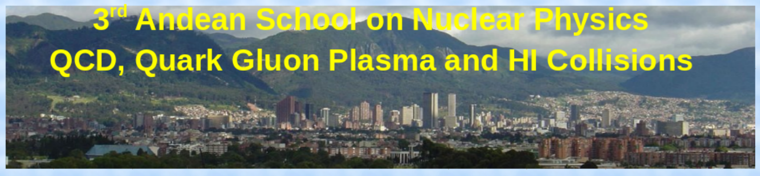


Three Lectures on

Strangeness Signatures of Quark-Gluon Plasma

Johann Rafelski
Department of Physics, The University of Arizona

July 26, 27, 28, 2017

Vocabulary: y; RHI; BNL; RHIC; CERN; SPS; LHC;...

CREDITS: Results obtained in collaboration with
Jeremiah Birrell, Inga Kuznetsowa, Michal Petran, Giorgio Torrieri

Former Graduate Students at The University of Arizona

Objective of Lecture I

1. RECREATE THE EARLY UNIVERSE IN LABORATORY:
   Survey the research program development from early day and describe in historical perspective how we got to recognize a characteristic signature – strangeness and differentiate the different main ideas.
2. PROBING OVER A LARGE DISTANCE THE CONFINING VACUUM STRUCTURE
3. STUDY OF THE ORIGIN OF MASS OF MATTER
4. OPPORTUNITY TO PROBE ORIGIN OF FLAVOR?

50 years ago 1964/65: Coincident Beginning

- Quarks + Higgs $\rightarrow$ Standard Model of Particle Physics
- Hagedorn Temperature, Statistical Bootstrap
  $\rightarrow$ QGP: A new elementary state of matter

Topics today:

1. Convergence of 1964/65 ideas and discoveries:
   understanding back to 10 ns our Universe
2. Roots of QGP: from Hagedorn T_{H} $\rightarrow$ Big Bang; to
3. QGP on Laboratory & Discovery
4. Strangeness in QGP: a sample of ideas and results
5. A short outlook

1964: Quarks + Higgs → Standard Model

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

G. Zweig *)
CERN - Geneva

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time

A schematic model of baryons and mesons

M. Gell-Mann

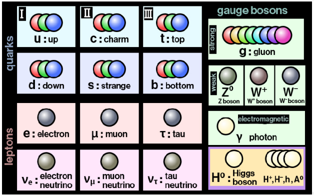
California Institute of Technology, Pasadena, California, USA

Received 4 January 1964,

Physics Letters

Volume 8, Issue 3,

1 February 1964, Pages 214–215



Nearly 50 years after its prediction, particle physicists have finally captured the Higgs boson.

Mass

Broken Symmetries and the Masses of Gauge Bosons

Peter W. Higgs

Phys. Rev. Lett. 13, 508 (1964)

Published October 19, 1964

Broken Symmetry and the Mass of Gauge Vector Mesons

F. Englert and R. Brout

Phys. Rev. Lett. 13, 321 (1964)

Published August 31, 1964

Hagedorn Temperature October 1964 in press:
Hagedorn Spectrum January 1965 $\Rightarrow$ March 1966

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

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

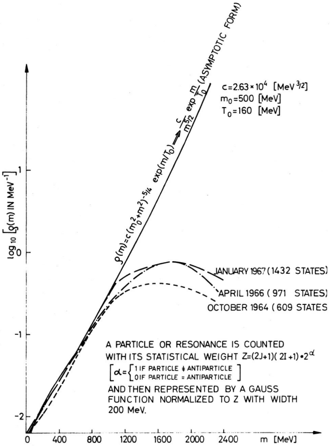
R. Hagedorn
CERN - Geneva

A B S T R A C T

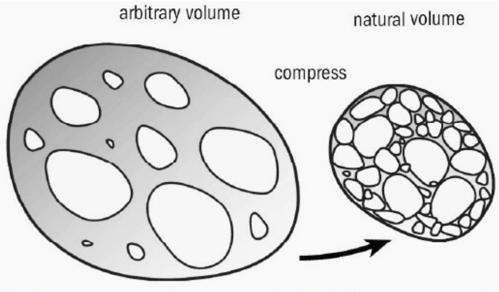
In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those 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.



What is the Statistical Bootstrap Model (SBM)?



A volume comprising a gas of fireballs compressed to natural volume is itself again a fireball.

$$\tau(m^2)\mathrm{d}m^2 \equiv \rho(m)\mathrm{d}m \quad \rho(m) \propto m^{-a}\exp(m/T_{\mathrm{H}}).$$

Exponential Mass Spectrum
We search and discover new particle checking this extreme idea

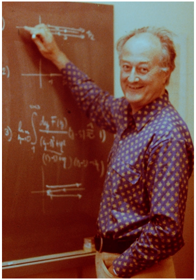
by 1967 – Hagedorn's SBM: Statistical Bootstrap Model
'the' initial singular Hot Big-Bang theory

Actes de la Société Helvétique des Sciences Naturelles.
Partie scientifique et administrative 148 (1968) 51
Persistenter Link: http://dx.doi.org/10.5169/seals-90676

Siedende Urmaterie

R. HAGEDORN, CERN (Genève)

Wenn auch niemand dabei war, als das Universum entstand, so erlauben uns doch unsere heutigen Kenntnisse der Atom-, Kern- und Elementarteilchenphysik, verbunden mit der Annahme, dass die Naturgesetze unwandelbar sind, Modelle zu konstruieren, die mehr und mehr auf mögliche Beschreibungen der Anfänge unserer Welt zusteuern.



Boiling Primordial Matter *Even though no one was present when the Universe was born, our current understanding of atomic, nuclear and elementary particle physics, constrained by the assumption that the Laws of Nature are unchanging, allows us to construct models with ever better and more accurate descriptions of the beginning.*

Hagedorn Temperature T_H
Singular point of partition function

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

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

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

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

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

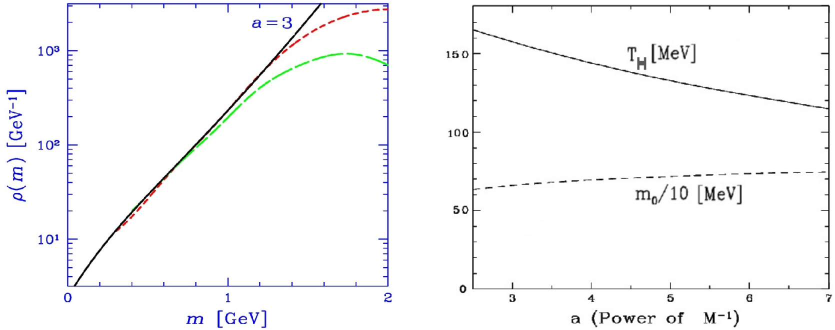
$$Z_1(\beta,V)\underset{T\to T_0}{\sim}\begin{cases} C+C\Delta T^{a-5/2}\,, & a\neq 5/2\\ C-\ln\dfrac{\Delta T}{T_0}\,, & a=5/2\end{cases}$$

a	P	n	ε	$\delta\varepsilon/\varepsilon$	$C_V=\mathrm{d}\varepsilon/\mathrm{d}T$
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	$P_0-C\Delta T$	$n_0-C\Delta T$	ε_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.

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.

CERN Courier June 2016

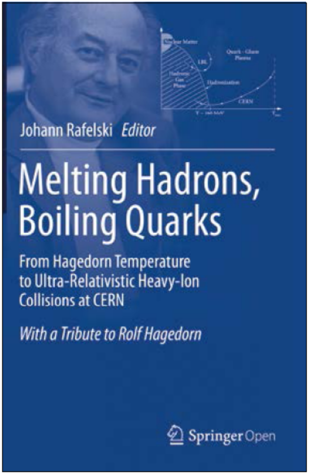
Melting Hadrons, Boiling Quarks: From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN. With a Tribute to Rolf Hagedorn

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.

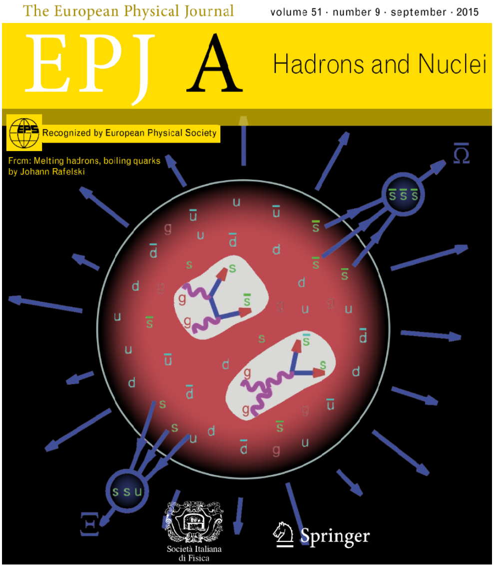
The book is undoubtedly an ideal companion to all those who wish to recall the birth of one of the main areas of today's concepts in high-energy physics, and it is definitely a well-deserved credit to one of the great pioneers in their development.

● *Frithjof Karsch, Bielefeld University, Germany.*

Bookshelf

My expertise:

Cooking strange quarks $\rightarrow$ strange antibaryons etc



APS car sticker from period

Birth of QGP/RHI formation: CERN theory division 1977-80

- 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-matter: 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

QGP has fleeting presence in laboratory

We need to Diagnosis and Study QG properties at 10^{-23} s scale

Diletpons and photons 1970's: 'weakly' coupled probes: access to early staged masked by abundant secondary production.

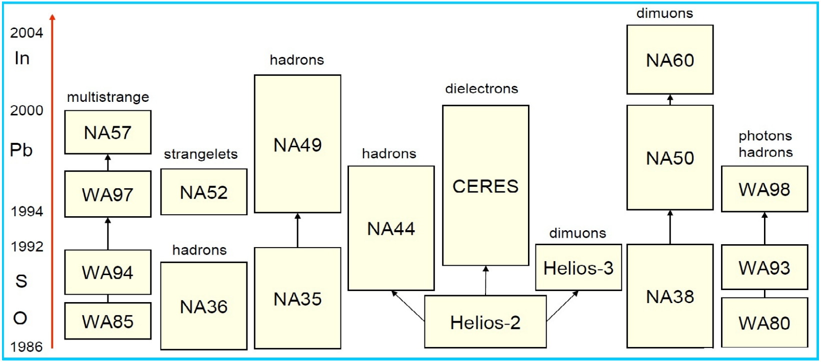
J/Ψ suppression 1986: 'one measurement', ongoing and evolving interpretation.

Jet quenching 1983: signal of dense matter (not very characteristic)

Dynamics of quark matter flow : demonstrates presence of collective quark matter dynamics

Strange quark strongly interacting probes: a diverse set of observables addressing both initial and final stages of the fireball: Strangeness enhancement (1980), Strange antibaryon enhancement (1982), Strange resonances (2000); all this generalizes to heavy flavor (c, b) with and without strangeness.

CERN RHI experimental SPS program is born 1980-86

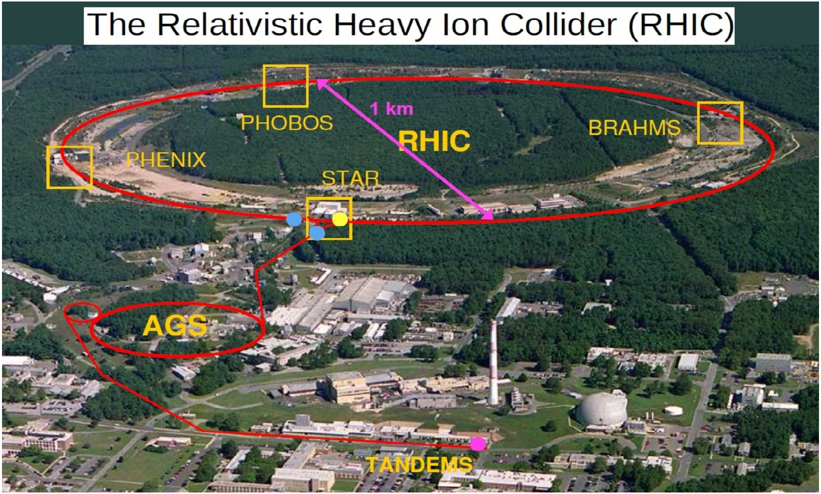


SPS and later LHC for heavy ions

A picture to remember: Hadrons in Collision, Tucson 1988 - Arguably a first meeting with Heavy Ion Data

Do you know anyone seen in this family picture?

A new 'large'collider is build at BNL: 1984-2001/operating today



First question; is there a fireball of matter?
Two extreme views on stopping in RHI collisions

Fly-through

PHYSICAL REVIEW D VOLUME 22, NUMBER 11 1 DECEMBER 1980

Central collisions between heavy nuclei at extremely high energies: The fragmentation region

R. Anishetty*
Physics Department, University of Washington, Seattle, Washington 98195

P. Koehler and L. McLerran†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 11 August 1980)

We discuss central collisions between heavy nuclei of equal baryon number at extremely high energies. We make a crude estimation of the energy deposited in the fragmentation regions of the nuclei. We argue that the fragmentation-region fragments thermalize, and two hot fireballs are formed. These fireballs would have rapidities close to the rapidities of the original nuclei. We discuss the possible formation of hot, dense quark plasmas in the fireballs.

The collisions of very-high-energy nuclei are likely to be the subject of intense experimental investigation in the next few years.

We shall discuss the theory of such collisions in this paper. We shall concentrate on describing central collisions between nuclei of equal baryon number.

The fragmentation regions of the nuclei represent an area of phase space where new phenomena might occur. "Fragmentation region" refers to the region of phase space of particles where the particles have longitudinal momentum close to that of the original nucleus projectile or target. In the fragmentation region, the nucleus fragments and inelastically produced particles might form a hot, dense fireball. We shall soon see that this forma-

full stopping

Volume 97B, number 1 PHYSICS LETTERS 17 November 1980

HOT HADRONIC MATTER AND NUCLEAR COLLISIONS ☆

R. HAGEDORN
CERN, Geneva, Switzerland

and

J. RAFELSKI [1]
CERN, Geneva, Switzerland
and Institut für Theoretische Physik der Universität, D-6000 Frankfurt a/M, Fed. Rep. Germany

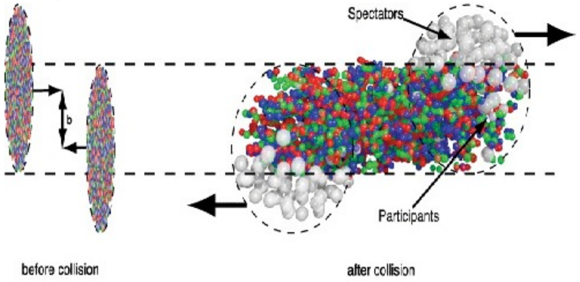
Received 22 August 1980

we develop a description of hadronic matter with particular emphasis on hot nuclear matter as created in relativistic heavy ion collisions. We apply our theory to calculate temperatures and of hadronic fireballs.

Two opposite views: SPIRES 262 and 231 citations today.

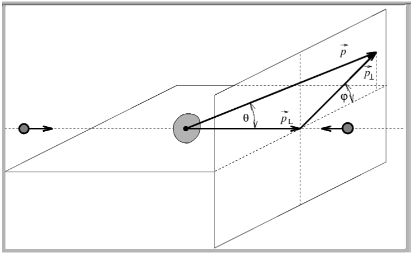
Experiment: Look at particle yields as function of y ($p_\perp$-integrated spectra)

Particle yields allow exploration of the source bulk properties in the co-moving frame – collective matter flow dynamics integrated out. This avoids the dynamical mess:



One of our key interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze fully integrated spectra (also integrated in y).

ABC of relativistic kinematics ($c = 1$)



$$E = \sqrt{m^2 + \vec{p}_\perp^{\,2} + p_L^2} = \sqrt{m_\perp^2 + p_L^2},$$

$$m_\perp = \sqrt{m^2 + \vec{p}_\perp^{\,2}},$$

$$p_L \equiv m_\perp \sinh y, \to E = m_\perp \cosh y,$$

$$\to \quad v_L \equiv \frac{c p_L}{E} = c \tanh y$$

$$y = \frac{1}{2}\ln\left(\frac{1+v_L}{1-v_L}\right) = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right) = \ln\left(\frac{E+p_L}{m_\perp}\right); \quad \cosh y = \frac{1}{\sqrt{1-v_L^2}} \equiv \gamma_L,$$

The longitudinal momentum p_L of a particle depends in a nonlinear way on the velocity. The rapidity y is additive under successive Lorentz transformations along the same direction. With

$$\cosh y_c = \gamma_c, \quad \sinh y_c = \gamma_c v_c \quad E' = \gamma_c(E + v_c p_L), \quad p_L' = \gamma_c(p_L + v_c E).,$$

$$\to \; E' = m_T \cosh(y + y_c), \quad p_L' = m_T \sinh(y + y_c).$$

Non-identified particles and pseudorapidity

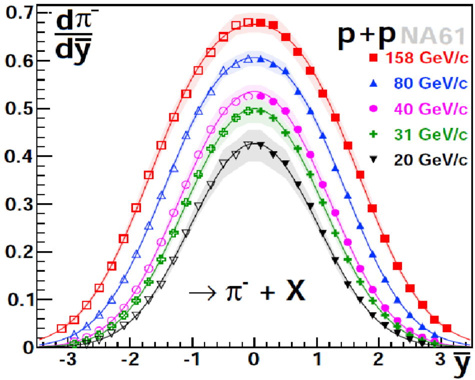
Often we do not know what is the mass of the particle observed. For relativistic particles $E = \sqrt{p^2 + m^2} \to p$, so often the value of m will not matter. When m is ‘small’ we introduce pseudorapidity η:

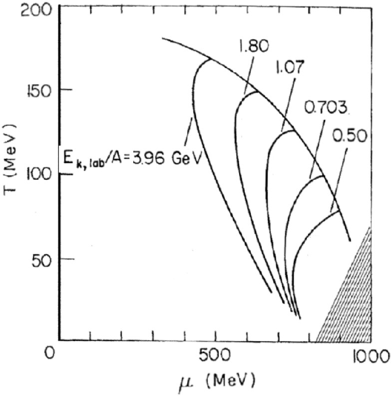
$$p = p_\perp \cosh\eta, \qquad p_L = p_T \sinh\eta,$$

$$y(m \to 0) \to \eta = \frac{1}{2}\ln\left(\frac{p + p_L}{p - p_L}\right) = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = \ln\left(\cot\frac{\theta}{2}\right).$$

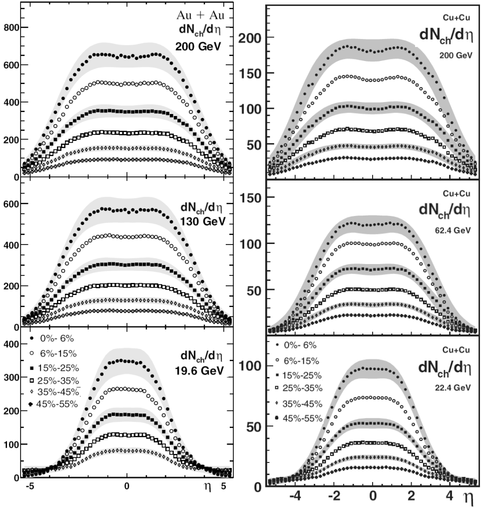
θ is the particle-emission angle relative to the beam axis. Thus we obtain a remarkably simple way to measure pseudorapidity spectra when mass m can be neglected this is also the rapidity y.

Two views of full stopping (Fig 2a HR reflected)





RHIC-PHOBOS stopping experiment (no part. ID)



Strangeness - a popular QGP diagnostic tool

EXPERIMENTAL REASONS

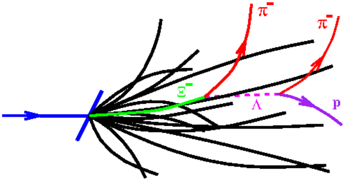
A: There are many strange particles allowing to study different physics questions $(q = u, d)$:

$$K(q\bar{s}),\quad \overline{K}(\bar{q}s),\quad K^*(890),\quad \Lambda(qqs),\quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),\quad \Lambda(1520)$$

$$\phi(s\bar{s}),\quad \Xi(qss),\quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}),\quad \Omega(sss),\quad \overline{\Omega}(\bar{s}\bar{s}\bar{s})$$

B: Production rates hence statistical significance is high

C: Strange hadrons are subject to a self analyzing decay within a few cm from the point of production (more detail in⇓)



Hadrons and Quark–Gluon Plasma

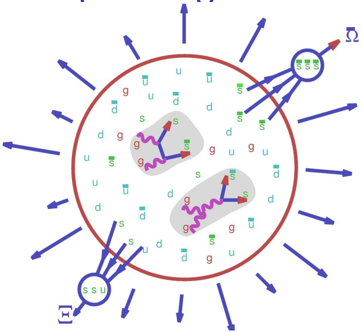
Series: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology (No. 18)

Jean Letessier
Université de Paris VII (Denis Diderot)

Johann Rafelski
University of Arizona

Hardback (ISBN-13: 9780521385367 | ISBN-10: 0521385369) Also available in Paperback | Adobe eBook

Two-step strange hadron formation



1. $GG \rightarrow s\bar{s}$ (thermal gluons collide)
   $GG \rightarrow c\bar{c}$ (initial parton collision)
   gluon dominated reactions
2. hadronization of pre-formed $s,\ \bar{s},\ c,\ \bar{c},\ b,\ \bar{b}$ quarks

Evaporation-recombination formation of complex rarely produced (multi)exotic flavor (anti)particles from QGP is signature of quark mobility thus of deconfinement. Enhancement of flavored (strange, charm,...) antibaryons progressing with 'exotic' flavor content. P. Koch, B. Muller, and J. Rafelski; *Strangeness in Relativistic Heavy Ion Collisions*, Phys.Rept. **142** (1986) pp167-262

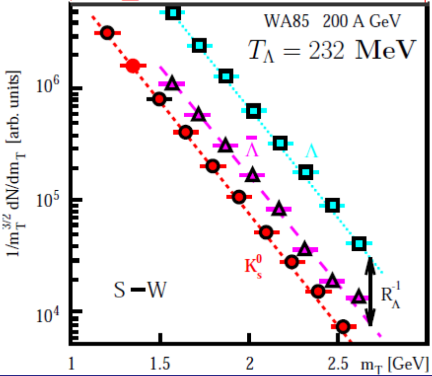
Induces matter-antimatter symmetry

Initial symmetry of $m_\perp$ spectra of (strange) baryons and antibaryons; if present in i final state originating from baryon rich environment this implies a negligible antibaryon annihilation, thus a nearly free-streaming particle emission by a quark source

Discovered in S-induced collisions, very pronounced in Pb-Pb Interactions.

Why is the slope of baryons and antibaryons precisely the same?
Why is the slope of different particles in same m_t range the same?
Analysis+Hypothesis 1991: QGP quarks coalescing in SUDDEN hadronization

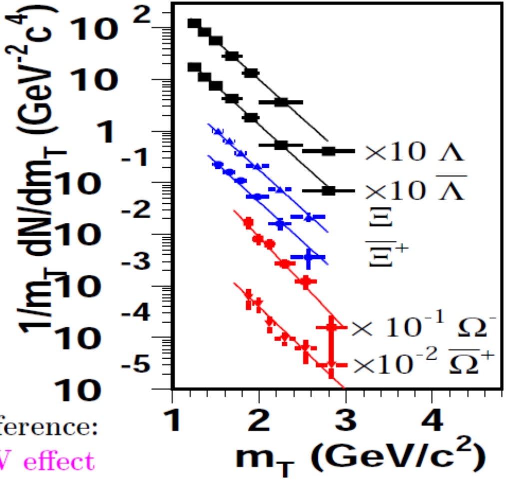
$m_\perp$ slope universality



Pb-Pb SPS collisions also show matter-antimatter symmetry

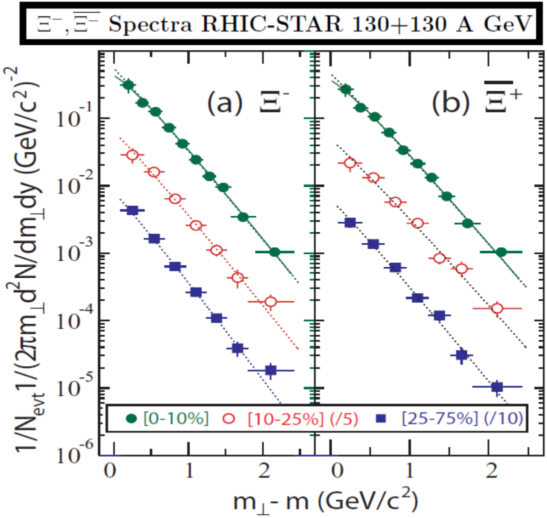
WA97	$T_\perp^{\rm Pb}$ [MeV]
$T^{\rm K^0}$	230 ± 2
T^{Λ}	289 ± 3
$T^{\overline{\Lambda}}$	287 ± 4
T^{Ξ}	286 ± 9
$T^{\overline{\Xi}}$	284 ± 17
$T^{\Omega+\overline{\Omega}}$	251 ± 19

Λ within 1% of $\overline{\Lambda}$

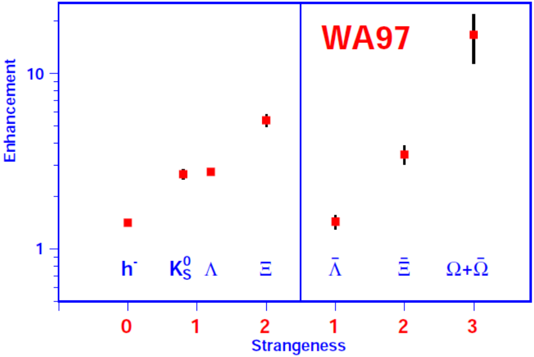


Kaon – hyperon difference:
EXPLOSIVE FLOW effect

RHIC collisions also show matter-antimatter symmetry..

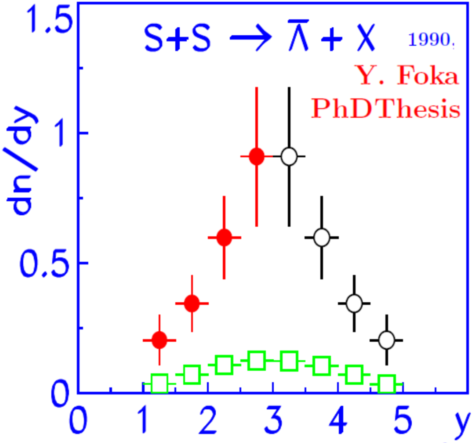


WA97 SPS Antihyperons: The largest observed QGP medium effect



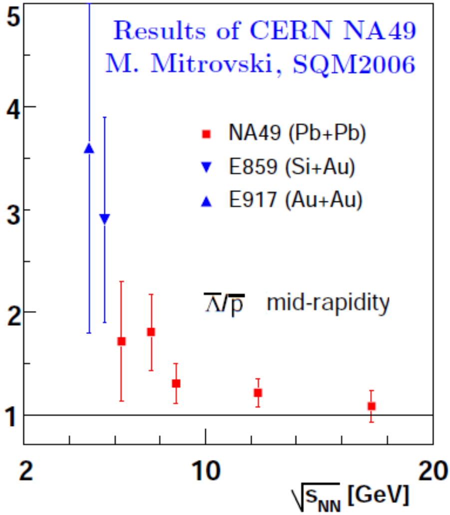
Enhancement GROWS with a) strangeness b) antiquark content as predicted. Enhancement is defined with respect to yield in p–Be collisions, scaled up with the number of 'wounded' nucleons.

NA35 S-S SPS collisions: central excess of Antilambdas

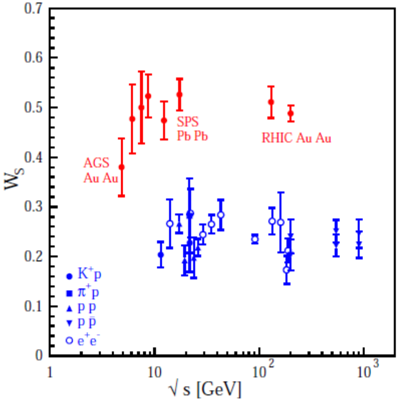


SPS-NA35II EXCESS $\bar{\Lambda}$ emitted from a localized source.

NA49 Pb-Pb SPS confirmation $\overline{\Lambda}/\bar{p} > 1$ (1980 prediction)



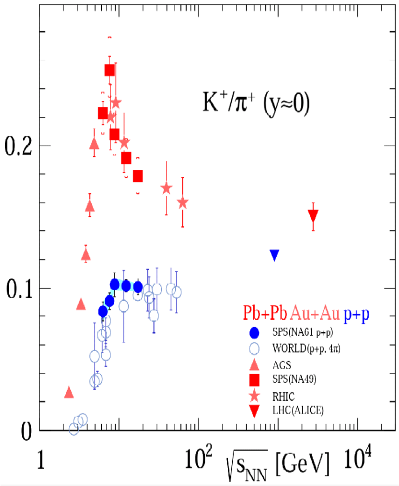
Strangeness pair enhancement (1980 prediction)

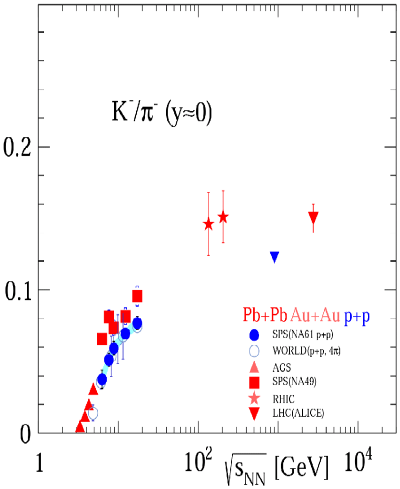


$$\text{Wróblewski ratio } W = \frac{2\langle s\bar{s}\rangle}{\langle d\bar{d} + u\bar{u}\rangle}$$

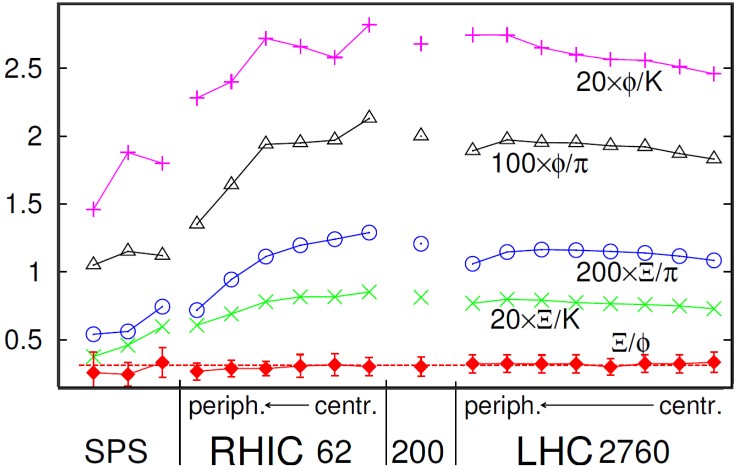
only newly made s- and q-pairs are counted

Evidence for a threshold: Marek's horn in baryon rich matter

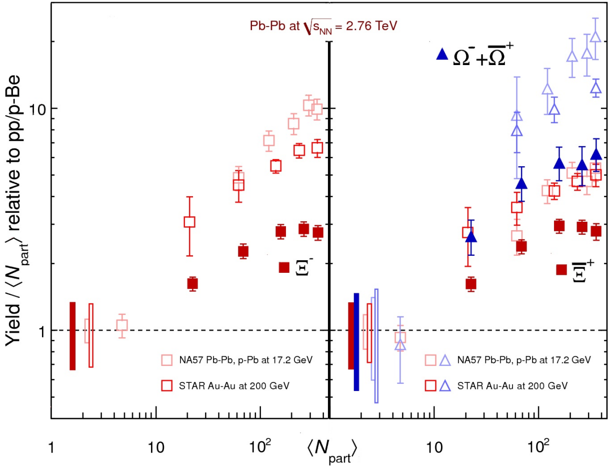


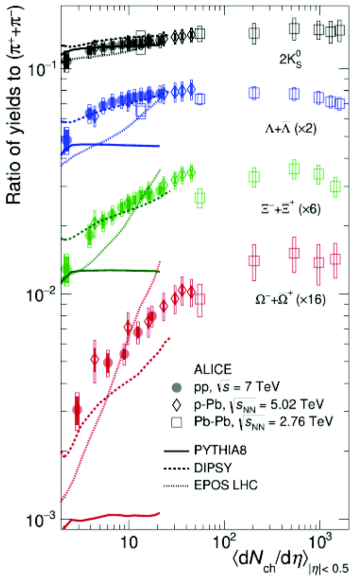


Note $\Xi(ssq)/\phi(s\bar{s})$ constant!!



Prediction: 1980-86 confirmed by experimental results: Particle yields=integrated spectra





Nature Physics 2017; doi:10.1038/nphys4111 ALICE

Significant enhancement of strangeness with multiplicity in high multiplicity pp events

pp behavior resamble p-Pb : both in term of value of the ratio and shape

No evident dependence on cms energy: strangeness production apparently driven by final state rather than collision system or energy

At high mult. pp ratio reaches values similar to the one in Pb-Pb (when ratio saturates)

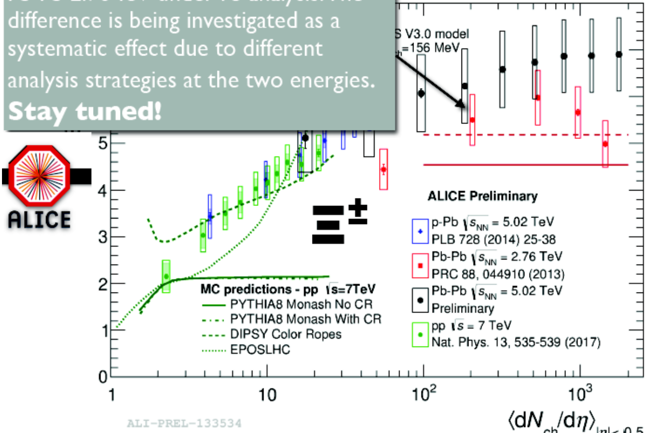
Models fail to riproduce data. Only DIPSY gives a qualitative description.

ALI-PUB-106878

Alessandro Grelli **10/7/2017**

Note $\Xi(ssq)$ from Alice 2014 needs attention

Pb-Pb 2.76 TeV under re-analysis. The difference is being investigated as a systematic effect due to different analysis strategies at the two energies. **Stay tuned!**



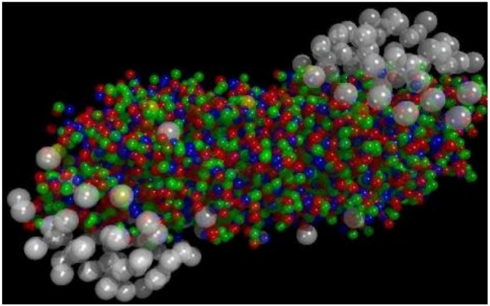
Ratio of p_T-integrated yield to pions show compatibility

No evident energy dependence. Smooth trend among systems

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.

Preeminent signature: Strange antibaryon enhancement

press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

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

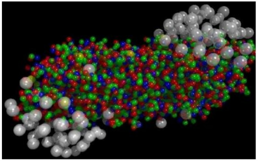
Preeminent property: non-viscous flow

When and how did we discover QGP?

CERN press office

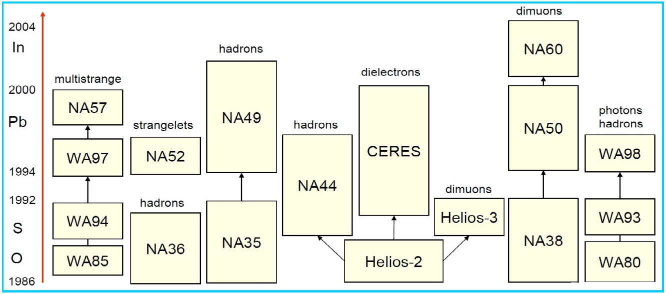
New State of Matter created at CERN

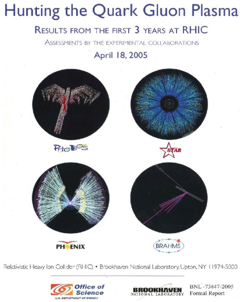
10 Feb 2000



At the April 2005 meeting of the American Physical Society, held in Tampa, Florida a press conference took place on Monday, April 18, 9:00 local time. The public announcement of this event was made April 4, 2005:

EVIDENCE FOR A NEW TYPE OF NUCLEAR MATTER At the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (BNL), two beams of gold atoms are smashed together, the goal being to recreate the conditions thought to have prevailed in the universe only a few microseconds after the big bang, so that novel forms of nuclear matter can be studied. At this press conference, RHIC scientists will sum up all they have learned from several years of observing the worlds most energetic collisions of atomic nuclei. The four experimental groups operating at RHIC will present a consolidated, surprising, exciting new interpretation of their data. Speakers will include: Dennis Kovar, Associate Director, Office of Nuclear Physics, U.S. Department of Energy's Office of Science; Sam Aronson, Associate Laboratory Director for High Energy and Nuclear Physics, Brookhaven National Laboratory. Also on hand to discuss RHIC results and implications will be: Praveen Chaudhari, Director, Brookhaven National Laboratory; representatives of the four experimental collaborations at the Relativistic Heavy Ion Collider; and several theoretical physicists.





By 1980: SBM ⇒ Quark-Gluon Plasma
HI collisions+strangeness

JR & Michael Danos of NIST

JR & Rolf Hagedorn of CERN

Volume 97B, number 2 PHYSICS LETTERS 1 December 1980

THE IMPORTANCE OF THE REACTION VOLUME IN HADRONIC COLLISIONS

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Received 10 October 1980

The pair production in the thermodynamic model is shown to depend sensitively on the (hadronic) reaction volume. Strangeness production in nucleus–nucleus collisions is treated as an example.

We consider particle production in the frame of the thermodynamic description [1] and explore the physical consequences arising from the conservation of quantum numbers which are conserved exactly during the strong interaction. An example treated here is the direct and associated production of strange particles.

The motivation for this study is the recent interest in high energy nucleus–nucleus (N–N) collisions. The main difference from the p–p scattering arises from the possibility of large reaction volumina. We will show that particle multiplicities can depend sensitively on the size of the reaction volume. Specifically, the production of heavy flavors (strangeness, etc.) is significantly enhanced.

[1] Guestworker, National Bureau of Standards.
[2] Supported in part by Deutsche Forschungsgemeinschaft.

PLB **97** pp.279-282 (1980)

FROM HADRON GAS TO QUARK MATTER II *)

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Institut für Theoretische Physik
der Universität Frankfurt

and

R. Hagedorn
CERN--Geneva

Ref.TH.2969-CERN
13 October 1980

We describe a quark-gluon plasma coincident with the bootstrap critical curve found in the first lecture. We therefore argue that these possibly coinciding critical curves separate two phases in which strongly interacting matter can exist: a hadronic phase and a quark-gluon plasma phase. There is a finite region of coexistence between these two phases, which is determined by the usual Maxwell construction. Having thus joined the two models along their possibly common critical curves, we try to confront our model with experiments on relativistic heavy ion collisions. A signature of the quark-gluon phase surviving hadronization is suggested.

*) Invited lecture presented by J.R. at the "International Symposium on Statistical Mechanics of Quarks and Hadrons" University of Bielefeld, Germany, August 1980.

The idea of 1980 in detail:CERN-TH-2969 of October 1980; Published in “Statistical Mechanics of Quarks and Hadrons”, H. Satz, editor, Elsevier 1981; Also other conferences 1980 incl Quark Matter I

-17-

In order to observe properties of quark-gluon plasma we must design a thermometer, an isolated degree of freedom weakly coupled to the hadronic matter. Nature has, in principle (but not in praxis) provided several such thermometers: leptons and heavy flavours of quarks. We would like to point here to a particular phenomenon perhaps quite uniquely characteristic of quark matter; first we note that, at a given temperature, the quark-gluon plasma will contain an equal number of strange (s) quarks and antistrange ($\bar{s}$) quarks, naturally assuming that the hadronic collision time is much too short to allow for light flavour weak interaction conversion to strangeness. Thus, assuming equilibrium in the quark plasma, we find the density of the strange quarks to be (two spins and three colours):

$$\frac{s}{V} = \frac{\bar{s}}{V} = 6\int\frac{d^3p}{(2\pi)^3}\, e^{-\sqrt{p^2+m_s^2}/T} = 3\frac{T m_s^2}{\pi^2} K_2\left(\frac{m_s}{T}\right) \qquad (26)$$

(neglecting, for the time being, the perturbative corrections and, of course, ignoring weak decays). As the mass of the strange quarks, m_s, in the perturbative vacuum is believed to be of the order of 280-300 MeV, the assumption of equilibrium for $m_s/T \sim 2$ may indeed be correct. In Eq. (26) we were able to use the Boltzmann distribution again, as the density of strangeness is relatively low. Similarly, there is a certain light antiquark density ($\bar{q}$ stands for either $\bar{u}$ or $\bar{d}$):

$$\frac{\bar{q}}{V} \simeq 6\int\frac{d^3p}{(2\pi)^3}\, e^{-|p|/T-\mu_q/T} = e^{-\mu_q/T}\cdot T^3\frac{6}{\pi^2} \qquad (27)$$

-18-

where the quark chemical potential is, as given by Eq. (3), $\mu_q = \mu/3$. This exponent suppresses the $q\bar{q}$ pair production as only for energies higher than μ_q is there a large number of empty states available for the q.

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

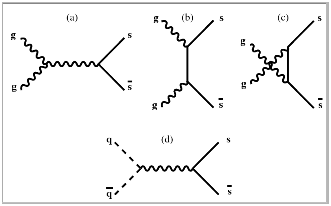
$$\frac{\bar{s}}{\bar{q}} = \frac{1}{2}\left(\frac{m_s}{T}\right)^2 K_2\left(\frac{m_s}{T}\right) e^{\mu/3T} \qquad (28)$$

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.

When the quark matter dissociates into hadrons, some of the numerous $\bar{s}$ may, instead of being bound in a $q\bar{s}$ Kaon, enter into a $(\bar{q}\bar{q}\bar{s})$ antibaryon and, in particular, a $\bar{\Lambda}$ or $\bar{\Sigma}^0$. The probability for this process seems to be comparable to the similar one for the production of antinucleons by the antiquarks present in the plasma. What is particularly noteworthy about the $\bar{s}$ carrying antibaryons is that they can only be produced in direct pair production reactions. Up to about $E_{k,lab}/A = 3.5$ GeV this process is strongly suppressed by the energy-momentum conservation and because for free p-p collisions the threshold is at about 7 GeV. We thus would like to argue that a study of the $\bar{\Lambda}$, $\bar{\Sigma}^0$ in nuclear collisions for $2 < E_{k,lab}/A < 4$ GeV could shed light on the early stages of the nuclear collisions in which quark matter may be formed.

THEORETICAL CONSIDERATIONS

A: production of strangeness dominated by gluon fusion $\boxed{GG \rightarrow s\bar{s}}$ 1982 Rafelski-Müller PRL, strangeness linked to gluons from QGP;



B:coincidence of scales:

$$\boxed{m_s \simeq T_c} \rightarrow \boxed{\tau_s \simeq \tau_{\rm QGP}} \rightarrow$$

strangeness a clock for reaction

C: Often $\boxed{\bar{s} > \bar{q}}$ $\rightarrow$ strange antibaryon enhancement and (anti)hyperon dominance of (anti)baryons.

Strangeness as Deconfinement Signatures

A: TOTAL Strangeness YIELD: $\boxed{s \text{ strangeness}/\ S \text{ entropy}}$

depends primarily on initial conditions and evolution a dynamics

B: Strangeness at QGP break-up:

i:Is QGP near chemical equilibrium?

$$\left.\frac{n_{\rm s}(t,T(t))}{n_{\rm s}(\infty,T(t))}\right|_{\rm QGP} \equiv \gamma_{\rm s}^{\rm QGP}(t) \to 1? \qquad \boxed{\gamma_{\rm s}^{HG} \simeq 3\gamma_{\rm s}^{\rm QGP}}$$

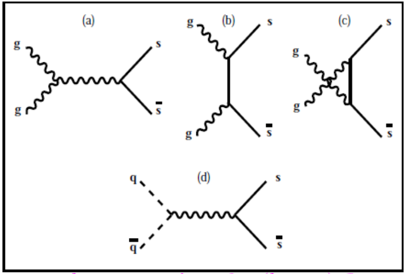
ii: For consistency we need also to consider $\boxed{\gamma_q^{\rm HG} > 1}$

over population controls ENTROPY enhancement

C: STRANGENESS MOBILITY IN QGP implies

s–$\bar{s}$ phase space symmetry, relevant in baryon rich (SPS, RHIC) environment; imprinted on hadron abundances at hadronization.

Strangeness cross sections



The generic angle averaged cross sections for (heavy) flavor s, $\bar{s}$ production processes $g+g \to s+\bar{s}$ and $q+\bar{q} \to s+\bar{s}$, are:

$$\bar{\sigma}_{gg\to s\bar{s}}(s) = \frac{2\pi\alpha_s^2}{3s}\left[\left(1+\frac{4m_s^2}{s}+\frac{m_s^4}{s^2}\right)\tanh^{-1}W(s) - \left(\frac{7}{8}+\frac{31m_s^2}{8s}\right)W(s)\right],$$

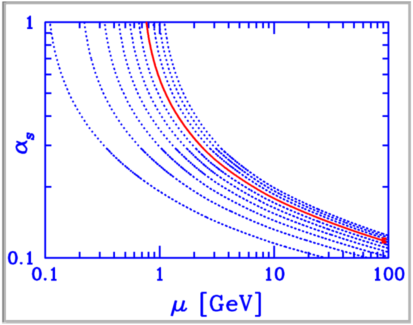
$$\bar{\sigma}_{q\bar{q}\to s\bar{s}}(s) = \frac{8\pi\alpha_s^2}{27s}\left(1+\frac{2m_s^2}{s}\right)W(s). \qquad W(s) = \sqrt{1-4m_s^2/s}$$

QCD resummation: running α_s and m_s taken at the energy scale $\mu \equiv \sqrt{s}$.

Is perturbative QCD appropriate for strangeness?

An essential prerequirement for the perturbative theory to be applicable in domain of interest to us, is the relatively small experimental value

$\alpha_s(M_Z) \simeq 0.118$



$\alpha_s^{(4)}(\mu)$ as function of energy scale μ for a variety of initial conditions. Solid line: $\alpha_s(M_Z) = 0.118$ (experimental point, includes the error bar at $\mu = M_Z$).

Had instead $\alpha_s(M_Z) > 0.125$ been measured in 1996 than our perturbative strangeness production approach would have been in question.

Thermal averages

Kinetic (momentum) equilibration is faster than chemical, use thermal particle distributions $f(\vec{p}_1, T)$ to obtain average rate:

$$\langle \sigma v_{\rm rel} \rangle_T \equiv \frac{\int d^3p_1 \int d^3p_2 \sigma_{12} v_{12} f(\vec{p}_1, T) f(\vec{p}_2, T)}{\int d^3p_1 \int d^3p_2 f(\vec{p}_1, T) f(\vec{p}_2, T)} .$$

Invariant reaction rate in medium:

$$A^{gg\to s\bar{s}} = \frac{1}{2}\rho_g^2(t)\, \langle \sigma v \rangle_T^{gg\to s\bar{s}}, \quad A^{q\bar{q}\to s\bar{s}} = \rho_q(t)\rho_{\bar{q}}(t) \langle \sigma v \rangle_T^{q\bar{q}\to s\bar{s}}, \quad A^{s\bar{s}\to gg,q\bar{q}} = \rho_s(t)\, \rho_{\bar{s}}(t)\, \langle \sigma v \rangle_T^{s\bar{s}\to gg,q\bar{q}}.$$

$1/(1+\delta_{1,2})$ introduced for two gluon processescompensates the double-counting of identical particle pairs, arising since we are summing independently both reacting particles.

This rate enters the momentum-integrated Boltzmann equation which can be written in form of current conservation with a source term

$$\partial_\mu j_s^\mu \equiv \frac{\partial \rho_s}{\partial t} + \frac{\partial \vec{v} \rho_s}{\partial \vec{x}} = A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} - A^{s\bar{s}\to gg,q\bar{q}}$$

Strangeness relaxation to chemical equilibrium

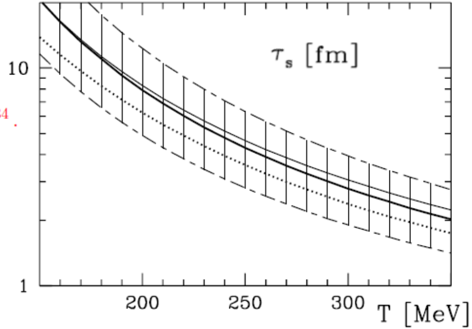
Strangeness density time evolution in local rest frame:

$$\frac{d\rho_s}{d\tau} = \frac{d\rho_{\bar s}}{d\tau} = \frac{1}{2}\rho_g^2(t)\,\langle\sigma v\rangle_T^{gg\to s\bar s} + \rho_q(t)\rho_{\bar q}(t)\langle\sigma v\rangle_T^{q\bar q\to s\bar s} - \rho_s(t)\,\rho_{\bar s}(t)\,\langle\sigma v\rangle_T^{s\bar s\to gg,q\bar q}$$

Evolution for s and $\bar s$ identical, which allows to set $\rho_s(t) = \rho_{\bar s}(t)$.
characteristic time constant τ_s:

$$2\tau_s \equiv \frac{\rho_s(\infty)}{A^{gg\to s\bar s} + A^{q\bar q\to s\bar s} + \ldots}$$

$$A^{12\to 34} \equiv \frac{1}{1+\delta_{1,2}}\gamma_1\gamma_2\rho_1^\infty\rho_2^\infty\langle\sigma_s v_{12}\rangle_T^{12\to 34}.$$



Dominant uncertainty: mass of strange quark
Dotted - fixed value $\alpha_s = 0.6$ used in 1981/2

Strangeness / Entropy

s/S: **ratio of the number of active degrees of freedom in QGP,**

For IN PLASMA chemical equilibrium :

$$\frac{s^Q}{S^Q} \simeq \frac{1}{4}\frac{n_s}{n_s + n_{\bar{s}} + n_q + n_{\bar{q}} + n_G} = \frac{\frac{g_s}{2\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{(g2\pi^2/45)T^3 + (g_s n_f/6)\mu_q^2 T} \simeq \frac{1}{35} = 0.0286$$

with $\mathcal{O}(\alpha_s)$ **interaction** $s/S \to 1/31 = 0.0323$

CENTRALITY A, and ENERGY DEPENDENCE: $\gamma_s^Q \to 1$

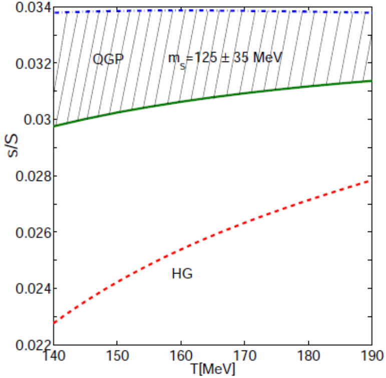
Chemical non-equilibrium occupancy of strangeness γ_s^Q

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

Analysis of experiment: we count all strange/nonstrange hadrons in final state, we extrapolate to unmeasured particle yields and/or kinematic domains, and evaluate resonance contributions and cascading:

$$\frac{s^Q}{S^Q} \simeq \frac{\text{count of primary strange hadrons}}{(\text{nonstrange} + \text{strange})\ \text{entropy} = 4\,\text{number of primary mesons} + \ldots}$$

Strangeness / Entropy: QGP-HG comparison in chemical equilibrium



Strangeness to entropy ratio $s/S(T; \mu_B = 0, \mu_S = 0)$ for the chemically equilibrated QGP (green, solid line for $m_s = 160$ MeV, blue dash-dot line for $m_s = 90$ MeV); and for chemically equilibrated HG (red, dashed).

When counting strangeness we remember that a lot of strangeness is hidden $s\bar{s}$-states η, η', ϕ

Time evolution of $s^{\mathrm{Q}}/S^{\mathrm{Q}}$, γ_s^{Q} computable

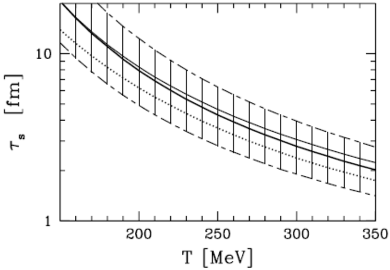
(*drop henceforth superscript Q* $\qquad \gamma_s \simeq n_s/n_s^{\text{Chem.Eq.}}$)

strangeness production dominated by thermal gluon fusion $\boxed{GG \to s\bar{s}}$
at 10% level also: quark-antiquark fusion, initial parton/string dynamics;

Kinetic equations for time evolution of s/S and γ_s

$$\frac{d}{d\tau}\frac{s}{S} = \frac{\tilde{g}_s}{g^{\mathrm{QGP}}} z^2 K_2(z) \left[\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d\ln[\tilde{g}_s z^2 K_2(z)/g^{\mathrm{QGP}}]}{d\tau}\right] \qquad z = \frac{m_s}{T}, \quad \frac{S}{V} \equiv \frac{4\pi^2}{90} g^{\mathrm{QGP}} T^3$$

$$\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d\ln[\tilde{g}_s z^2 K_2(z)/g^{\mathrm{QGP}}]}{d\tau} = \frac{A_G}{2n_s^\infty}\left[\gamma_{\mathrm{G}}^2 - \gamma_s{}^2\right] + \frac{A_q}{2n_s^\infty}\left[\gamma_{\mathrm{q}}^2 - \gamma_s{}^2\right]$$



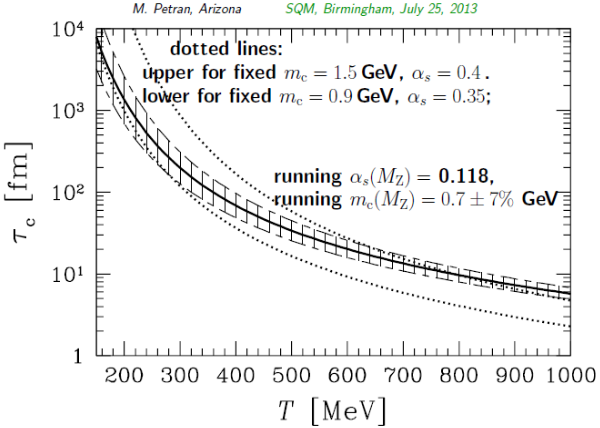
pQCD invariant production rate A
($\delta_{GG} = 1$ for GG fusion):

$$A^{12\to s\bar{s}} \equiv \frac{1}{1+\delta_{GG}} \rho_1^\infty \rho_2^\infty \langle \sigma_s v_{12} \rangle_T^{12\to s\bar{s}}.$$

and the related time constant τ_s:

$$2\tau_s \equiv \frac{\rho_s(\infty)}{A^{GG\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} + \ldots}$$

What about charm? $m_s \rightarrow m_c$



We see soft (thermal) charm production within time for $T \rightarrow 1000$ MeV probably not accessible at LHC. CONVERSELY: Charm is produced relatively abundantly in first parton collisions with a yield that is much greater than the expected chemical equilibrium yield in QGP. Thus some reannihilation of charm in plasma expansion is to be expected.

Chemical potential tutorial

particle fugacity: $\Upsilon_i \equiv e^{\sigma_i/T} \Longleftrightarrow \sigma_i$ **particle 'i' chemical potential**

Phase space density is:

$$\frac{d^6 N_i}{d^3p d^3x} = g_i \frac{\Upsilon_i}{(2\pi)^3} e^{-E_i/T}, \qquad \frac{d^6 N_i^{\mathrm{F/B}}}{d^3p d^3x} = \frac{g_i}{(2\pi)^3} \frac{1}{\Upsilon_i^{-1} e^{E_i/T} \pm 1}, \qquad \Upsilon_i^{\mathrm{B}} \leq e^{m_i/T},$$

each hadron comprise two chemical factors associated with the two different chemical equilibria, example of NUCLEONS:

$$\Upsilon_N = \gamma_N e^{\mu_b/T}, \qquad \Upsilon_{\overline{N}} = \gamma_N e^{-\mu_b/T};$$

$$\sigma_N \equiv \mu_b + T \ln \gamma_N, \qquad \sigma_{\overline{N}} \equiv -\mu_b + T \ln \gamma_N.$$

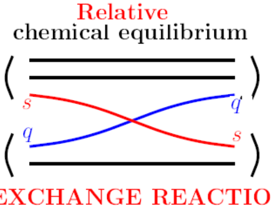
γ **determines the number of nucleon-antinucleon pairs,**

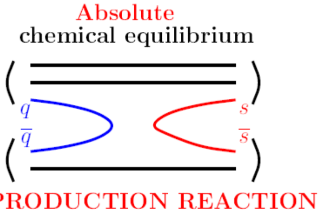
$\gamma_i(t)$ **rises from 0 (initially absent) to 1 for chemical equilibrium.**

The (baryo)chemical potential μ_b, controls the particle difference = baryon number.

Chemical reactions involving quarks

EXAMPLE: Strangeness in HG:





Absolute equilibrium $\gamma \to 1$ require more rarely occurring truly inelastic collisions with creation of new particles.

γ_i	controls overall abundance of quark 'i' pairs	Absolute chemical equilibrium
λ_i	controls difference between strange and non-strange quarks 'i'	Relative chemical equilibrium

Statistical Hadronization Model (SHM)

FERMI STATISTICAL HADRONIZATION MODEL (SHM)
Assuming equal hadron production strength irrespective of produced hadron type particle yields depend only on the available phase space

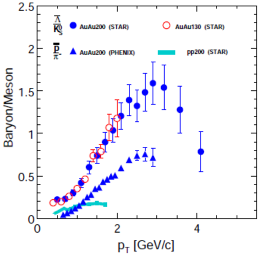
- Fermi Micro-canonical phase space
  sharp energy and sharp number of particles
  E. Fermi, Prog.Theor.Phys. 5 (1950) 570: HOWEVER

  Experiments report event-average rapidity particle abundances, model should describe an average event

- Canonical phase space: sharp number of particles
  ensemble average energy $E \rightarrow T$ temperature
  T may be, but needs not be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles: $N \rightarrow \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

Sudden hadronization context

new and dominant hadronization mechanism is visible in e.g.:



Baryon to Meson Ratio

Ratios $\overline{\Lambda}/K_S$ and $\overline{p}/\pi$ in Au-Au compared to pp collisions as a function of $p_\perp$. The large ratio at the intermediate $p_\perp$ region: evidence that particle formation (at RHIC) is distinctly different from fragmentation processes for the elementary e^+e^- and pp collisions.

To describe recombinant yields: non-equilibrium parameters needed

- γ_q $(\gamma_s, \gamma_c, \ldots)$: u, d $(s, c, \ldots)$ quark phase space yield, absolute chemical equilibrium: $\gamma_i \to 1$

$$\frac{\text{baryons}}{\text{mesons}} \propto \frac{\gamma_q^3}{\gamma_q^2} \cdot \left(\frac{\gamma_s}{\gamma_q}\right)^n$$

- γ_s/γ_q shifts the yield of strange vs non-strange hadrons:

$$\frac{\overline{\Lambda}(\bar{u}\bar{d}\bar{s})}{\overline{p}(\bar{u}\bar{u}\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \qquad \frac{\mathrm{K}^+(u\bar{s})}{\pi^+(u\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \qquad \frac{\phi}{h} \propto \frac{\gamma_s^2}{\gamma_q^2}, \qquad \frac{\Omega(sss)}{\Lambda(sud)} \propto \frac{\gamma_s^2}{\gamma_q^2},$$

TO DESCRIBE PRODUCED HADRON YIELDS

- Average per collision yield of hadron i is calculated from integral of the distribution over phase space

$$\langle N_i \rangle \to \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_i; \quad n_i(\varepsilon_i; T, \Upsilon_i) = \frac{1}{\Upsilon_i{}^{-1} e^{\varepsilon_i/T} \pm 1}$$

$$= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{n m_i}{T}\right)^2 K_2\left(\frac{n m_i}{T}\right)$$

• Hadron mass	PDG Tables
• Degeneracy (spin), $g_i = (2J+1)$	PDG Tables
• Overall normalization	outcome of SHM fit
• Hadronization temperature	outcome of SHM fit
• Fugacity Υ_i for each hadron	– see next slide outcome of SHM fit

STANDARDIZED PROGRAM TO FIT SHM PARAMETERS

Statistical HAdronization with REsonances: (SHARE)

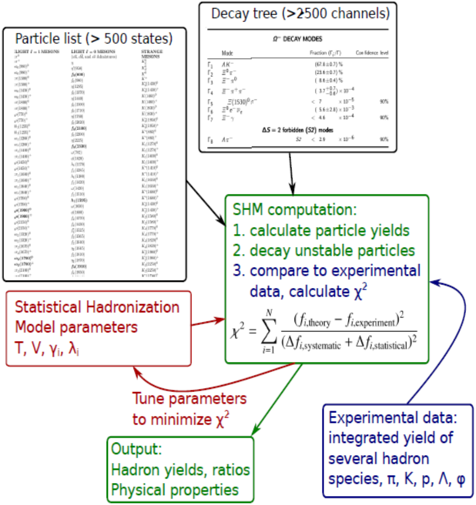
- SHM implementation in publicly available program
  Giorgio Torrieri et al, Arizona + Krakow; SHAREv1 (2004), SHAREv2 + Montreal, added fluctuations (2006)
  Michal Petran SHARE with CHARM: (2013)

SHARE INCORPORATES MANY THOUSANDS LINES OF CODE

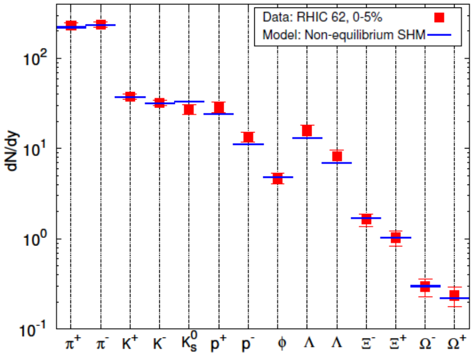
- Hadron mass spectrum $>$ 500 hadrons (PDG 2012)
- Hadron decays $>$ 2500 channels (PDG 2012)
- Integrated hadron yields, ratios and decay cascades
- OUT:Experimentally observable $\lesssim$ 30 hadron species
- AND: Physical properties of the source at hadronization – also as input in fit e.g. constraints: $Q/B \simeq 0.39, \ \langle s - \bar{s} \rangle = 0$

PROCEDURE – FITTING SHM PARAMETERS TO DATA

1. Input: T, V, γ_q, γ_s, λ_q, λ_s.λ_3
2. Compute yields of all hadrons
3. Decay feeds – particles experiment observes
4. Compare to exp. data (χ^2)
5. Including bulk properties, constraints
6. Tune parameters to match data (minimize χ^2)



SHM AT RHIC 62 WORKS FOR US



SHM results: Petran et al., Acta Phys.Polon.Supp. 5 (2012) 255-262
Data from: [STAR Collaboration], Phys.Rev.C79, 034909 (2009)
[STAR Collaboration], Phys.Rev.C79, 064903 (2009).

MODEL PARAMETERS

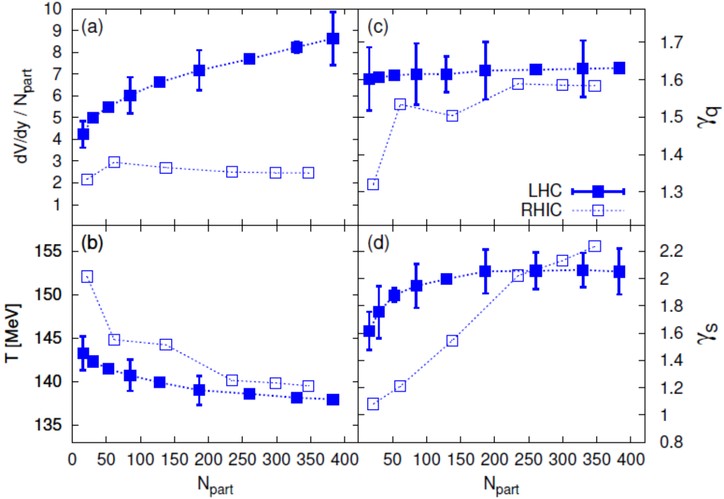
- $T = 140\,\mathrm{MeV}$
- $dV/dy = 850\,\mathrm{fm}^3$
- $\gamma_q = 1.6$
- $\gamma_s = 2.2$
- $\lambda_q = 1.16$
- $\lambda_s = 1.05$
- $\Rightarrow \mu_B = 62.8\,\mathrm{MeV}$
- $\chi^2/ndf = 0.38$

PHYS. PROPERTIES

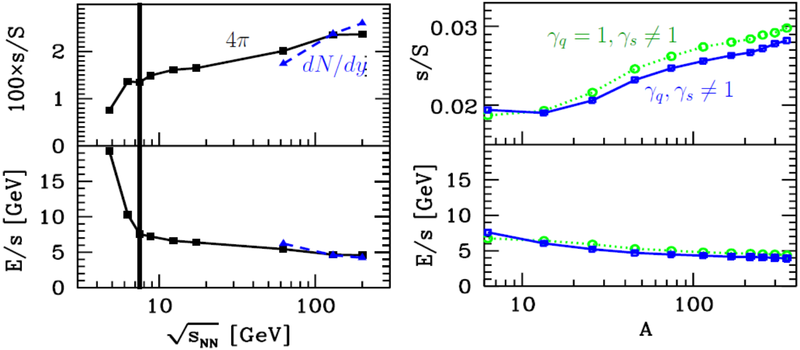
- $\varepsilon = 0.5\,\mathrm{GeV/fm}^3$
- $P = 82\,\mathrm{MeV/fm}^3$
- $\sigma = 3.3\,\mathrm{fm}^{-3}$

SHM parameters as function of centrality
LHC compared to RHIC

M.Petran et al., Phys. Rev. C 88, 034907 (2013)



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



Left: Energy dependence; Right: Centrality dependence

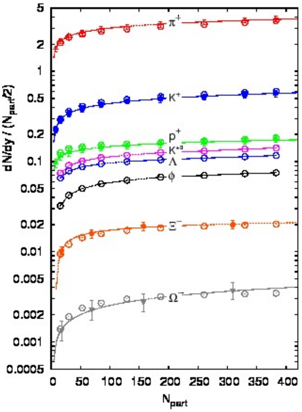
Interest in (thermal) energy cost of strangeness pair E/s as it should show appearance of a more effective strangeness production reaction mechanism.

Statistical Hadronization Model Interpretation (SHM)

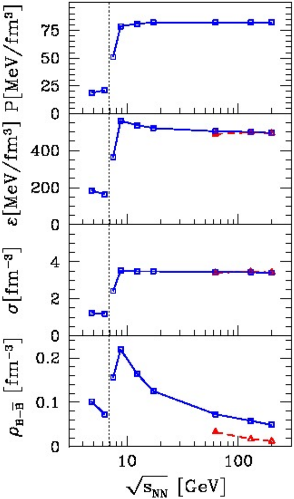
equal hadron production strength

yield depending on available phase space

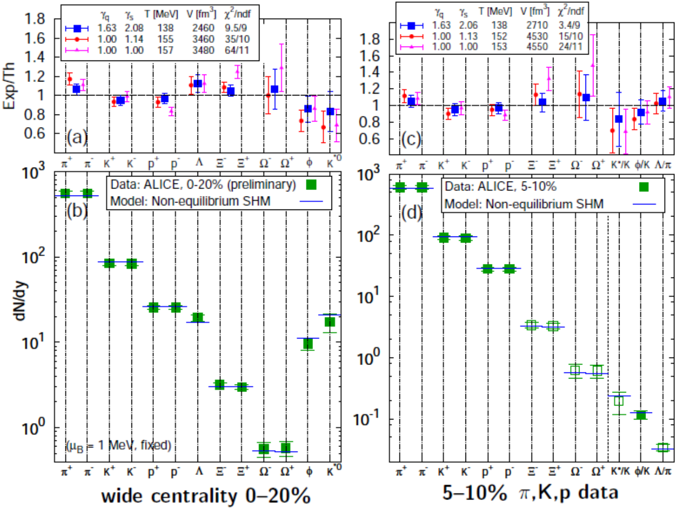
Example data from LHC⇓



SPS, RHIC, LHC ⇓ bulk



SHM fits LHC Pb-Pb 2.76 TeV data; $\gamma_q \neq 1$

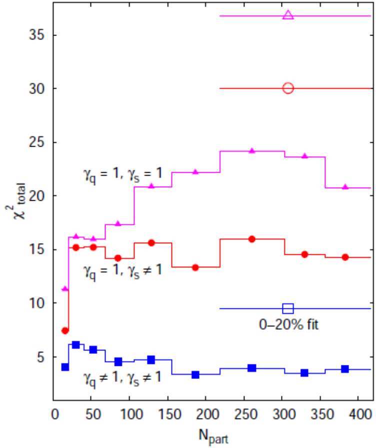


SHM fit Quality LHC Pb-Pb 2.76 TeV data

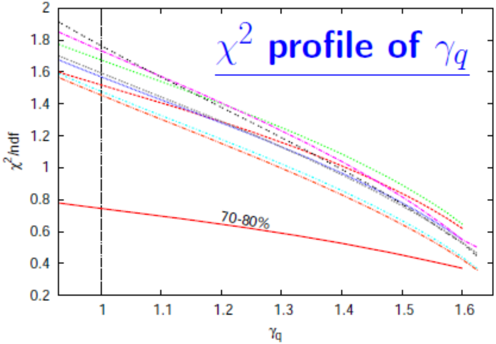
Chemical non-equilibrium SHM works at all centralities

Non-equilibrium

- $\chi^2/\mathrm{ndf} \simeq 4.5/9 = 0.5$,
- constant across centrality
- improvement by factor of 3 resp. 5 comparing to $\gamma_q = 1$
- Only in peripheral collisions $\gamma_q \simeq 1$ maybe possible



SHM fit: is $\gamma_a \neq 1$? LHC Pb-Pb 2.76 TeV data

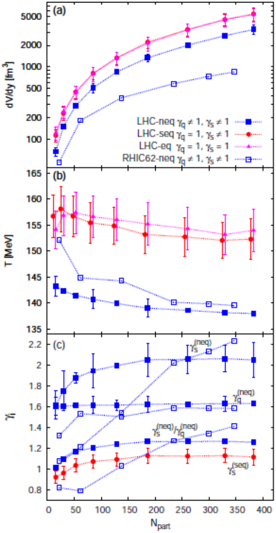


$\gamma_q = 1$ – no special meaning for SHM

Special role of $\gamma_q \to \gamma_q^{\rm crit} \equiv e^{m_\pi/2T} \simeq 1.61$
– B-E condensation of π^0

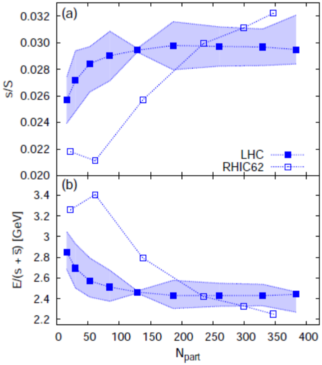
χ^2 in most peripheral bin may allow equilibrium

SHM fit: RHIC-LHC parameter comparison



- dV/dy 4 times bigger than RHIC-62
- $T_{LHC} \simeq T_{RHIC} \simeq 140 - 145$ MeV
- always $\gamma_q \neq 1$
- $\gamma_s \simeq 2$, constant for $N_{part} \geq 100$
  - only difference to RHIC

Strangeness at LHC grows faster compared to RHIC as function of A



Panel (a): strangeness per entropy s/S content of the fireball at LHC2760 (filled squares) and at RHIC62 (open squares) as a function of centrality;. Colored bands represent uncertainty based on γ_s uncertainty. Main difference RHIC-LHC: volume-like result for LHC much earlier compared to RHIC. Indication of higher specific strangeness content in most central RHIC collisions.

Panel (b): the thermal energy cost to make a strange–anti-strange quark pair. Shows transit from pp-like peripheral process to thermal QGP process.

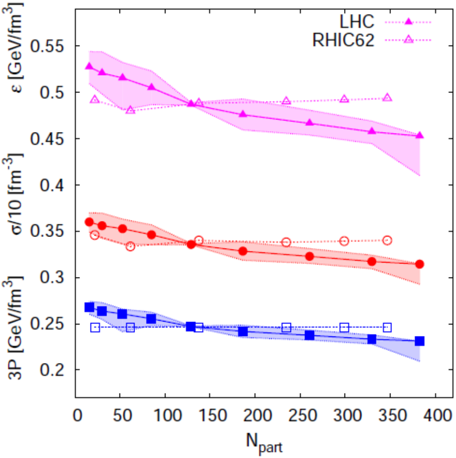
Universality of Hadronization Condition: Bulk intensive properties

FIREBALL

PHYSICAL

PROPERTIES

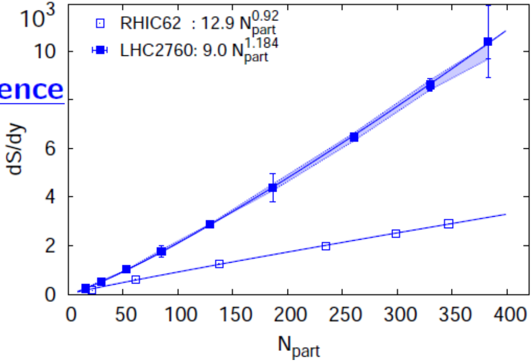
- LHC Compatible with RHIC-62
- Error band is γ_s uncertainty
- Slight decrease with centrality
- Decrease $\rightarrow$ super–cooling
- Compare $\varepsilon = 0.5$ GeV/fm^3 $\simeq$ $\simeq 3.3\varepsilon_{\rm nucl}$



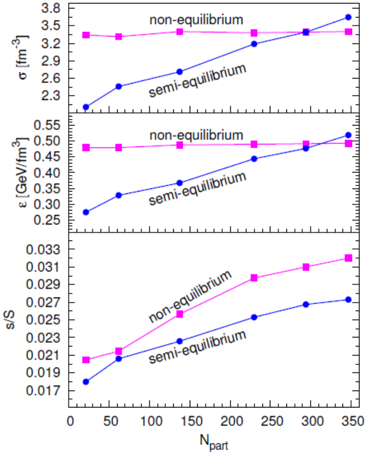
Volume only quantity to change comparing QGP production at RHIC and LHC

Main RHIC-LHC difference

- VOLUME
  Size related to initial stage
- Almost linear centrality dependence at RHIC-62
- Faster rise at LHC: additional entropy production? charm?



Universality requires chemical nonequilibrium $\gamma_q \neq 1$



M.Petran et al.,Acta Phys.Polon.Supp. 5 (2012) 255-262

$dV/dy|_{central} = 17 \times dV/dy|_{peripheral}$

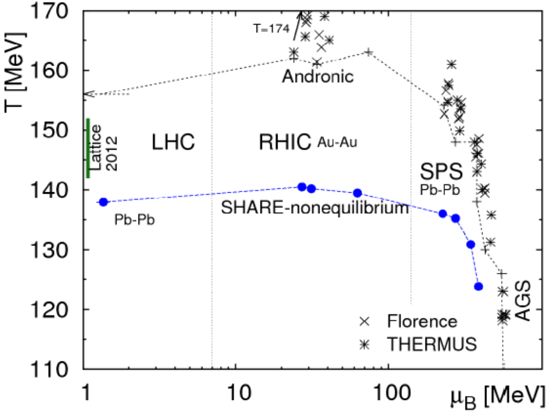
RHIC 62 GeV

Non-equilibrium result $\gamma_q \neq 1$: universal hadronization

AND: SAME PHYSICAL CONDITIONS AS AT SPS FOR ALL RHIC-62 CENTRALITIES

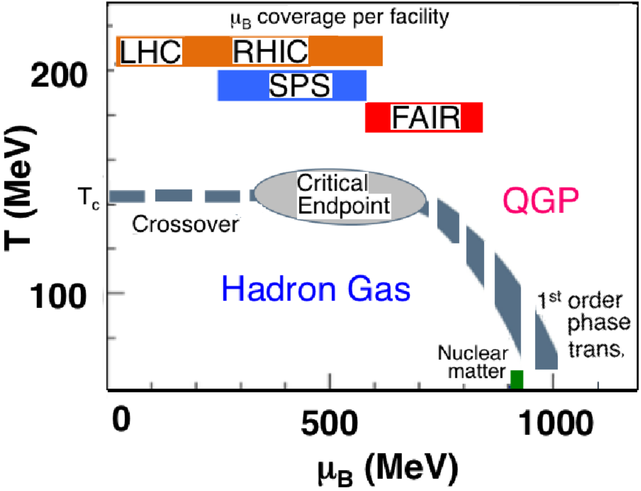
- Entropy density $\sigma = 3.3\,\mathrm{fm}^{-3}$
- Energy density $\varepsilon = 0.5\,\mathrm{GeV/fm}^3$
- Critical pressure $P = 82\,\mathrm{MeV/fm}^3$
- s/S near chemical equilibrium QGP $s/S \simeq 0.03$

Consistency of SHM models with Lattice-QCD

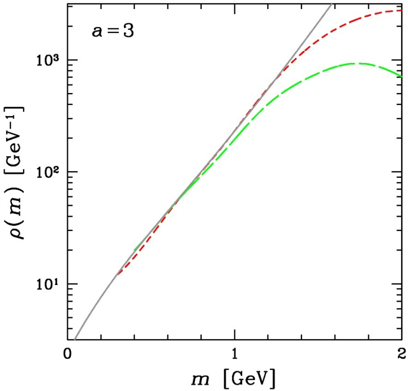


Chemical freeze-out MUST be below lattice results. For direct free-streaming hadron emission from QGP, T-SHM is the QGP source temperature, there cannot be full chemical equilibrium.

Current interest: Exploration of the QGP phase diagram



Current interest: Exploration of exponential mass spectrum



Slope for prescribed pre-exponential shape is the Hagedorn Temperature: another way to determine critical properties of deconfinement phase change

Summary

- 50 years ago abundant particle production in pp reactions prompted Hagedorn to propose exponential mass spectrum of hadrons and he introduced slope parameter $T_{\rm H}$; soon after recognized as the critical temperature at which matter surrounding us dissolves into primordial new phase of matter made of quarks and gluons – QGP.
- 35 years ago we proposed to recreate a new primordial phase of matter smashing heaviest nuclei.
- We developed laboratory observables of this quark-gluon phase of matter: cooking strange quark flavor in the QGP fireball.
- 10-15 years ago CERN and BNL Laboratories announced the discovery of new phase, the QGP
- Today: We understand the properties of QGP
- I use the chemical nonequilibrium SHM implemented in the SHARE program suite. Among key results is the universal hadronization behavior of the QGP formed in vastly different environments of SPS, RHIC, LHC.

Dear Neelima:

thank you for organizing a true school on QCD, QGP and RHI collisions with an excellent mix of speakers in the pleasant environment of Universidad de los Andes in Bogota. In every aspect of my visit I have been surprised. Nothing was the way I had imagined before this memorable week. The University, the city, the visitors, the students all had their interesting surprises. But most impressive has been yours and Marek's personal hospitality.

THANK YOU
with warm regards
JAN