Thermodynamically Anomalous Properties and Possible New Signals of Mixed Phase Formation in Central Nuclear Collisions

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

Bogolyubov ITP, Kiev, Ukraine

E. Nikonov

Laboratory for Information Technologies, JINR, Dubna, Russia

D. H. Rischke

ITP, J.W. Goethe University, Frankfurt, Germany

I. Mishustin and L. Satarov

FIAS, J.W. Goethe University, Frankfurt, Germany

GSI, July 25, 2016

Outline

1. Motivation

2. Problems of single component Hadron Resonance Gas Models

3. Some results of multicomponent Hadron Resonance Gas Models

4. Novel and Old Irregularities at chemical freeze out

5. Shock adiabat model of A+A collisions

6. Meta-analysis of Hadronic and QGP event generators

7. Conclusions

Experiments on A+A Collisions

AGS (BNL) up to 4.9 GeV
SPS (CERN) 6.1 - 17.1 GeV
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)

Present Status

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

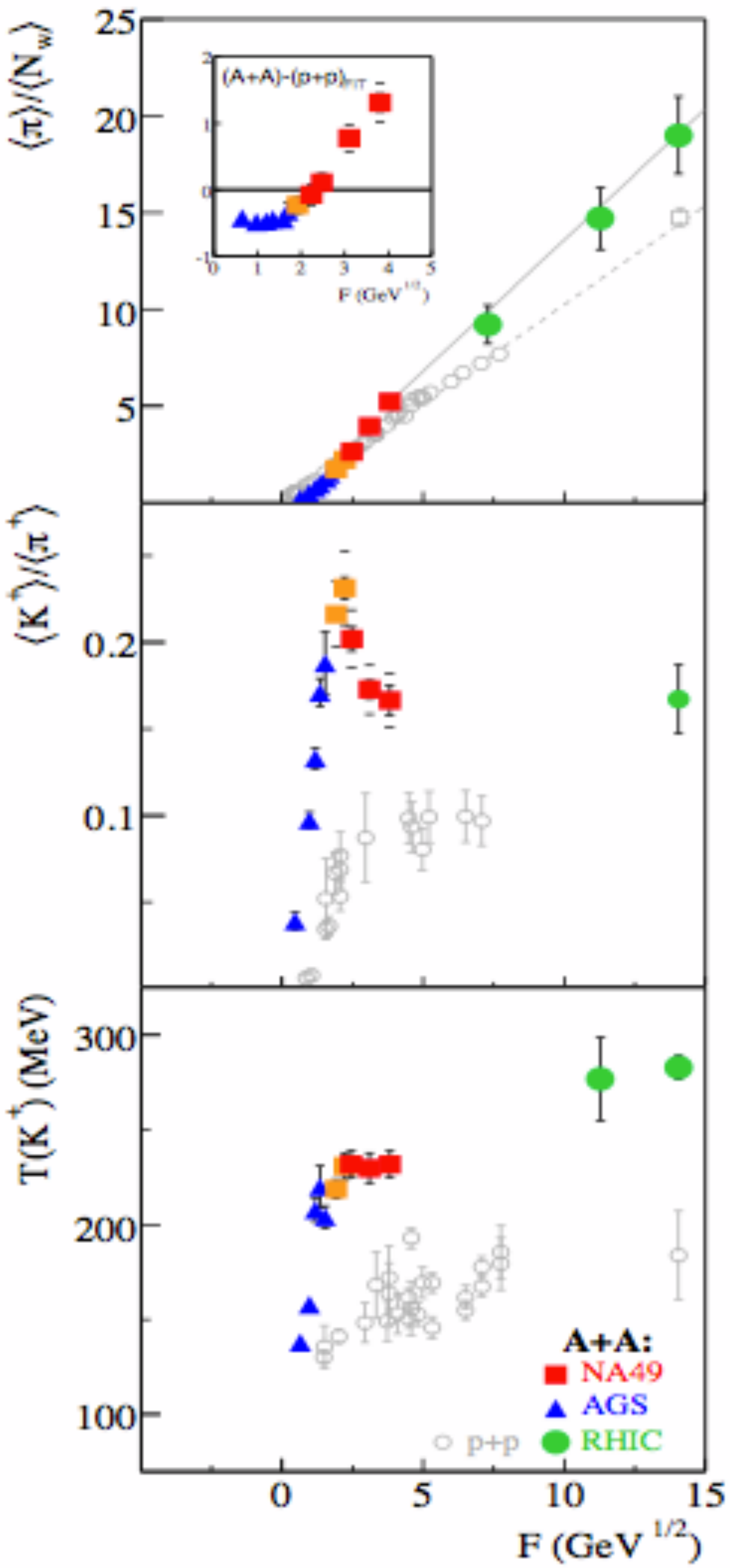
However, up to now we do not know:

1. whether deconfinement is a phase transition

2. where does the onset of deconfinement begin

In order to answer 2-nd question we need a very accurate tool to analyze data.

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

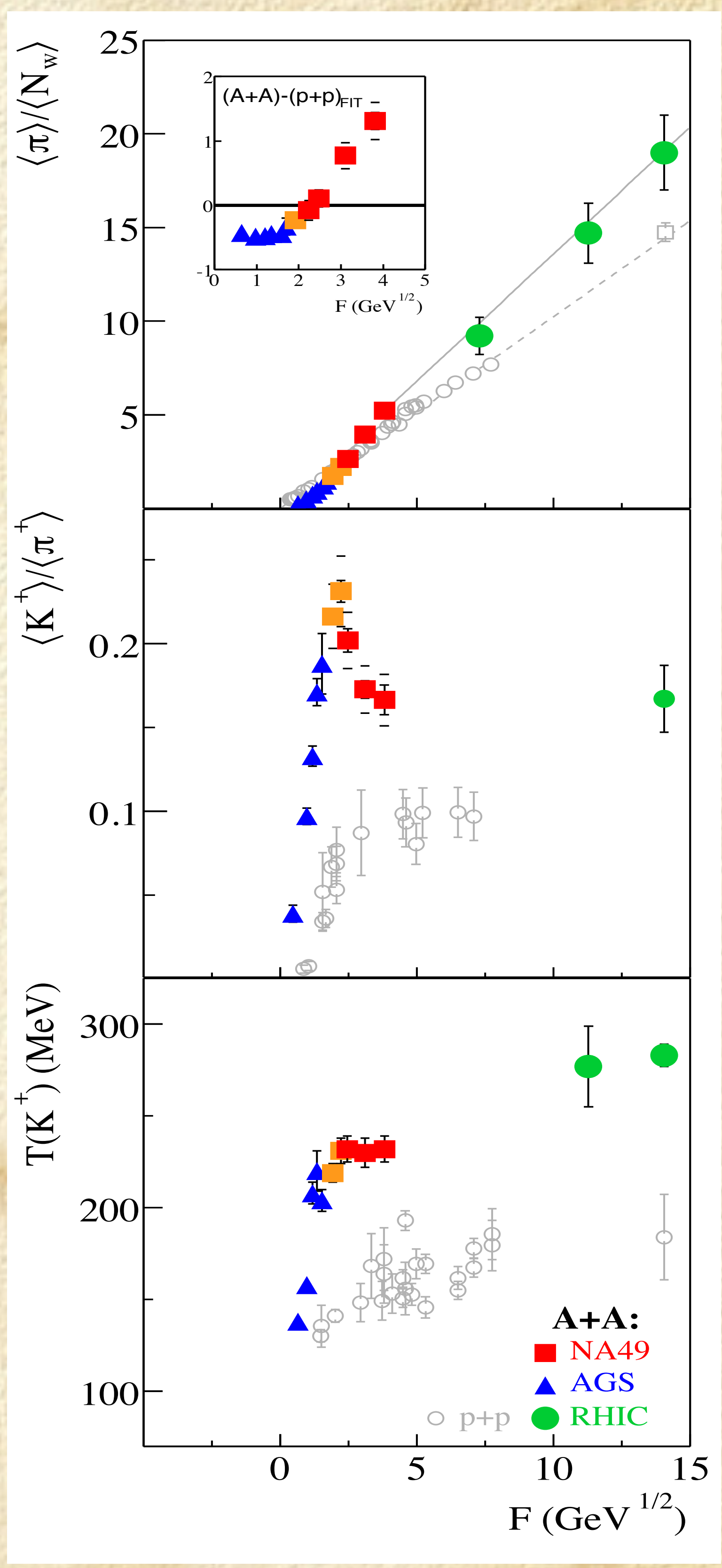
Claim that onset of deconfinement is at c.m. energy 7.6 GeV

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)

NA49 "Signals"= Irregularities



I. There is NO a single model which can simultaneously describe these «signals»!

II. These «signals» cannot be reproduced by existing hydrodynamic and hydro-cascade models with deconfinement phase transition.

Therefore, their relation to deconfinement is unclear!

Hence, these «signals» are irregularities which require an explanation!

Furthermore, it seems that there is also something wrong with our EOS!

If 7.6 GeV Is Not Onset, Then Where Is It?

30 years experience tells, that it is not difficult to invent a signal of QGP formation.

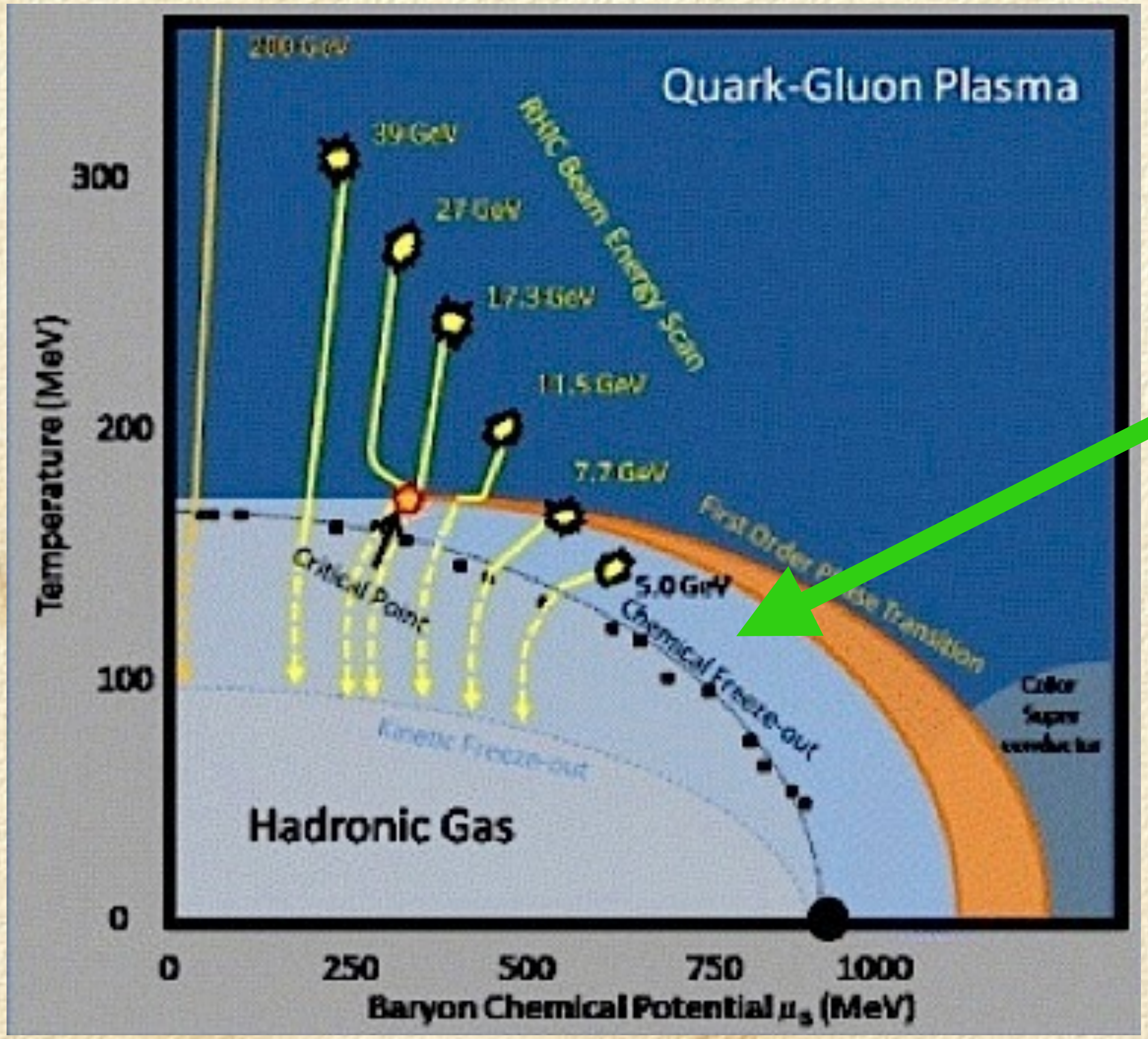
The most difficult part is to justify that it is related to phase transition.

In order to make such relations 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.

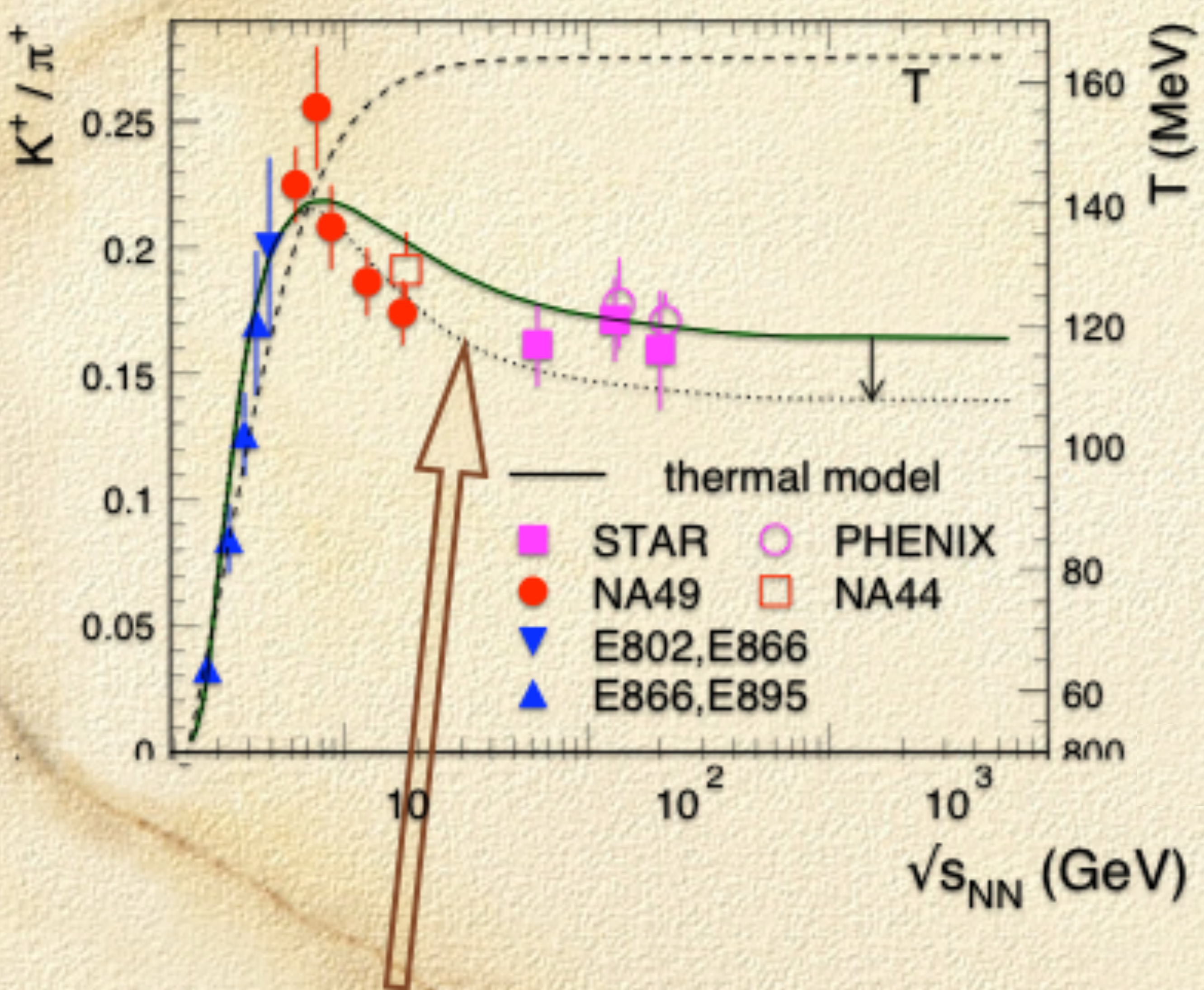
Horns Description in 1-component HRG

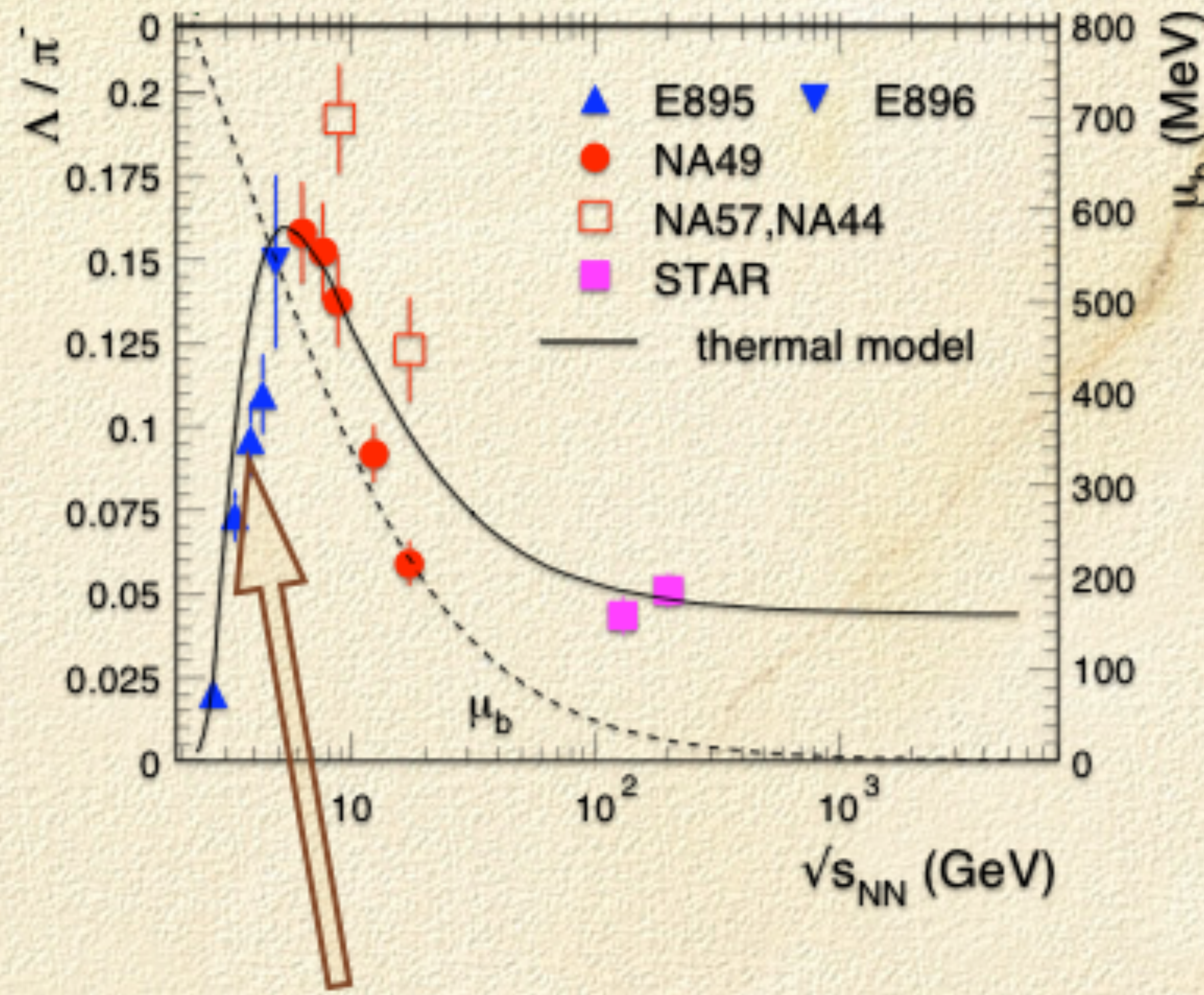
Too slow decrease after maximum!

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 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

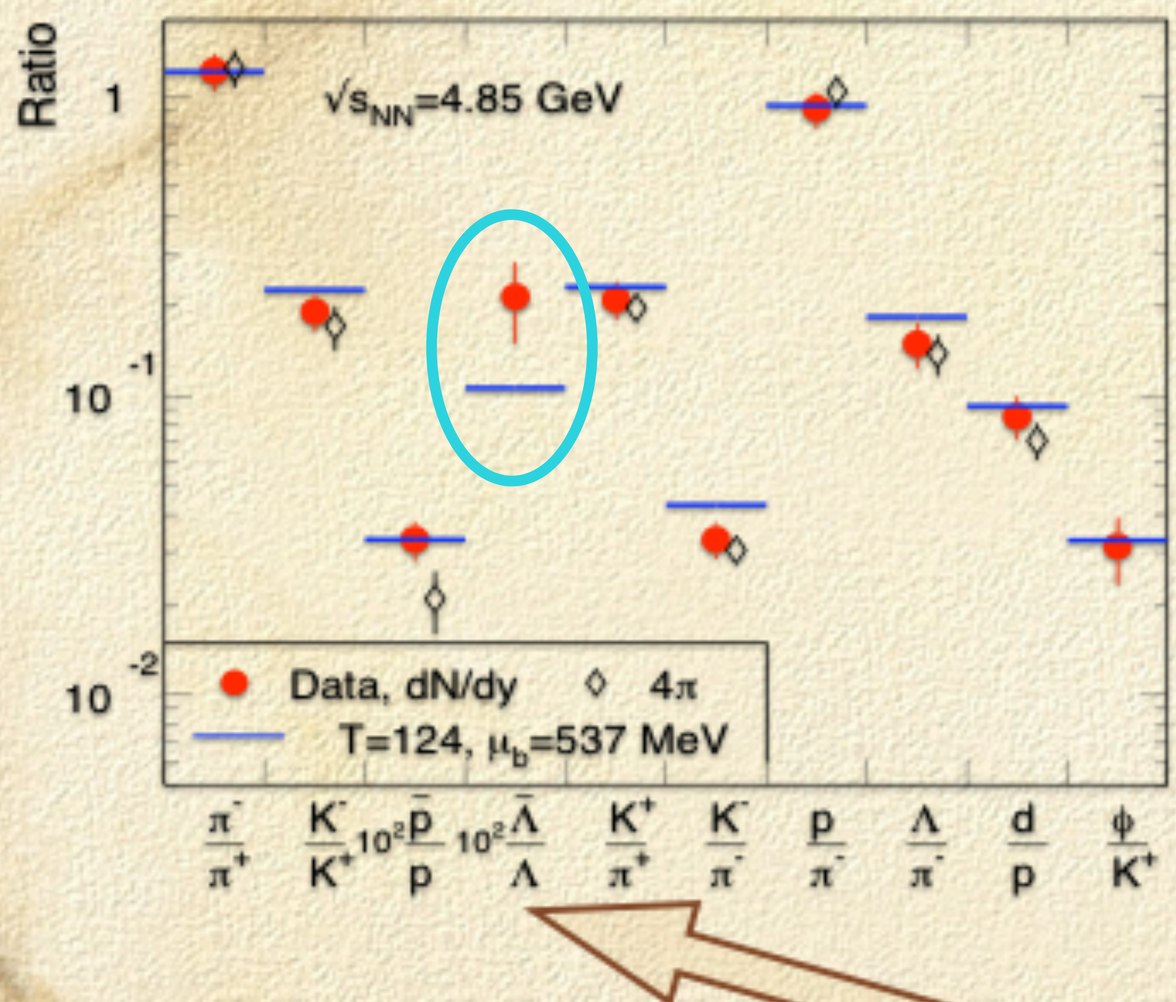
# of local fit parameters cannot be larger than 4 (for all energies) or larger than 5 (for energies above 2.7 GeV)

# 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

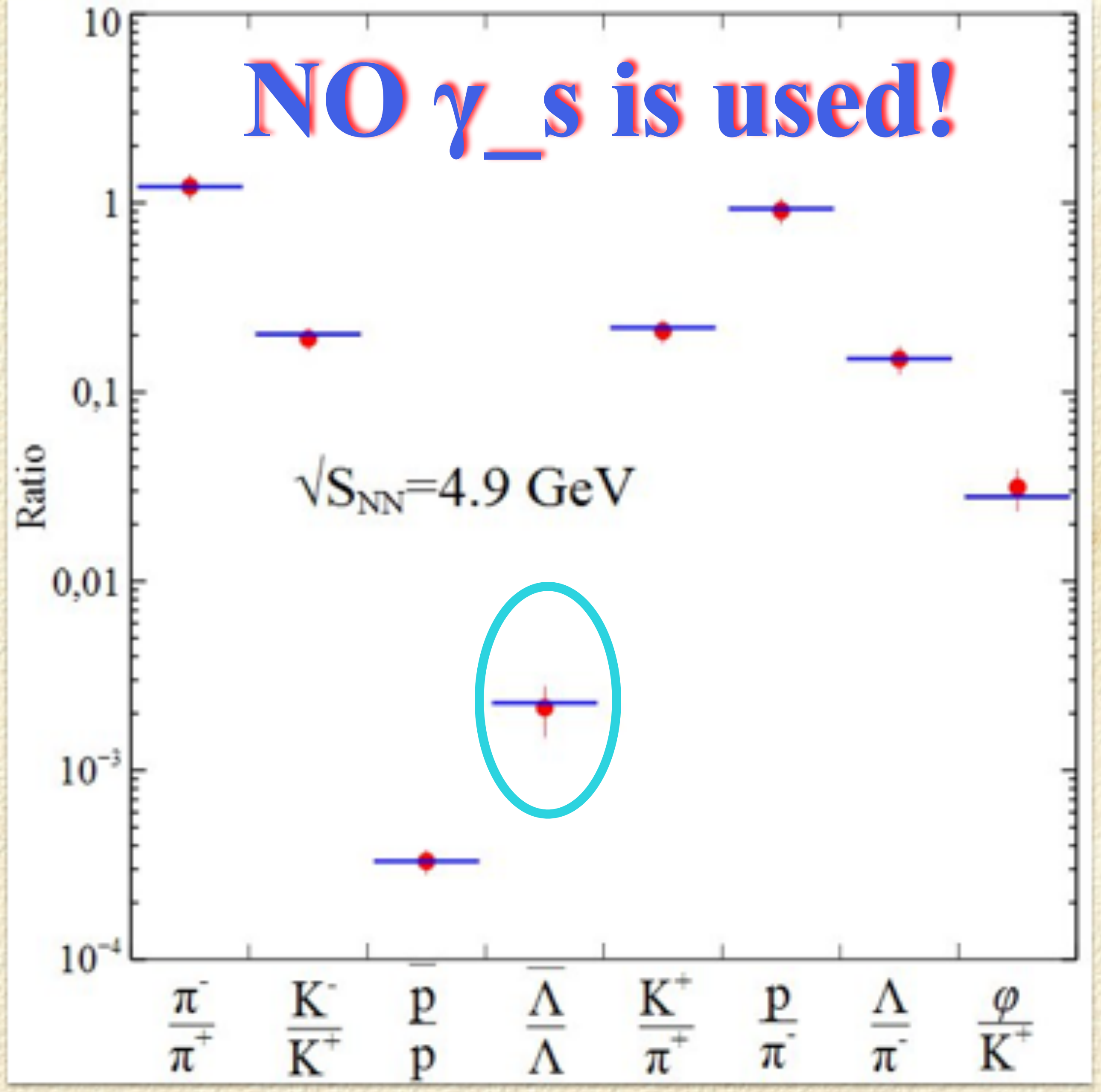
Results for Ratios (AGS)



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

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

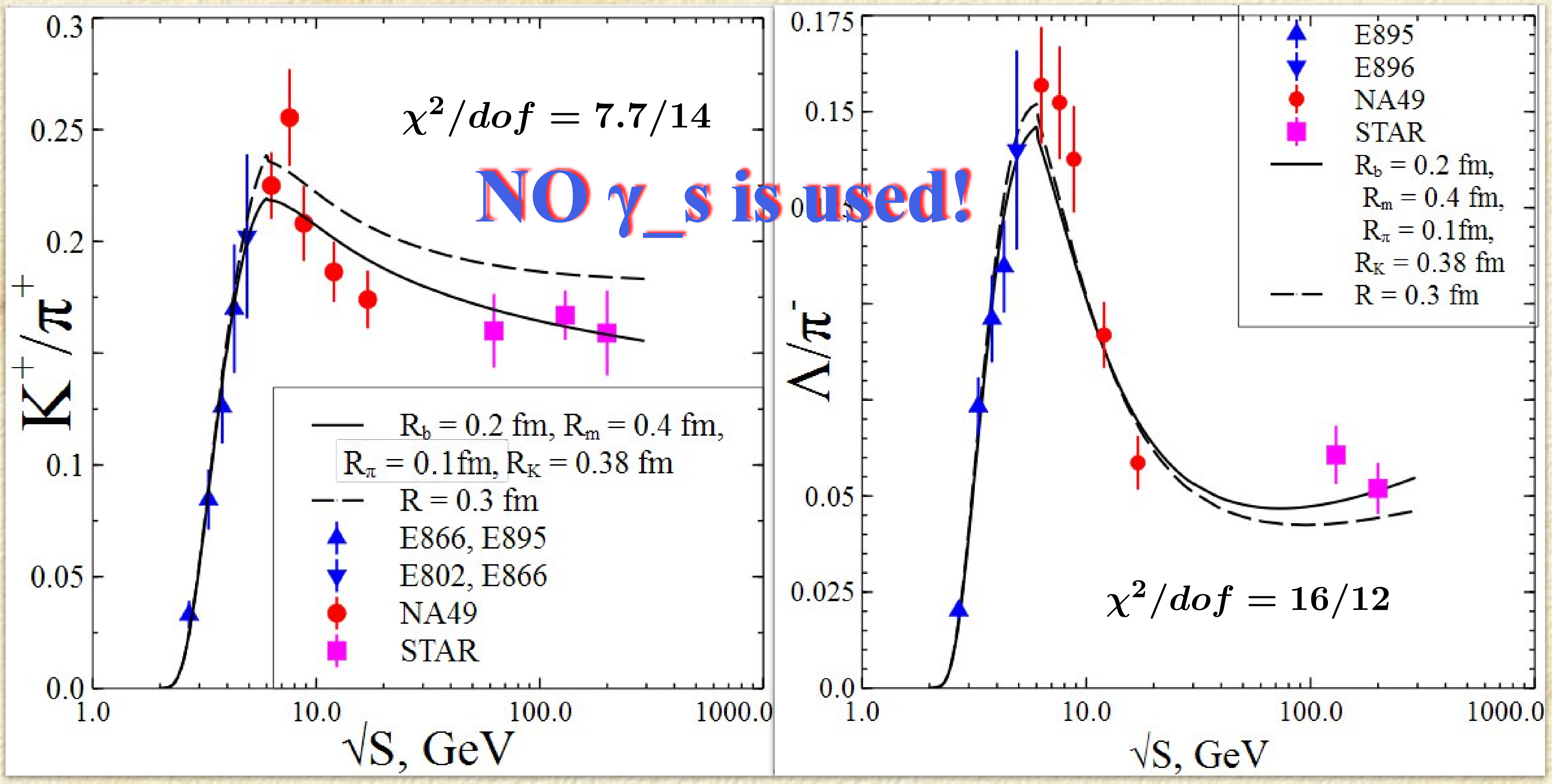
There is NO anti Lambda problem here and all ratios are well described!



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

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

Description of Horns at SPS



Best global fit of all ratios gives R_pi=0.1 fm, R_K =0.38 fm,

χ^2/dof =1.16 for fixed: R_baryons =0.2 fm, R_mesons = 0.4 fm

Note that Lambda and other hyperons can be described better!

K. A. Bugaev, D. R. Oliinychenko, A. S. Sorin and G. M. Zinovjev, Simple Solution to the Strangeness Horn Description Puzzle, 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**

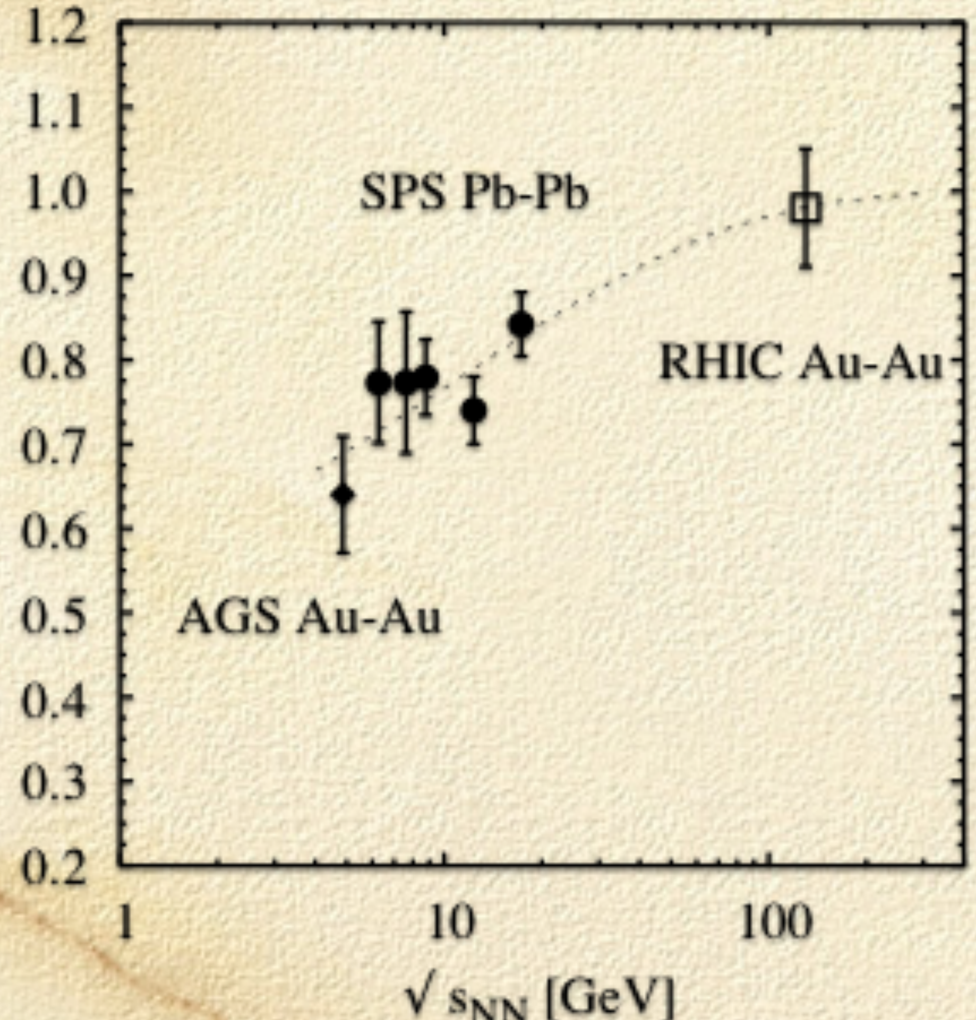
F. Becattini & Co found that γ_S **factor is** < 1

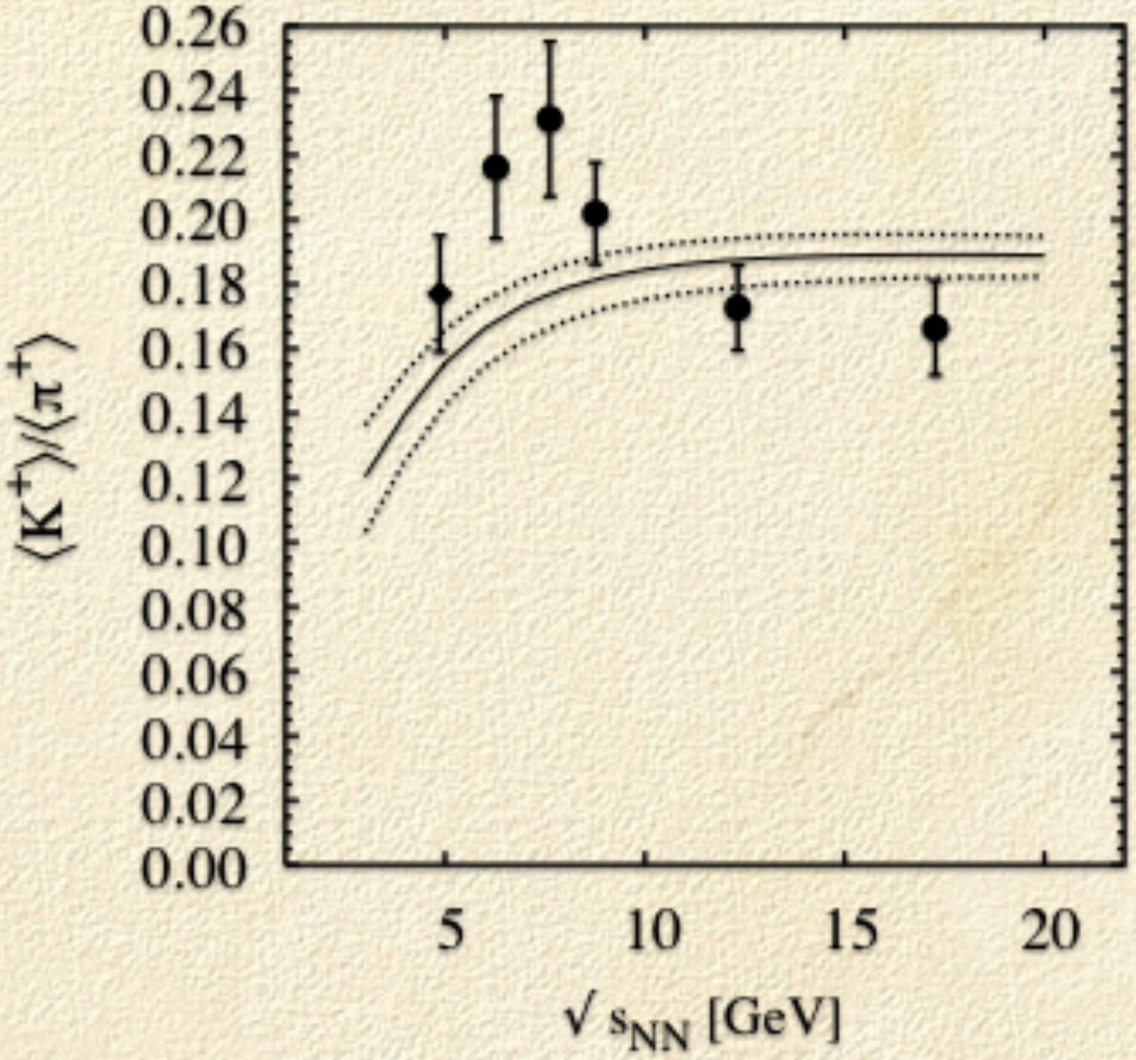
Systematics of Strangeness Suppression

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



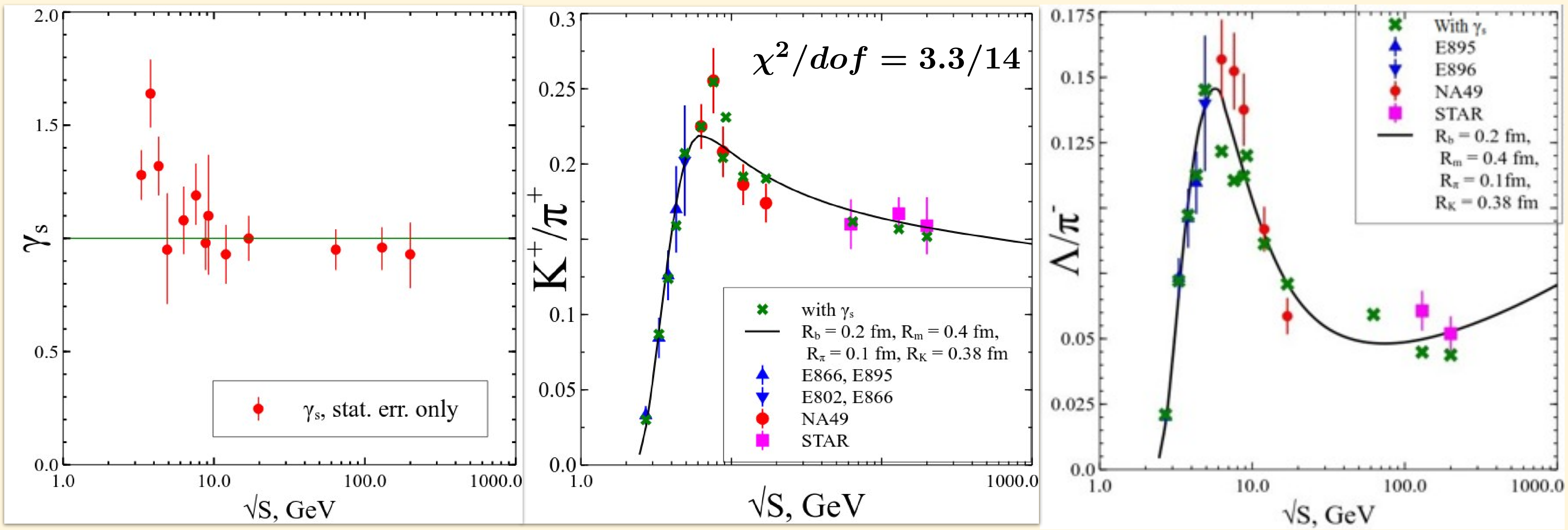


Single component model F. Becattini, J. Manninen and M. Gazdzicki, PRC 73 (2006) 044905

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

Our Results on Strangeness Enhancement in 2013

High quality description of hadron multiplicities requires T, μ_B, μ_{I3} and γ_S **factor**



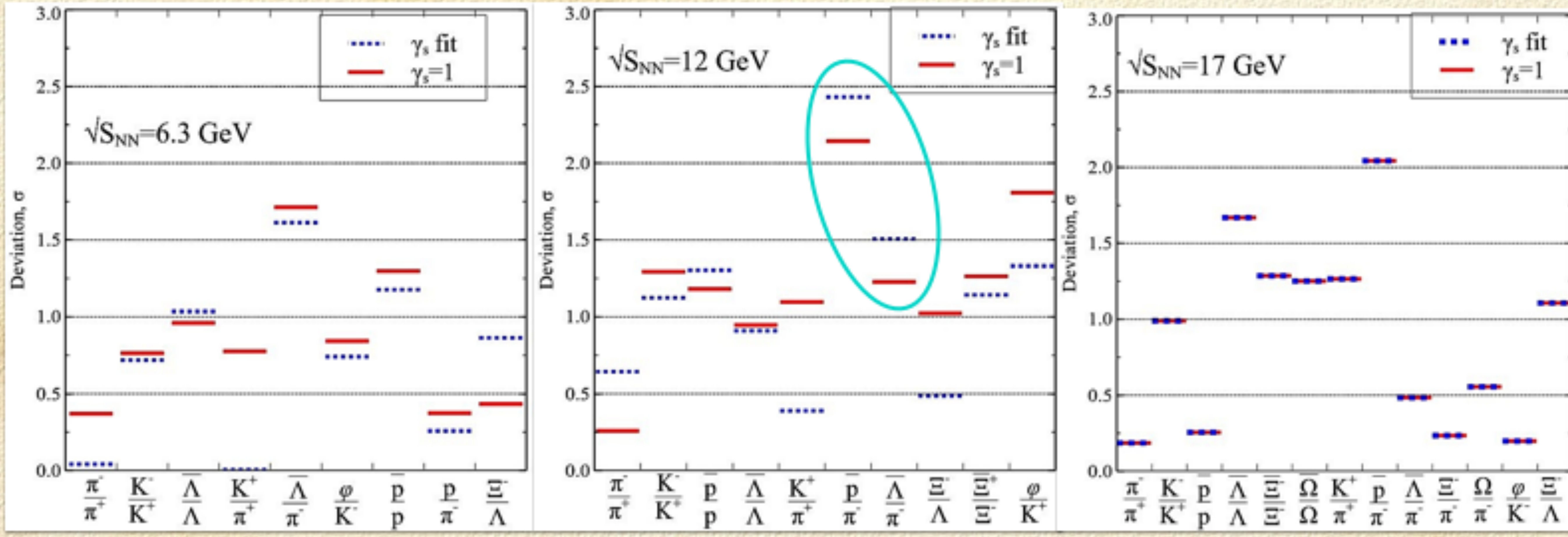
χ^2/dof =1.15 for 111 ratios measured for c.m. energies 2.7--200 GeV

K.A. Bugaev, D. R. Oliinychenko, J. Cleymans, A.I. Ivanytskyi, I.N. Mishustin, E.G. Nikonov and V.V. Sagun, Europhys. Lett. 104, 22002, (2013) p.1-6

Strangeness enhancement exists where we do not expect deconfinement!

Solving problem with Kaons leads to (anti)Λ selective suppression!

Particle Yield Ratios

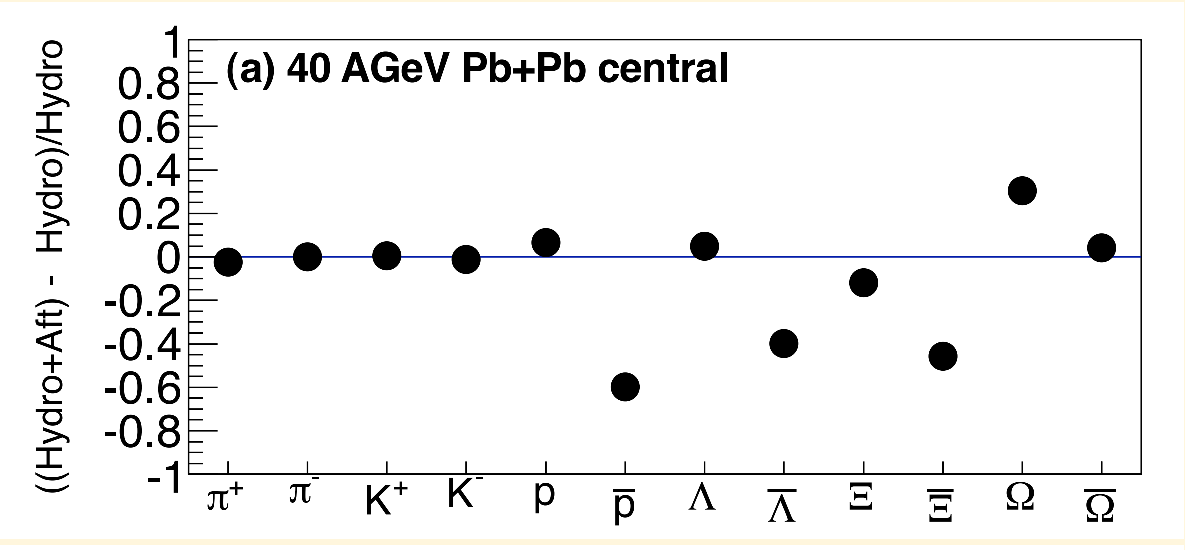


1. Some ratios are improved while some are not
2. At energies < 5 GeV and at 17 GeV there are almost no improvements
3. At low energies there are local minima at $\gamma_s < 1$!

But we took the deepest ones! => Becattini et al took the wrong one!

4. Many wrong results are based on Becattini et al work.

Solutions of (anti)Λ selective Suppression



F. Becattini et al., Phys.Rev. C85 (2012) 044921

R. Stock idea:
Use these deviations from UrQMD as new suppression factor!

Our solution:

1. Introduce Hard core radius for (anti)Λ hyperons

2. Refit globally all 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

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

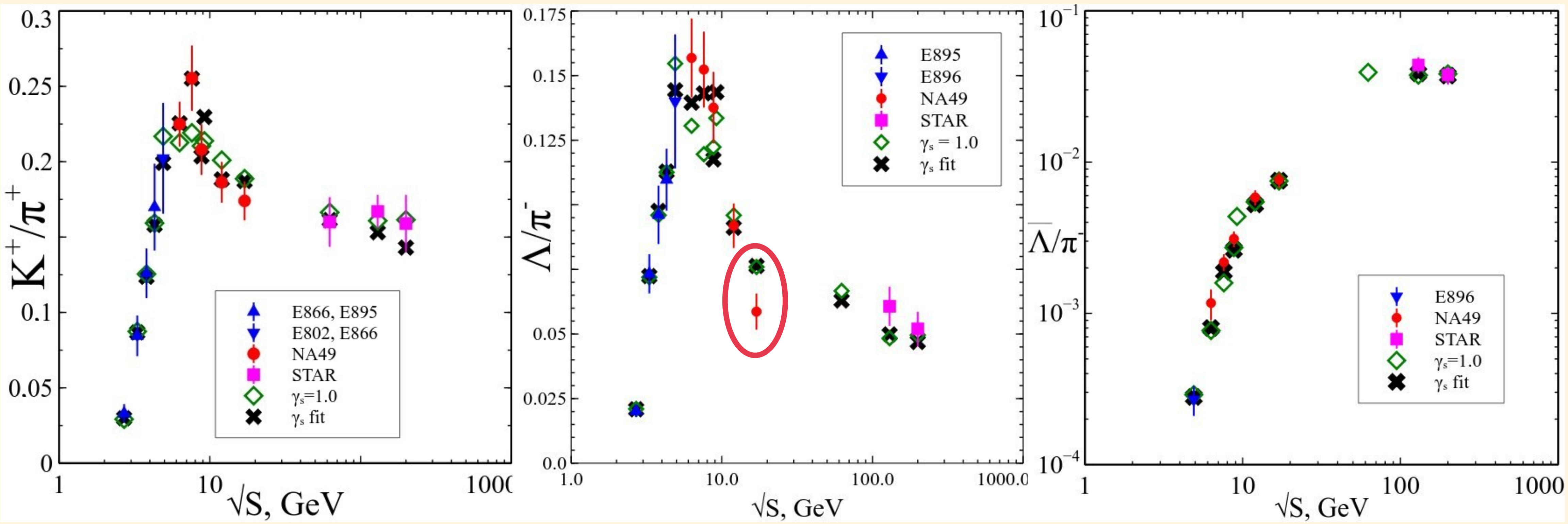
V. V. Sagun, D. R. Oliinychenko, K. A. Bugaev, J. Cleymans, A. I. Ivanytskyi, I. N. Mishustin and E. G. Nikonov, **Ukr. J. Phys.** 59, No 11, 1043-1050 (2014)

Strangeness Horn and Λ Horn in 2014

With new radii and γ_s fit

γ_s **factor is a strangeness fugacity**

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



$\chi^2/14 = 3.9/14$ $\chi^2/12 = 10.22/12$ $\chi^2/8 = 6.49/8$

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

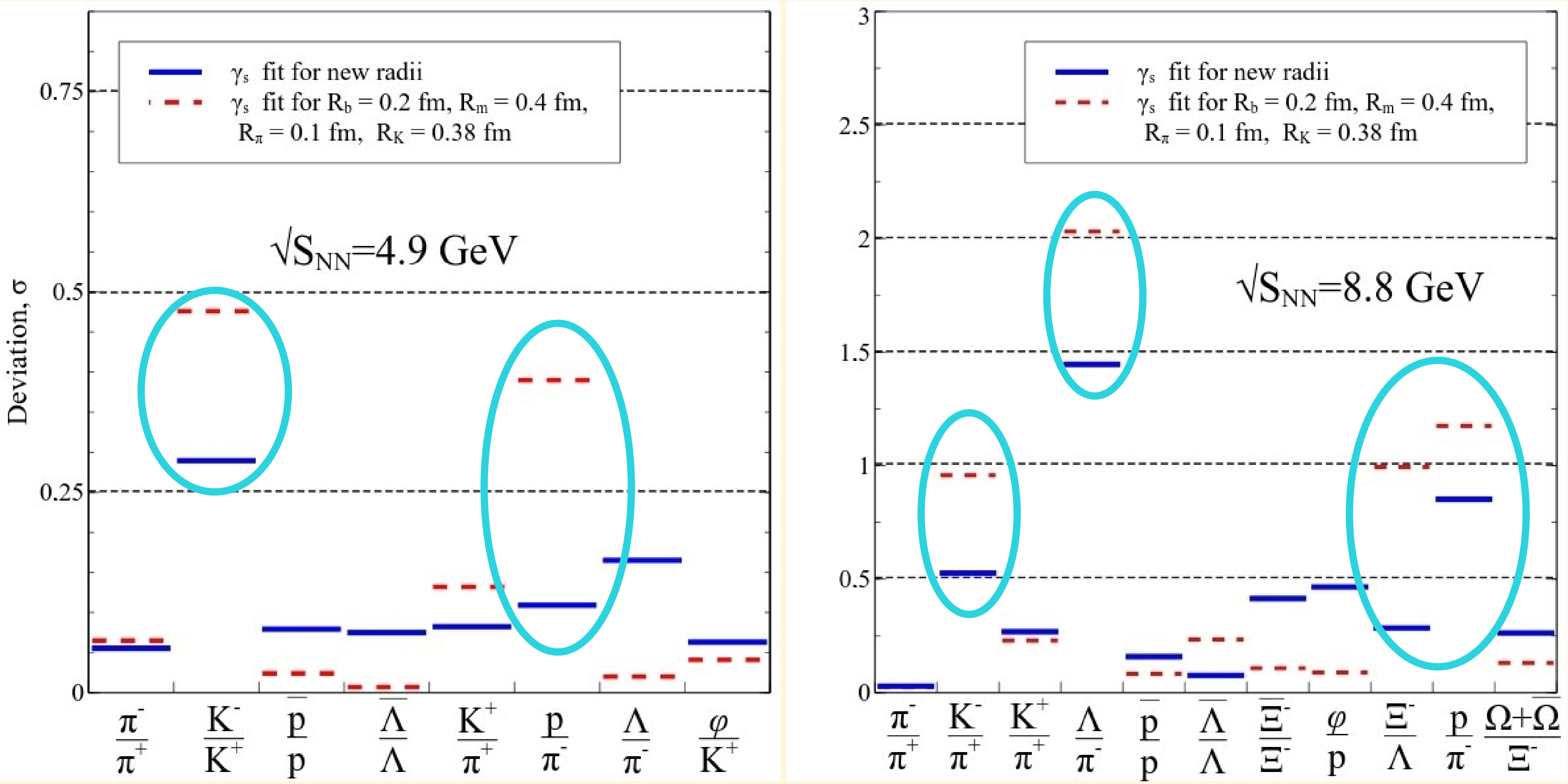
Total fit of 111 independent hadron ratios is the best of existing!

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)

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

Strangeness Horn and Λ Horn in 2014



Do We Need γ_s Factor At All?

Separate Chemical FO of Strange Hadrons

Parameters

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

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

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

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

Principal difference from other approaches

Conservation laws: + net strangeness =0

$$s_{FO} V_{FO} = s_{SFO} V_{SFO} \,, \quad \text{Entropy}$$

$$n^B_{FO} V_{FO} = n^B_{SFO} V_{SFO} \,, \quad \text{Baryonic charge}$$

$$n^{I_3}_{FO} V_{FO} = n^{I_3}_{SFO} V_{SFO} \,. \quad \text{3-rd component of isospin}$$

Getting rid of the effective volumes we obtain

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

Only T at SFO is independent!

=>

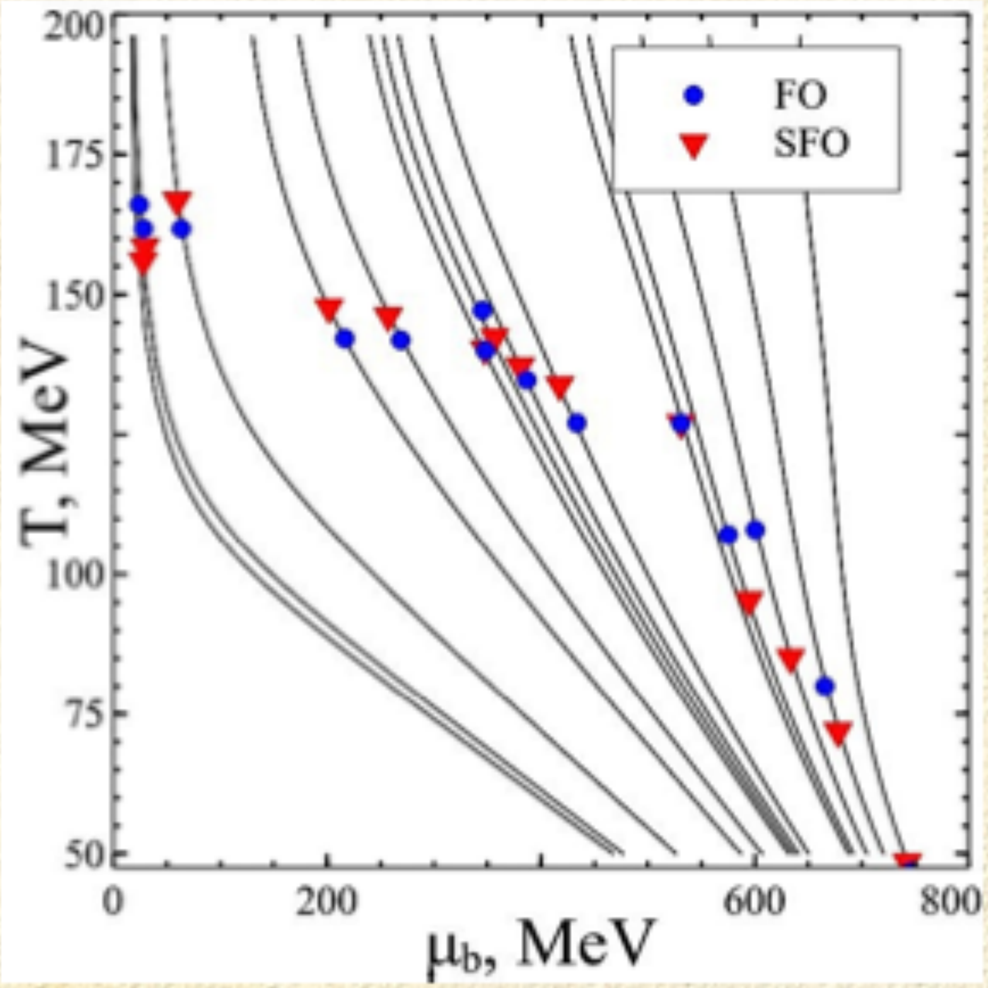
Total number of fitting parameters is same as for strangeness enhancement!

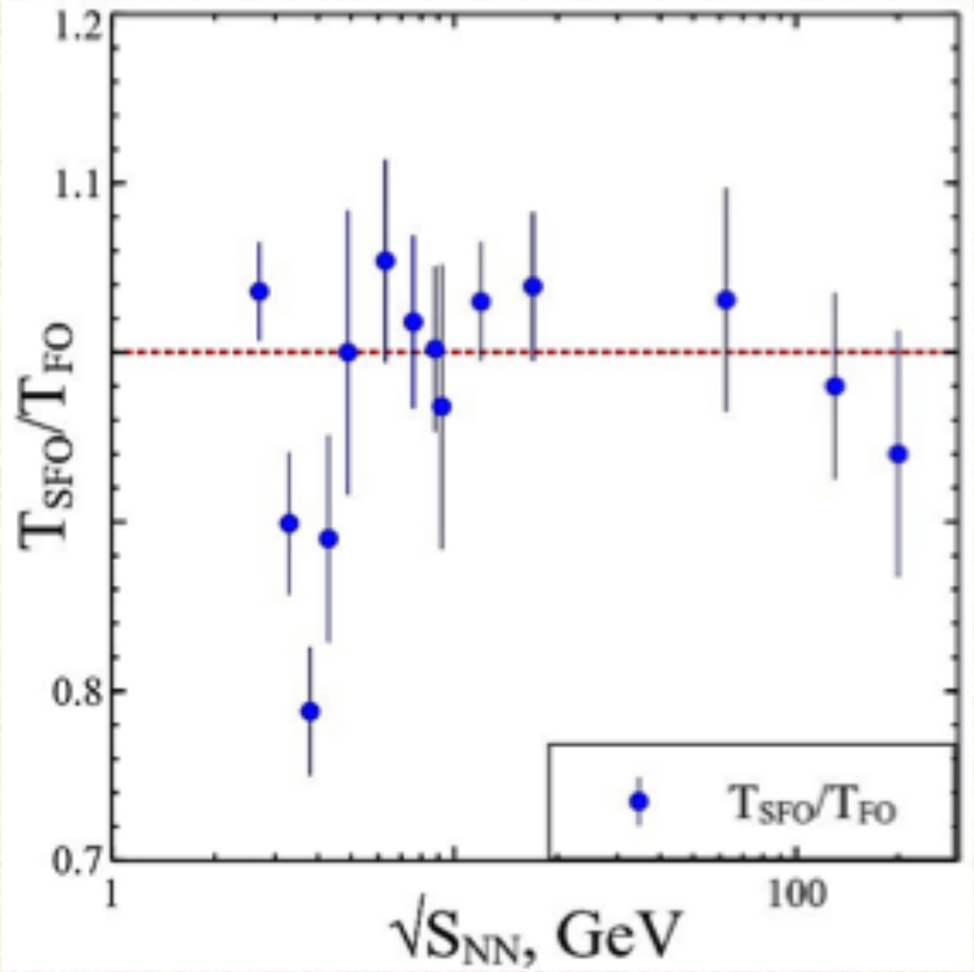
Decays:

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

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

FO versus Strange particle FO





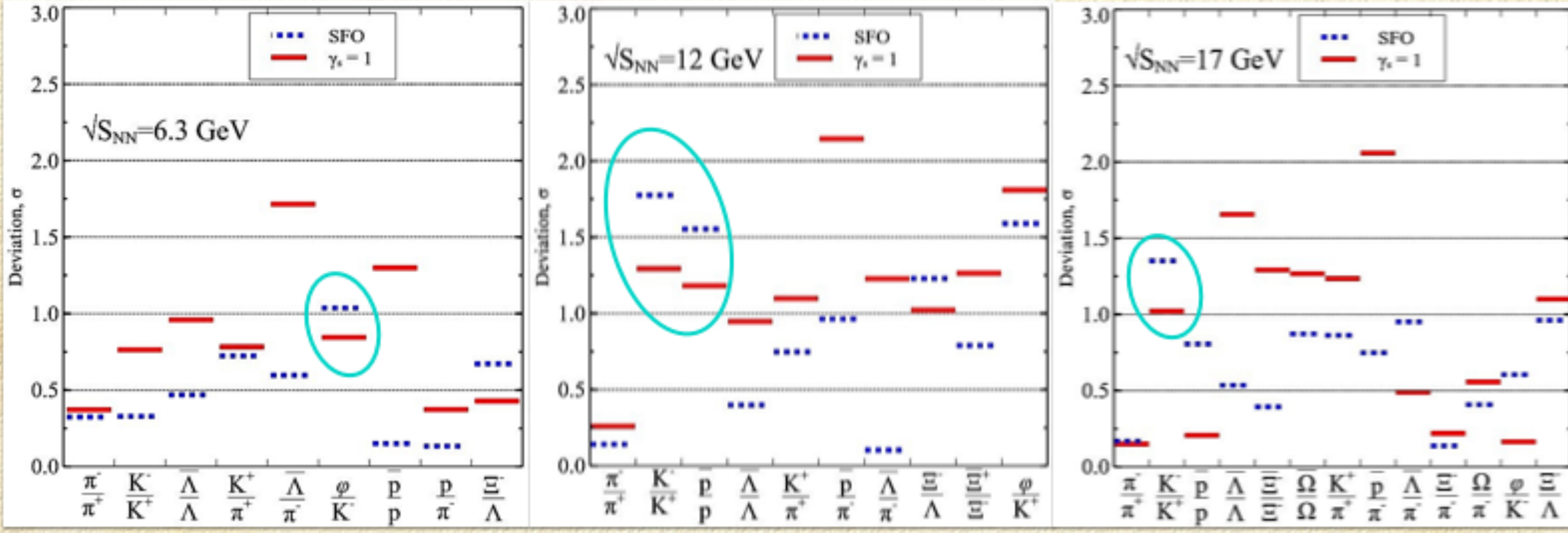
1. SFO temperature differs not more than on 20% =>
there are no problems with decays and entropy conservation!

2. At high energies SFO occurs almost at FO.

3. At low energies there are peculiar irregularities!

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

Yield Ratios for Strange particle FO



1. For all energies SFO gives not worse results than strangeness enhancement, bur in several case there is an essential improvement!

2. For the first time $\bar{p}/\pi^-$, $\bar{\Lambda}/\Lambda$, $\bar{\Xi}^-/\Xi^-$ and $\bar{\Omega}/\Omega$ **are described !**

3. There are no additional minima!

χ^2/dof =1.06 for all 111 ratios measured for c.m. energies 2.7--200 GeV

Intermediate Conclusions

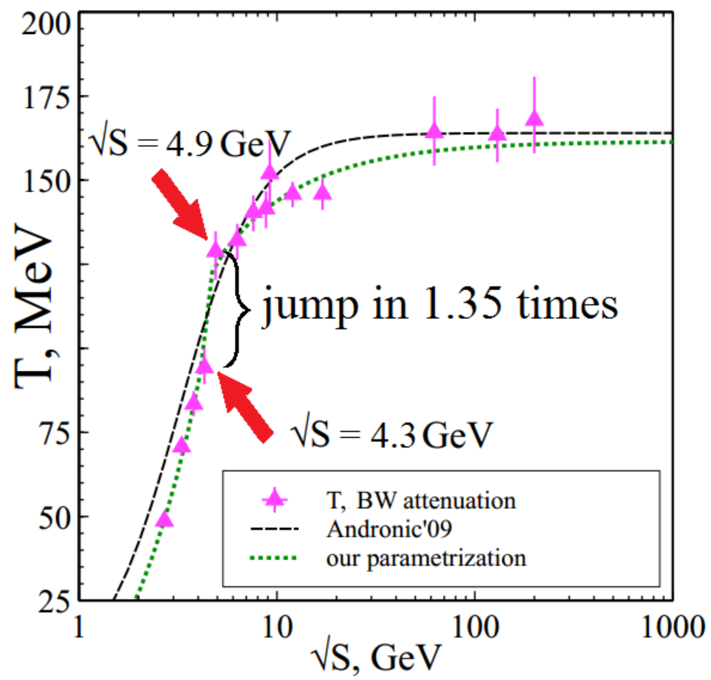
1. The multicomponent HRG model is a precise tool of HIC phenomenology

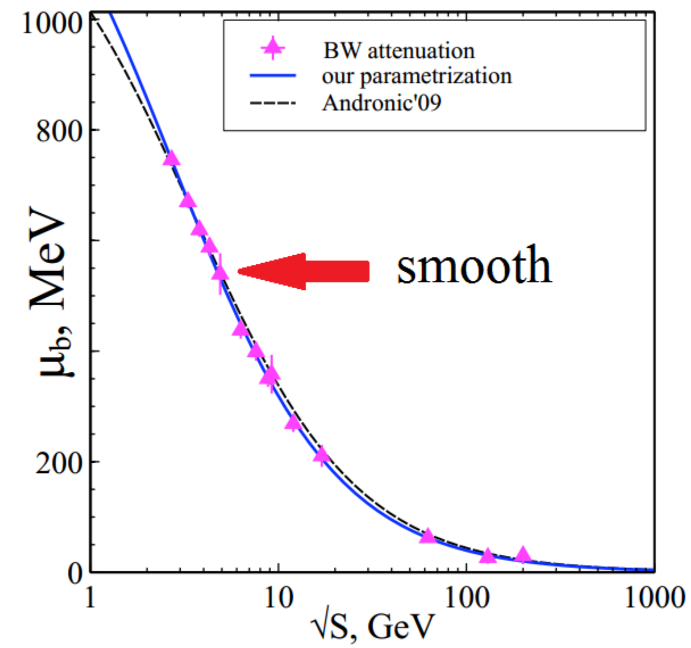
2. With high confidence we conclude that chemical enhancement of strangeness exists at very low energies where we do not expect deconfinement

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

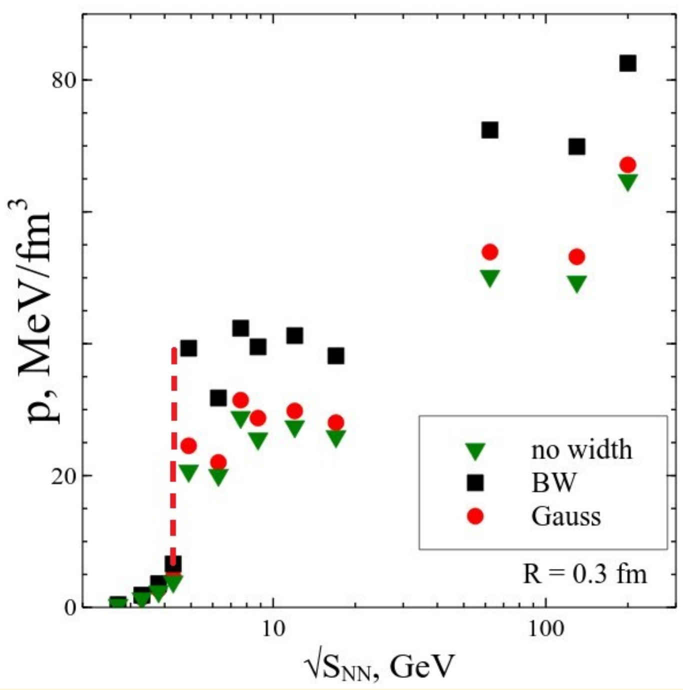
Jump of ChFO Pressure at AGS Energies

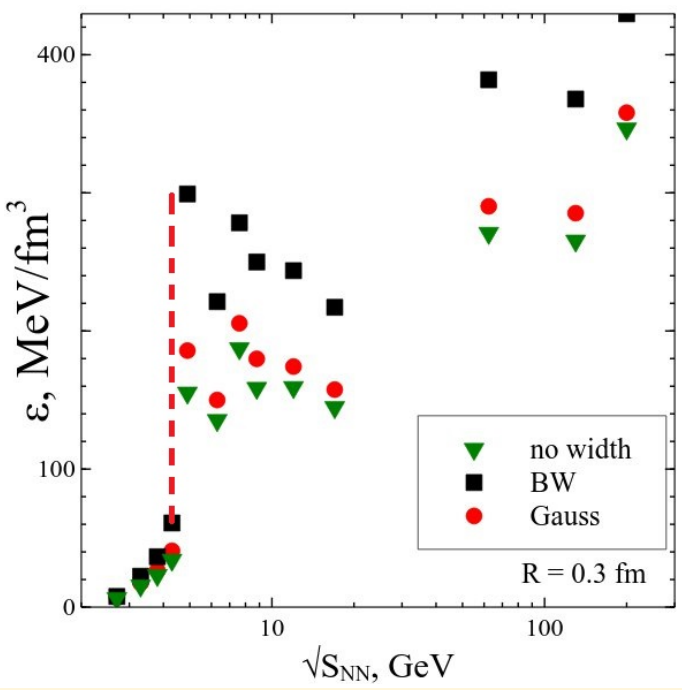
- Temperature T_{CFO} as a function of collision energy $\sqrt{s}$ is rather non smooth





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



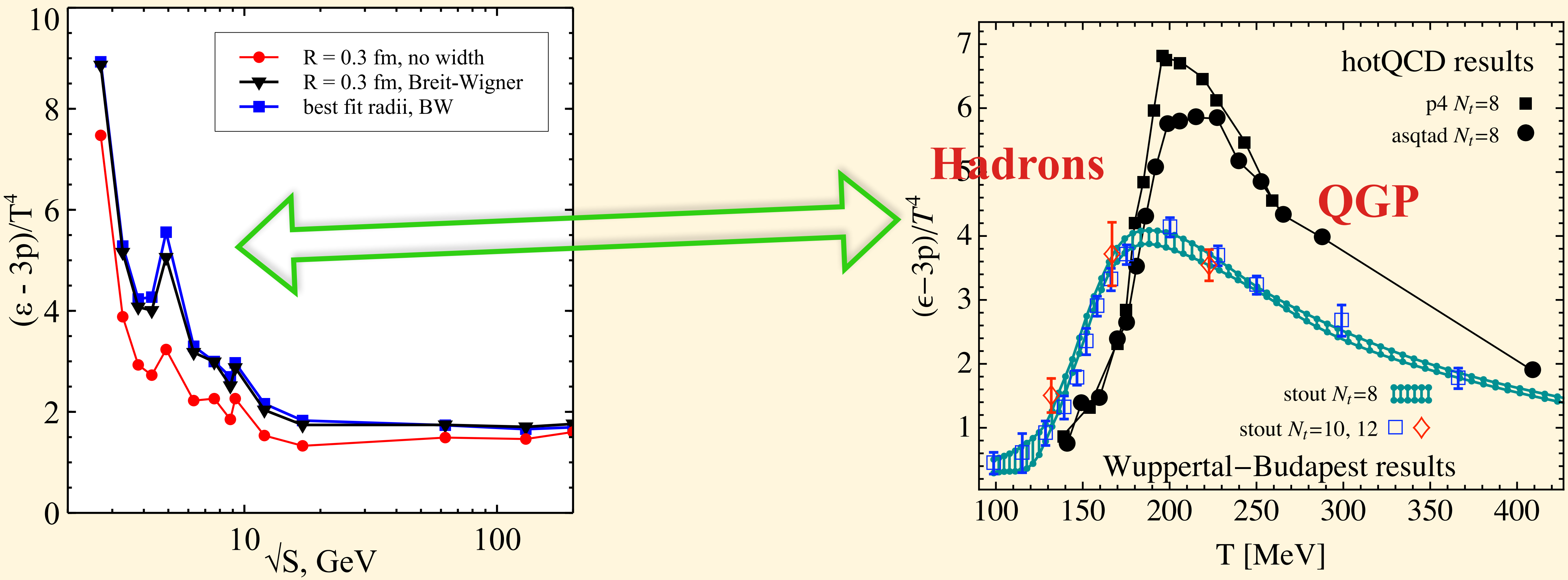


K.A. Bugaev et al., Phys. Part. Nucl. Lett. 12(2015) [arXiv:1405.3575];

Ukr. J. Phys. 60 (2015) [arXiv:1312.4367]

Trace Anomaly Peaks

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



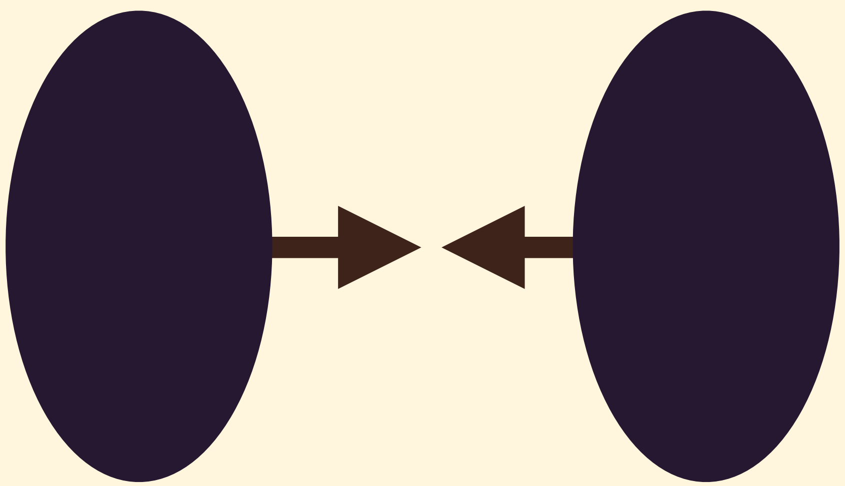
K.A. Bugaev et al., arXiv:1412.0718 [nucl-th]

WupBud EOS arxive: lat 1007.2580

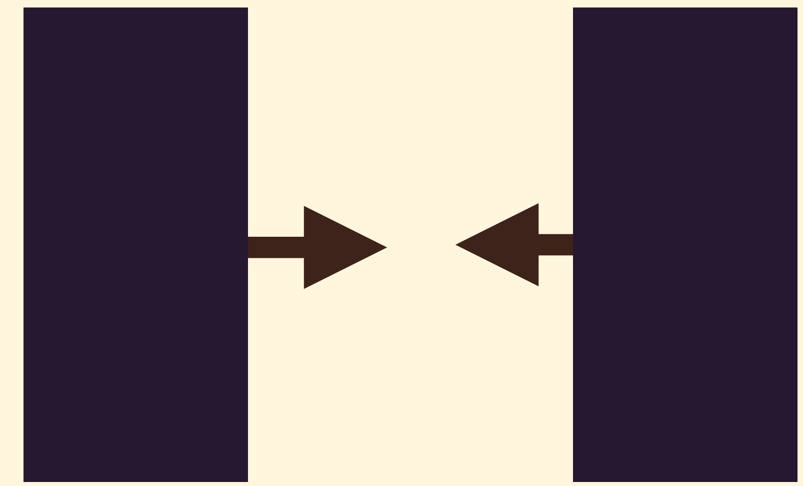
Are these trace anomaly peaks related to each other?

Shock Adiabat Model for A+A Collisions

A+A central collision at 1< Elab<30



Its hydrodynamic model

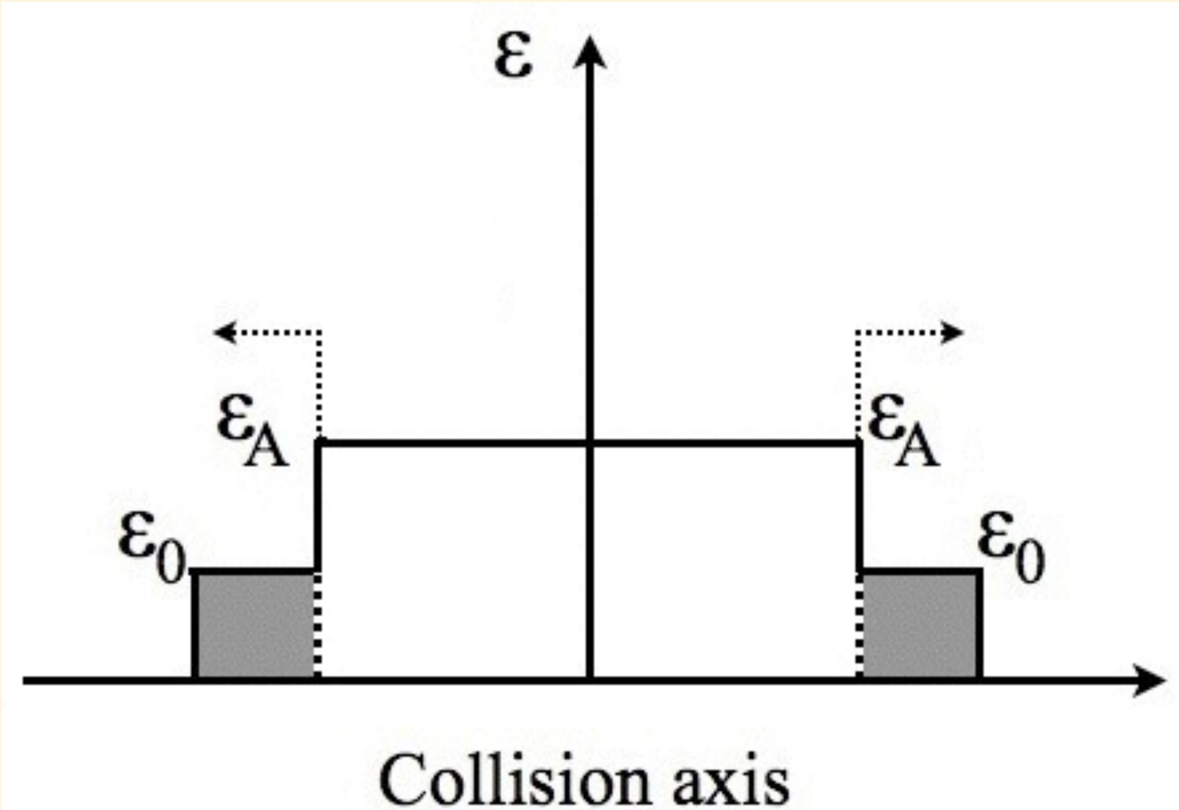


Works reasonably well at these energies.

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

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

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

ε is energy density, p is pressure,

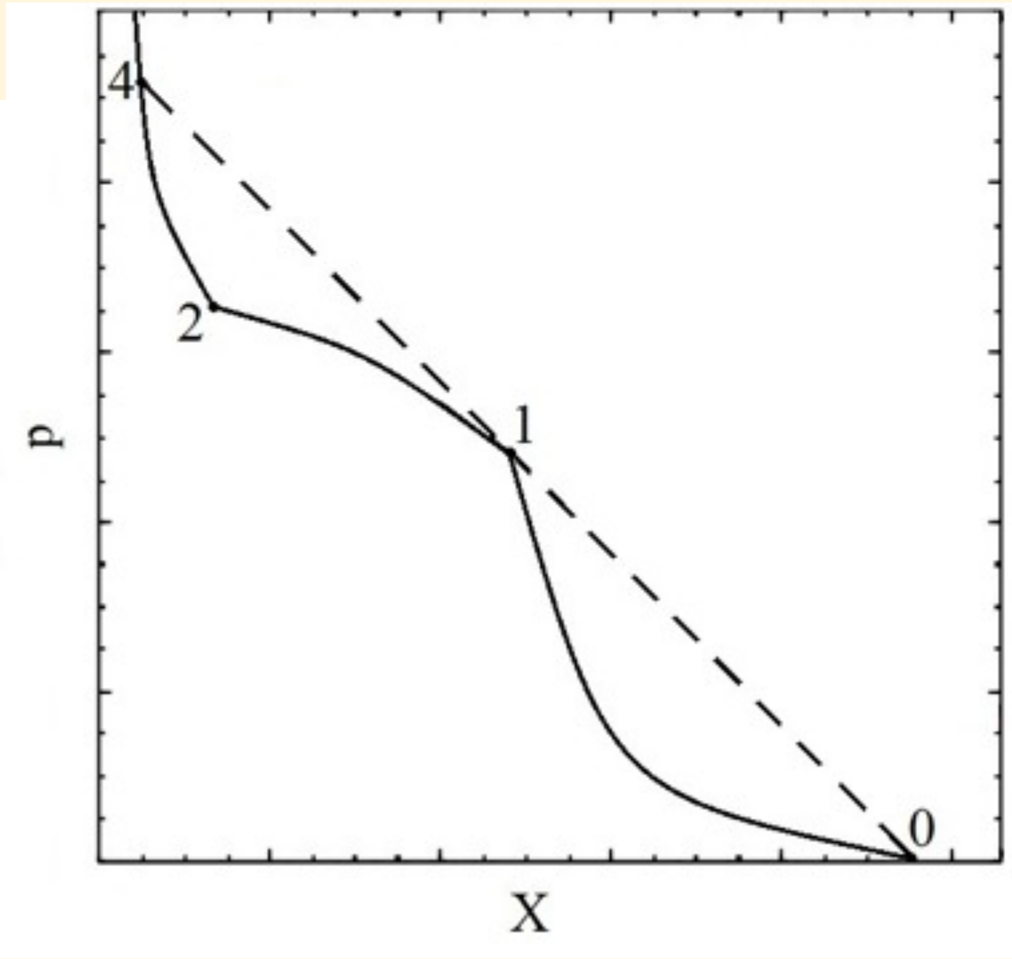
ρ_B is baryonic charge density

Anomalous properties otherwise.

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

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

Shock adiabat example

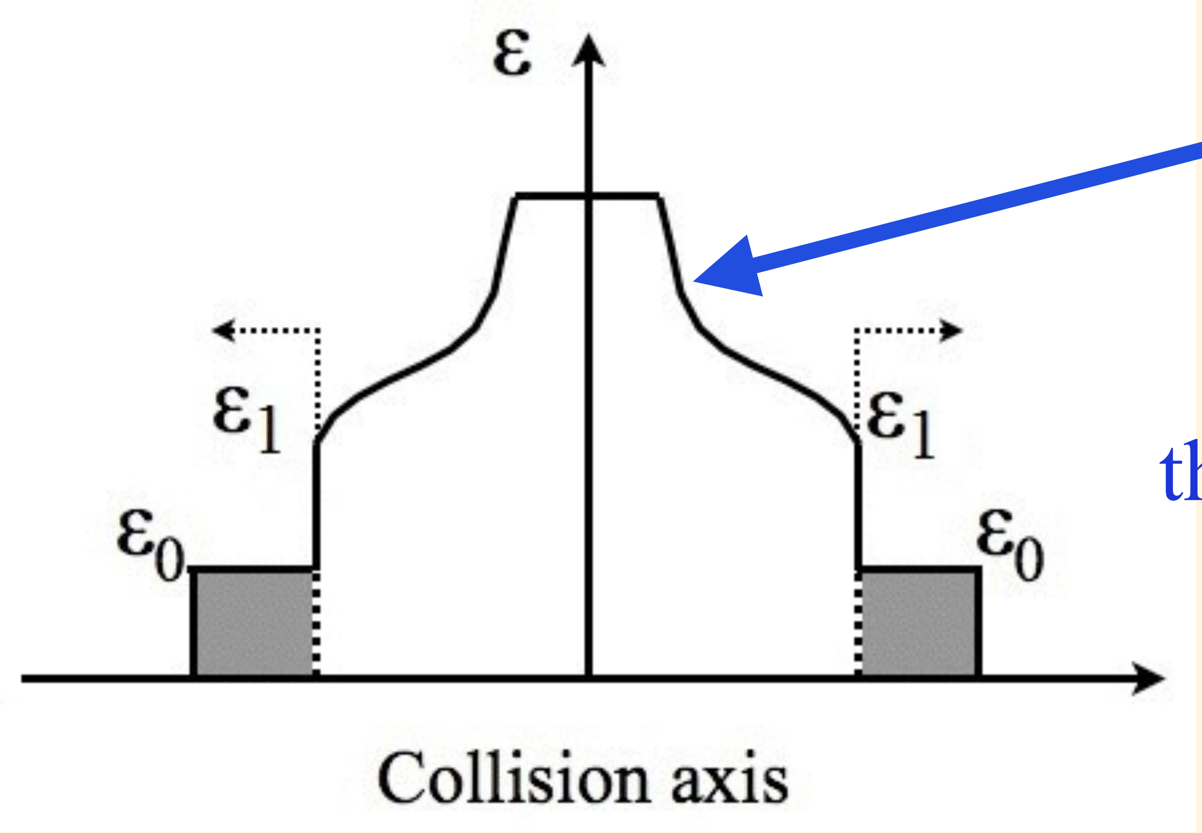


Region 1-2 is mixed phase with **anomalous properties.**

Generalized Shock Adiabat Model

In case of unstable shock transitions more complicated flows appear:

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



shock 01 + compression simple wave

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

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

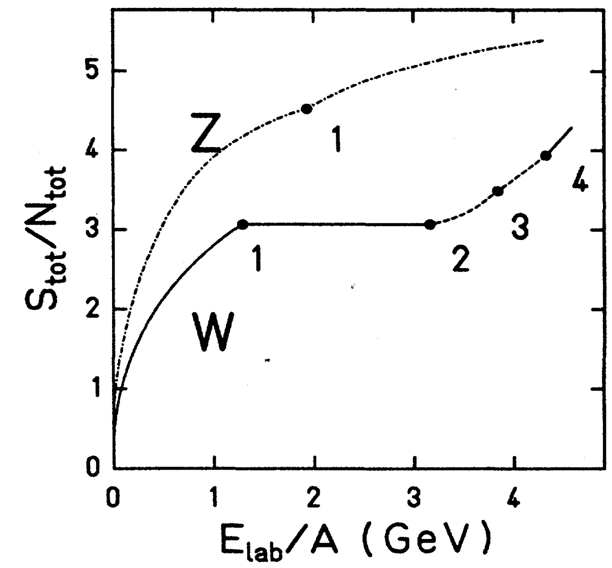


FIG. 9. The entropy per baryon as a function of the bombarding energy per nucleon of the colliding nuclei for models W and Z. The points 1, 2, 3, 4 on curve W correspond to those on the generalized adiabatic as displayed in Fig. 7. The point 1 on curve Z marks the boundary to the mixed phase.

Remarkably

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

Correlated Quasi-Plateaus

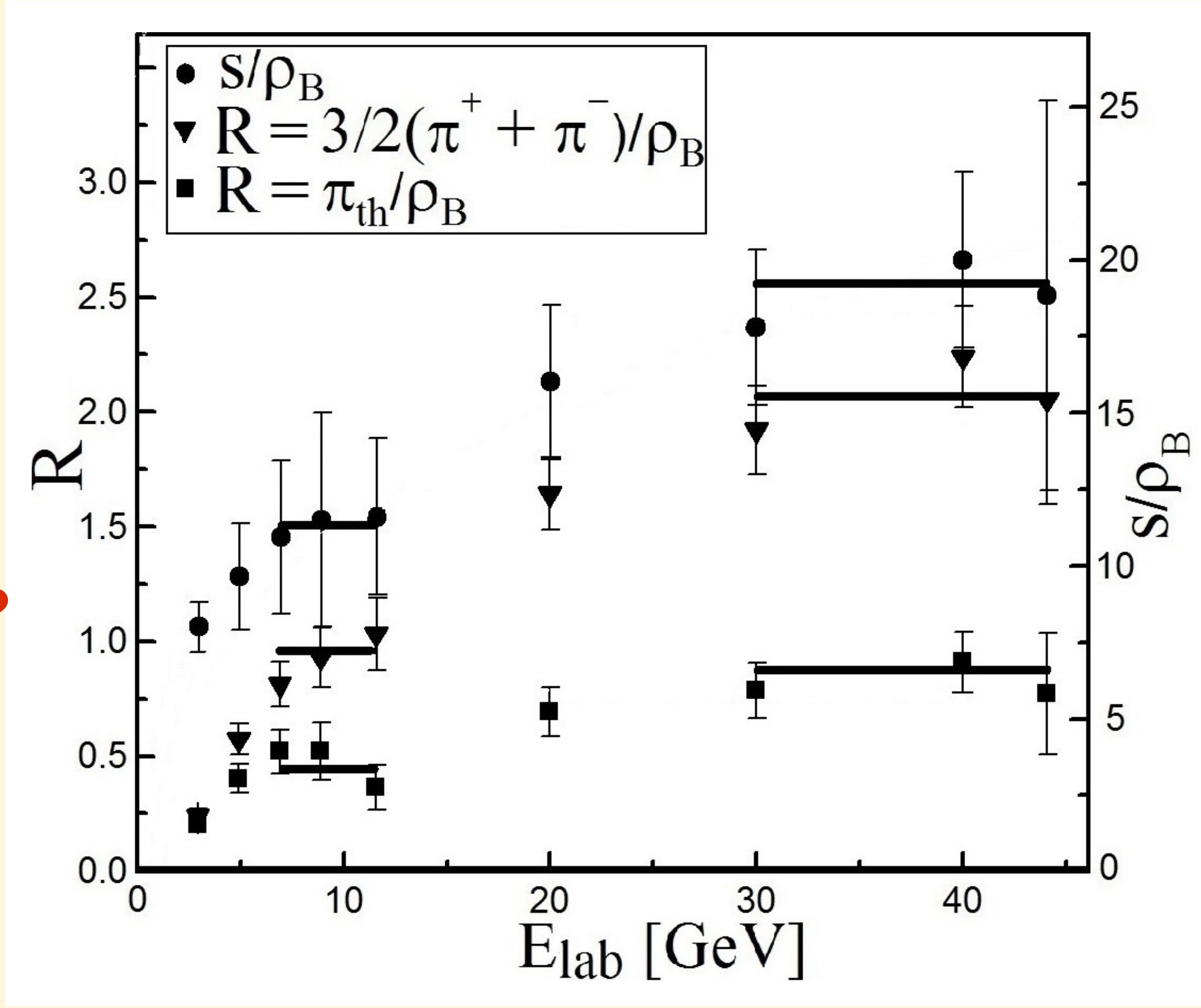
Since the main part of the system entropy is defined by thermal pions =>
thermal pions/baryon should have a plateau!

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

Entropy per baryon has wide plateaus due to large errors

Quasi-plateau in total pions per baryon ?

Thermal pions demonstrate 2 plateaus

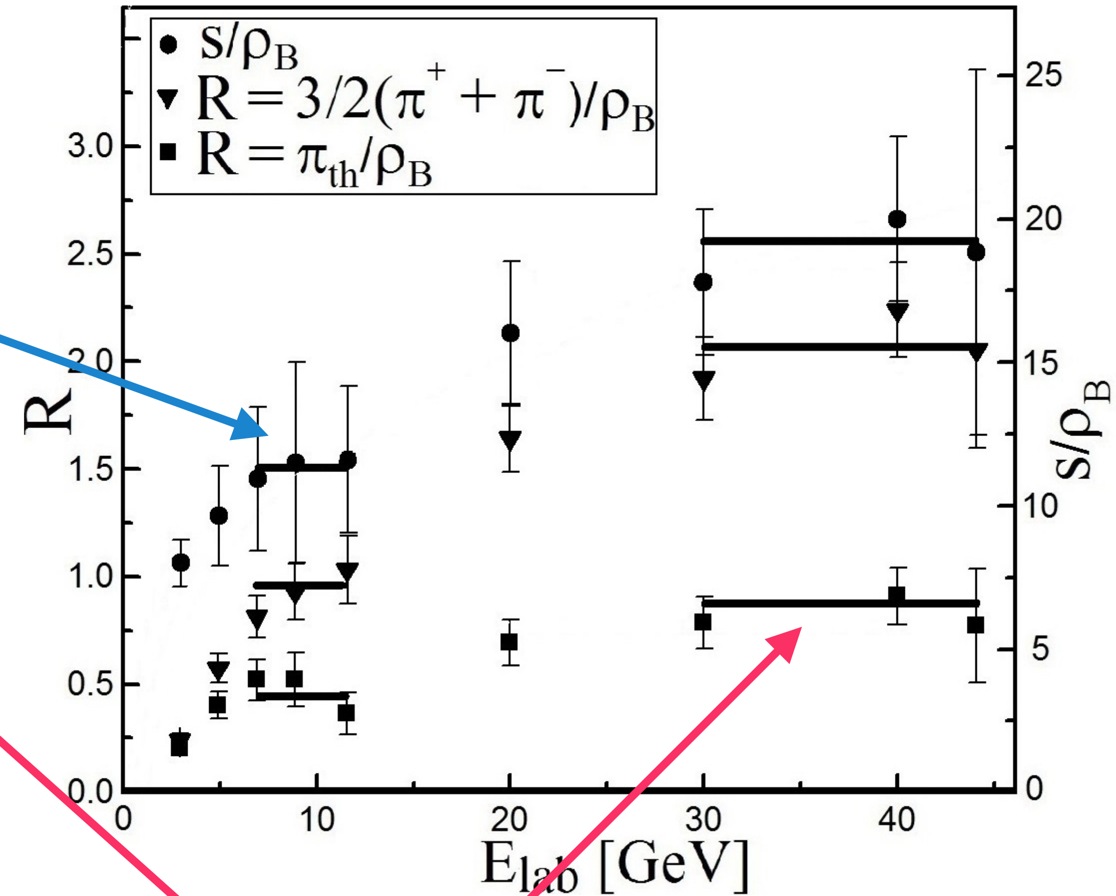


Details on Highly Correlated Quasi-Plateaus

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

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

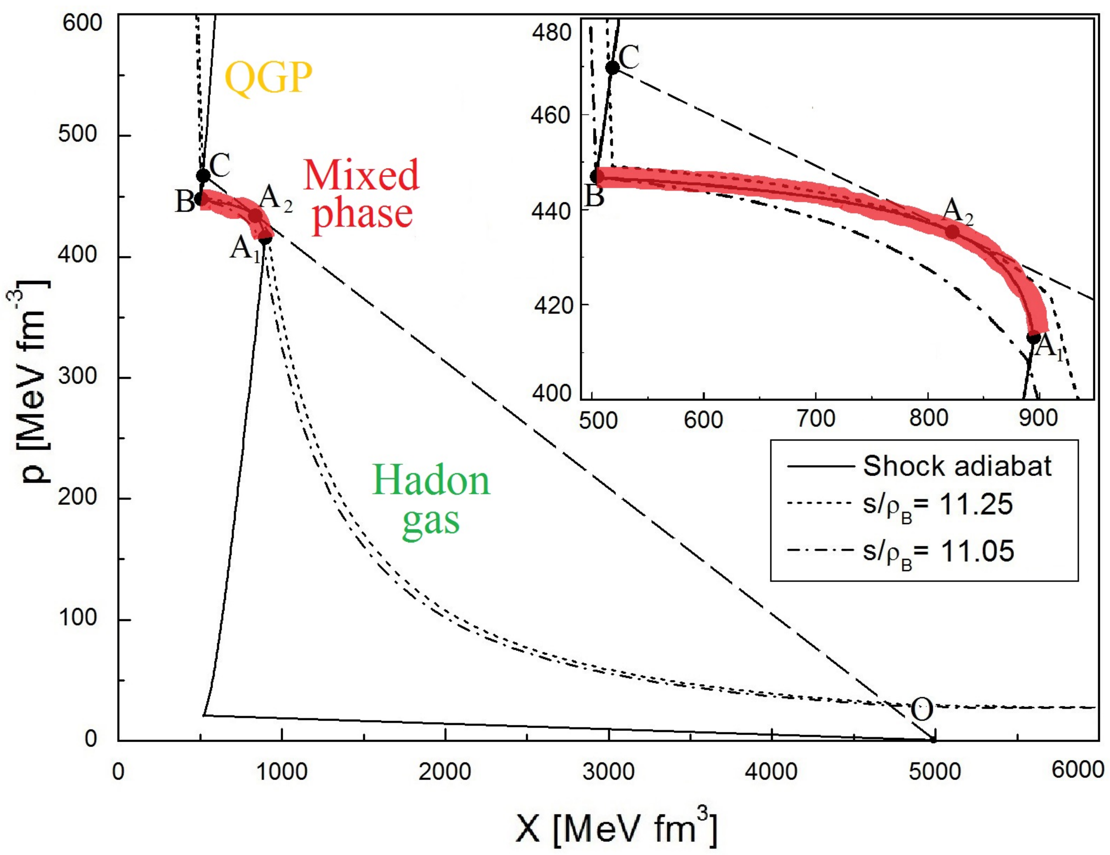
	Low energy plateau				
M	i_0	s/ρ_B	ρ_π^{th}/ρ_B	ρ_π^{tot}/ρ_B	χ^2/dof
2	3	11.12	0.52	0.85	0.17
3	3	11.31	0.46	0.89	0.53
4	2	10.55	0.43	0.72	1.64
5	2	11.53	0.47	0.84	4.45
	High energy plateau				
2	8	19.80	0.88	2.20	0.12
3	7	18.77	0.83	2.05	0.34
4	6	17.82	0.77	1.87	0.87
5	5	16.26	0.64	1.62	3.72



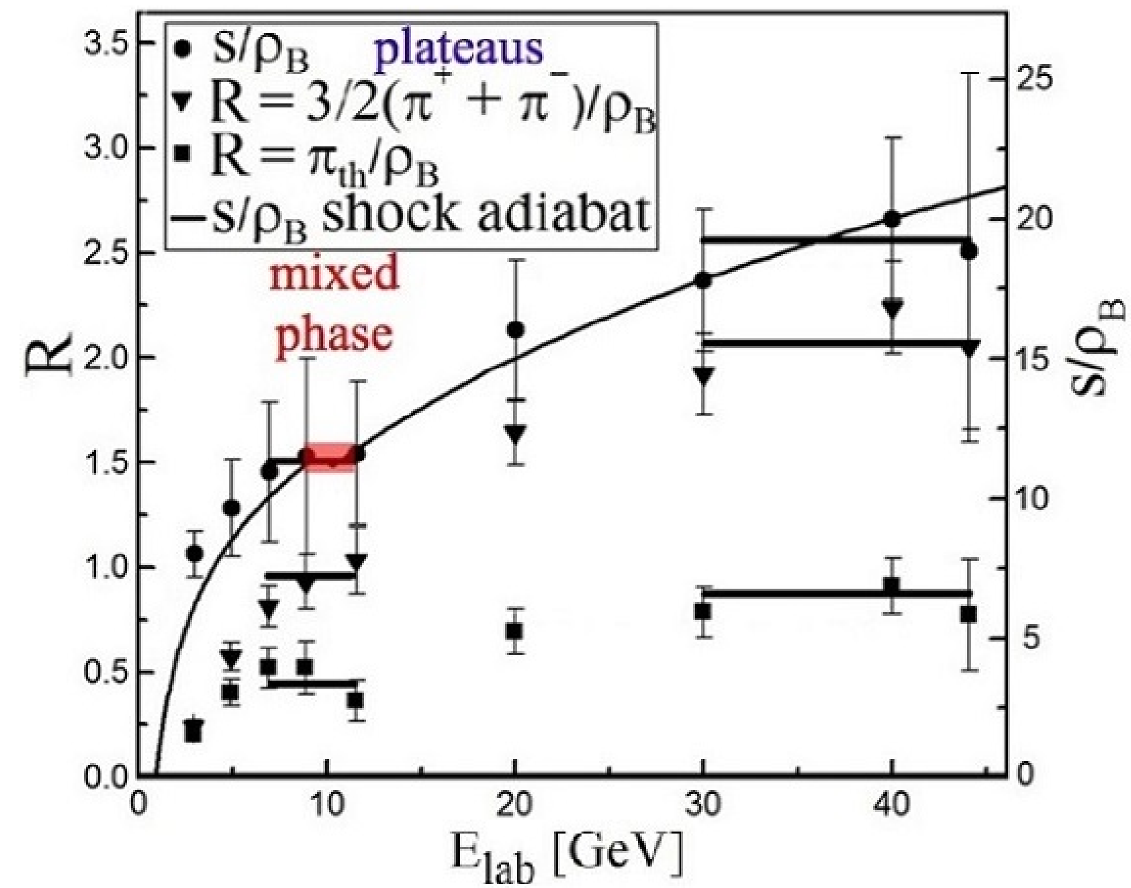
Unstable Transitions to Mixed Phase

$X = \frac{\varepsilon + p}{\rho_B^2}$ – 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!

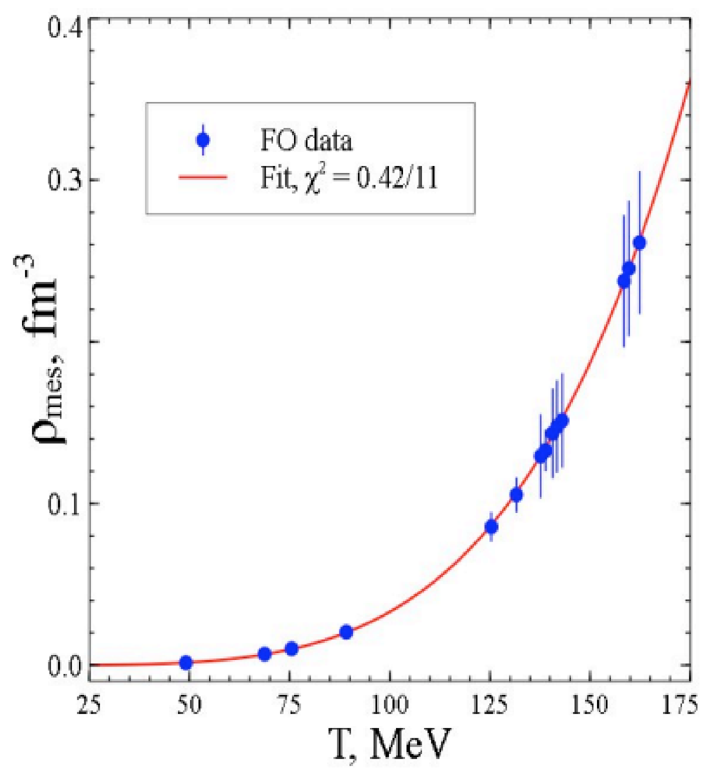
HadronGas EOS is simplified HRGM discussed above.

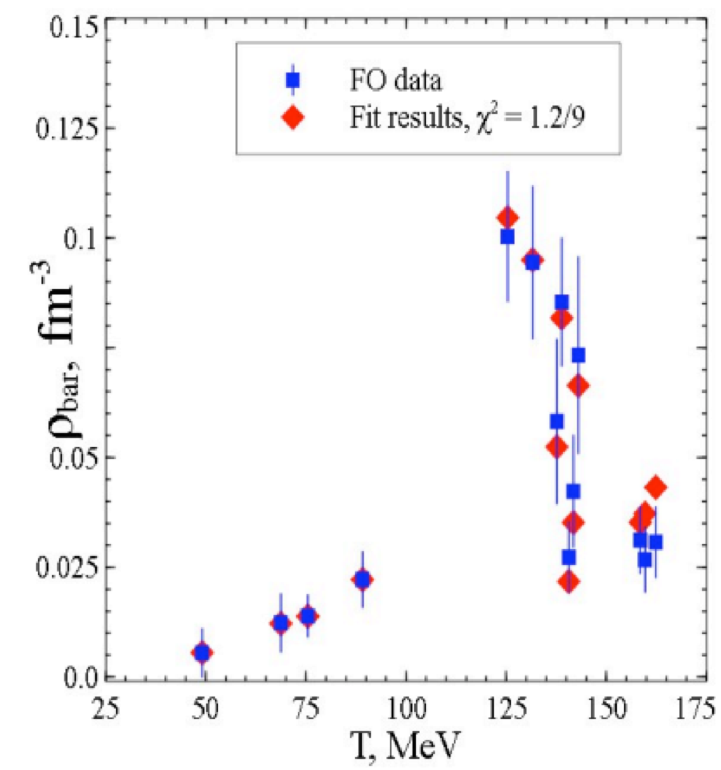
Details of Hadronic and QGP EOS

- Summation of hadronic spectrum $\Rightarrow$ (anti)baryonic and mesonic contributions

$$p = \Bigg[\overbrace{2C_B T^{A_B} \mathrm{ch}\left(\frac{\mu}{T}\right) e^{-\frac{m_B}{T}}}^{\text{(anti)baryons}} + \overbrace{C_M T^{A_M} e^{-\frac{m_M}{T}}}^{\text{mesons}} \Bigg] e^{-\frac{pV_H}{T}}$$

- Effective EoS describes (anti)baryonic and mesonic densities at CFO



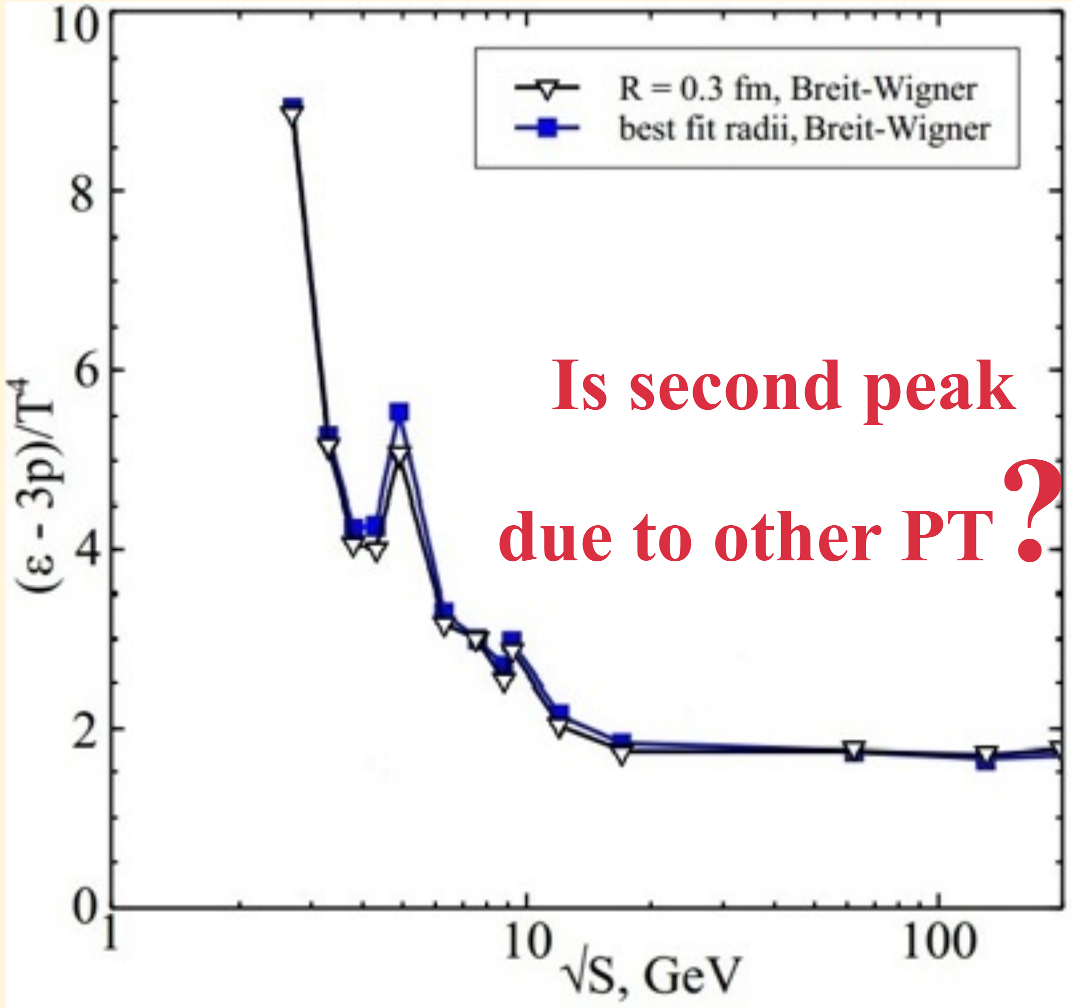


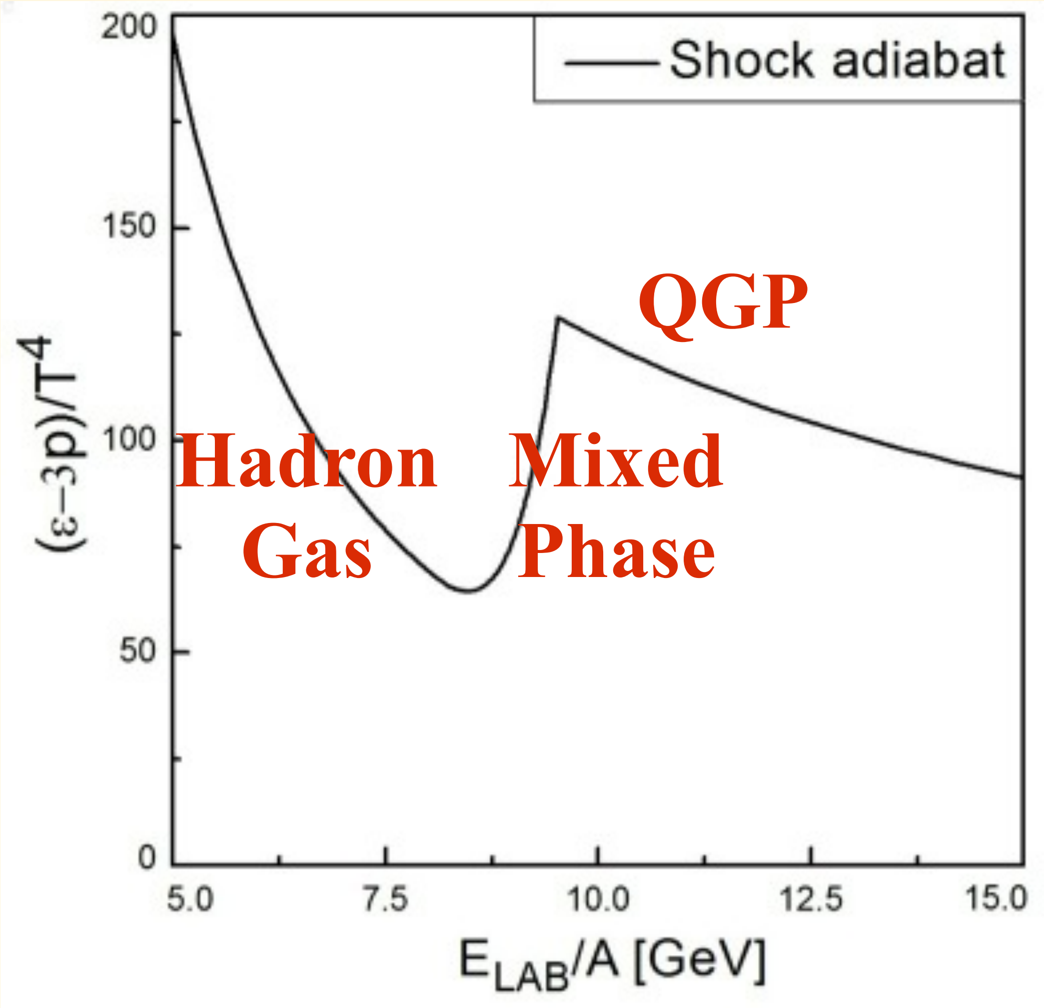
K.Bugaev et al. PoS Baldin ISHEPP XXI (2012) 017, arXiv:1212.0132 [hep-ph]

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

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

Trace Anomaly Along Shock Adiabat



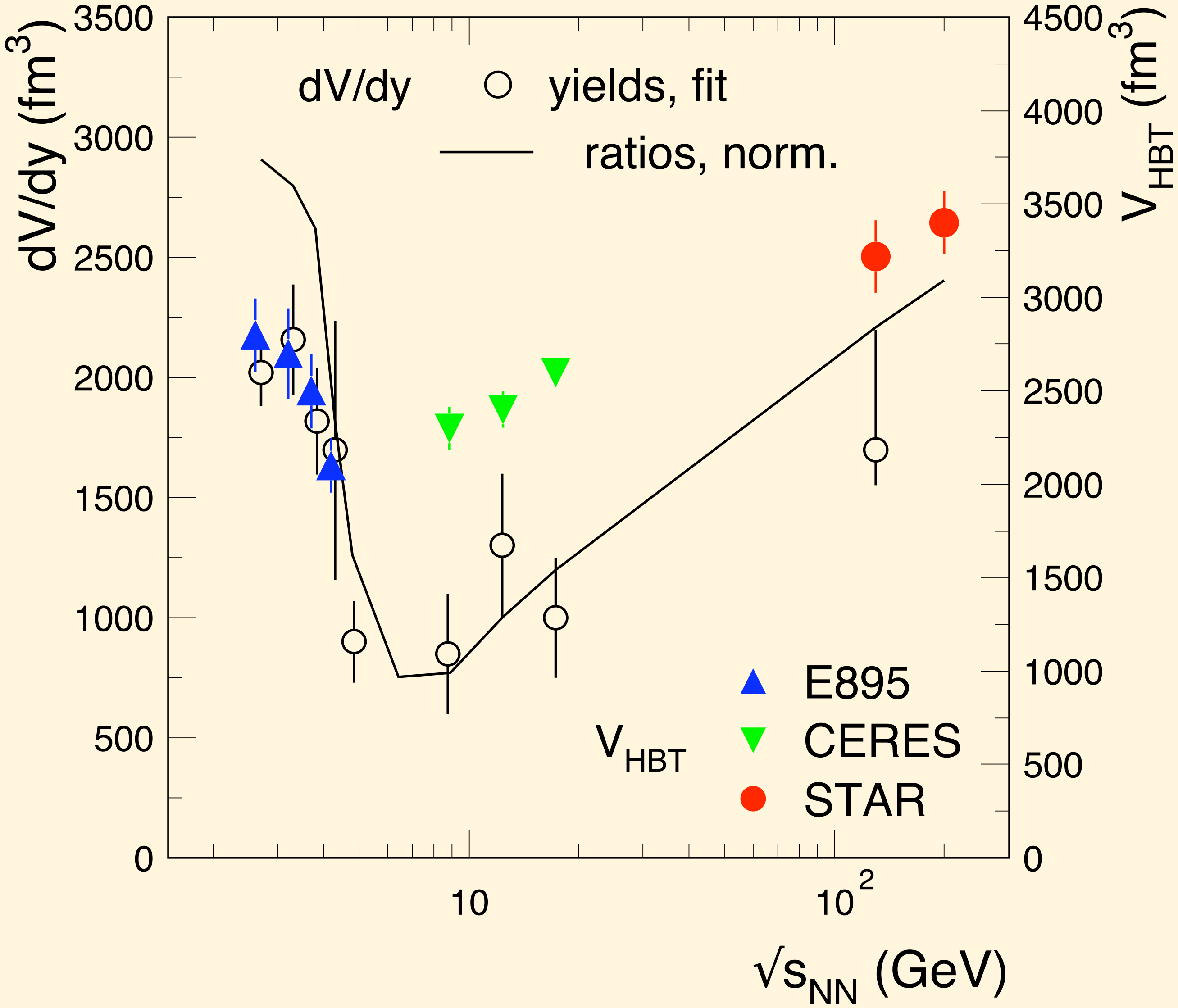


K.A. Bugaev et al., EPJ A (2016)

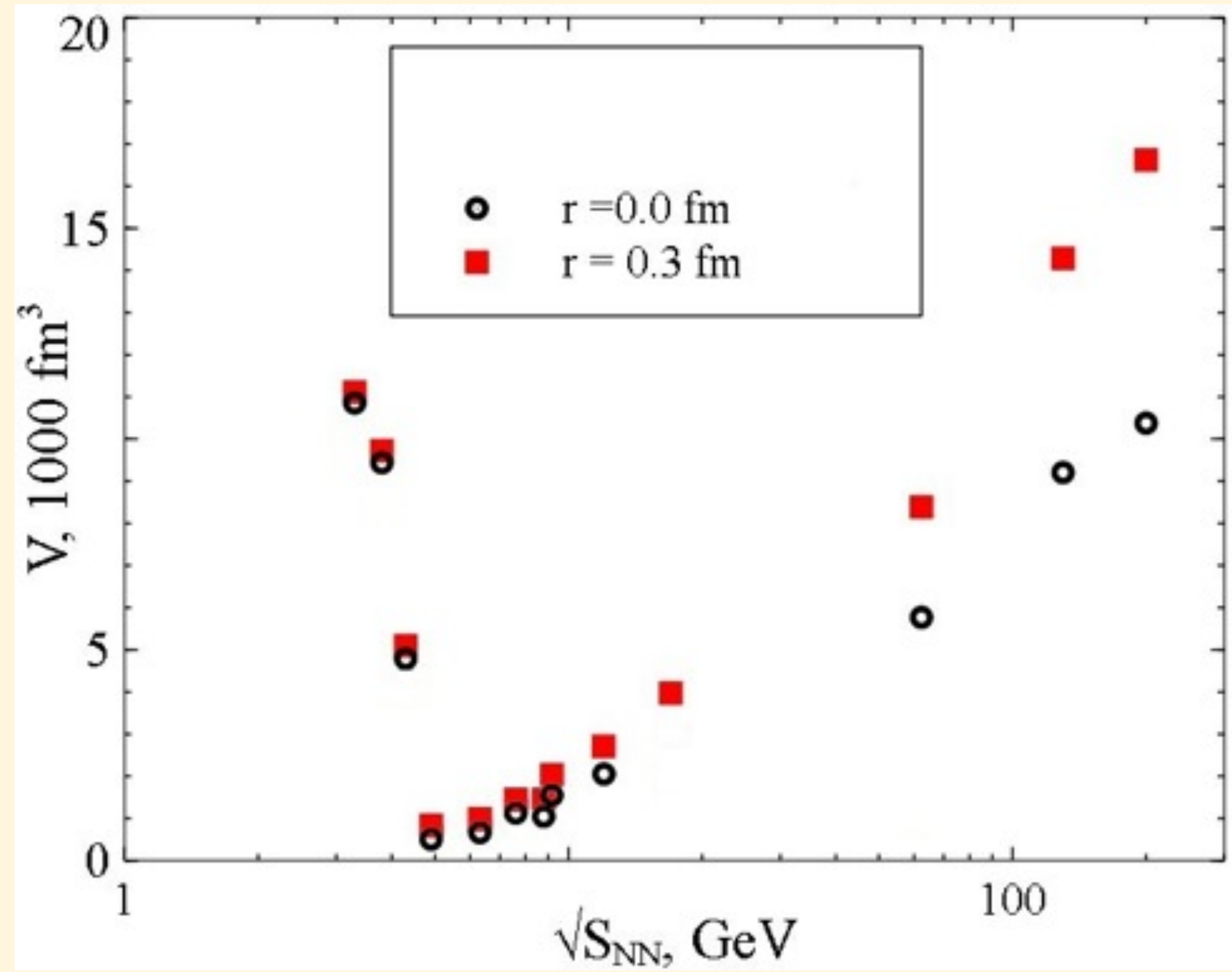
We found one-to-one correspondence between these two peaks.

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

Minimum of ChFO Volume at AGS Energies



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



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

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

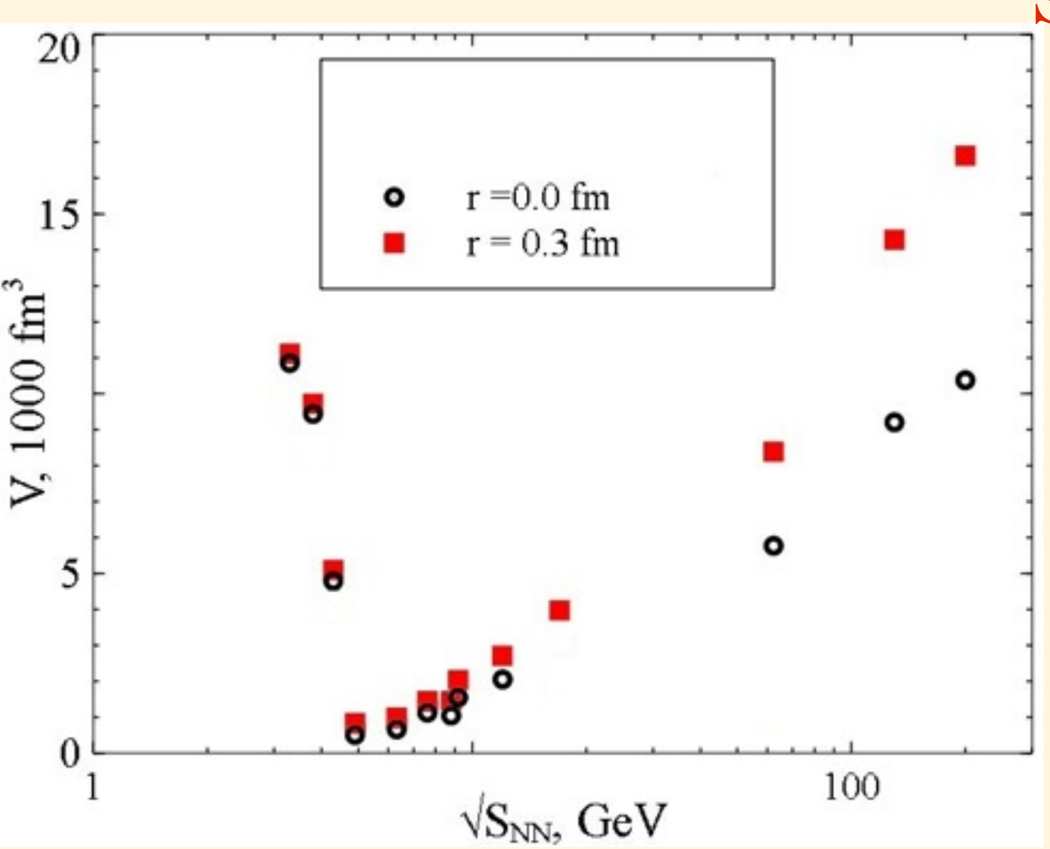
Are these minima related to deconfinement?

Other Minima at AGS Energies

min V at ChFO

SAME energy!

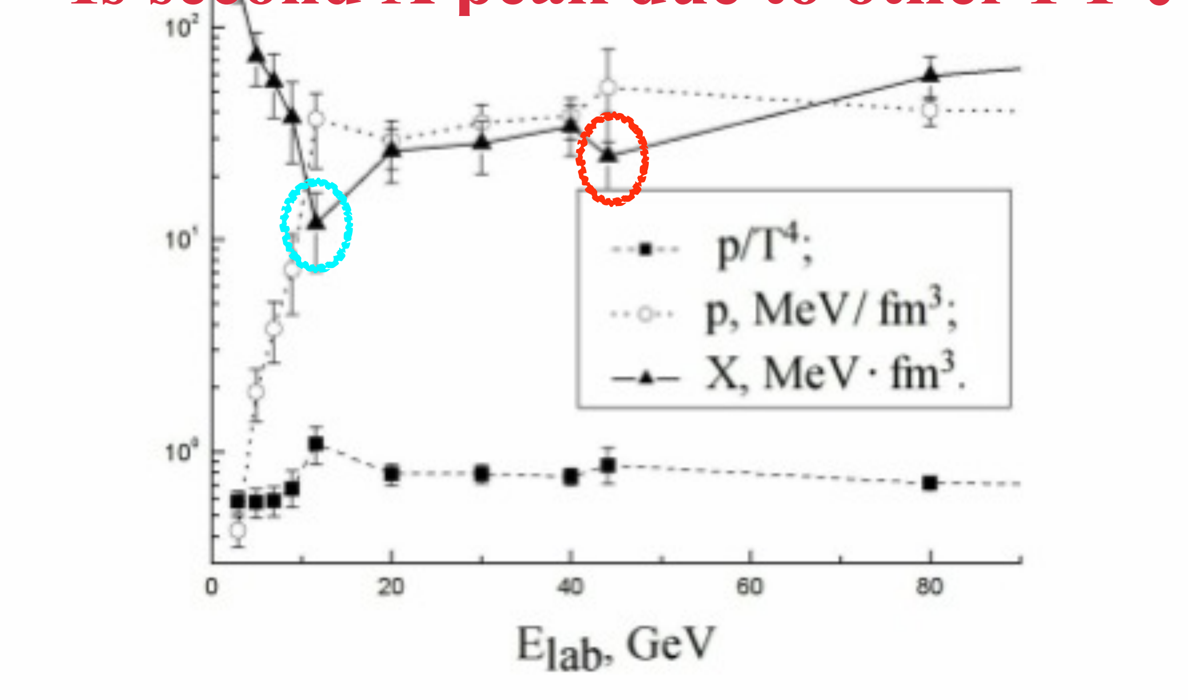
min X at ChFO



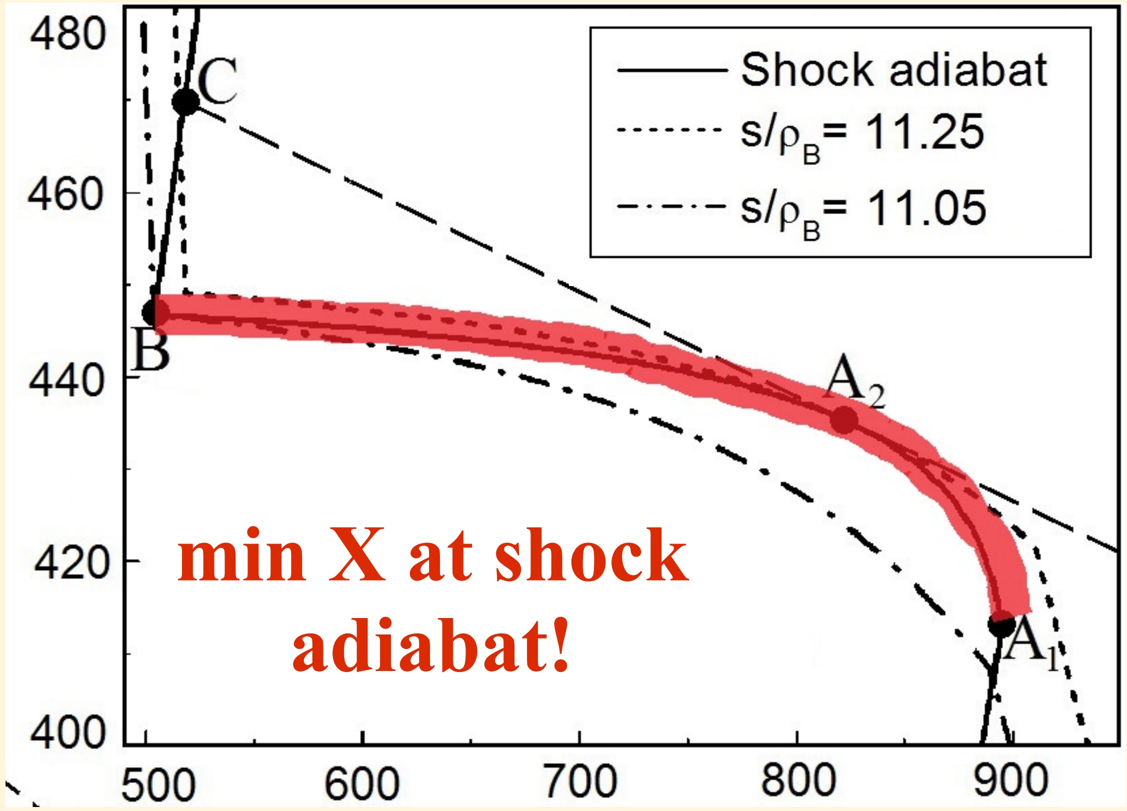
D.R. Oliinychenko, K.A. Bugaev and A.S. Sorin, Ukr. J. Phys. 58, (2013)

X is generalized specific volume

Is second X peak due to other PT ?



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



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

Comparison of Hadronic and QGP event generators of HIC

Quality of Data Description = QDD

$$\langle \chi^2/n \rangle_A^h \Big|_M = \frac{1}{n_d} \sum_{k=1}^{n_d} \left[\frac{A_k^{data,h} - A_k^{model,h}}{\delta A_k^{data,h}} \right]^2 \Big|_M$$

Mean deviation squared per data point of observable A, for hadron h, by model M

Error of QDD

$$\Delta_A \langle \chi^2/n \rangle_A^h \Big|_M \equiv \left[\sum_{k=1}^{n_d} \left[\delta A_k^{data,h} \frac{\partial \langle \chi^2/n \rangle_A^h \Big|_M}{\partial\ A_k^{data,h}} \right]^2 \right]^{\frac{1}{2}}$$

Meta-analysis of QDD for 6 HG models and for 4 QGP models:

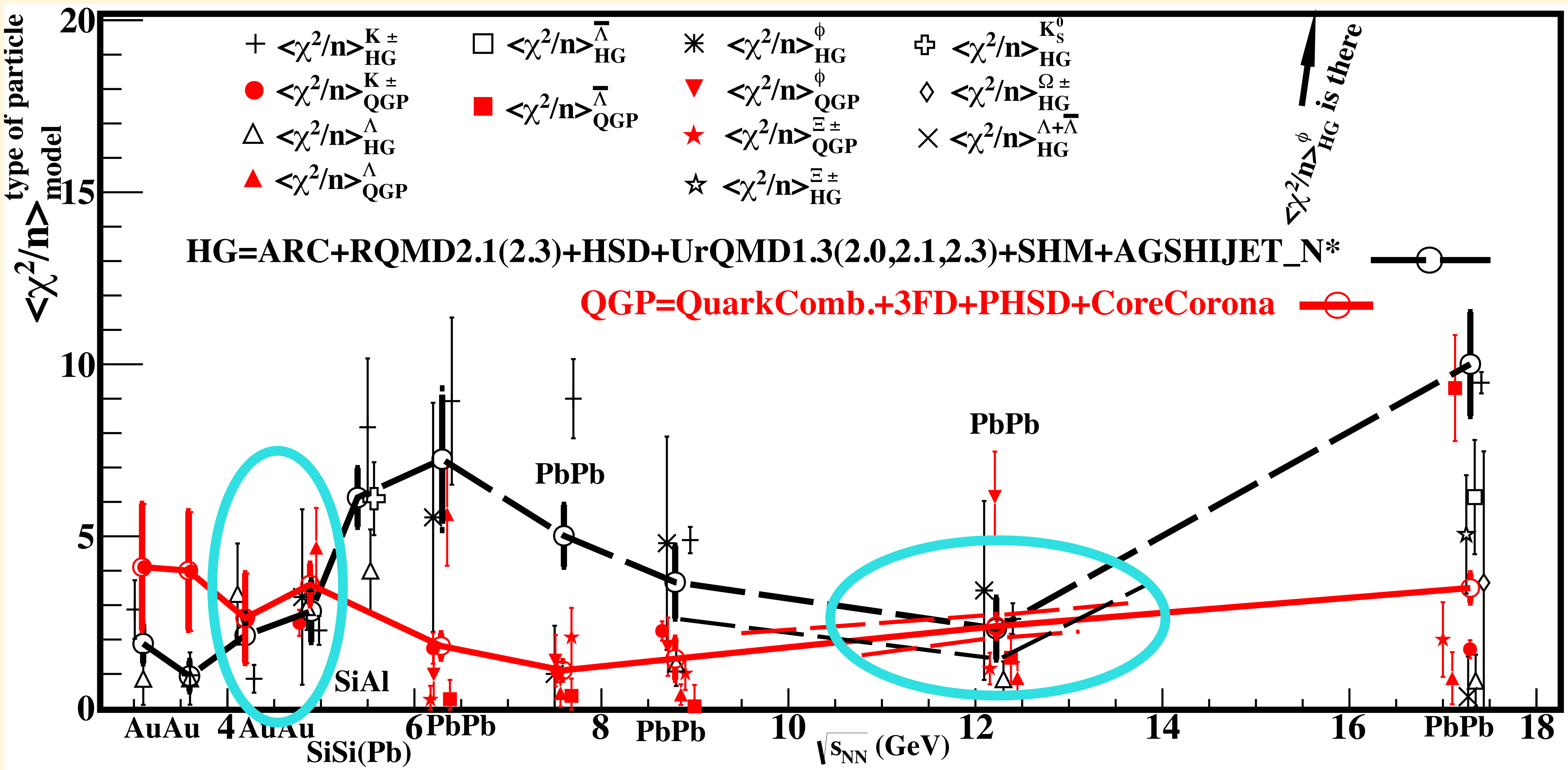
1. **scan of data and theoretical curves for strange hadrons**
2. **average QDD over observables and same kind of models**
3. **average QDD over hadrons and compare models**

	$\sqrt{s_{NN}}$ = 4.87 GeV		
	m_T-distribution	rapidity distribution	Yields
$\langle \chi^2/n \rangle =$ $K^\pm$ set 1	1.26 ± 0.34 HSD & UrQMD2.0 Fig.7, Ref. [31]	2.353 ± 0.626 QuarkComb. model Fig.5 Ref. [34]	4.3 ± 1.2 $\left(\frac{dN}{dy}\big\vert_{y=0}\& \quad 4\pi\right)$ HSD & UrQMD1.3(2.1) Fig.1, 2 Ref. [31]
$\langle \chi^2/n \rangle =$ $K^\pm$ set 2	1.23 ± 0.22 3 versions of HSD & UrQMD2.1 Figs. 8, 10, 12 Ref. [31]	N/A	N/A
$\langle \chi^2/n \rangle =$ K^+	1.15 ± 0.65 3FD Fig.1, Ref. [37]	N/A	7.65 ± 5.53 3FD Fig.9, Ref. [36]
$\langle \chi^2/n \rangle =$ K^-	1.51 ± 0.74 3FD Fig.1, Ref. [37]	N/A	0.15 ± 0.775 3FD Fig.9, Ref. [36]
$\langle \chi^2/n \rangle =$ Λ set 1	$2.54 \pm 0.01, 1.07 \pm 0.002$ ARC,RQMD2.1 Fig. 2 Ref. [21]	$2.75 \pm 1.66, 5.74 \pm 2.1$ ARC,RQMD2.1 Fig. 4 Ref. [21]	2.6 ± 1.3 $\left(\frac{dN}{dy}\big\vert_{y=0}\& \quad 4\pi\right)$ HSD & UrQMD1.3(2.1) Fig. 1 Ref. [31]
$\langle \chi^2/n \rangle =$ Λ set 2	$3.65 \pm 0.6,\ 2.4 \pm 0.55$ m_T+y:RQMD2.3(cascade), RQMD2.3(mean-field) Figs. 5, 7 Ref. [30]	4.67 ± 1.155 QuarkComb. model Fig. 5 Ref. [34]	N/A
$\langle \chi^2/n \rangle =$ ϕ	N/A	N/A	$3.46 \pm 3.72,\ 3.01 \pm 3.5$ SHM, UrQMD Fig. 17 Ref. [32]

V. A. Kizka, V. S. Trubnikov, K. A. Bugaev and D. R. Oliinychenko, arXiv:1504.06483 [hep-ph].

Newest Signal of QGP Formation

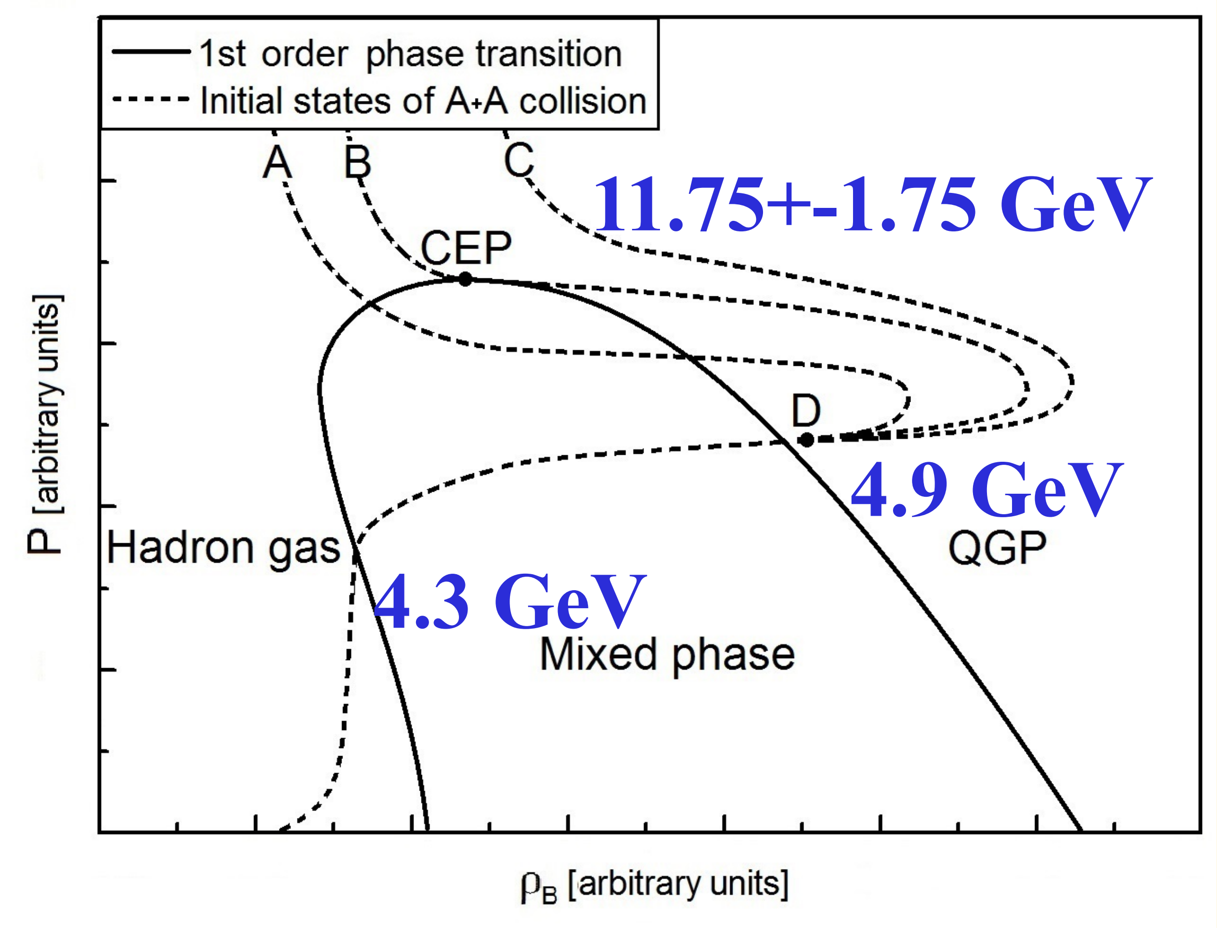
Idea: at high energies QGP QDD must be better than HG QDD,
at low energies vice versa!
Then equal QDD of two kinds of models is about mixed phase threshold

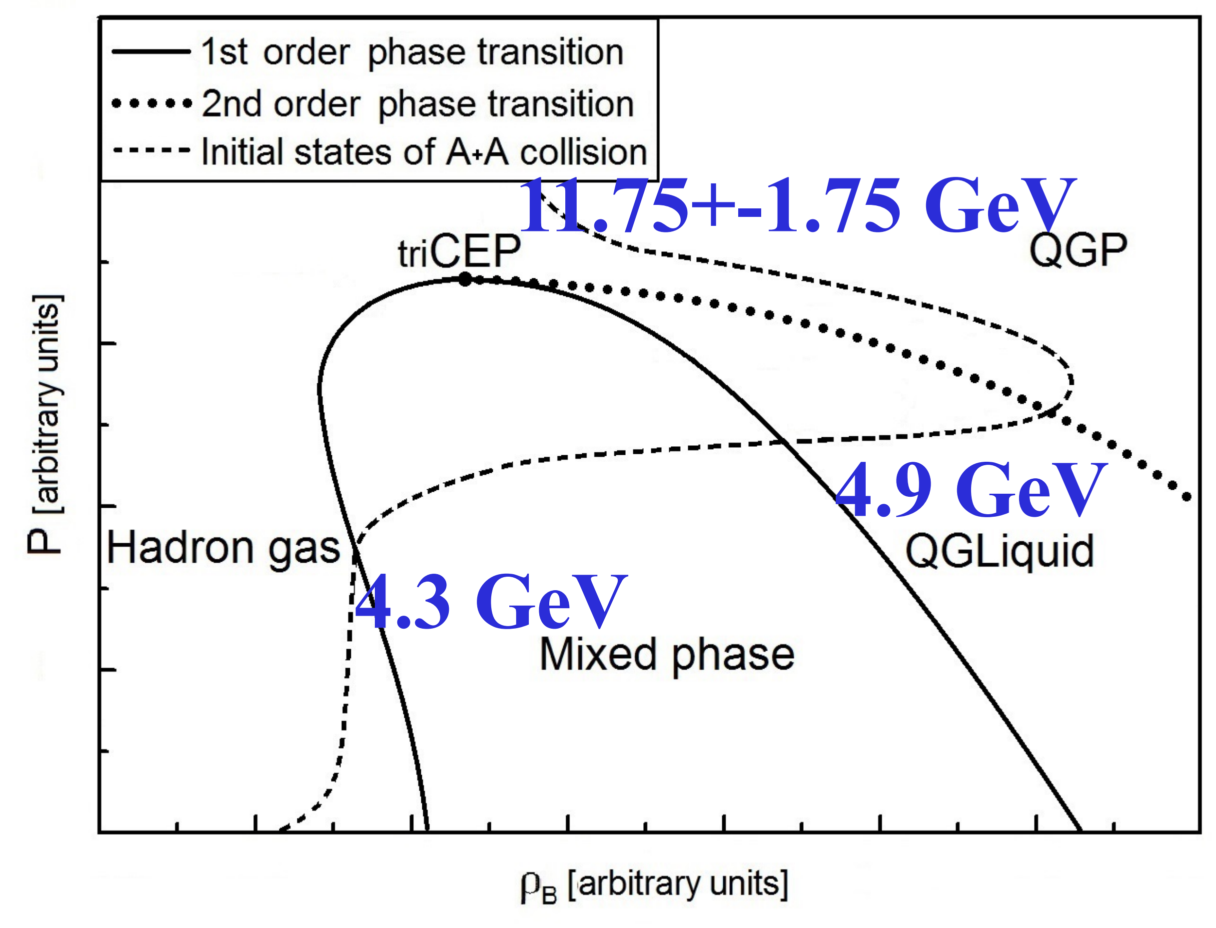


Meta-analysis gives 2 regions of intersection:
1-st mixed phase at c.m. energies 4.3-4.9 GeV
2-nd mixed phase (?) at c.m. energies 10-13.5 GeV
BOTH CAN BE CHECKED at NICA and FAIR!

Possible Interpretation

Evolution of possible «initial» states with collision energy





Appearance of 2-nd intersection at c.m. energies 10-13.5 GeV

probably means that trajectory goes near critical (left) or 3critical (right) endpoint

To resolve this problem we need RHIC data at 11.5, 14.5 and 19.6 GeV

Strangeness Enhancement as Deconfinement Signal

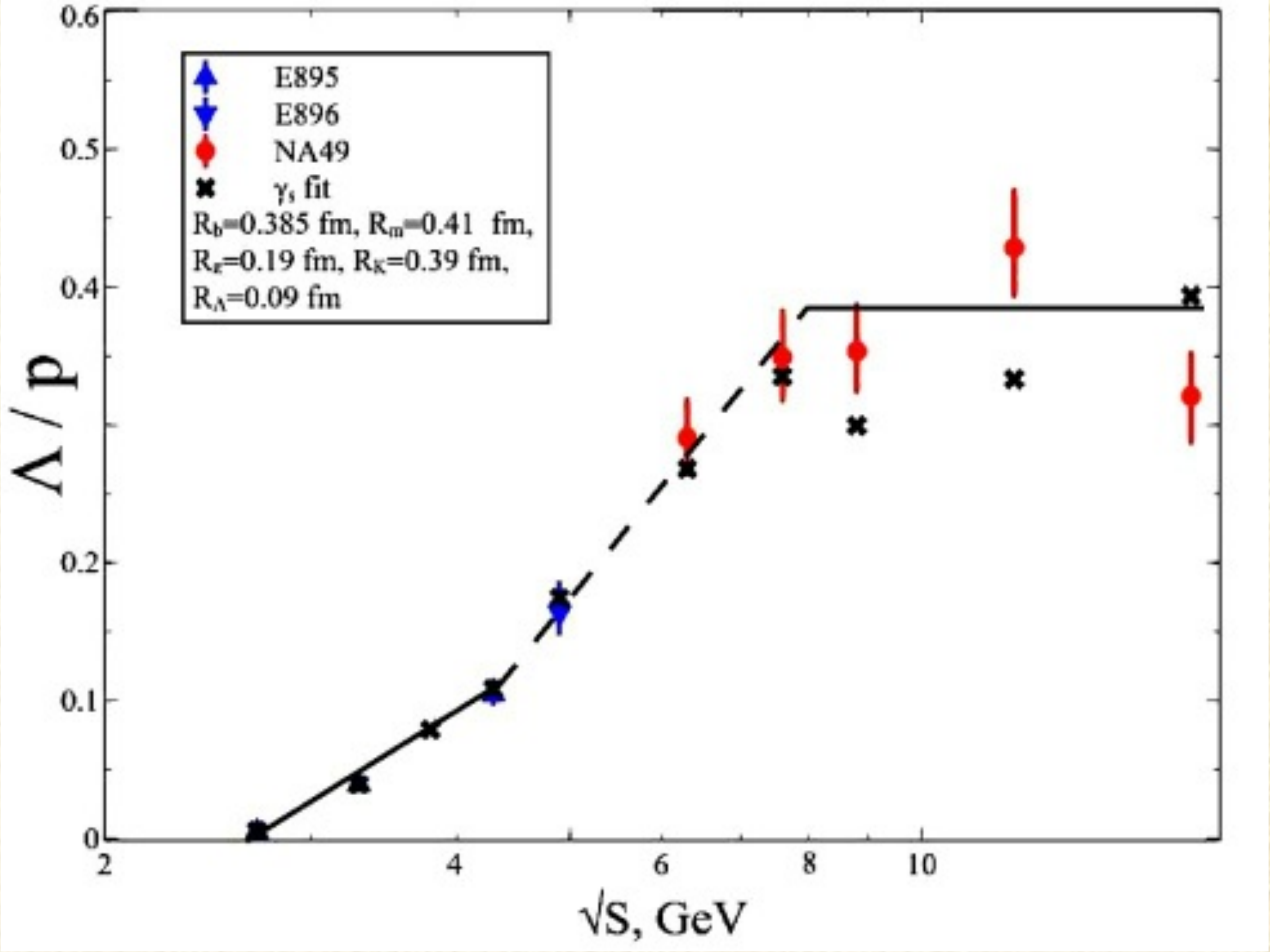
In 1982 J. Rafelski and B. Müller predicted that enhancement of strangeness production is a signal of deconfinement. Phys. Rev. Lett. 48(1982)

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

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

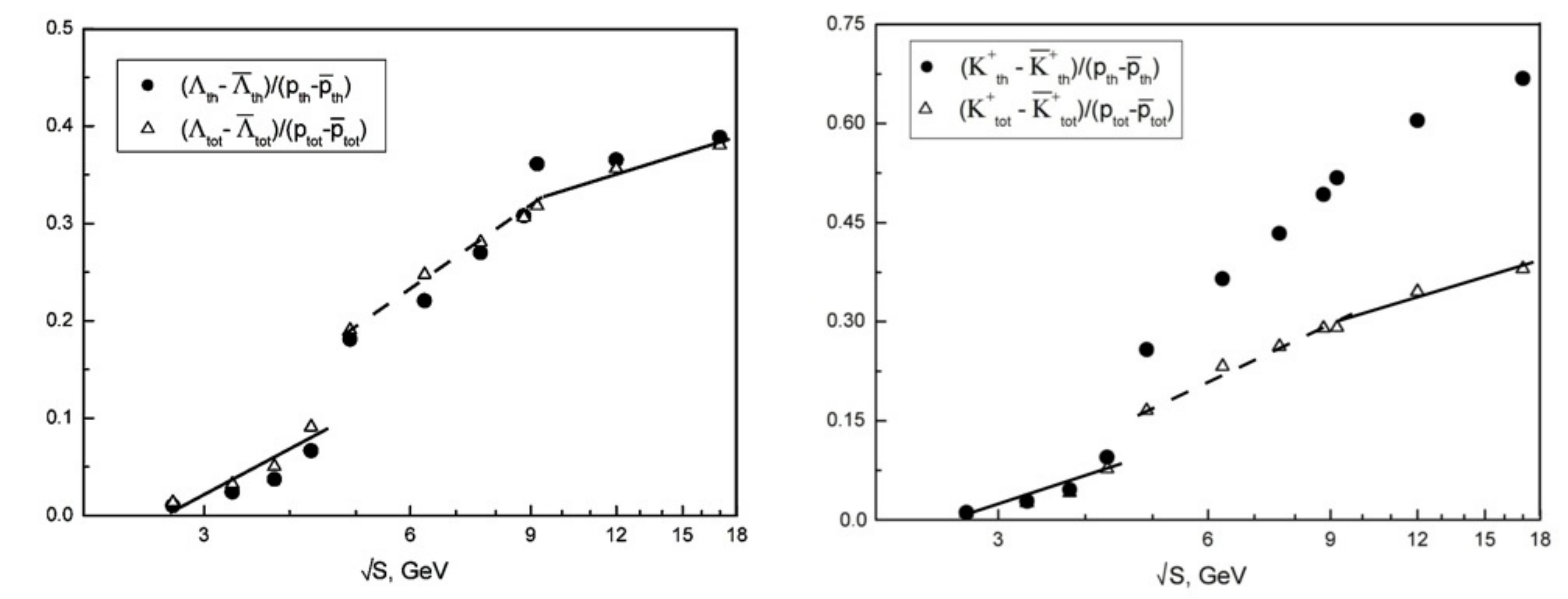
Below 4.3 GeV Lambdas appear in N+N collisions

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



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

What To Measure at FAIR & NICA ?



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

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

To locate the energy of SLOPE CHANGE we need MORE data at 7-13 GeV

Conclusions

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 25 years ago. The second set of plateaus may be a signal of another phase transition!?

3. Generalized shock adiabat model allowed us to describe entropy per baryon at chemical FO and determine the parameters of the QGP equation of state from the data.

4. The most interesting ranges of c.m. energies to probe at FAIR and NICA are 3.8-4.9 GeV and 10-13 GeV.

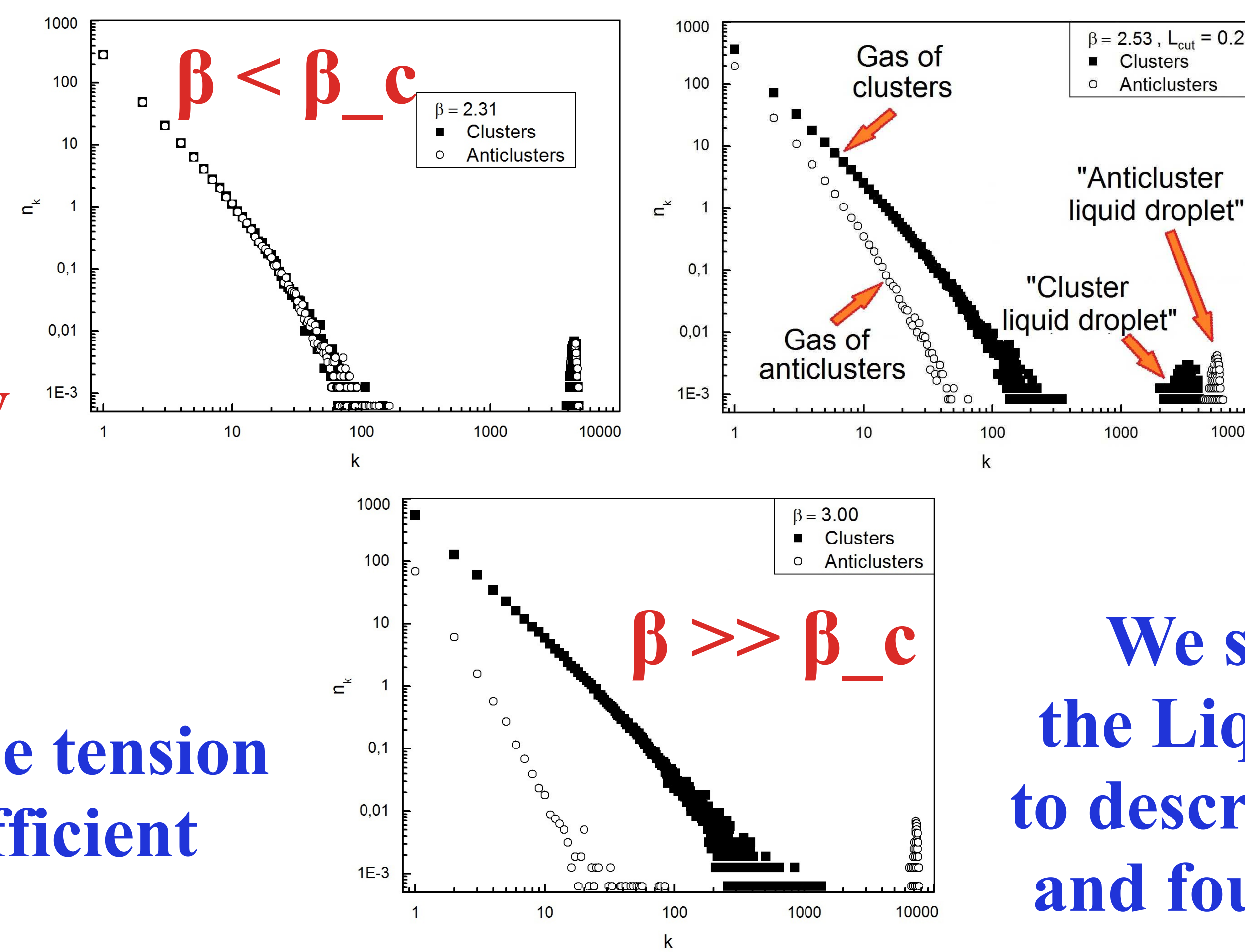
Announcement of Liquid Droplet Model for SU(2) Geometrical Clusters Formed by Polyakov Loops

A. Ivanytskyi, K.A. Bugaev et al., arXive 1606.04710 [hep-lat]

Polyakov loops - continuous spins, they form geometrical clusters: monomers, dimers, trimers, N-mers

Size distributions of (anti)clusters **β_c = 2.5115**

Spin UP and DOWN clusters have same distributions due to Z(2) symmetry



β > β_c

bulk free energy of cluster

surface tension coefficient

Distribution of clusters (A=cl) and anticlusters (A=acl)

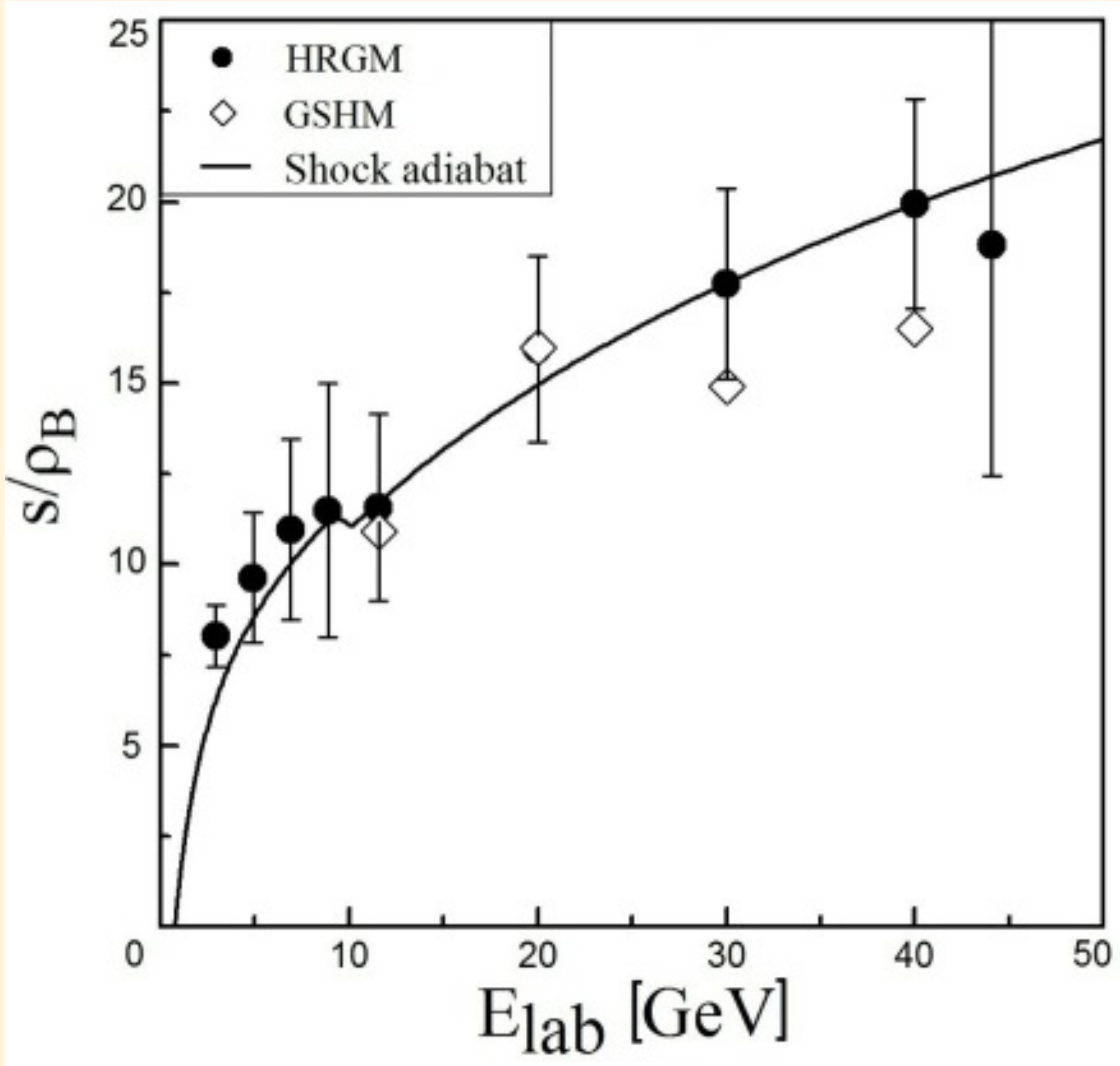
$$n_A^{th}(k) = C_A \exp\left(\mu_A k - \sigma_A k^{\varkappa} - \tau_A \ln k\right) ,$$

M. E. Fisher, Physics 3, 255 (1967).

We successfully applied the Liquid Droplet Formula to describe these distributions and found surface tension of gaseous (anti)clusters and Fisher topological exponent τ = 1.806

Thank You for Your Attention!

Stability of Entropy per Baryon at Ch. FO



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

GSHM: J. Letessier and J. Rafelski, Eur. Phys. J. A 35 (2008) 221.

Despite the difference, both models very well describe pions and baryons!