# Exploring the QCD Phase Diagram with Strangeness

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*The University of Arizona, Tucson, AZ*
Presented at INT –Seattle – October 13, 2016

# 1964/65: Two new fundamental ideas

- Quarks → Standard Model of Particle Physics
- Hagedorn Temperature → New State of Elementary Matter

Merging in 1979/80 into Quark-Gluon Plasma

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**Topics today:**

1. From Hagedorn temperature to heavy ion collisions
2. Strangeness
3. QGP discovery buzz
4. SHM data analysis
5. Phase diagram and the horn

## Hagedorn exponential mass spectrum: boundary of a new phase of matter



65/166/5 - TH. 520
25 January 1965

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

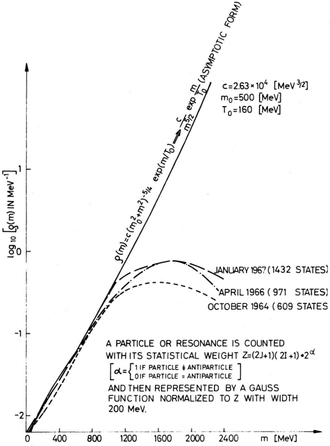
R. Hagedorn
CERN - Geneva

ABSTRACT

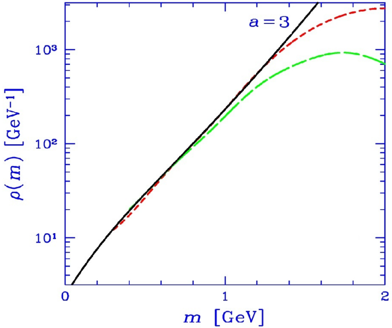
In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

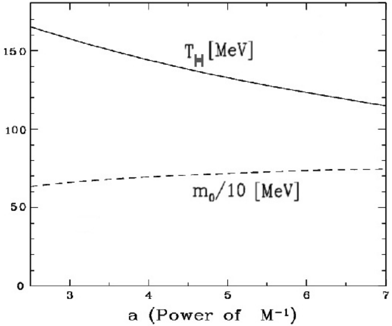
$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.} m^{-5/2} \exp\left(\frac{m}{T_0}\right).$$

$T_0$ is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_0^-$. $T_0$ is therefore the highest possible temperature for strong interactions. It should - via a Maxwell-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of hadrons (including e.m. form factors, etc.). There is experimental evidence for that, and then $T_0$ is about 158 MeV ($\approx 10^{12}$ °K). With this value of $T_0$ the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.



# Experimental mass spectrum defines $T_H$




To fix $T_H$ in a limited range of mass need prescribe value of $a$ obtained from SBM. In 1978 we noted that at $T_H$ sound velocity vanishes. This creates another way of fixing $T_H$ both in experiment and in lattice QCD and when this is done, the critical power $a$ is also determined.

# Hagedorn Temperature $T_{\mathrm{H}}$
# Singular point of partition function

$$Z_1(\beta,V) = \int \frac{2V_\mu^{\mathrm{ex}} p^\mu}{(2\pi)^3}\tau(p^2)\mathrm{e}^{-\beta_\mu p^\mu}\mathrm{d}^4 p\,.$$

Inserting $1 = \int \delta_0(m^2-p^2)\mathrm{d}m^2$

l replacing $\tau(m^2)\mathrm{d}m^2$ by $\rho(m)\mathrm{d}m$

$$Z_1(\beta,V) = \frac{V^{\mathrm{ex}}T}{2\pi^2}\int m^2\rho(m)K_2(m\beta)\mathrm{d}m\,.$$

$$Z_1(\beta,V) \underset{T\to T_0}{\sim} C\int_M^\infty m^{3/2-a}\mathrm{e}^{-(\beta-\beta_0)m}\mathrm{d}m + C\,.$$

$$Z_1(\beta,V) \underset{T\to T_0}{\sim} \begin{cases} C + C\Delta T^{a-5/2}\,, & a \neq 5/2 \\ C - \ln\dfrac{\Delta T}{T_0}\,, & a = 5/2 \end{cases}$$

| $a$ | $P$ | $n$ | $\varepsilon$ | $\delta\varepsilon/\varepsilon$ | $C_V = \mathrm{d}\varepsilon/\mathrm{d}T$ |
|---|---|---|---|---|---|
| 1/2 | $C/\Delta T^2$ | $C/\Delta T^2$ | $C/\Delta T^3$ | $C + C\Delta T$ | $C/\Delta T^4$ |
| 1 | $C/\Delta T^{3/2}$ | $C/\Delta T^{3/2}$ | $C/\Delta T^{5/2}$ | $C + C\Delta T^{3/4}$ | $C/\Delta T^{7/2}$ |
| 3/2 | $C/\Delta T$ | $C/\Delta T$ | $C/\Delta T^2$ | $C + C\Delta T^{1/2}$ | $C/\Delta T^3$ |
| 2 | $C/\Delta T^{1/2}$ | $C/\Delta T^{1/2}$ | $C/\Delta T^{3/2}$ | $C + C\Delta T^{1/4}$ | $C/\Delta T^{5/2}$ |
| 5/2 | $C\ln(T_0/\Delta T)$ | $C\ln(T_0/\Delta T)$ | $C/\Delta T$ | $C$ | $C/\Delta T^2$ |
| 3 | $P_0 - C\Delta T^{1/2}$ | $n_0 - C\Delta T^{1/2}$ | $C/\Delta T^{1/2}$ | $C/\Delta T^{1/4}$ | $C/\Delta T^{3/2}$ |
| 7/2 | $P_0 - C\Delta T$ | $n_0 - C\Delta T$ | $\varepsilon_0$ | $C/\Delta T^{1/2}$ | $C/\Delta T$ |
| 4 | $P_0 - C\Delta T^{3/2}$ | $n_0 - C\Delta T^{3/2}$ | $\varepsilon_0 - C\Delta T^{1/2}$ | $C/\Delta T^{3/4}$ | $C/\Delta T^{1/2}$ |

energy density diverges for $a < 7/2$. Thus only for $a < 7/2$ can we expect $T_0$ a maximum temperature.

From J.R. and R. Hagedorn: Thermodynamics of Hot Nuclear Matter in the Statistical Bootstrap Model 1979, in memorial volume.

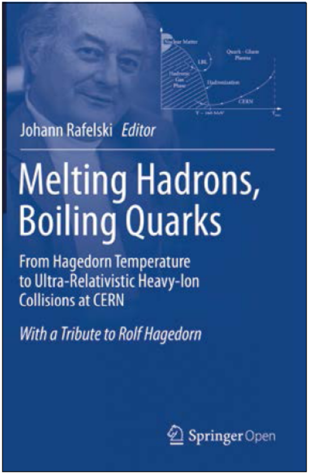
**Melting Hadrons, Boiling Quarks: From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN. With a Tribute to Rolf Hagedorn**

*By Johann Rafelski (ed.)*

**Springer**

The statistical bootstrap model (SBM), the exponential rise of the hadron spectrum, and the existence of a limiting temperature as the ultimate indicator for the end of ordinary hadron physics, will always be associated with the name of Rolf Hagedorn. He showed that hadron physics contains its own limit, and we know today that this limit signals quark deconfinement and the start of a new regime of strong-interaction physics.

This book is edited by Johann Rafelski, who was a long-time collaborator with Hagedorn and took part in many of the early conceptual developments of the SBM. It may perhaps be best characterised by pointing out what it is not. It is not a collection of review articles on the physics of the SBM and related topics, which could be given to newcomers as an introduction to the field. It is not a collection of reprints




relativistic heavy-ion programme at CERN that took place in the early 1980s. It starts with his thoughts about a possible programme of this kind, presented at the workshop on future relativistic heavy-ion experiments, held at the Gesellschaft fuer Schwerionenforschung (GSI). It also includes the draft minutes of the 1982 CERN SPC meeting, and some early works on strangeness production as an indicator for quark–gluon plasma formation, as put forward after many years by Rafelski.

The book is undoubtedly an ideal companion to all those who wish to recall the birth of one of the main areas of today's concepts in high-energy physics, and it is definitely a well-deserved credit to one of the great pioneers in their development.

● *Frithjof Karsch, Bielefeld University, Germany.*

# Bookshelf

# Research time-line: Quarks → QGP formation in RHICollision

- Cold quark matter in diverse formats from day 1: 1965
  D.D. Ivanenko and D.F. Kurdgelaidze, *Astrophysics* **1**, 147 (1965)
  *Hypothesis concerning quark stars*
- Interacting QCD quark-plasma: 1974
  P. Carruthers, *Collect. Phenomena* **1**, 147 (1974)
  *Quarkium: a bizarre Fermi liquid*
- Formation of quark matter in RHI collisions: 1978
  conference talks by Rafelski-Hagedorn (CERN)
  unpublished document (MIT web page) Chapline-Kerman
- Hot interacting QCD QGP: 1979 (first complete eval!)
  J. Kapusta, *Nucl. Phys. B* **148**, 461 (1979)*QCD at high temperature*
- Formation of QGP in RHI collisions 1979-80
  CERN Theory Division talks etc Hagedorn, Kapusta, Rafelski, Shuryak
- Experimental signature:
  Strangeness and Strange antibaryons 1980
  Rafelski (with Danos, Hagedorn, Koch (grad student), Müller
- Statistical materialization model (SHM) of QGP: 1982
  Rafelski (with Hagedorn, Koch(grad student), Müller

# First strangeness signature 1980: ratio of $\bar{s}/\bar{q}$ in $\overline{\Lambda}/\bar{p}$

What we intend to show is that there are many more $\bar{s}$ quarks than antiquarks of each light flavour. Indeed:

$$\frac{\bar{s}}{\bar{q}} = \frac{1}{2}\left(\frac{m_s}{T}\right)^2 K_2\left(\frac{m_s}{T}\right) e^{\mu/3T} \tag{28}$$

The function $x^2K^2(x)$ is, for example, tabulated in Ref. 15). For $x = m_s/T$ between 1.5 and 2, it varies between 1.3 and 1. Thus, we almost always have more $\bar{s}$ than $\bar{q}$ quarks and, in many cases of interest, $\bar{s}/\bar{q} \sim 5$. As $\mu \to 0$ there are about as many $\bar{u}$ and $\bar{q}$ quarks as there are $\bar{s}$ quarks.

FROM HADRON GAS TO QUARK MATTER II

J. Rafelski
Institut für Theoretische Physik
der Universität Frankfurt

and

R. Hagedorn
CERN--Geneva

Ref.TH.2969-CERN
13 October 1980



ABSTRACT

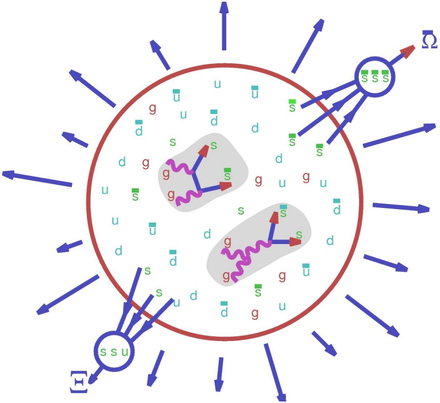
We describe a quark-gluon plasma in terms of an many questions remain open. A signature of the quark-gluon phase surviving hadronization is suggested.

Johann Rafelski, and Rolf Hagedorn, "From hadrons to quark matter II,"*Statistical mechanics of quarks and hadrons* proceedings of Bielefeld, August 24-31, 1980 / edited by **Helmut Satz**

Johann Rafelski, "Extreme States of Nuclear Matter," a Invited lecture at Quark Matter 1: *Workshop on Future Relativistic Heavy Ion Experiments,* held at GSI, Darmstadt, Germany, 7-10 October 1980; printed in: GSI81-6 Orange Report, pp. 282-324, R. Bock and R. Stock, editors.


⟶JR 1980;1982 JR,Berndt Müller; 1986 P. Koch

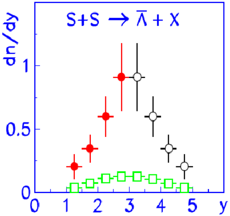
**Cooking strange quarks → strange antibaryons**

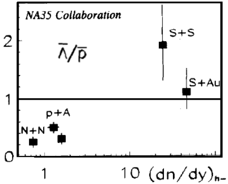


# A first meeting September 1988 with RHI data

it Hadronic Matter in Collision, Tucson, September 1988 – in the picture Wit Busza, Marek Gazdzicki, Roy Glauber, Mark Gorenstein, Hans Gutbrod, Berndt Muller, Stanislaw Mrowczynski, Emanuele Quercigh, Chris Quigg, Jan Rafelski, Gena Zinoview, and many more, and some who are in our memory: Peter Carruthers, Mike Danos, Maurice Jacob, Bob Thews, Leon VanHove.

# Joint MG+JR S+S analysis paper 1994: features $\overline{\Lambda}/\bar{p}$




$\overline{\Lambda}/\bar{p}$-ratio near midrapidity in proton-proton, minimum bias proton-nucleus and central nucleus-nucleus collisions at 200 GeV per nucleon as a function of the rapidity density of negatively charged hadrons at midrapidity.

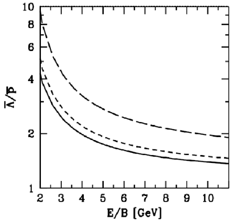
*Physics Letters B 366 (1996) 56–62* Fig. 3. p61 inclusion of secondary processes at a partonic and/or hadronic level is needed to explain the data. The string-hadronic RQMD model including secondary collisions underestimates the $\overline{\Lambda}$ production in central S+S collisions at 200 GeV per nucleon by a factor of 5 and the $\bar{p}$ yield by a factor of about 3 [1].

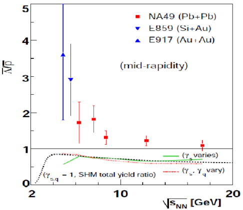
Attempts to describe the antibaryon yields within the RQMD model require the introduction of a new production mechanism beyond hadronic rescattering.

*J. Rafelski, Arizona* *Quarks in the Universe* *December 7, 2006, MLL-München,* *page* 11

**Ratio anomaly predicted 1980, status 2006: $\overline{\Lambda}/p > 1$**

$$\left.\frac{\overline{\Lambda}}{\bar{p}}\right|_{\rm QGP} = \frac{N_{\bar s}N_{\bar u}N_{\bar d}}{N_u N_u N_{\bar d}} \simeq \frac{\gamma_s^{\rm QGP}}{\gamma_q^{\rm QGP}}\left[\frac{1}{2}\frac{m_s^2}{T_h^2}K_2(m_s/T)\right] e^{(\mu_{\bar u}^{\rm QGP}-\mu_{\bar s}^{\rm QGP})/T} \rightarrow 0.9\, e^{\mu_{\bar u}^{\rm QGP}/T}$$




## Chemical freeze-out conditions in central S-S collisions at 200 *A* GeV

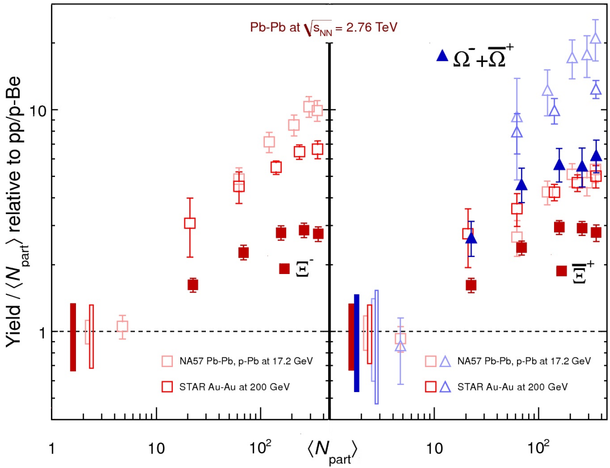
Josef Sollfrank[1], Marek Gaździcki[2,*], Johann Rafelski[3]

Received 5 August 1993;
ZEITSCHRIFT FÜR PHYSIK C
Z. Phys. C 61, 659–665 (1994)

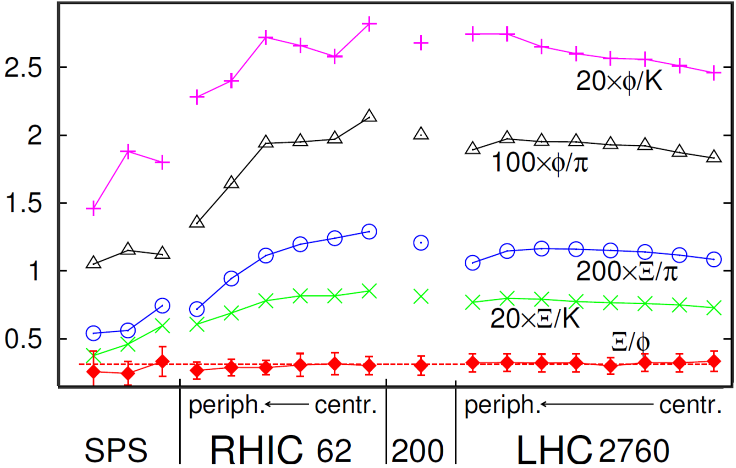


**Abstract.** We determine the chemical freeze-out parameters of hadronic matter formed in central S-S collisions at 200 A GeV, analyzing data from the NA35 collaboration at CERN. In particular we study the quark (baryon number) and strange quark fugacities, as well as the strange quark phase-space occupancy and the freeze-out temperature.

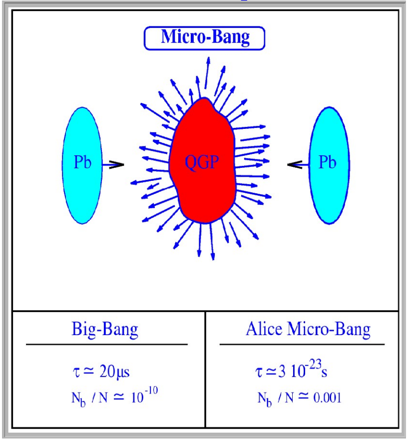
# Largest medium effect: Strange antibaryons



# Origin: Strangeness density at hadronization high strangeness abundance doubled



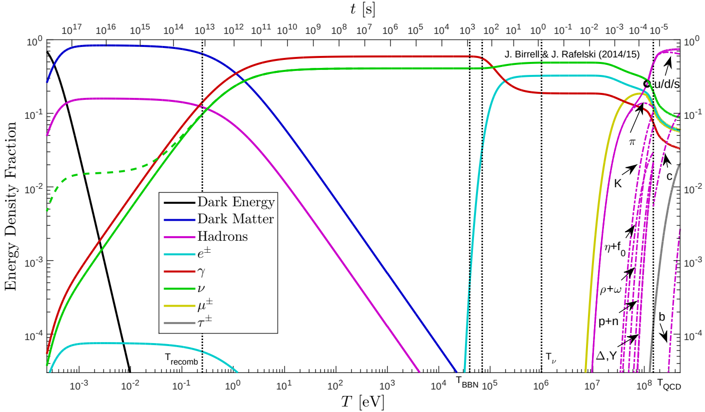
# Relevance: Cosmology Connection to Relativistic Heavy Ion Collisions




- Universe time scale 18 orders of magnitude longer, hence equilibrium of leptons & photons
- Baryon asymmetry six orders of magnitude larger in Laboratory, hence chemistry different
- Universe: dilution by scale expansion, Laboratory explosive expansion of a fireball

$\Longrightarrow$ Theory connects RHI collision experiments to Universe

# The Universe Composition Changes



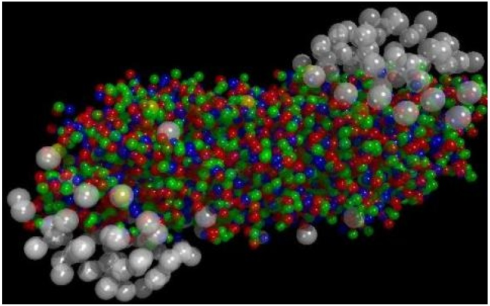

dark energy matter radiation $\nu, \gamma$ leptons hadrons

$\Longrightarrow$ Different dominance eras

# CERN press office

## New State of Matter created at CERN

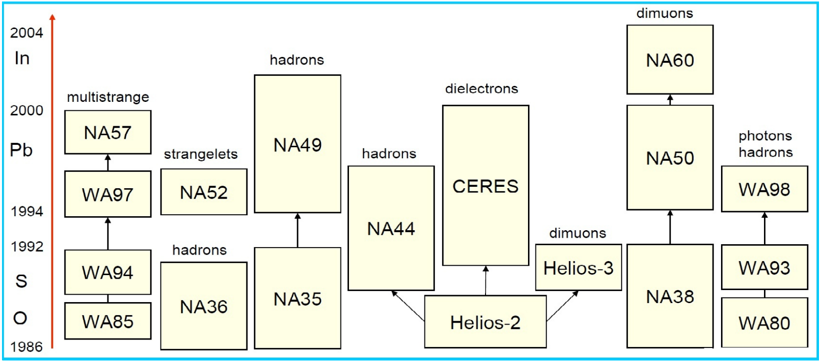
10 Feb 2000



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

**Global view on many properties observed**

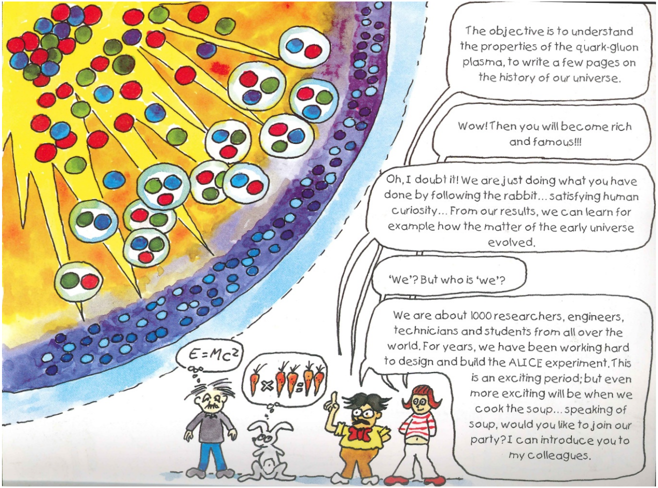
# CERN RHI experimental SPS program spans a wide range of observables



# 9AM, 18 April 2005; US – RHIC announces QGP Press conference APS Spring Meeting


New signatures show today a flow and quench smooth from SPS to RHIC to Alice: There is one and the same deconfined state of quarks and gluons

# LHC-Alice enters:



(FERMI-KOPPE) STATISTICAL HADRONIZATION MODEL (SHM) Very strong interactions: equal hadron production strength irrespective of produced hadron type particle yields depending only on the available phase space

- Fermi: Micro-canonical phase space
  sharp energy and sharp number of particles
  E. Fermi, Prog.Theor.Phys. 5 (1950) 570: SINCE
- Hagedorn: Large number of particles: use ensemble average energy $E \to T$ AND
- with hesitance use in $pp$ collisions of ensemble average over particles $N \to \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$
- Rafelski-Danos: (PLB 97, 279 (1980)) canonical suppression when particle numbers (strangeness) small

Our interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated spectra. IMPLEMENTATION: SHARE G. Torrieri et al, Comput. Phys. Commun. 167, 229 (2005), ibid 175, 635 (2006) ibid 185, 2056 (2014)

# QGP+ Statistical Hadronization Model =Hadron Gas Abundances without Hadron Gas

## Why the hadronic gas description of hadronic reactions works: the example of strange hadrons

P. Koch and J. Rafelski
Institute of Theoretical Physics and Astrophysics, University of Cape Town, Rondebosch

The degree to which, in hadronic reactions, the strangeness quark flavour is equilibrated in its abundance with the light quarks' flavours is proposed as a measure of the relevance of gluonic degrees of freedom in hadronic reactions. The transitory presence of gluons manifests itself by generating strange quark abundance near the hadronic gas equilibrium in pp and pN reactions. Nucleus–nucleus collisions below 5 GeV/n appear to be in the regime of individual nucleon collisions in which the intrinsic QCD degrees of freedom are frozen. In consequence, the measured strangeness abundance in these nuclear collisions falls short of the values expected from the hadronic gas equilibrium. Should the quark–gluon plasma state be formed at higher energies, the signal for this process would be the equilibration of total strangeness abundance almost as if an equilibrated hadronic gas had been formed. Anomalies in the abundance of strange antibaryons remain the characteristic and global signal of plasma state formation.

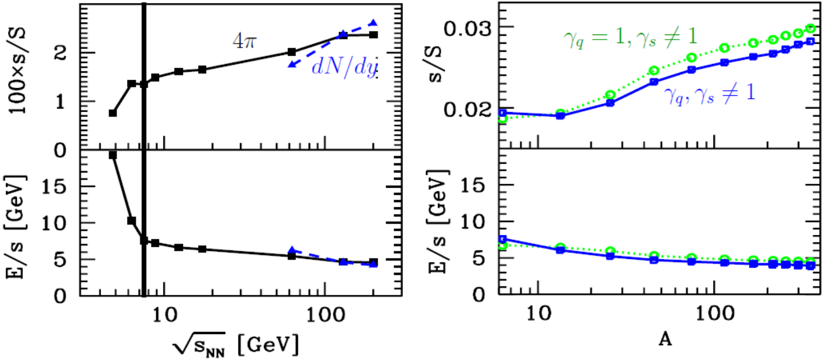
*S. Afr. J. Phys.* 9 (1986) 8–23

### 1. Introduction

The observation that soft multihadron production ($p_\perp <$ 1 GeV) shows many features of an underlying statistical reaction mechanism has inspired Hagedorn's Statistical Bootstrap [1, 2] long before anything about quantum chromodynamics (QCD) was known. But since QCD has been accepted as the underlying gauge field theory of strong interactions, it seems today rather 'oldfashioned' to treat high energetic hadronic collisions in the framework of phenomenological statistical models. A contrary understanding may be adopted following the present discussion. Our point of view is that the transitory formation of a quark–gluon plasma-like state is the prerequisite in order that statistical models can be used. The number of accessible states in hadronic reactions may be many times larger than a naive hadronic phase space counting indicates and a statistical description may indeed also be necessary in order to describe

South African Journal Physics **9** 8-23 (1986)

# Data analysis 2003-2008 as a function of $\sqrt{s_{NN}}$ and $A$

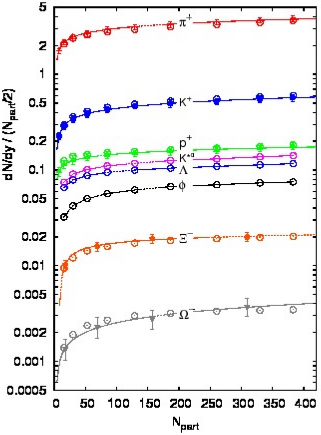


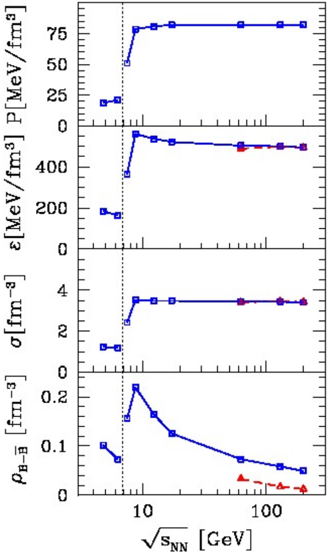

Left: Energy dependence; Right: Centrality dependence

Interest in (thermal) energy cost of strangeness pair $E/s$ as it should show appearance of a more effective strangeness production reaction mechanism. See EPJA 35, 221 (2008) & PRC 72, 024905 (2005), ibid 73, 014902 (2006)

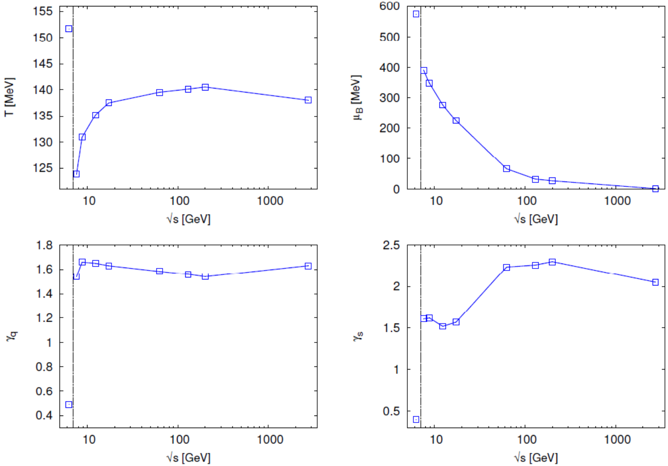
**AGS,SPS,RHIC bulk properties⇒**

**⇓Fit to ALICE data⇓**

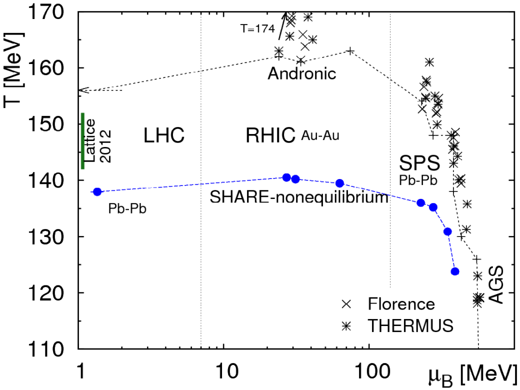


# Comparison Across Energy SPS-RHIC-LHC: SHM parameters



# Consistency with Lattice-QCD




Chemical freeze-out MUST be below lattice results. For direct free-streaming hadron emission from QGP, $T$-SHM is the QGP source temperature, there cannot be full chemical equilibrium.

# Strangeness enhancement: relative to entropy $s/S$

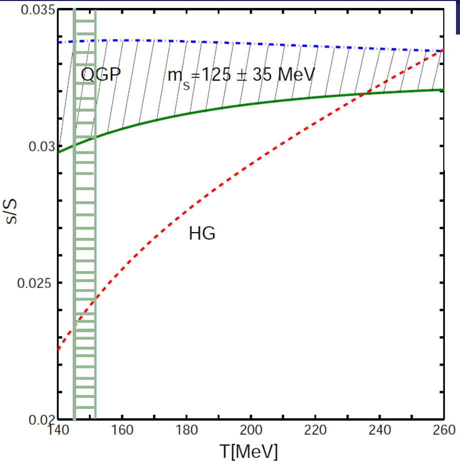
Relative $s/S$ yield measures the number of relaxed active degrees of freedom and the degree of relaxation when strangeness production freezes-out. Perturbative expression in chemical equilibrium:

$$\frac{s}{S} = \frac{\frac{g_s}{2\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{(g2\pi^2/45)T^3 + (g_s n_{\rm f}/6)\mu_q^2 T} \simeq \frac{1}{35} = 0.029$$

much of $\mathcal{O}(\alpha_s)$ interaction effect largely cancels out, estimate of effect raises ratio $s/S \to 1/31 = 0.0323$. Now introduce QGP nonequilibrium

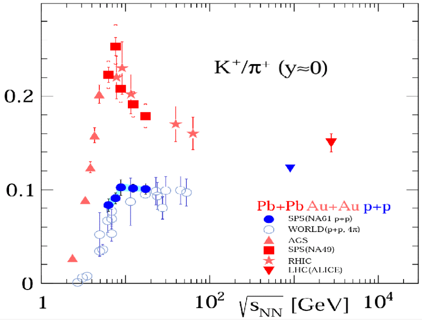
$$\frac{s}{S} = \frac{0.03\gamma_s^{\rm QGP}}{0.4\gamma_{\rm G} + 0.1\gamma_s^{\rm QGP} + 0.5\gamma_q^{\rm QGP} + 0.05\gamma_q^{\rm QGP}(\ln\lambda_q)^2} \to 0.03\gamma_s^{\rm QGP}.$$

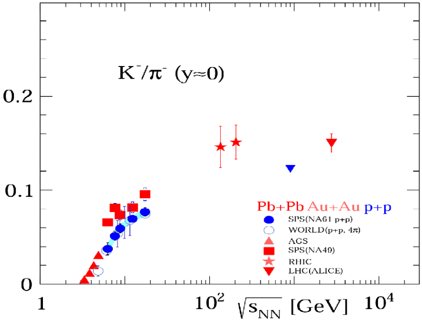
# Two phases




I. Kuznetsova and J. Rafelski, “Heavy flavor hadrons in statistical hadronization of strangeness-rich QGP” EPJC 51, 113 (2007) Phase transformation domain from S. Borsanyi, “Thermodynamics of the QCD transition from lattice,”NPA A 904–905, (2013) 270c arXiv:1210.6901]

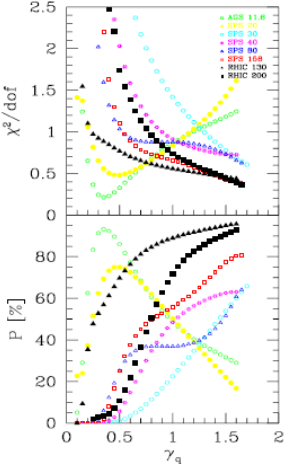
# Marek's Discovery: The HORN is doing well today



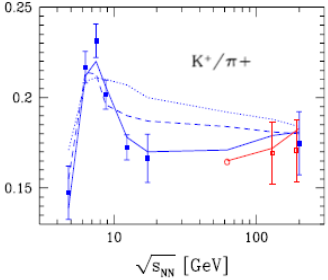

Evidence of drastic change in matter properties – far from equilibrium hadrons turn at the peak into a quark-gluon plasma ball in near equilibrium. Use of non-equilibrium physics essential in understanding the Horn and understanding the threshold of QGP formation.

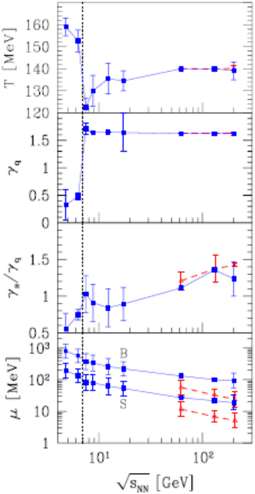
# Use of nonequilibrium and the rôle of $s/S$= strangeness/multiplicity



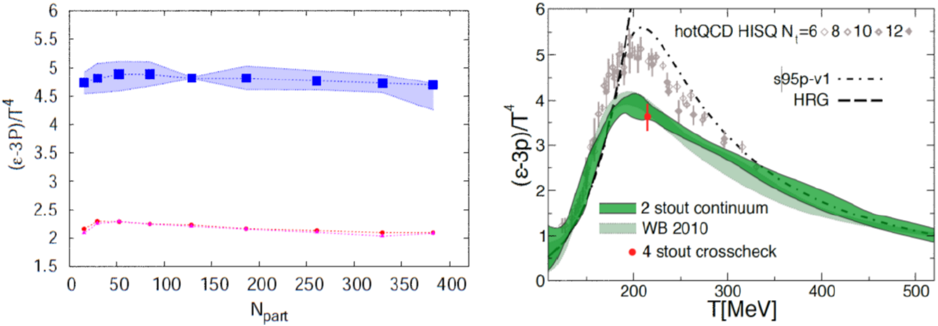

## To describe the horn we need $\gamma_q \neq 1$

Looking a the fit $\chi^2$ we see that between 20 and 30GeV results favor that $\gamma_q$ jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The individual fits relevant to understanding how the horn is created have good quality - see $P\%$.



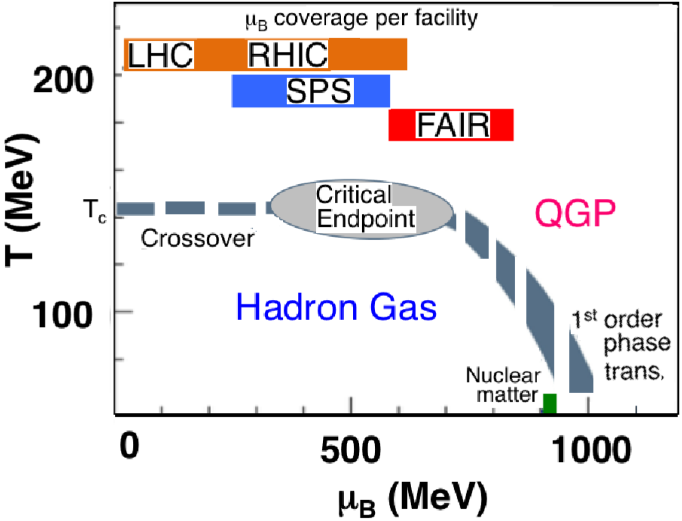



## Interaction measure/trace anomaly




SHM measured trace anomaly for LHC-Alice, fit results as function of centrality. The top band obtained with $\gamma_q > 1$, bottom lines assuming $\gamma_q = 1$, correspond to a hadron resonance gas (HRG) value. Right: Lattice QCD trace anomaly as function of a temperature parameter from, Borsanyi 2013 Loc. Cit.

# Our future: exploration of the phases of QGP in $T, \mu_B$



# Summary

- 50 years ago particle production in $pp$ reactions prompted introduction of Hagedorn Temperature $T_H$; soon after recognized as the critical temperature at which matter surrounding us dissolves into the fundamental phase of quarks and gluons – the QGP.
- Global effort to discover QGP - followed. I speak for my expertise: Strangeness played a pivotal role, confirmed; QGP consistency. Some people will keep arguing mainly for lack of information: ...
- ...overall there is little doubt that the totality of evidence is evidence for a Strange-rich QGP phase of primordial matter; each small item in the long list can be explained in some other way but all of the list emerges in a simple new paradigm.
- In near future fixed target program at RHIC using well developed detectors can scan baryon rich deconfined phase of matter. Discoveries will determine where the field goes.