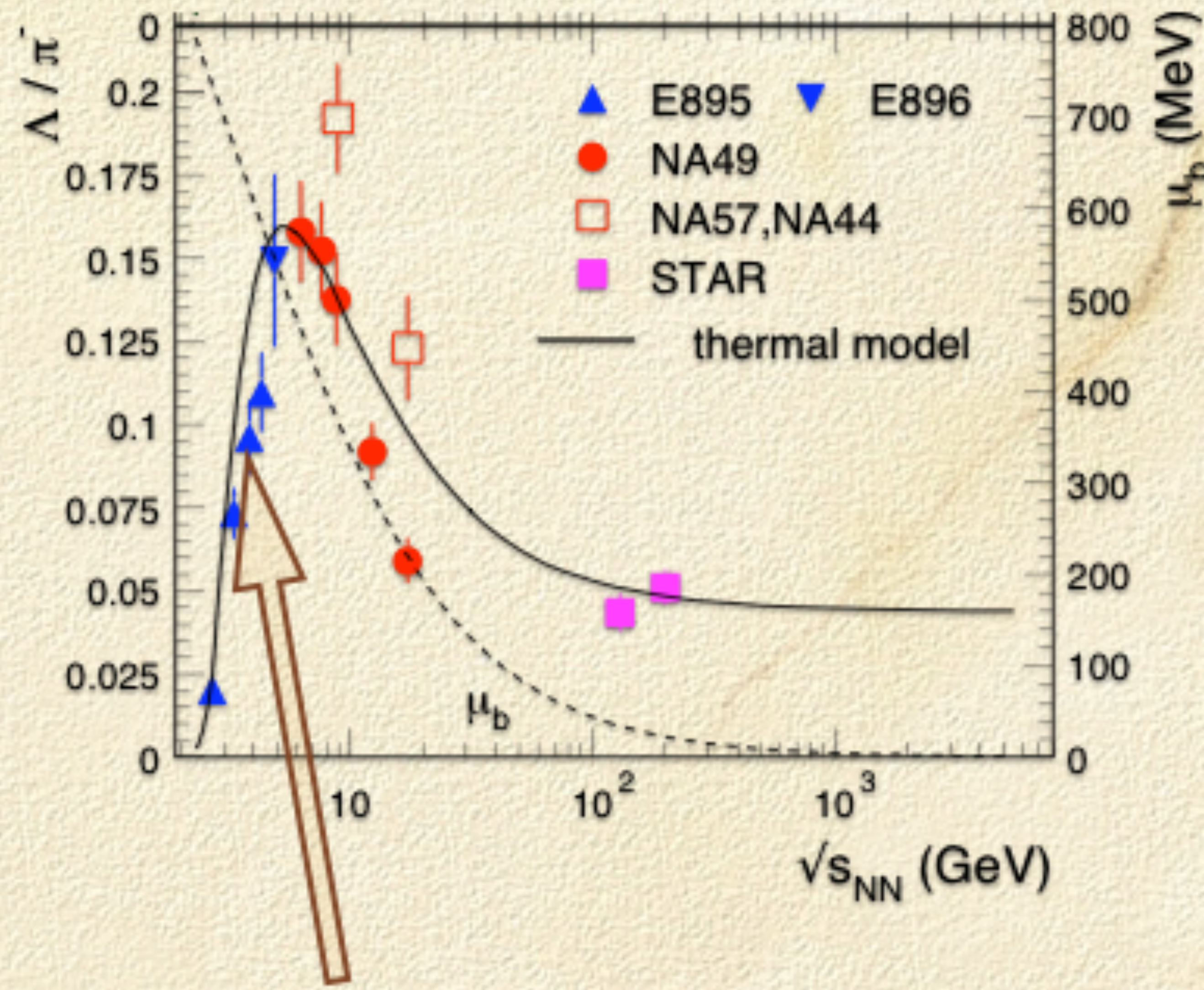
Too slow decrease after maximum!

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

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

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





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 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 $b_{ij} \equiv \frac{2\pi}{3}(R_i + R_j)^3$

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

NO strangeness suppression is included!

the variables ξ_i are the solution of the following system:

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

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

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

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)

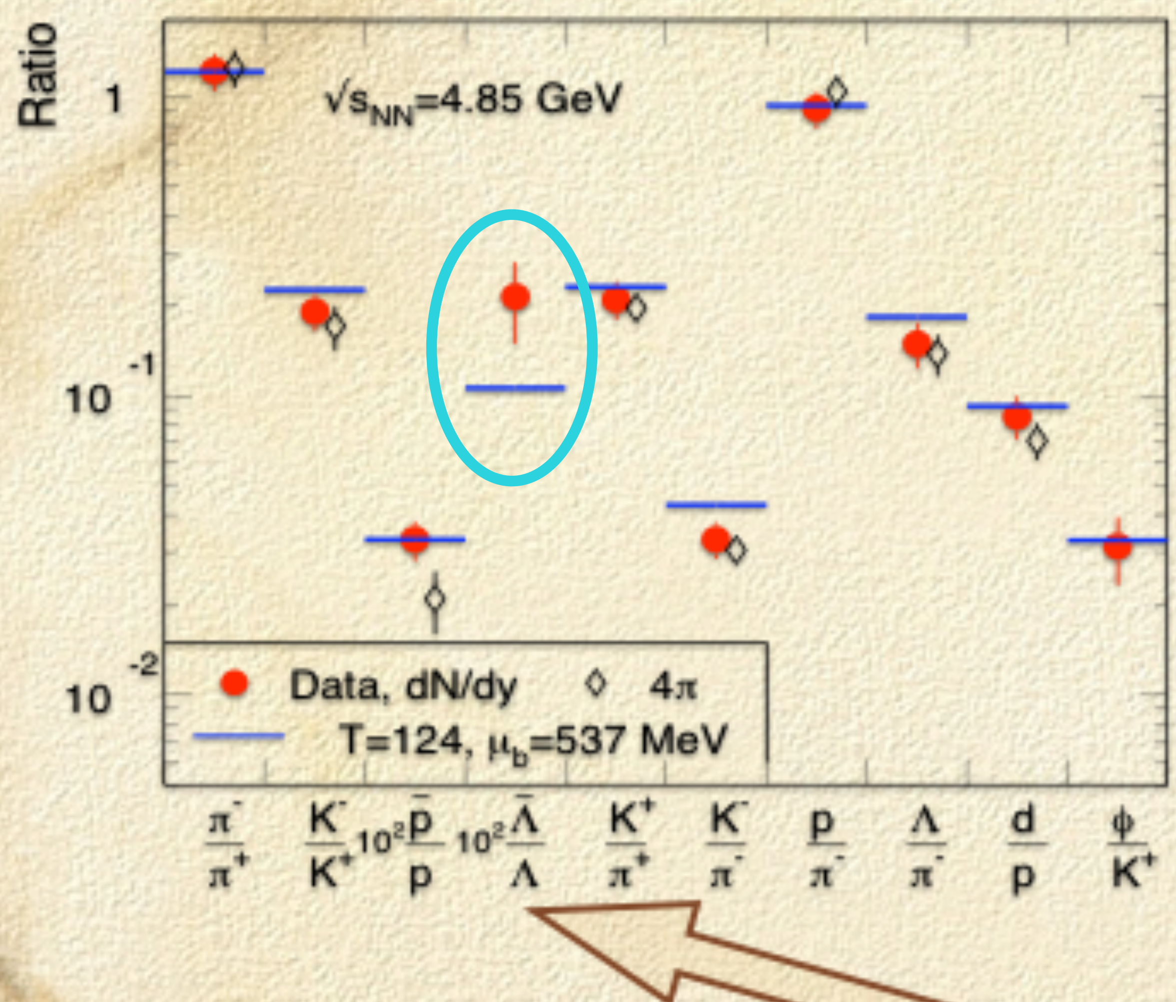
# of local fit parameters for each collision energy = 3 (no γ_S factor)
T, mu_B, mu_I3
Total # for 14 energies = 42

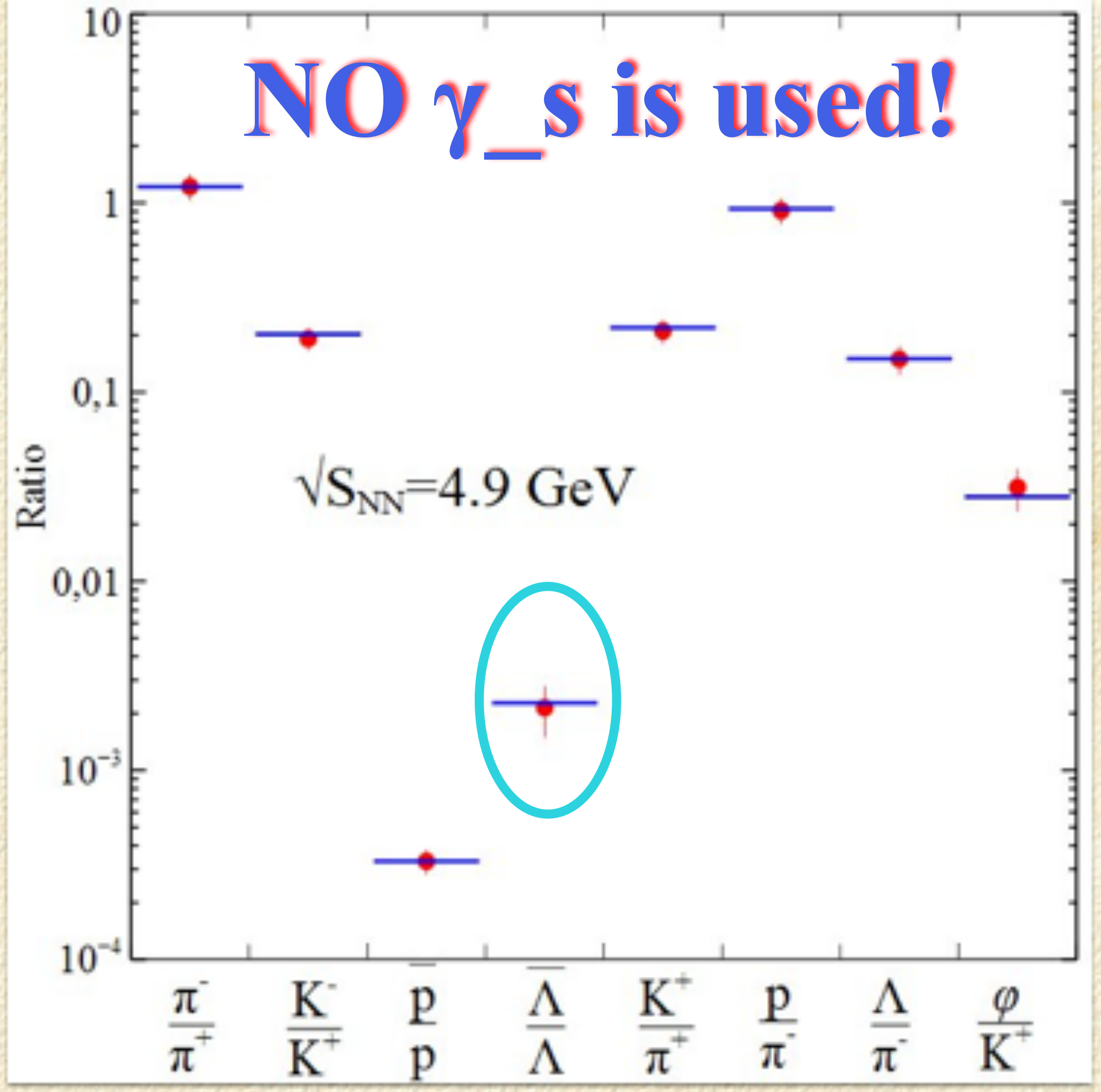
# of fit parameters with γ_S factor is 4
Total # for 14 energies = 56

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

Results for Ratios (AGS)

There is NO anti Lambda problem here and all ratios are well described!





There is an anti Lambda problem! Also K-/K+ and K/pi and Lambda/pi- are not well described!

$T \simeq 131$ MeV, $\mu_B \simeq 539$ MeV, $\mu_{I3} \simeq -16$ MeV

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

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

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

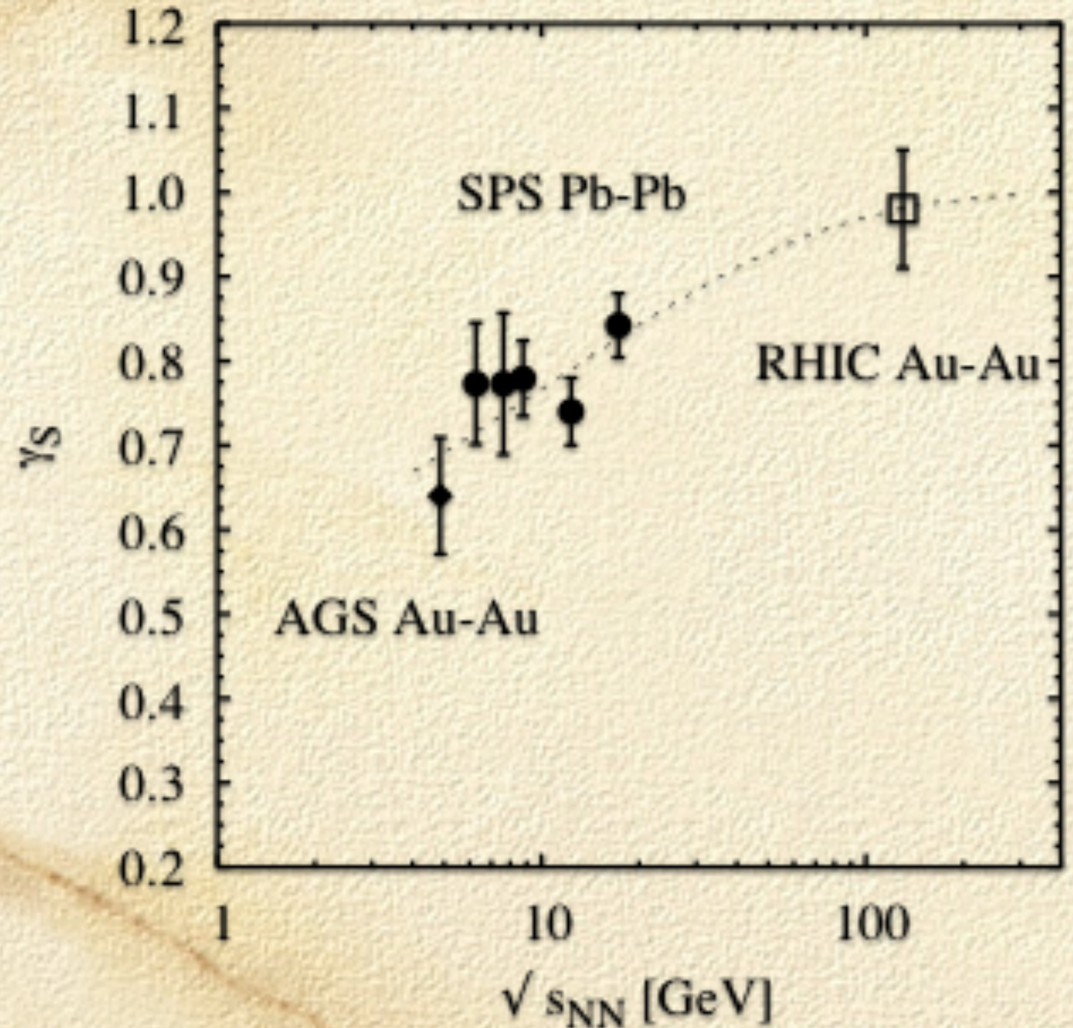
F. Becattini & Co found that γ_S factor is < 1

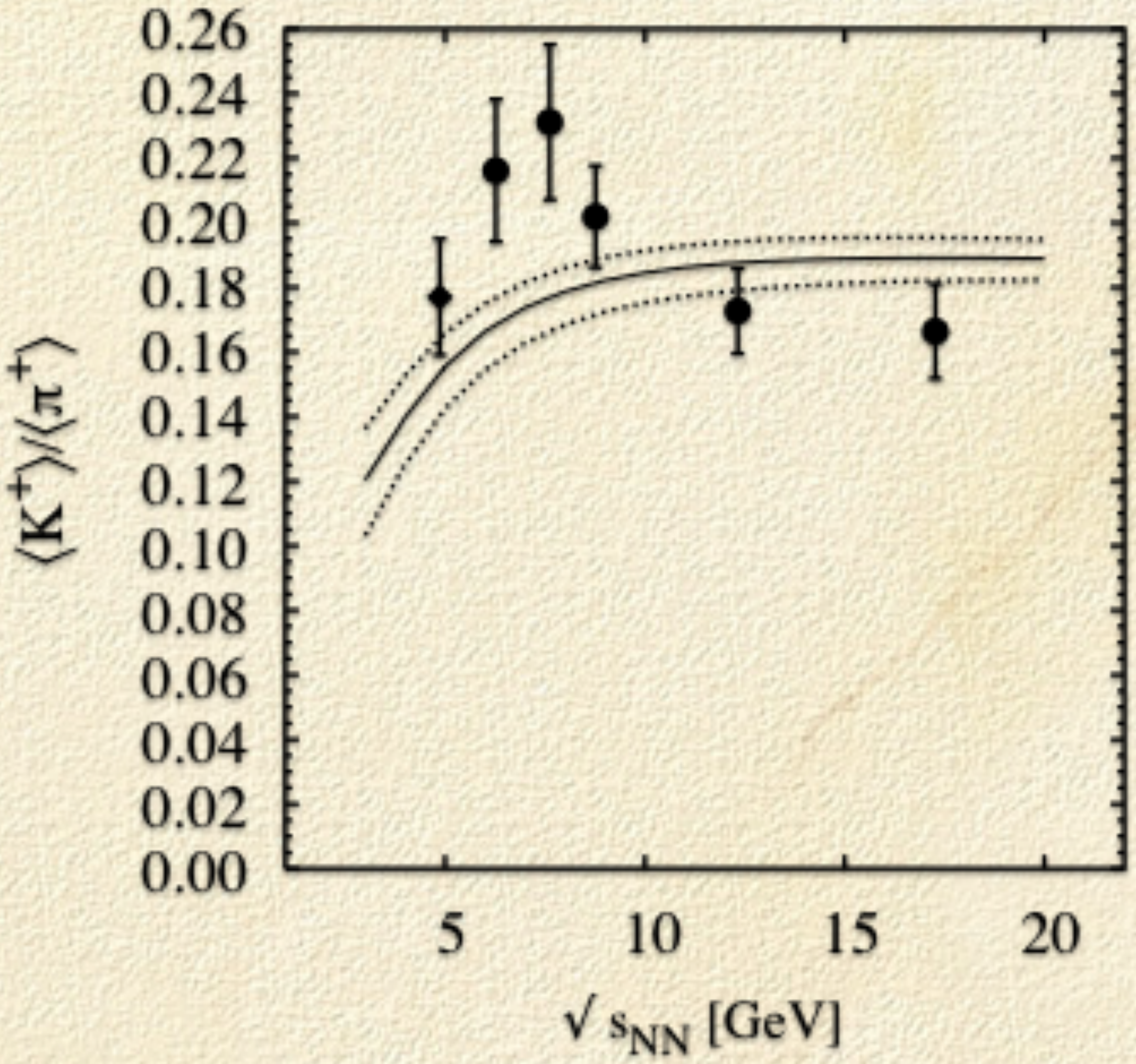
Systematics of Strangeness Suppression

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**

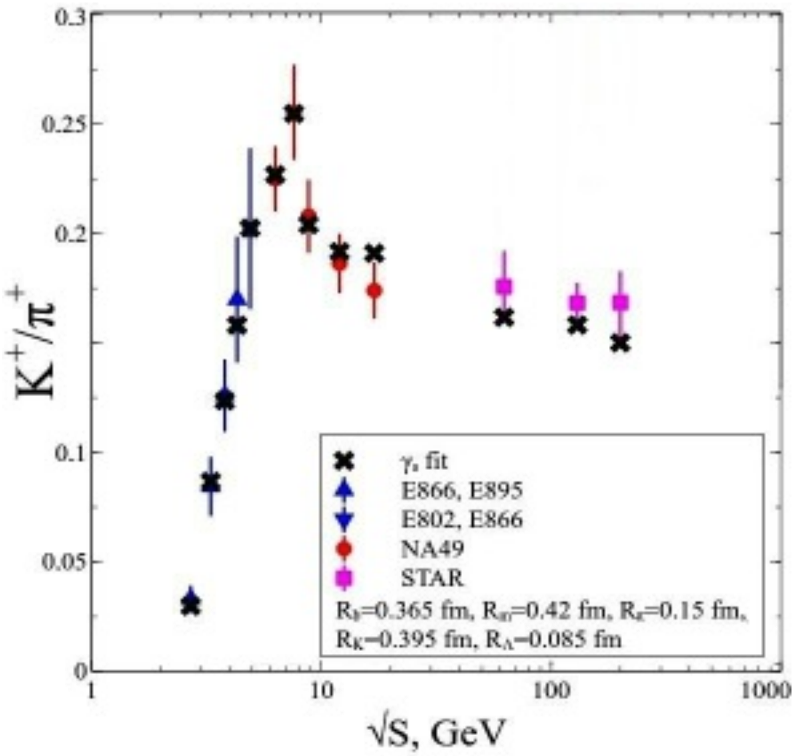


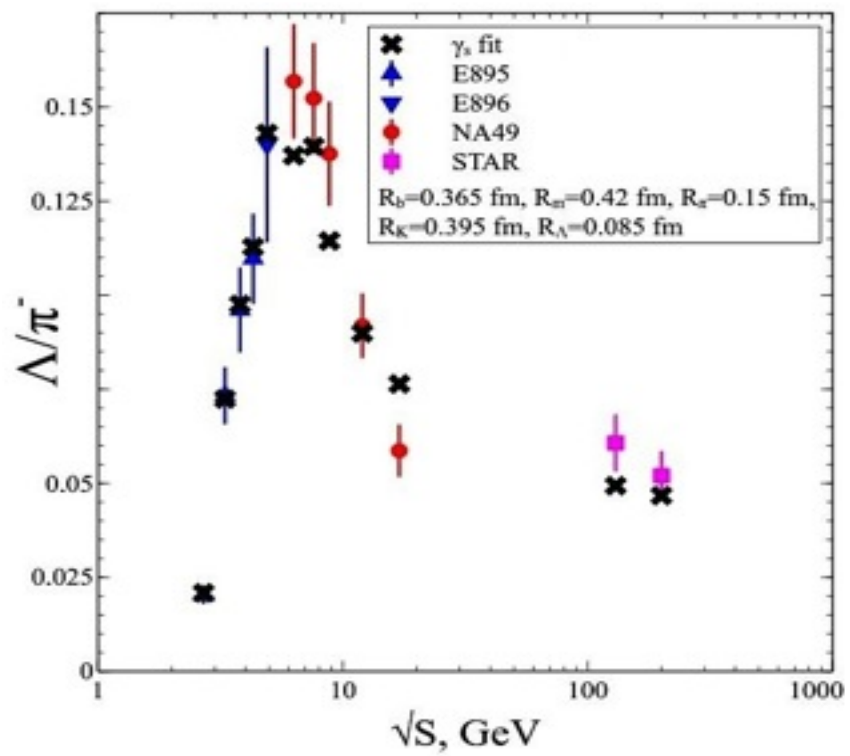


Single component model **F. Becattini, J. Manninen and M. Gazdzicki, PRC 73 (2006) 044905**

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

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



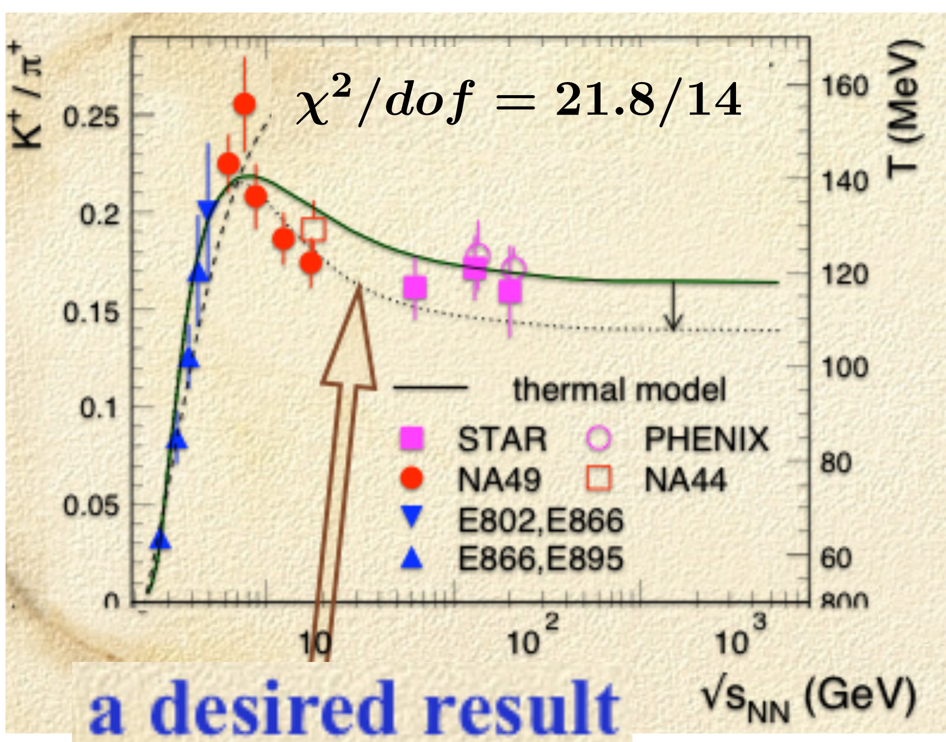


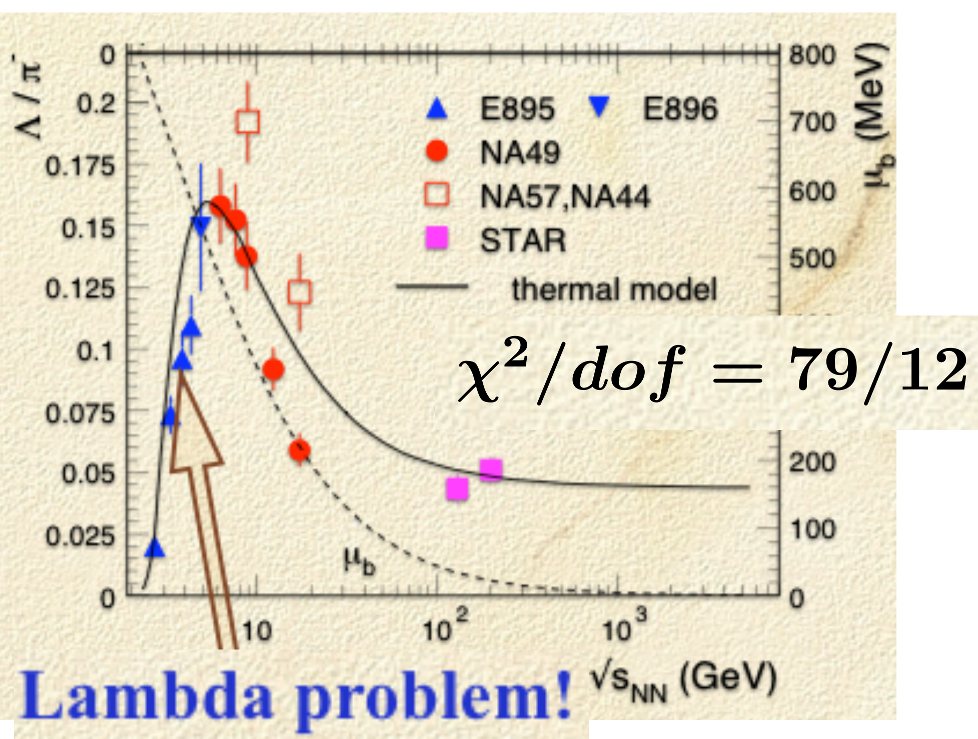
IST EOS: $\chi^2/dof \simeq 3.29/14$ $\chi^2/dof \simeq 11.62/12$

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!



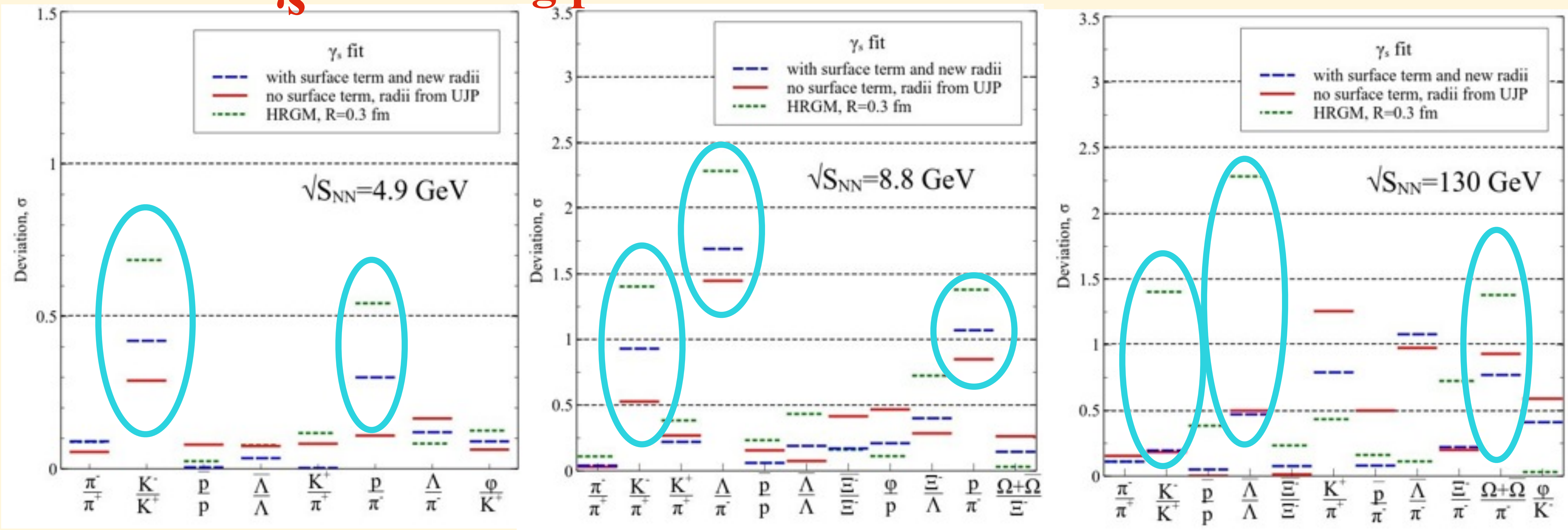


Conventional one component HRGM by PBM and Co:
A. Andronic, PBM, J. Stachel NPA (2006), PLB (2009)

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)

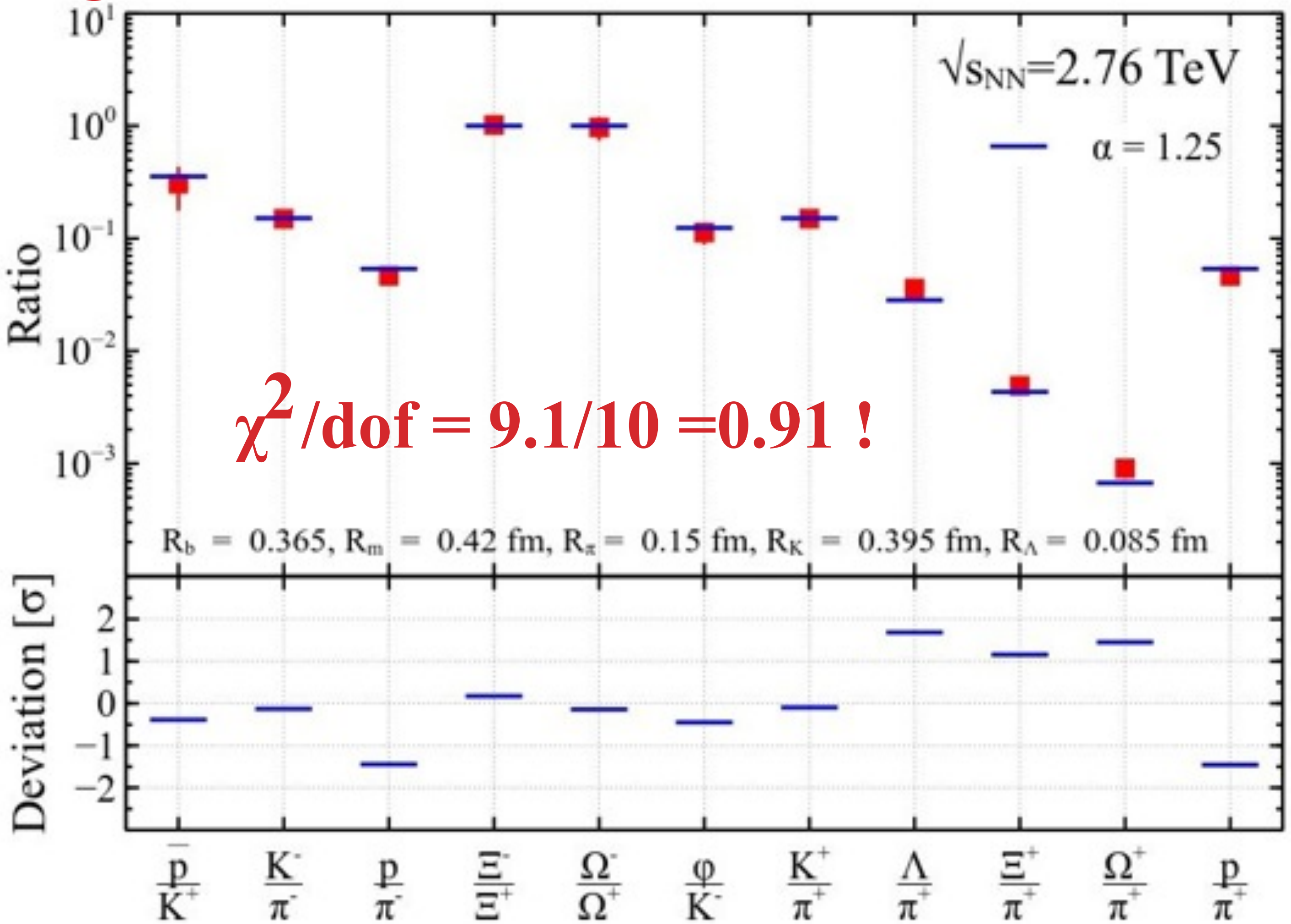
Red bars Multicomponent Van der Waals EoS

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!

BUT the puzzle of light (anti)nuclei remained unresolved!

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

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

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

- One component case with $\alpha > 1$

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

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

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

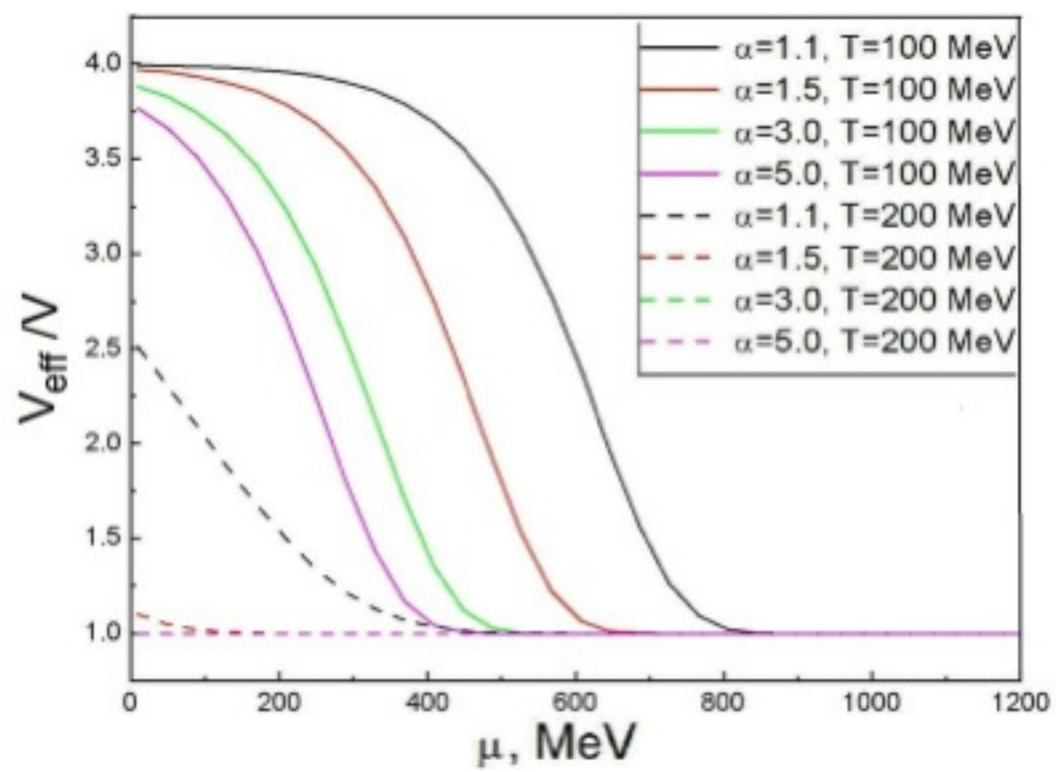
$\Rightarrow$

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!

Higher Virial Coefficients of IST EOS

- Virial expansion of one component EoS with induced surface tension

$$p = nT\Big[1 + \overbrace{4V_o}^{a_2} n + \overbrace{\Big(16 - 18(\alpha-1)\Big)V_o^2}^{a_3} n^2 + \underbrace{\Big(64 - 216(\alpha-1) + \frac{243}{2}(\alpha-1)^2\Big)V_o^3}_{a_4} n^3\Big] + \mathcal{O}(n^5)$$

- Second virial coefficient of hard spheres $a_2 = 4V_o$ is reproduced always

- Fourth virial coefficient of hard spheres

$a_4 \simeq 18.365 V_o^3 \;\Rightarrow\; \alpha \simeq 2.537,\; a_3 \simeq -11.666 V_o^2$ - not reproduced

$\alpha \simeq 1.245,\; a_3 \simeq 11.59 V_o^2$ - reproduced with 16 % accuracy

One parameter reproduces two (3rd and 4th) virial coefficients and allows generalization for multicomponent case

=> IST EoS is valid for packing fractions $\eta < 0.22$

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

IST EOS for Nano particles?

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

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

for one-component case **Σ~ R**

for two-component case, if r <<R => **Σ~ R**

ИЗВЕСТИЯ РАН. СЕРИЯ ФИЗИЧЕСКАЯ, 2016, том 80, № 6, с. 768–771

УДК 539.211

On dimensional dependence of surface energy and surface tension of metallic nano particles

О РАЗМЕРНОЙ ЗАВИСИМОСТИ ПОВЕРХНОСТНОЙ ЭНЕРГИИ И ПОВЕРХНОСТНОГО НАТЯЖЕНИЯ МЕТАЛЛИЧЕСКИХ НАНОЧАСТИЦ

© 2016 г. В. М. Самсонов, А. А. Чернышова, Н. Ю. Сдобняков

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С использованием многочастичного потенциала сильной связи и его более раннего аналога – потенциала Гупта проведены расчеты удельной полной поверхностной энергии малых нанокластеров переходных ГЦК-металлов. Расчеты проводились с использованием как теоретической модели, так и компьютерного моделирования по методу Монте-Карло. В качестве разделяющей поверхности рассматривалась эквимолекулярная поверхность. Установлено, что при малых радиусах нанокластеров поверхностная энергия и энергетическое поверхностное натяжение возрастают линейно с ростом радиуса частицы. Значения коэффициента пропорциональности между удельной поверхностной энергией и радиусом нанокластера сопоставлены с имеющимися литературными данными, в том числе с экспериментальными данными.

DOI: 10.7868/S0367676516060296

Вывод формулы Толмена относится к случаю больших раудисов $R \gg \delta$. Для противоположного предельного случая малых R А.И. Русанов [3] получил линейную формулу

$$\gamma = KR, \qquad (2)$$

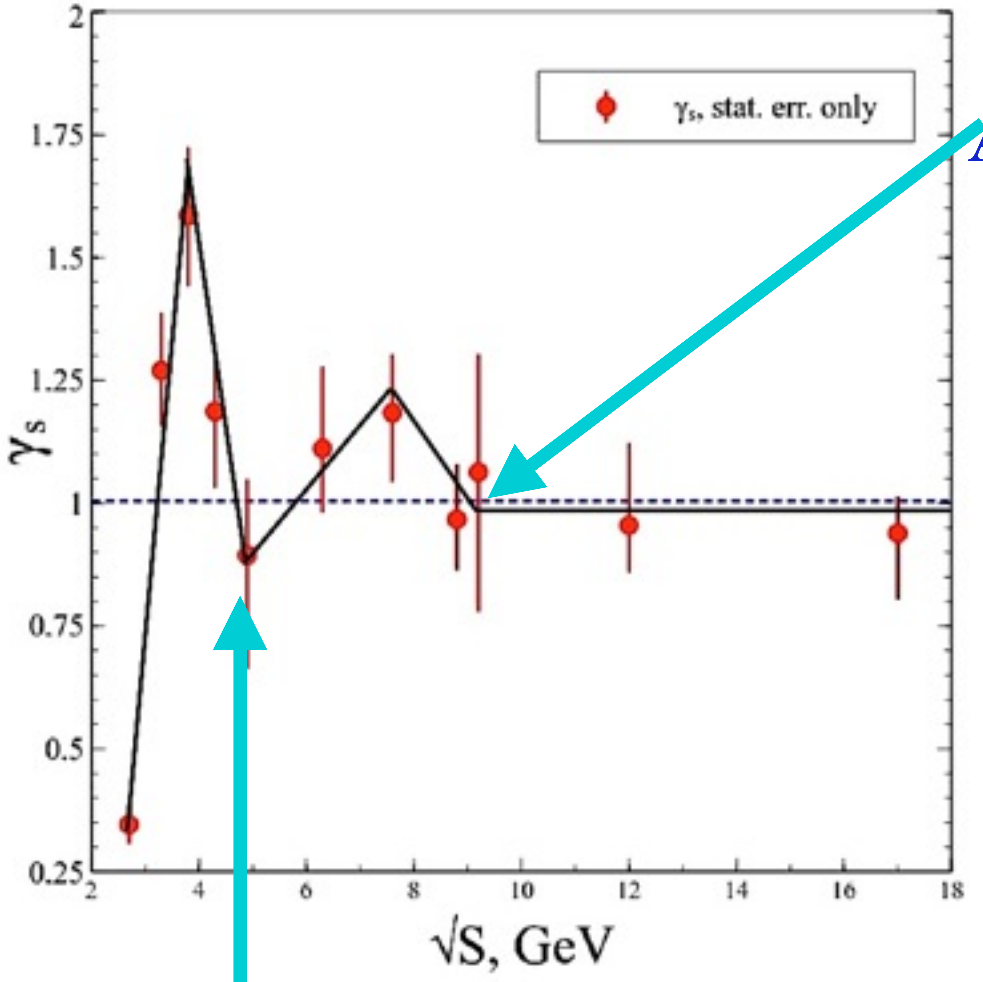
где K – параметр, зависящий от температуры и давления. Вывод этой формулы также относится к поверхности натяжения. В течение длительного

Derivation of the Tolman formula is related to the case of large radii **R>> δ.** In opposite limit A.I. Rusanov [3] derived **linear formula**

$$\gamma = K R, \qquad (2)$$

where K is a temperature and pressure dependent parameter. **(Similar to IST EoS!)**

Strangeness Irregularities



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

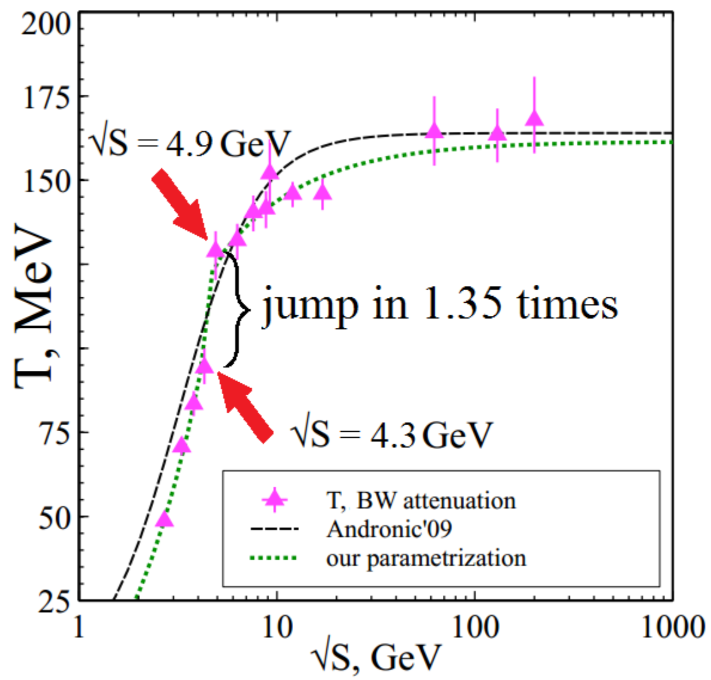
At c.m. energy below 4.9 GeV strange particles are also in chemical equilibrium, while at lower and higher energies of collision there is strangeness enhancement. Why?

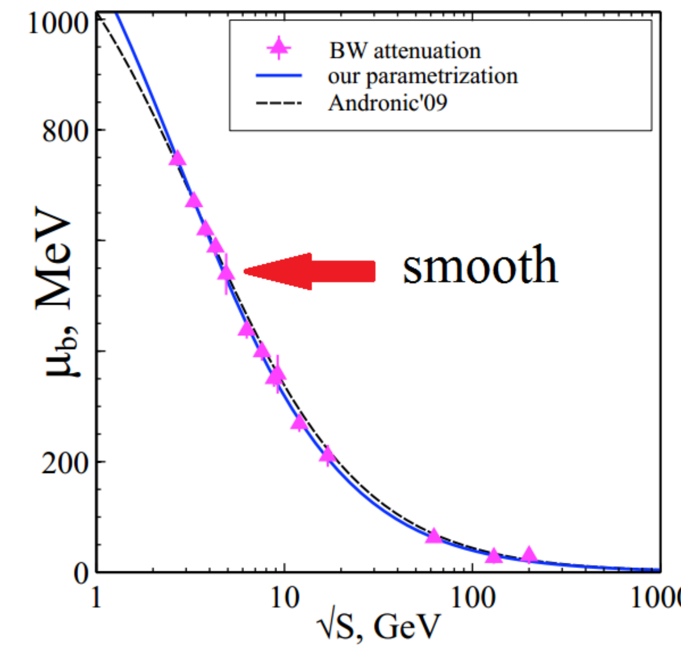
Explanation of such peculiar behavior was found in 2017. See

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

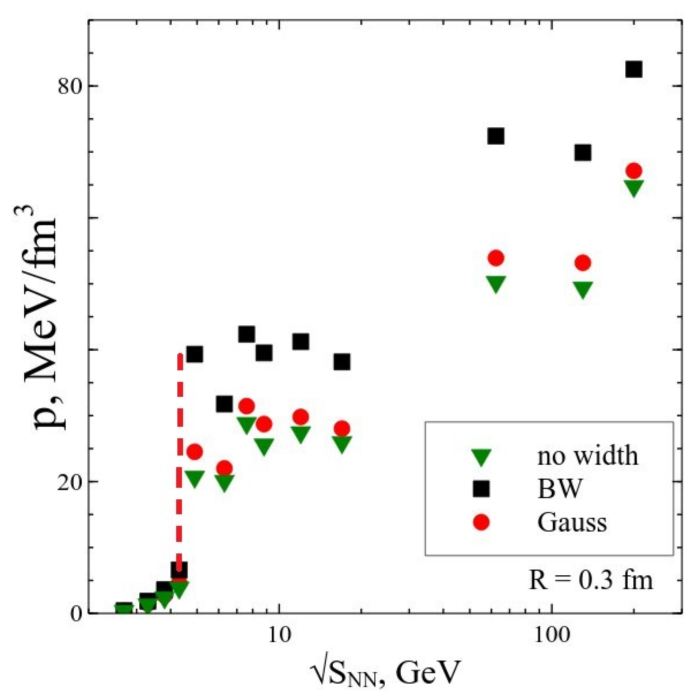
Jump of CFO Pressure at AGS Energies

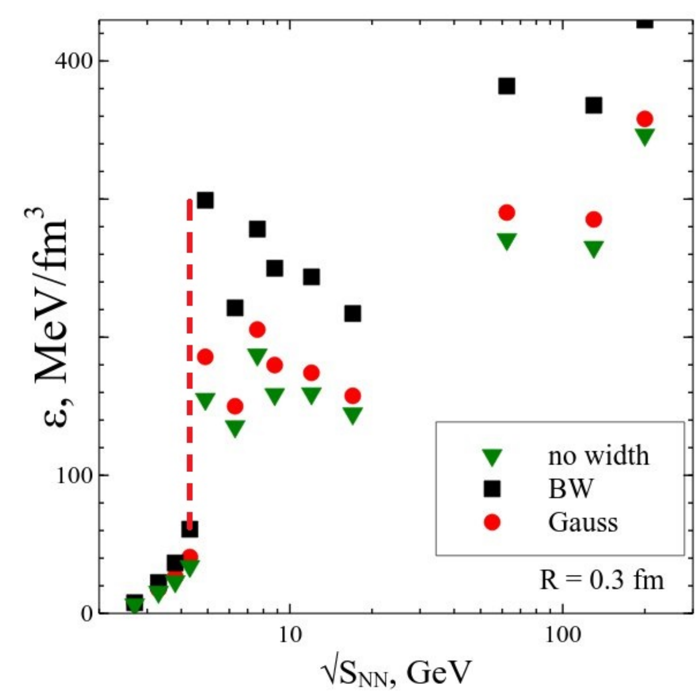
- Temperature T_{CFO} as a function of collision energy $\sqrt{s}$ is rather non smooth





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



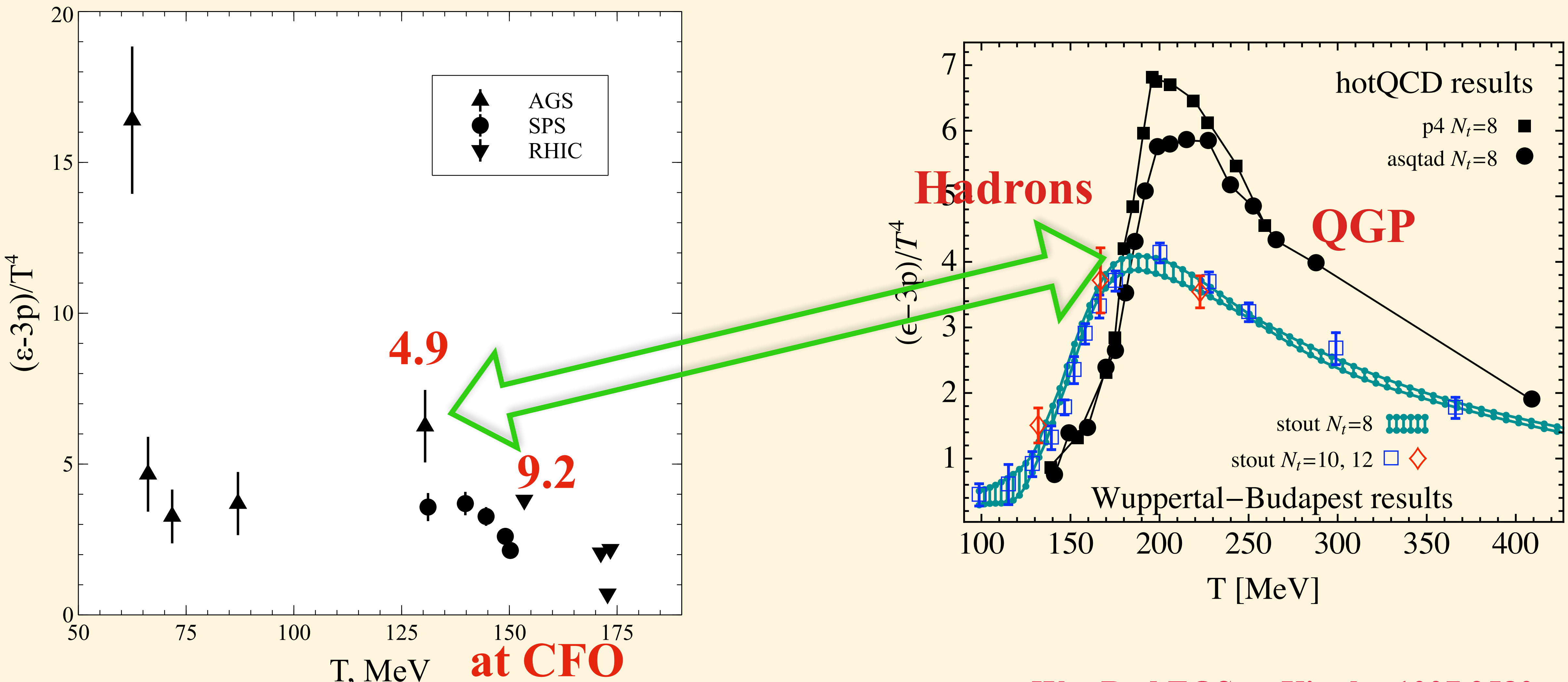


K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015) [arXiv:1405.3575];

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

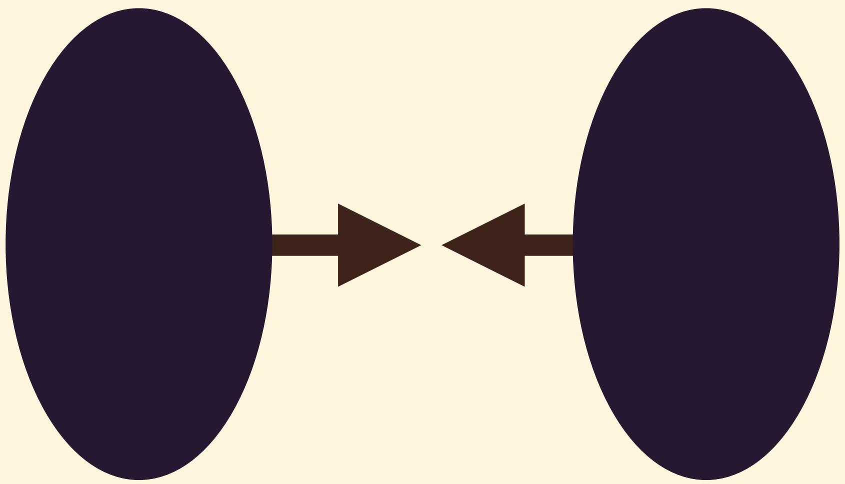
Model from V.V. Sagun et al., Eur. Phys. J. A (2018) 54: 100,

arXiv:1703.00009 [hep-ph]

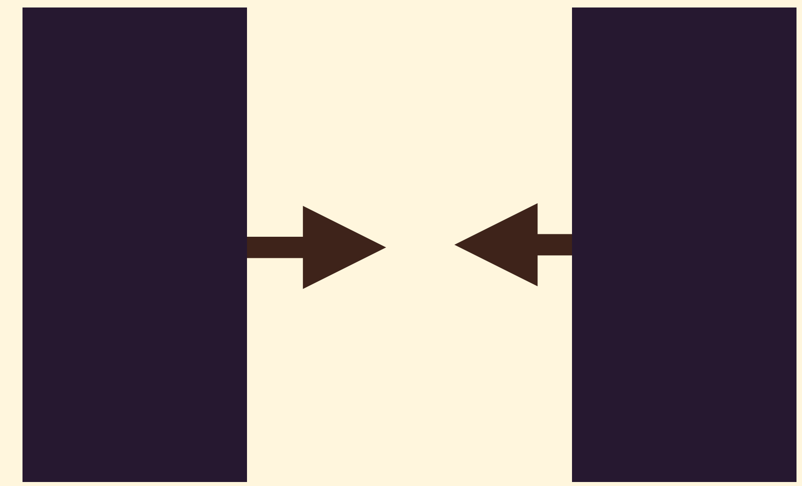
Are these trace anomaly peaks related to each other?

Shock Adiabat Model for A+A Collisions

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



Its hydrodynamic model

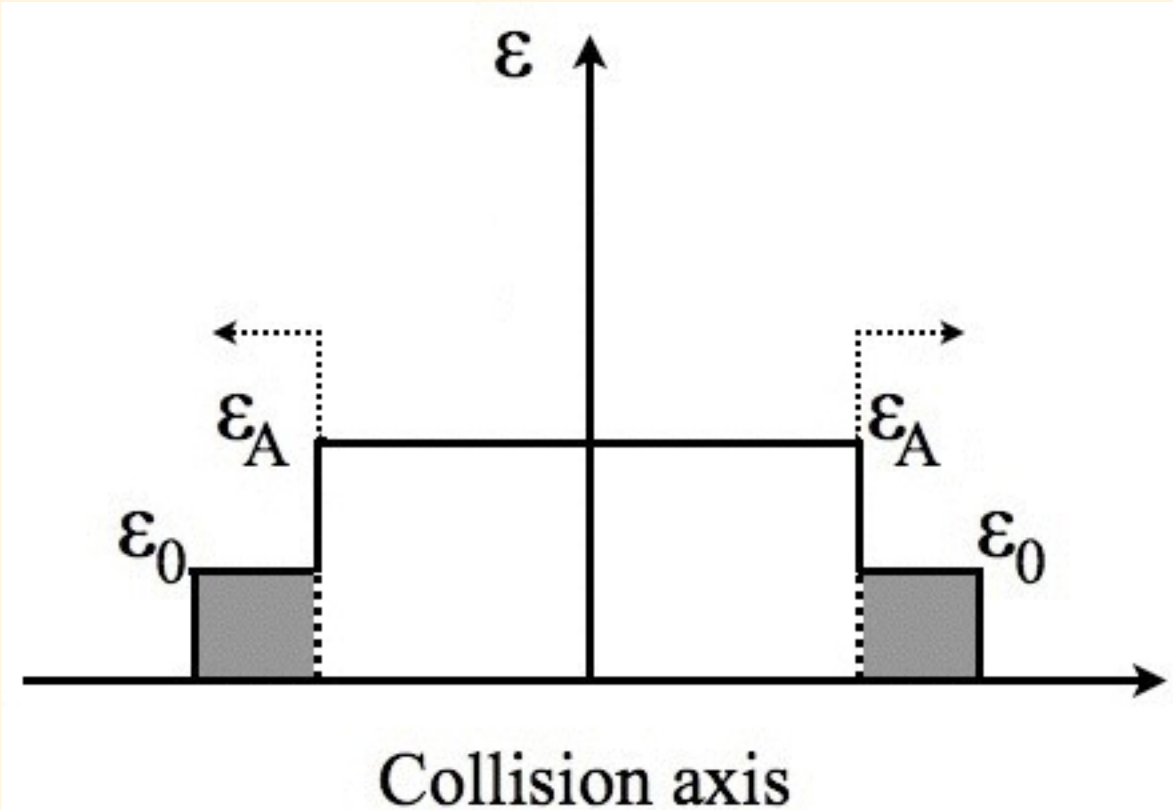


Works reasonably well at these energies.

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



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,

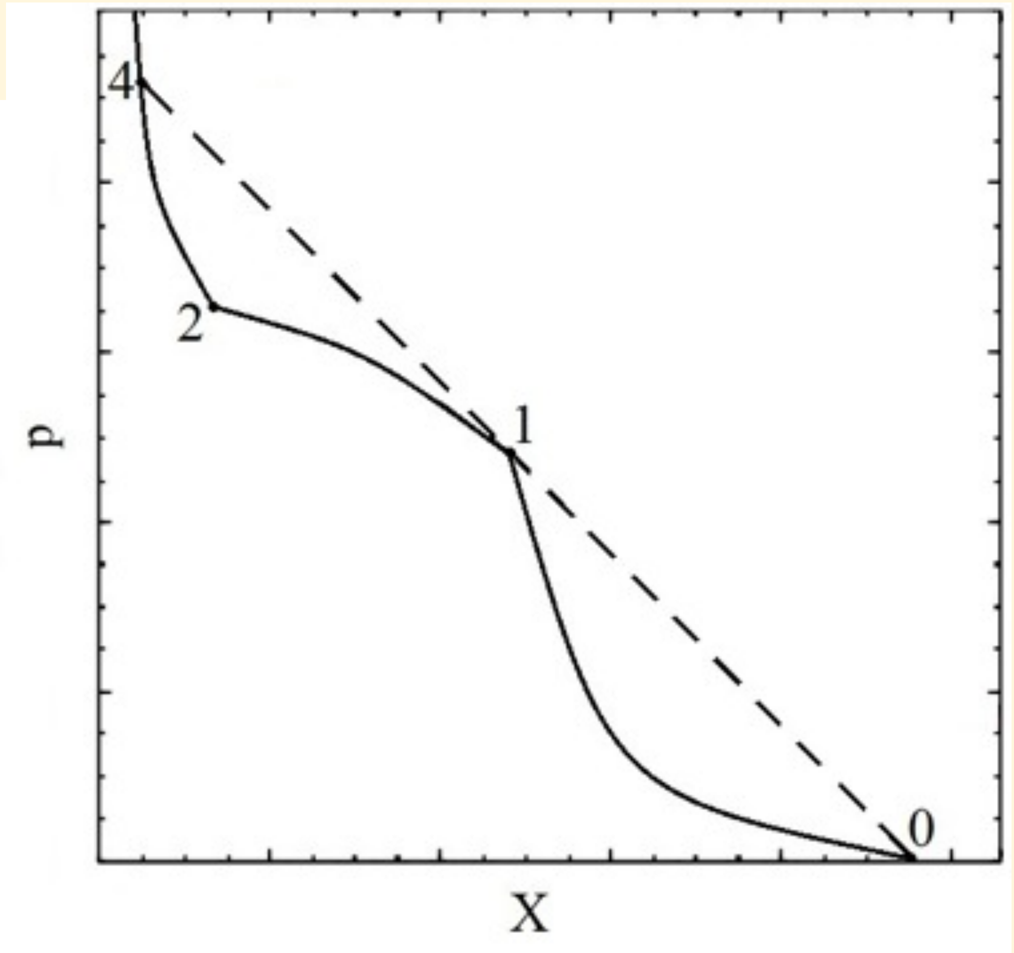
ρ_B is baryonic charge density

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.**

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!

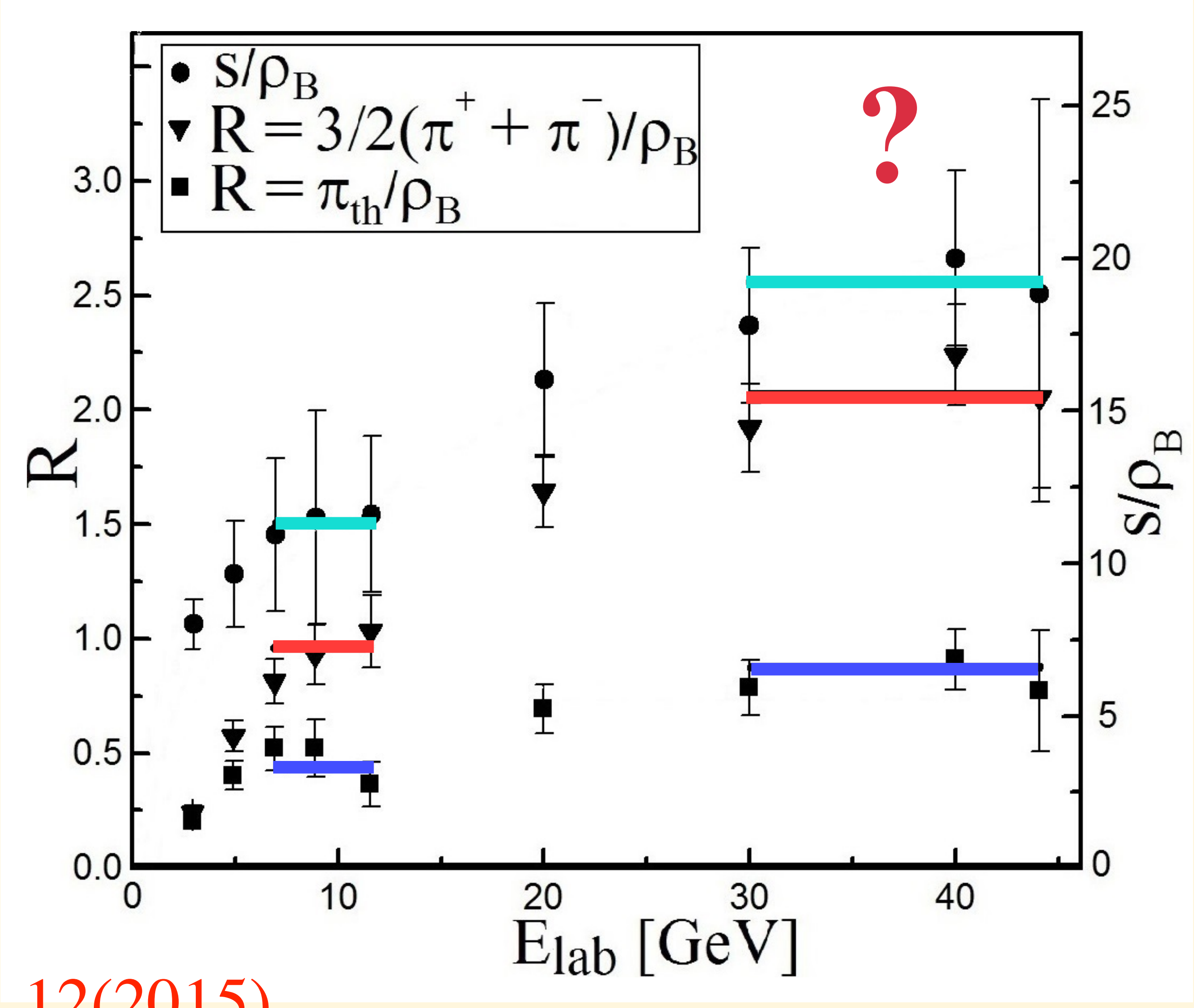
Also the total number of **pions per baryons should have a (quasi)plateau!**

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

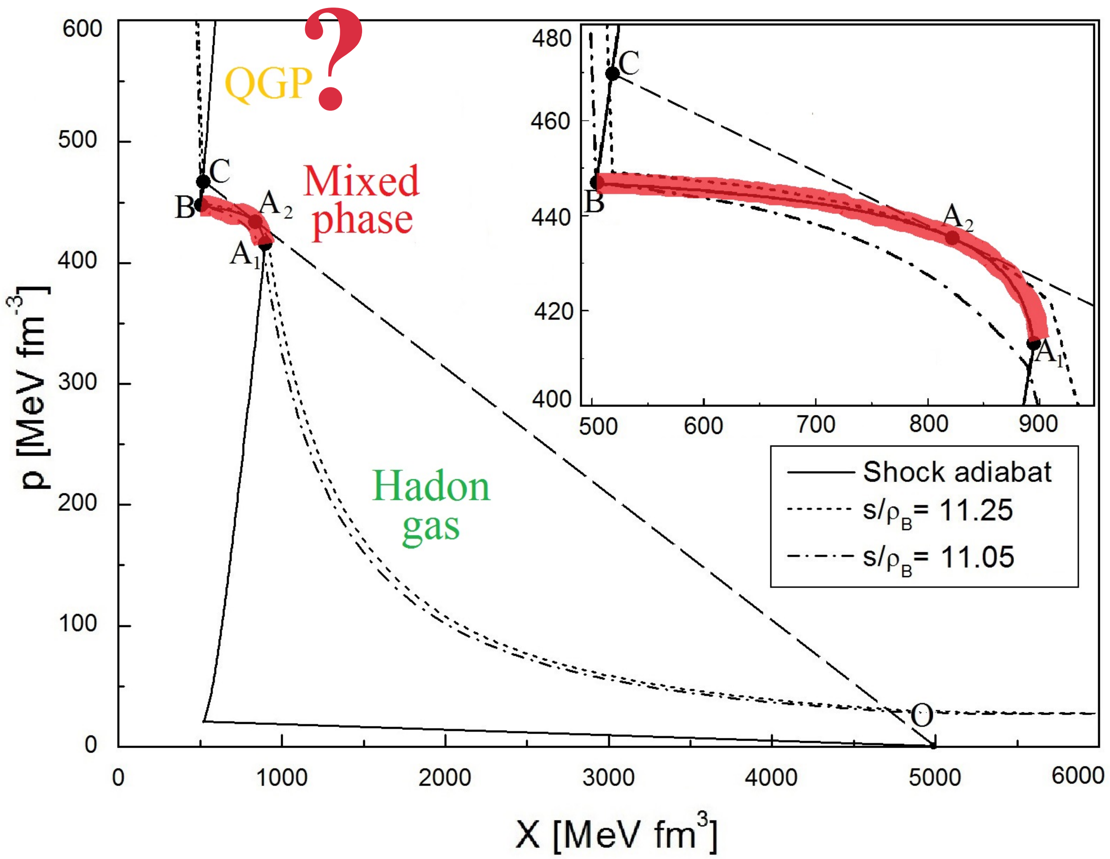


K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015)

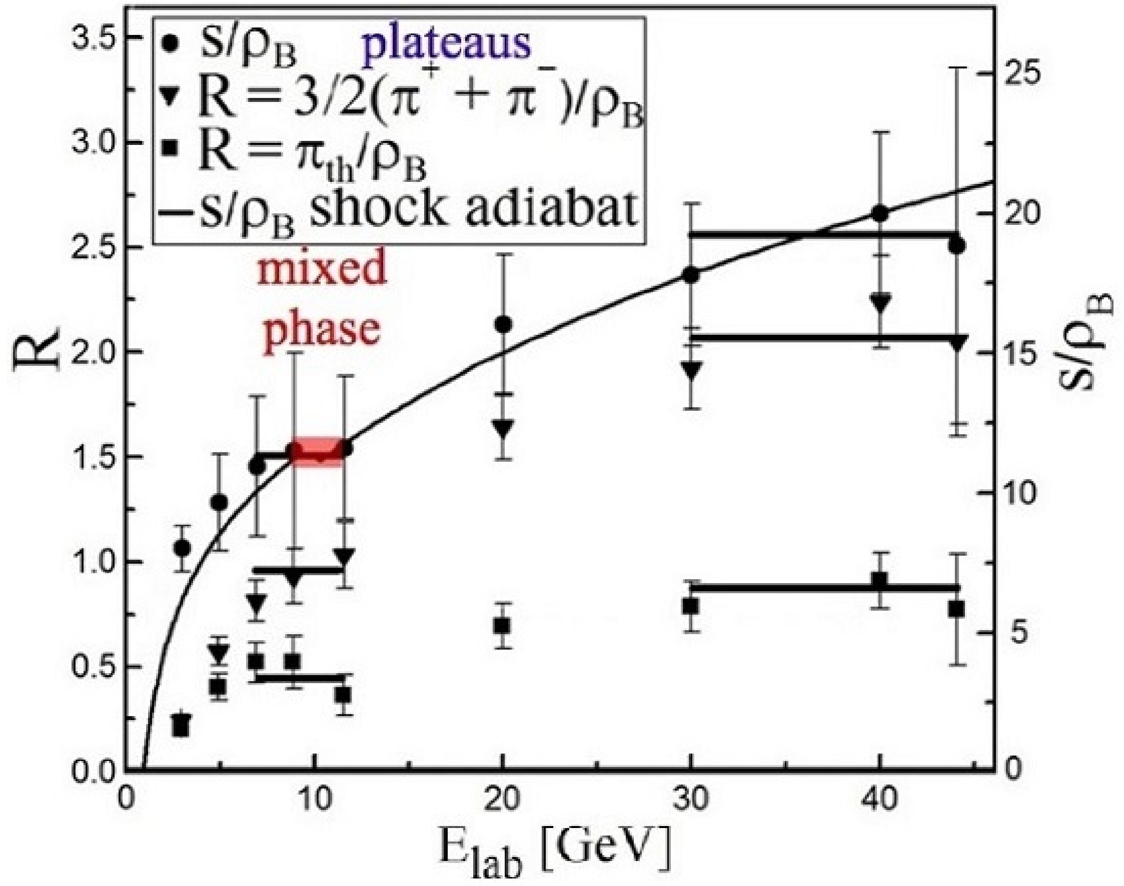
Unstable Transitions to Mixed Phase

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

other PT?



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

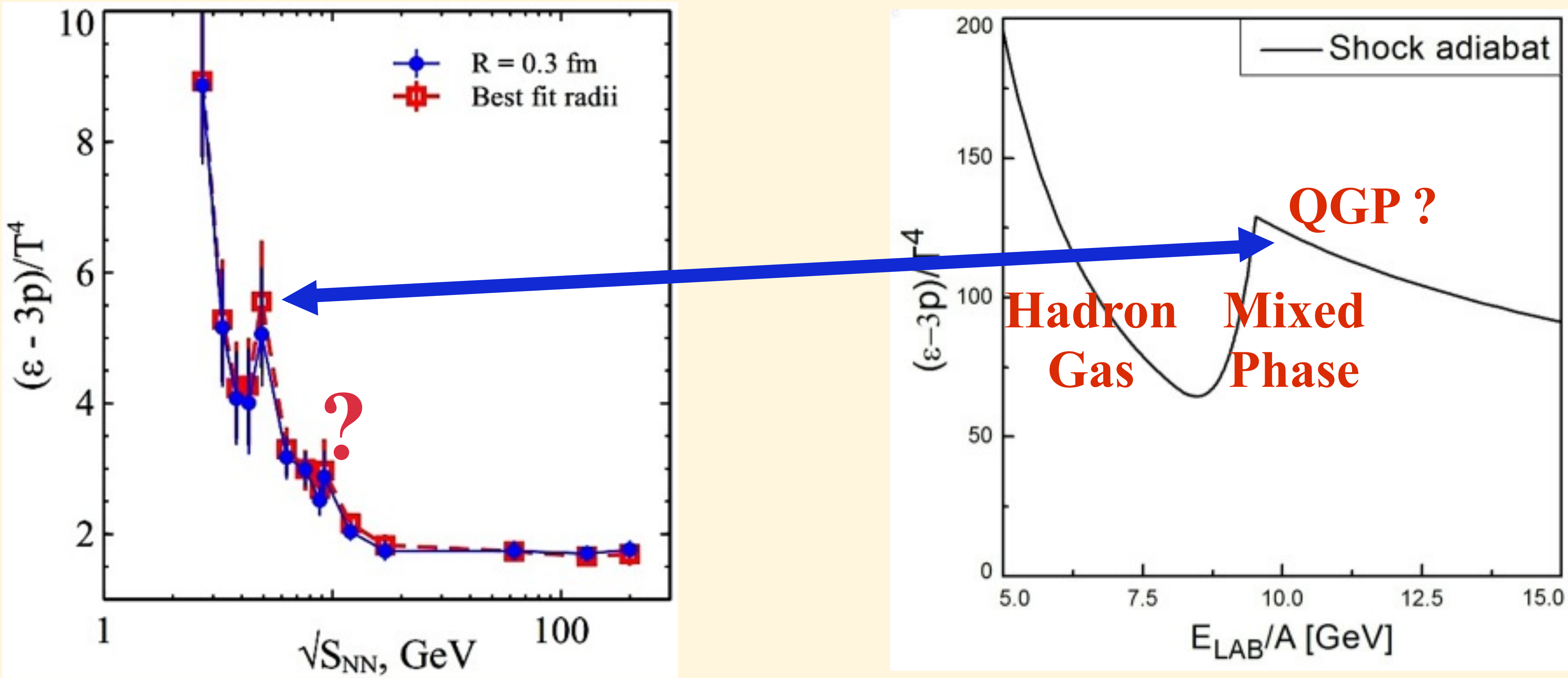


GSA Model explains irregularities at CFO as a signature of mixed phase

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



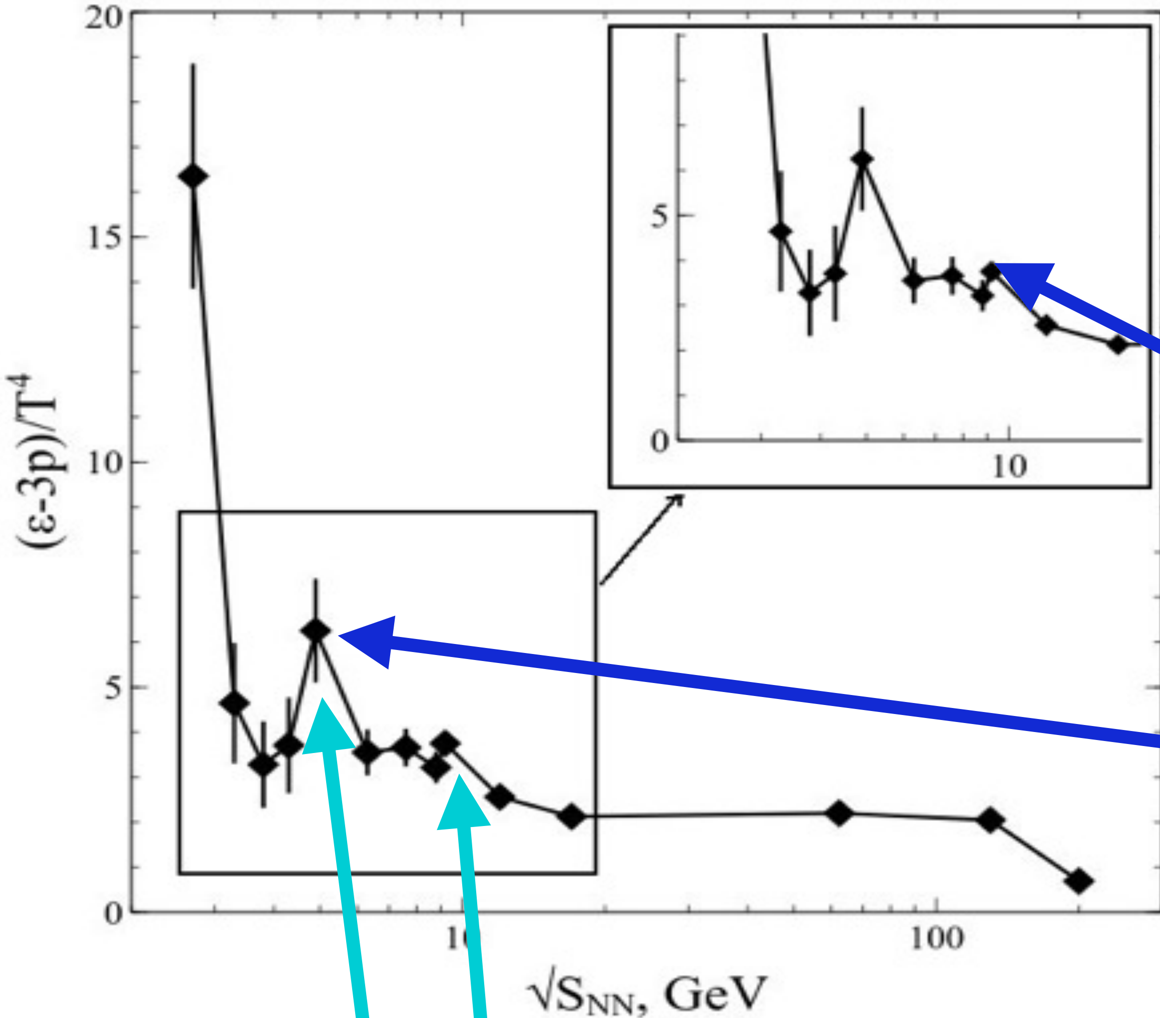
K.A. Bugaev et al., EPJ A (2016)

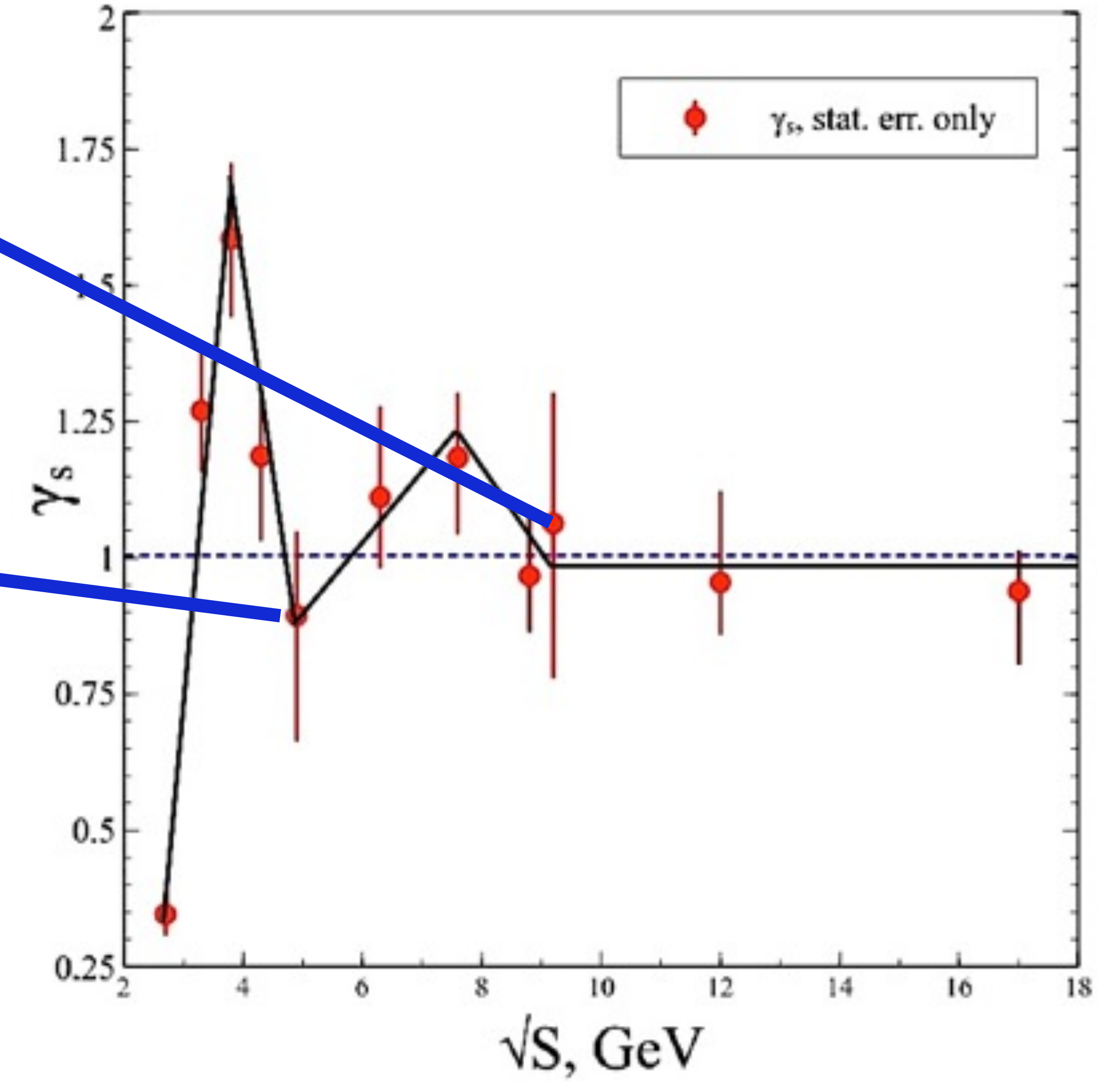
We found one-to-one correspondence between these two peaks.

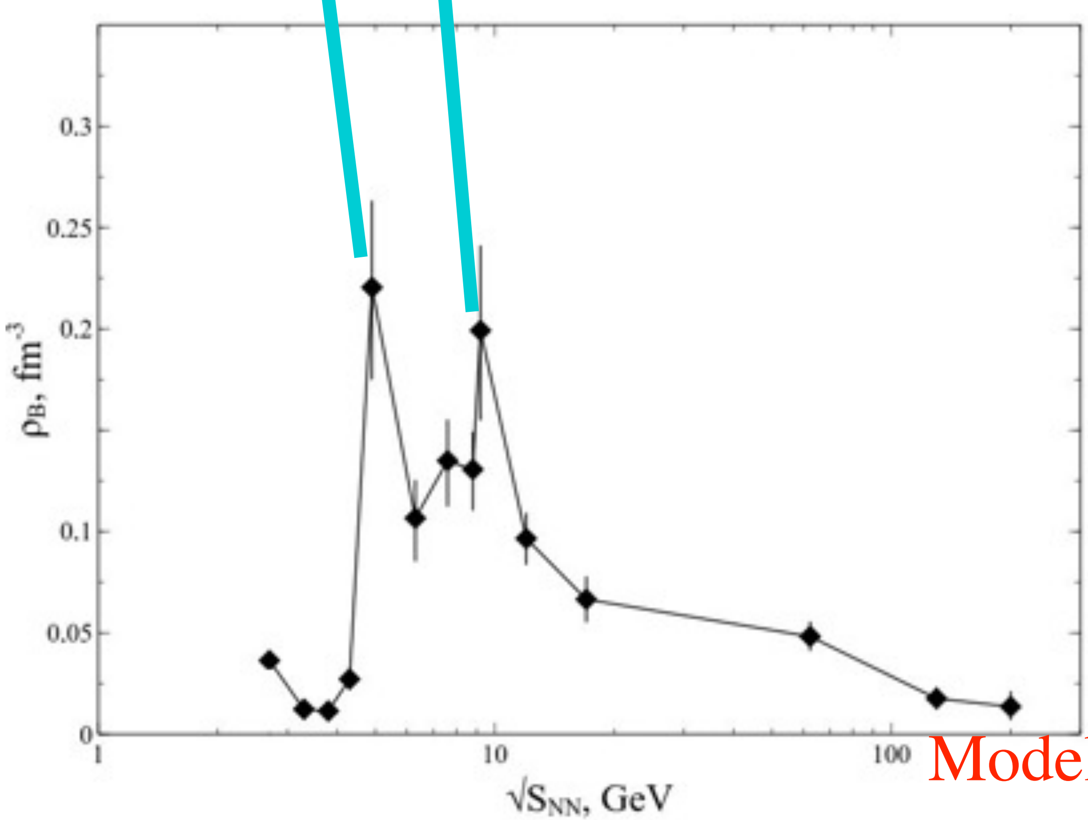
Thus, sharp peak of trace anomaly at c.m. energy 4.9 GeV evidences for mixed phase formation. But what is it?

Is second peak at c.m. energy 9.2 GeV due to another PT?

Related Peaks (2017)





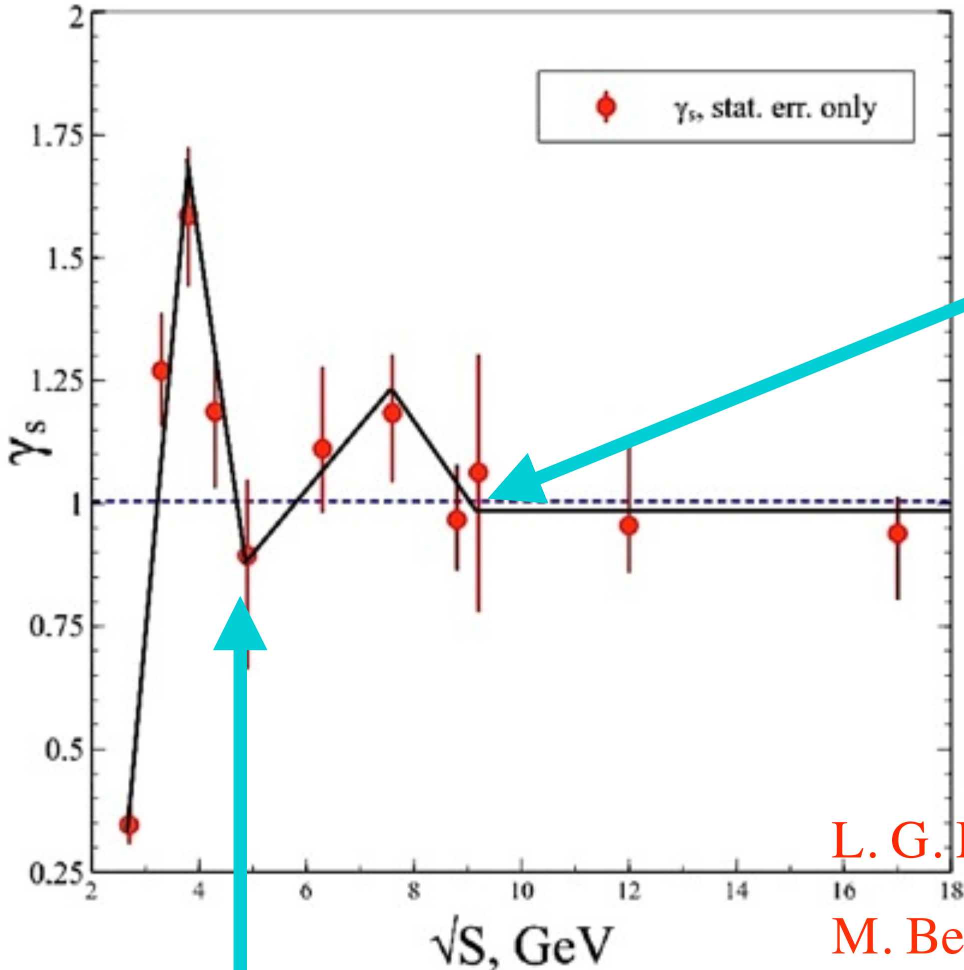


Trace anomaly peaks and baryonic density peaks are related to each other.

Can we relate them to γ_s irregularities?

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

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!

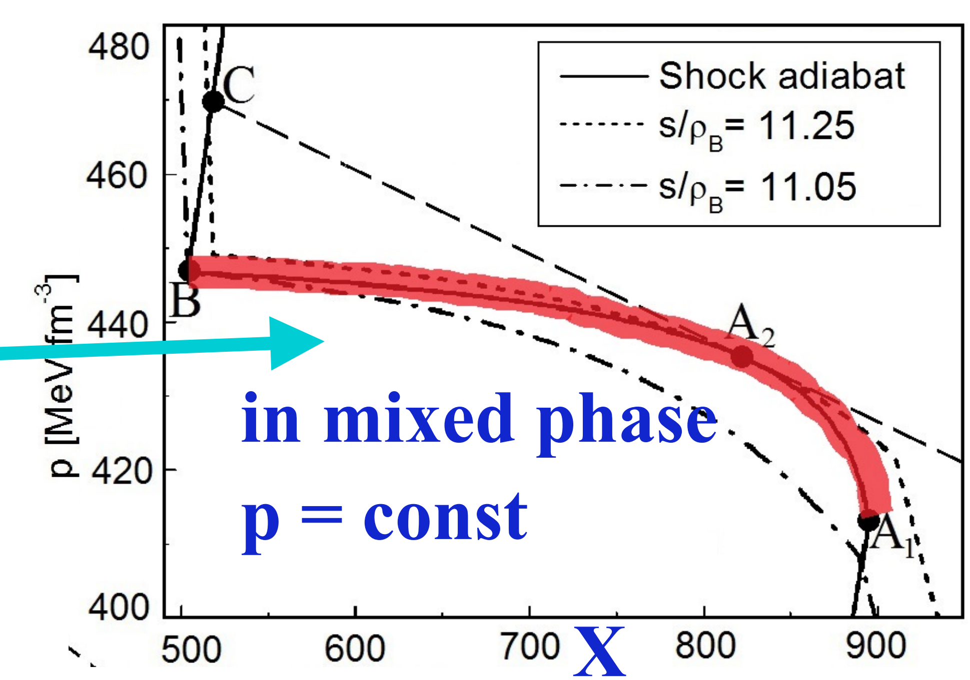
Hagedorn mass spectrum is a perfect thermostat and a perfect particle reservoir! => Hadrons born from such bags will be in a full equilibrium!

$$\frac{dN}{dM} \sim \exp\left[+M/T_H\right]$$

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 4.9 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!**

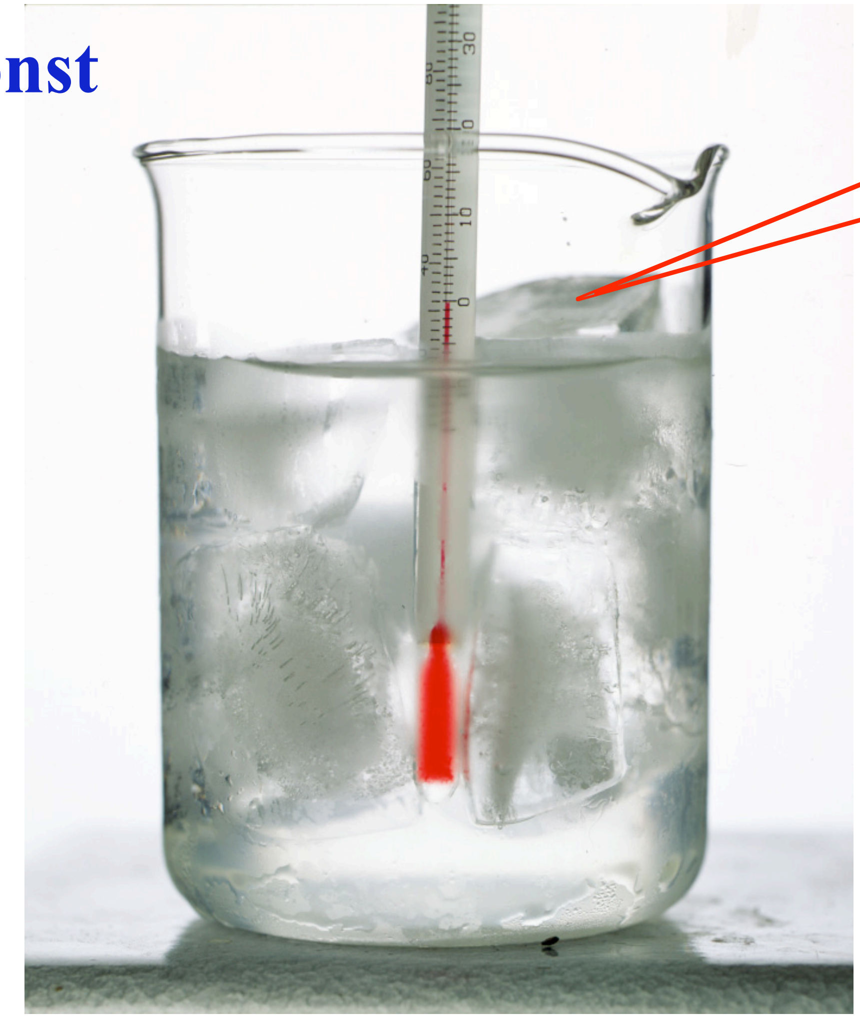
L. G. Moretto, K. A. B., J. B. Elliott, L. Phair, Europhys. Lett. 76, 402 (2006)

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



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

Besides Quasi-plateaus There Exist Additional Hints for 2 Phase Transitions

Our explanation: **K.A. Bugaev et al., Phys. Part. Nucl. Lett. 15 (2018)**

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 $\sqrt{s}$ > 8.8 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:

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 II

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

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

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

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

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

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

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

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

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 quarkyonic phase!?

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

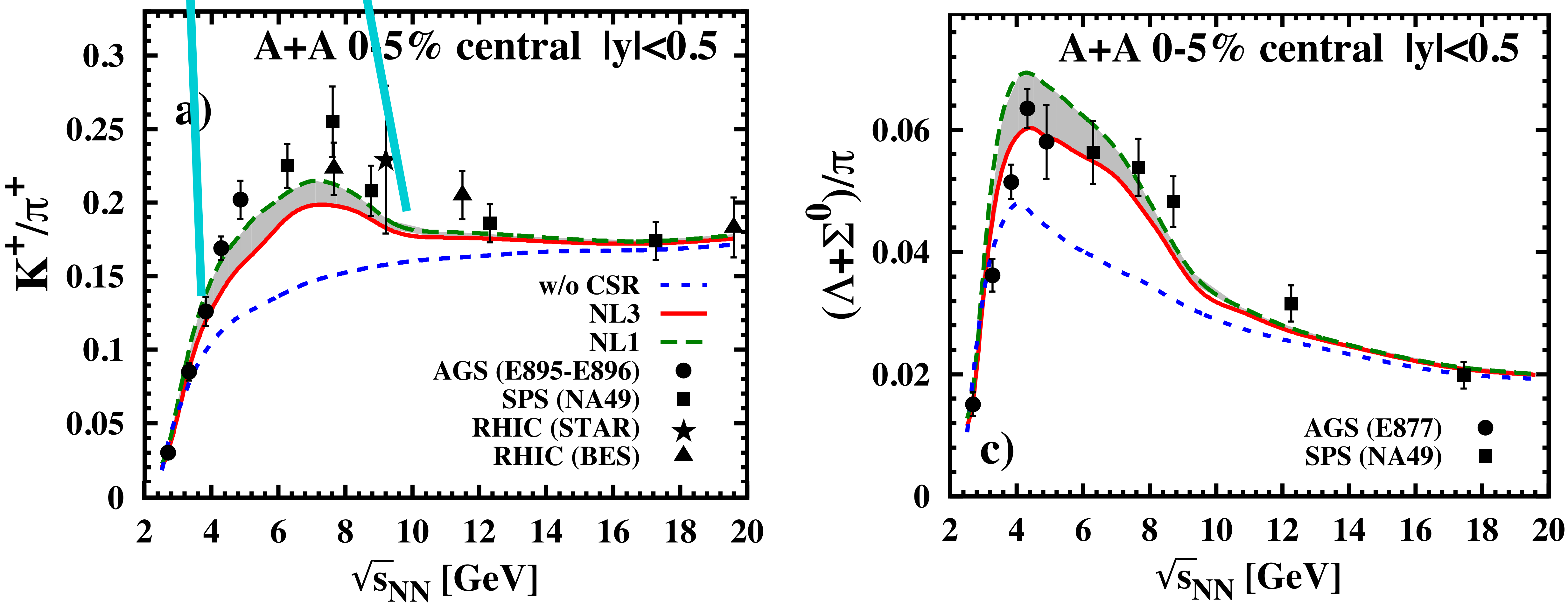
5. 1800 of massless dof may evidence about something else…

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).



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 28 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., 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!

ALICE Data on Snowballs in Hell: Is Tcfo of Nuclei Same as of Hadrons?

For all nuclei of A nucleons the hard-core radius is 0.365 $\sqrt[3]{A}$ fm

1. all loosely bound nuclei are frozen together with hadrons =>

$$T_{CFO} \simeq 153 \pm 7\text{MeV} \quad \Rightarrow \quad \chi^2/dof = (9.7+8.7)/(11+8-2) = 18.4/17 \simeq 1.08$$

2. all loosely bound nuclei are frozen separately from hadrons =>

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

Hadrons $T_{CFO} \simeq 150 \pm 7$ MeV

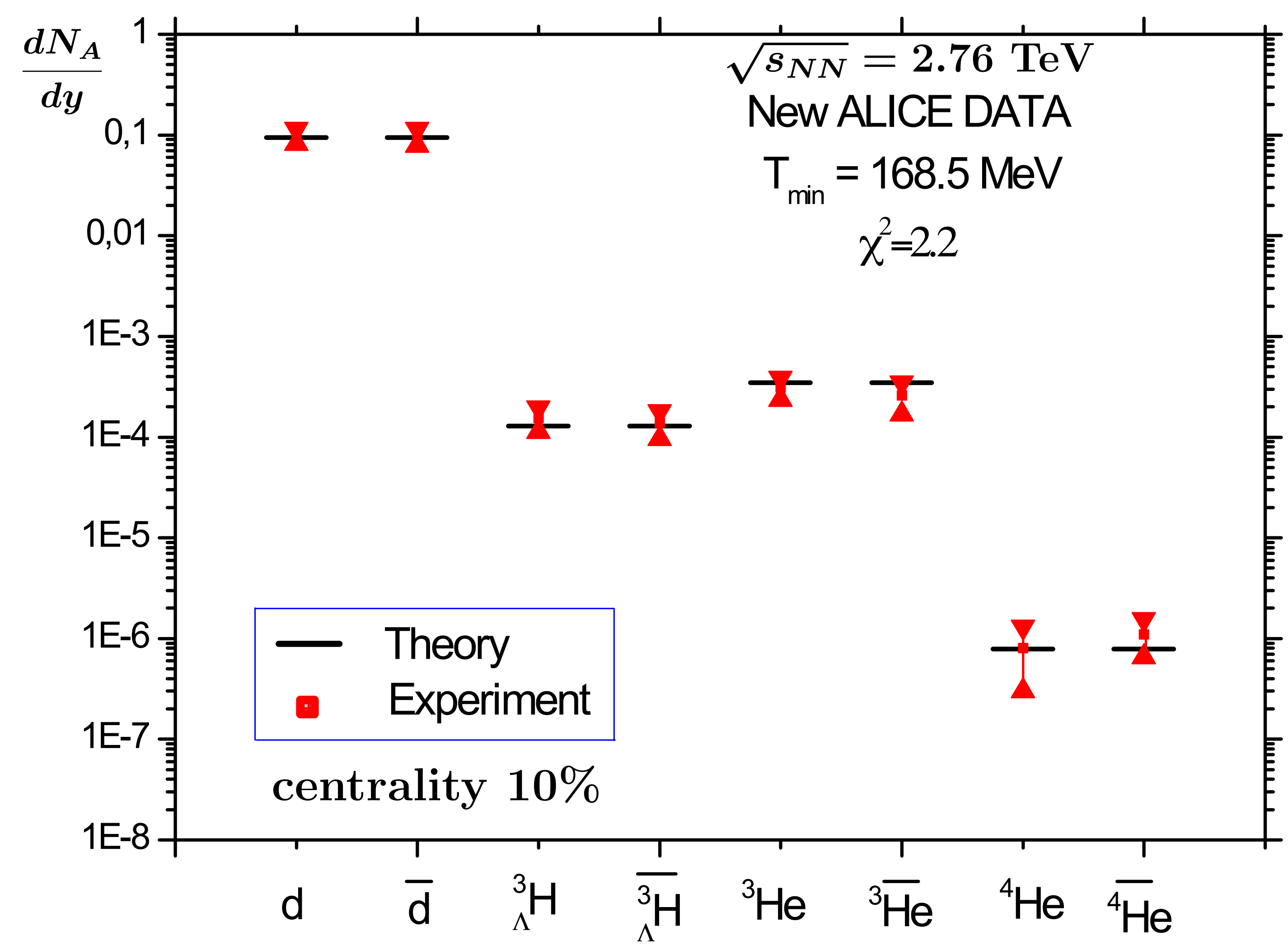
(anti)Nuclei $T_{CFO} \simeq 168.5 \pm 7$ MeV

$$\chi^2/dof = (9.1+2.2)/(11+8-3) = 11.3/16 \simeq 0.71$$

Remarkable improvement of the fit quality!

But why are the (anti)nuclei frozen at so high temperature?

KAB et al., arXiv:1812.02509v1 [hep-ph]



ALICE Data on Snowballs in Hell: Why Are They Thermalized?

Hagedorn mass spectrum of QGP bags $\frac{dN}{dM} \sim \exp\left[+M/T_H\right]$
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)

Moreover, the analysis of micro canonical partition function of a system containing of 1 Hagedorn bag and N Boltzmann particles shows that at the end of mass spectrum (where it terminates) the temperature depends on the mass of particle and the mass of QGP bag: a few heavier particles will be hotter than many light ones!

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

K. A. B., J. B. Elliott, L. G. Moretto and L. Phair, arXiv:hep-ph/0504011

Evidence for Chiral Symmetry Restoration?

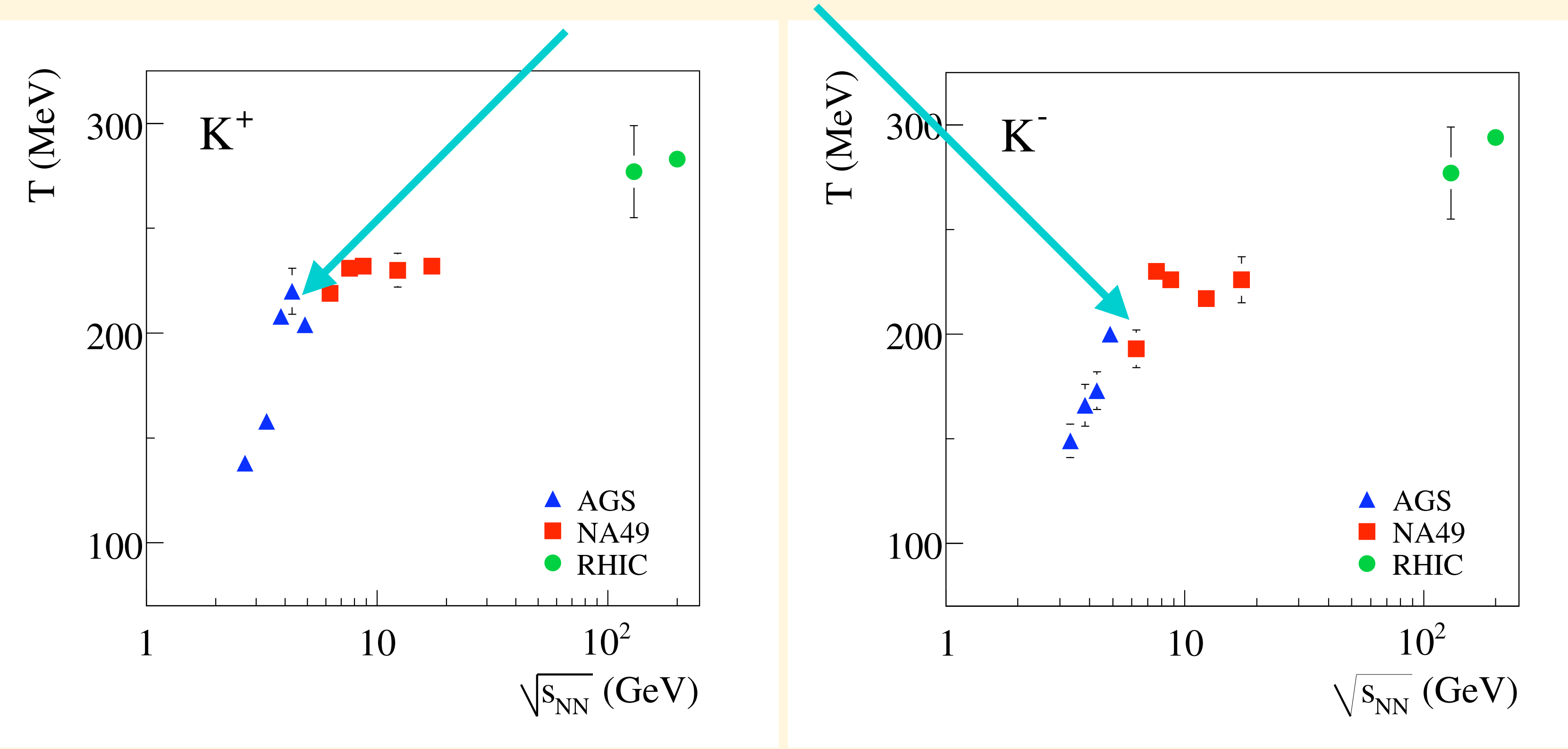
There are KINKs in apparent temperature of K+ and K- at 4.3-6.3 GeV

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!

So far Unobserved Signals

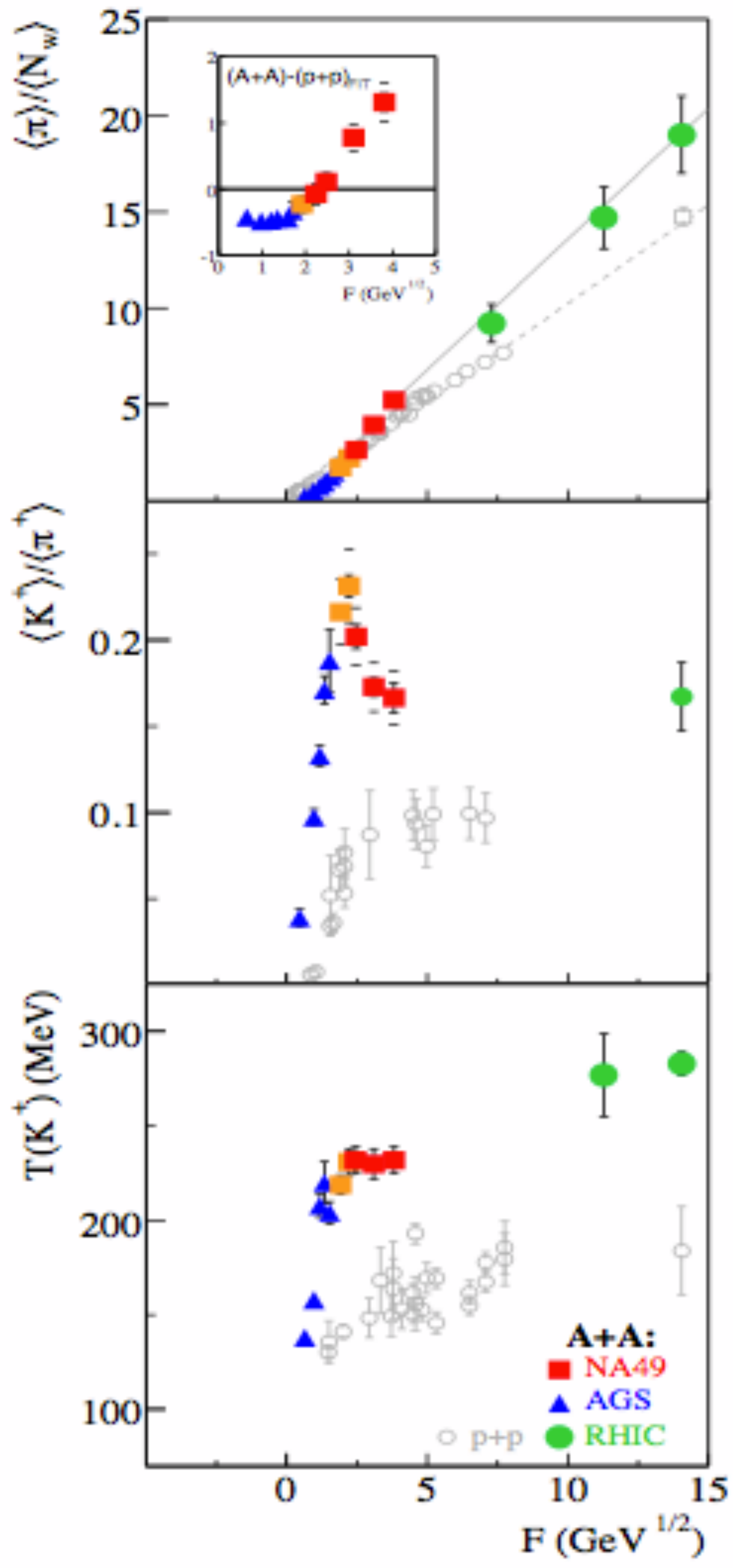
Several MOST PROMISING signals of the DECONFINEMENT phase transition were suggested in 80-th and 90-th to observe it:

real or virtual photons production;
p_T distribution of secondary hadrons;
strangeness enhancement;
J/ Ψ suppression...

So far, NONE of them was OBSERVED in a suggested way!

- The first reason is that in the presence of quarks the deconfinement PT HAS NO well defined ORDER PARAMETER! Thus, we have to study what is not well defined.
- The second reason is due to TREMENDOUS COMPLEXITY of the phenomena to be modeled and understood!

Popular NA49 "Signals"



Kink in $\frac{\langle \pi \rangle}{\langle N_w \rangle} \approx g^{\frac{1}{4}} F$ shows that the number of d.o.f. g changes at about $E_{lab} = 30$ GeV

F is Fermi variable ~ s^1/4

It was suggested in M. Gazdzicki, Z. Phys. C 66 (1995).

Horn in $\frac{\langle K^+ \rangle}{\langle \pi^+ \rangle}$ ratio shows that elementary d.o.f. of strangeness are changing from K$^{\pm}$ to s_q at about $E_{lab} = 30$ GeV

Claim that onset of deconfinement is at c.m. energy 7.6 GeV

It was suggested in M. Gazdzicki and M.I. Gorenstein, Acta Phys. Polon. B 30 (1999)

Step in K$^{\pm}$ inverse slopes shows that $\approx F$ independent initial pressure develops at about $E_{lab} = 30$ GeV

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

analog of caloric curve!

I suggested to write that it is a mixed phase at c.m. energy 7.6GeV

Problems of Statistical Model of Early Stage

It «predicted Strangeness Horn», but

M. Gazdzicki and M.I. Gorenstein, Acta Phys. Polon. B 30 (1999)

1. it has phase transition at temperatures above 200 MeV

this contradicts to lattice QCD at 0 baryonic density

2. the high density phase has wrong number of degrees of freedom compared to QCD (too few!)

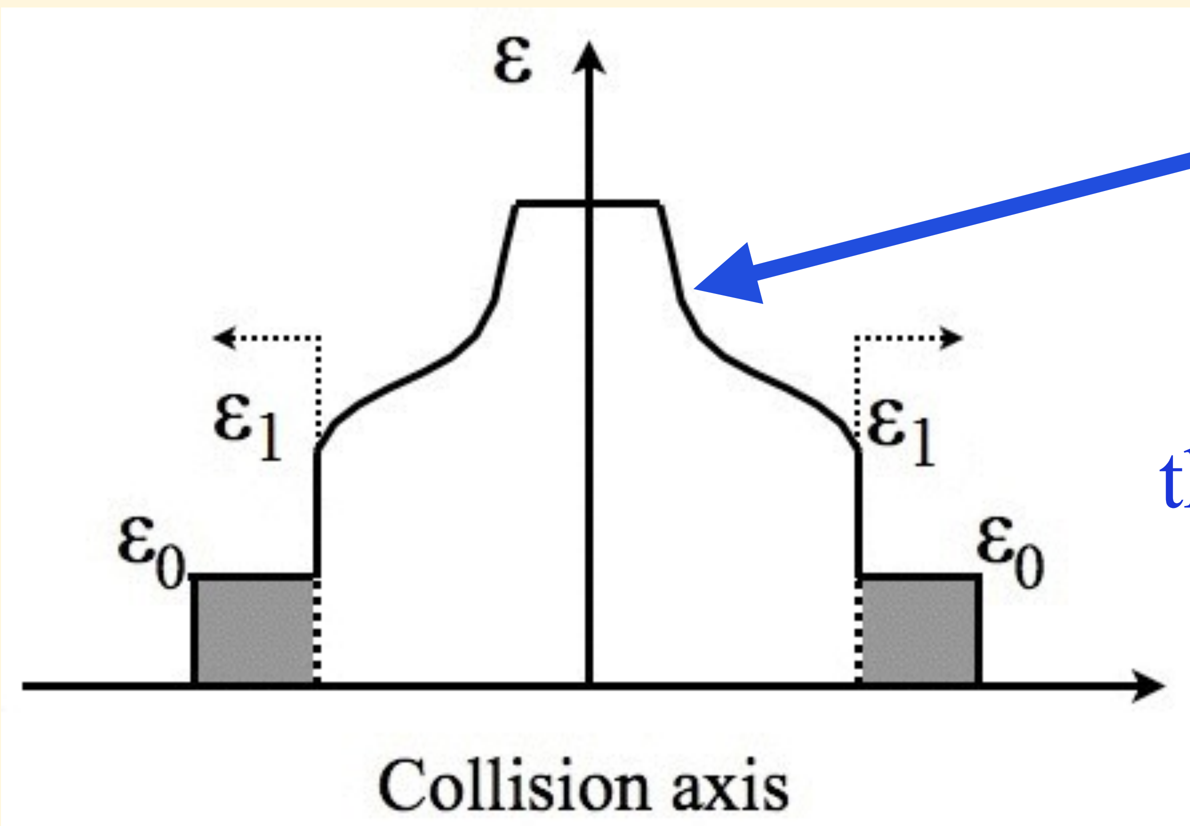
=> from two false statements one get deduce the true one

Nevertheless, due to inability to reproduce the Strangeness Horn many researchers believed that this is a signal of some non-hadronic physics

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!

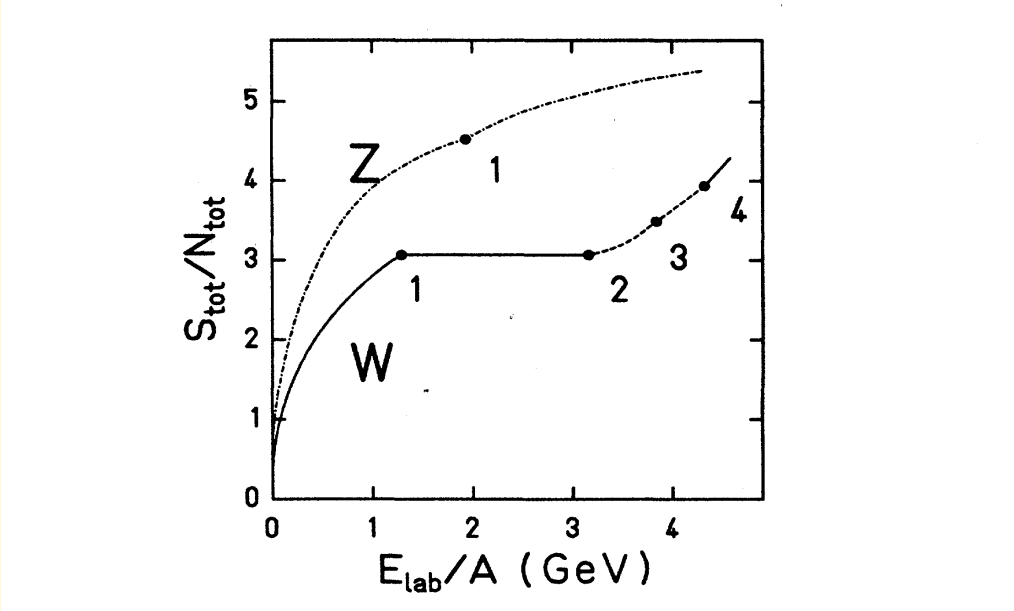


FIG. 9. The entropy per baryon as a function of the bombarding energy per nucleon of the colliding nuclei for models W and Z. The points 1, 2, 3, 4 on curve W correspond to those on the generalized adiabatic as displayed in Fig. 7. The point 1 on curve Z marks the boundary to the mixed phase.

Remarkably

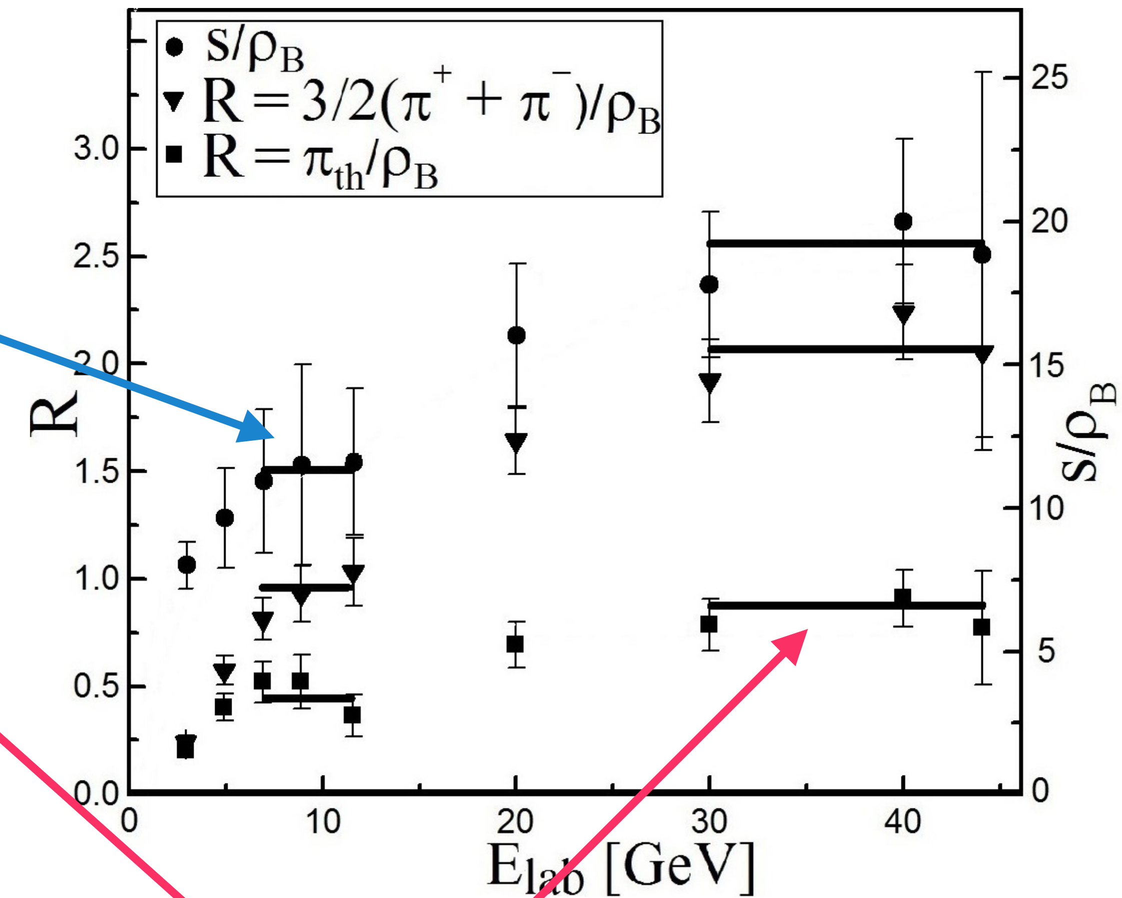
Z model has stable RHT adiabat,
which leads to quasi plateau!

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

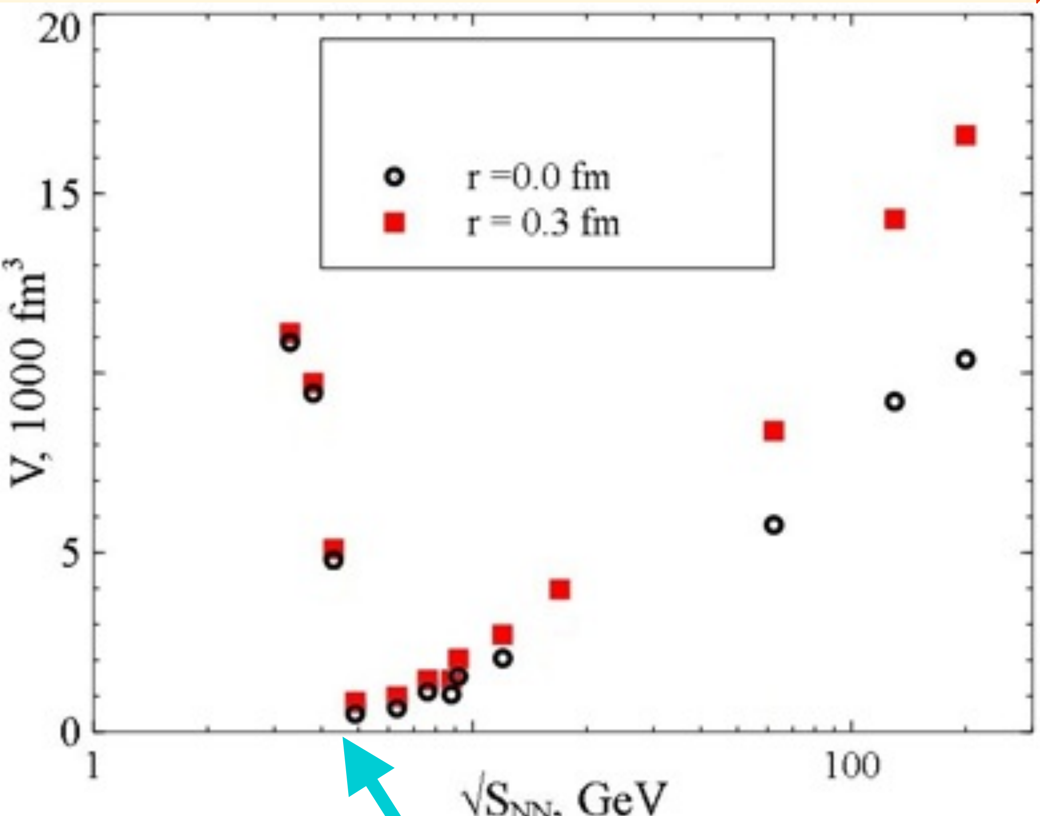


Other Minima at AGS Energies

min V at ChFO

SAME energy!

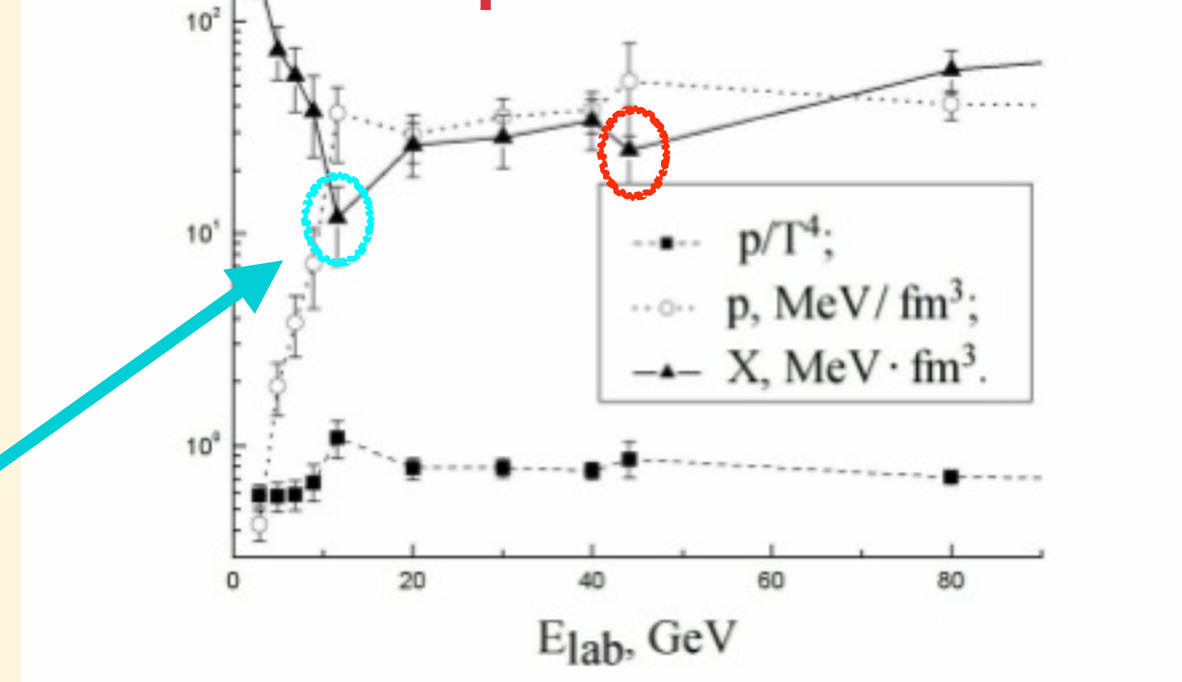
min X at ChFO



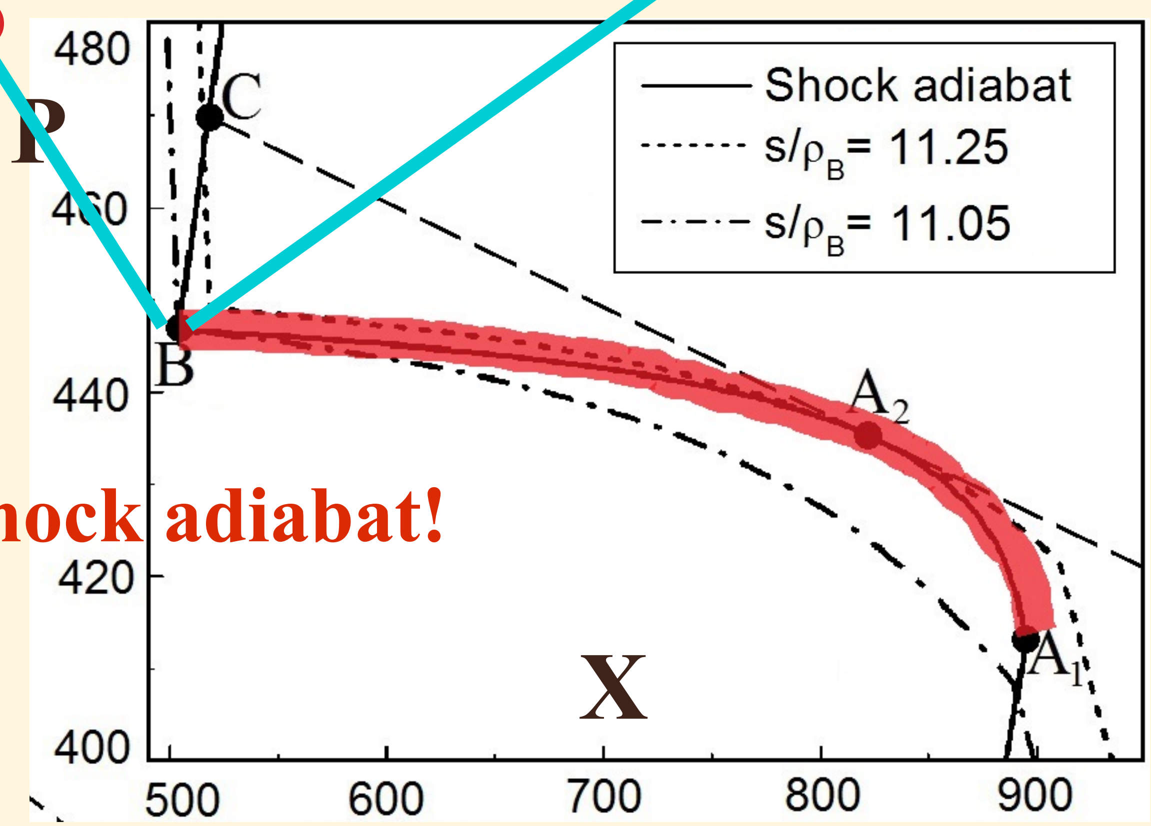
D.R. Oliinychenko, K.A. Bugaev and A.S. Sorin, Ukr. J. Phys. 58, (2013)

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!

Effective Number of Degrees of Freedom I

One look at this EoS:

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

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

In our fit of entropy per baryon along the shock adiabat we used the QGP EoS

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

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

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

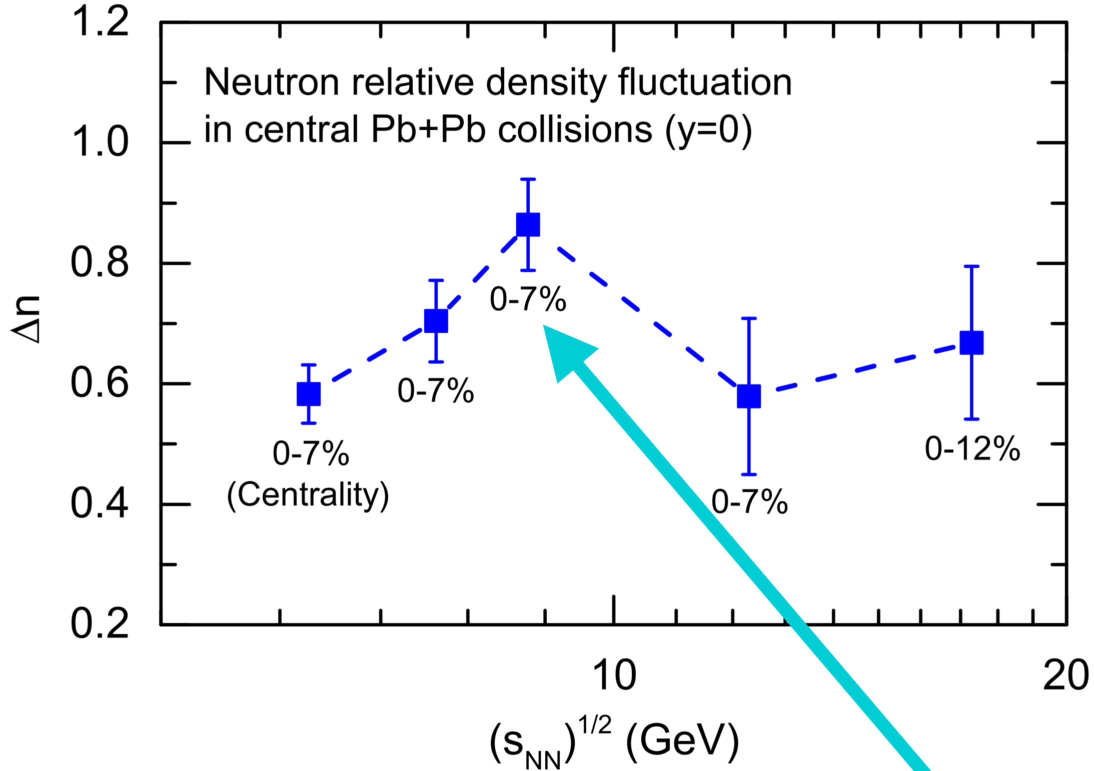
$$A_4 \simeq 1.001 \cdot 10^{-9}\ \mathrm{MeV}^{-3} \mathrm{fm}^{-3}$$

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

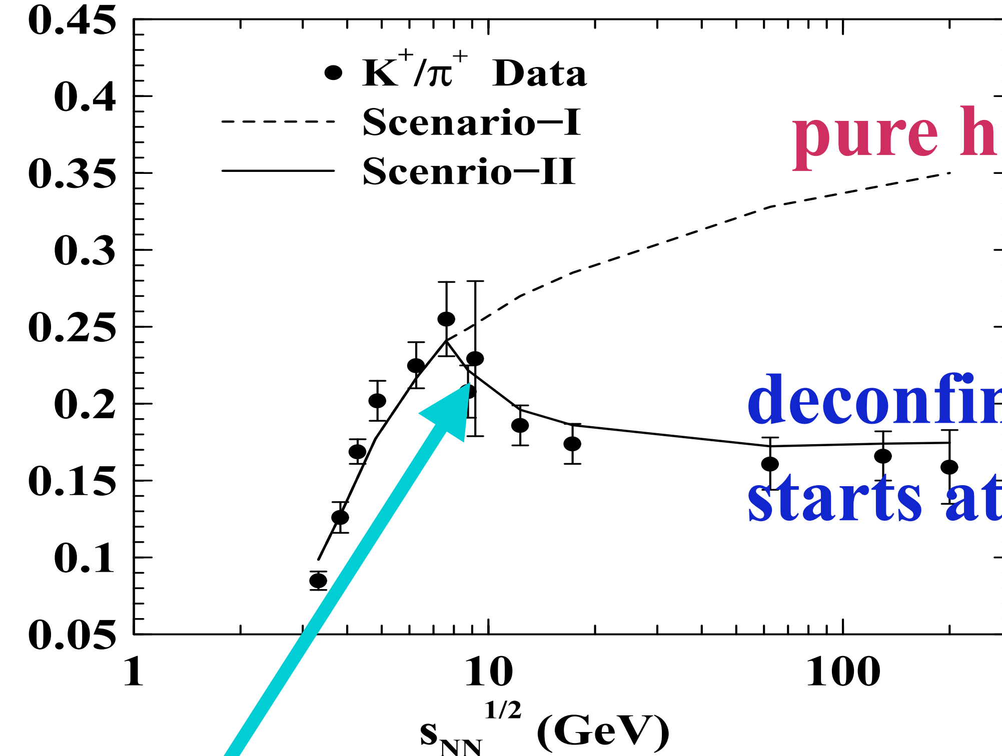
K.A. Bugaev et al., Eur. Phys. J. A (2016) 52: 175

Onset of Deconfinement in Other Models

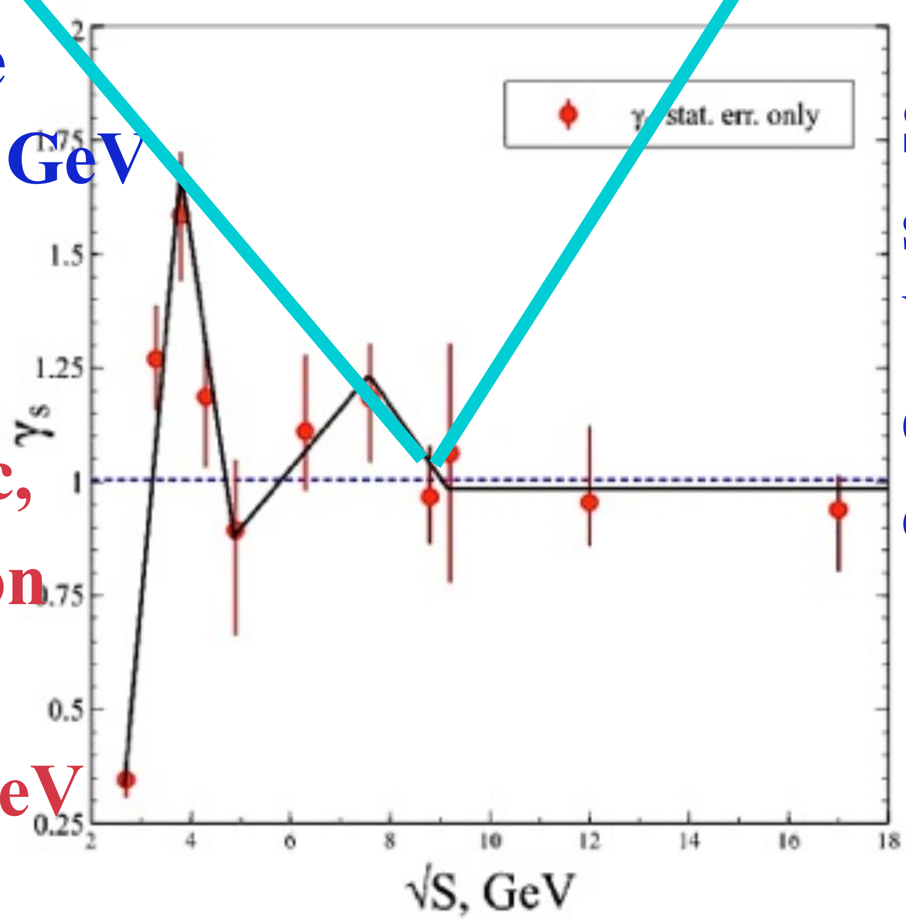
Che Ming Ko et al., arXiv 1702.07620 [nucl-th]]



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



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