Strangeness from Quark-Gluon Plasma

Presented at ODU Physics Colloquium, Sept. 19, 2017

Quark-Gluon Plasma filled the early Universe in first 20 microseconds. It has been recreated in experiments carried out colliding atomic nuclei. The energy threshold for the formation of quark-deconfined state is near 3.5 GeV per nucleon-CM. This is allowing exploration of QGP properties. The experimental challenge is fireball explosion requiring recognition of characteristic signatures operating at sub-nuclear time scale. An in-depth discussion of the strangeness observable, including a survey of the past and ongoing experimental effort at CERN-SPS, BNL-RHIC, and CERN-LHC will show how we know QGP was formed and how a measurement of physical properties of QGP is achieved..

We will be talking about creation of (anti)matter from energy

CREDITS: Results obtained in collaboration with:
Long ago: Berndt Müller, Peter Koch,
and
Jeremiah Birrell, Inga Kuznetsowa, Michal Petran, Giorgio Torrieri
Former Graduate Students at The University of Arizona

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

- RHI: Relativistic Heavy Ion Collision(s)
  heavy ions = atomic nuclei
- BNL: Brookhaven National Laboratory, Long Island, NY
- RHIC = RHI Collider, at BNL
- LHC: Large Hadron Collider (25 $\times$ higher energy).
- CERN: Laboratory in Geneva, Switzerland - home of European particle physics with strong nuclear physics presence. Acronym from French precursor organization
- SPS: Super Proton Synchrotron at CERN, in early 70's top accelerator in the world. converted to S$p\bar{p}$S proton-antiproton collider where in '80s W, Z mesons were discovered, today the injector of the LHC with protons and RHI, still used as RHI stand alone beam source

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 $T_{\rm H}$ $\rightarrow$ Big Bang; to
3. QGP in Laboratory & Discovery
4. Strangeness in QGP: ideas and results

1964: Quarks + Higgs → Standard Model

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

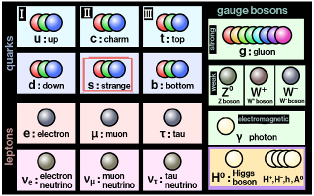
8182/TH.401
17 January 1964

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

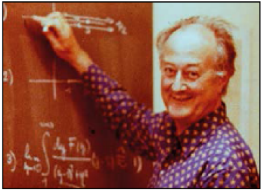
Hagedorn Strongly Interacting Matter

Birth of the Hagedorn temperature

CERN Courier December 2014

The statistical bootstrap model and the discovery of quark–gluon plasma.

On 3 February 1978, Rolf Hagedorn handed me a copy of his secret, unpublished manuscript on "Thermodynamics of distinguishable particles: a key to high-energy strong interactions?" – CERN preprint TH 483, dated 12 October 1964. The original had a big red mark, showing that it was the original, not to be lost, with the number "0" meaning less than "1" (see below). Hagedorn kept just one red-marked copy, and mentioned that another was in the CERN



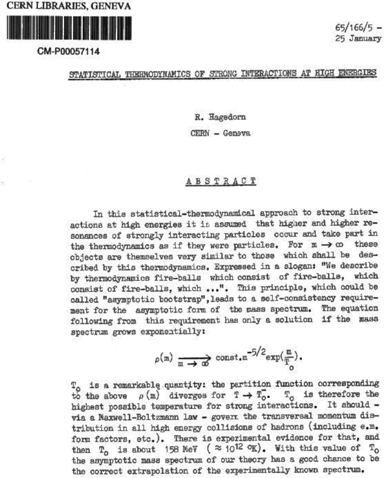
Rolf Hagedorn at the blackboard in 1978. (Image credit: Jan Rafelski.)

In the SBM, the exponential mass spectrum required for limiting temperature arose naturally *ab initio*, as did the close relation between the limiting temperature, the exponential mass-spectrum slope and the lightest hadron mass. The CERN-TH 520

thermal physics – not unusual in the particle and nuclear context in the early 1970s. He remembered our discussions in Frankfurt a few years later, resuming my education at CERN as if we had never been interrupted. Looking back to those long sessions in the winter of 1977/1978, I see a blackboard full of clean, exact equations – and his sign not to clean the board, because he knew we would resume early the next morning.

But how did Hagedorn, with his uncanny physics instinct, by way of limiting temperature and the statistical bootstrap, lay foundations for a new interdisciplinary field of physics – relativistic heavy-ion collisions and the study of quark–gluon plasma – now a vibrant research programme not only at CERN, but also for example, at Brookhaven, GSI and Dubna? The idea of a limiting temperature transformed into what today is the temperature at which the confining QCD

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

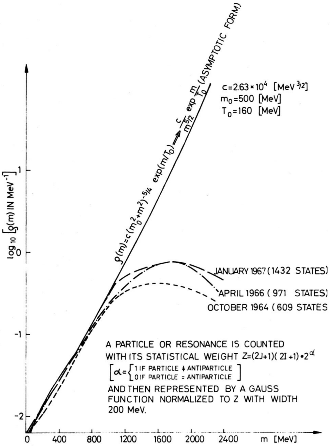
R. Hagedorn
CERN - Geneva

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:

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

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o^-$. T_o 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_o is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_o the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.



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

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

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

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

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

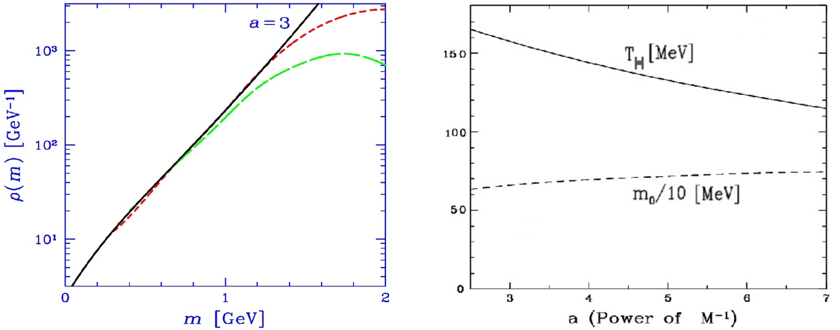
a	P	n	ε	$\delta\varepsilon/\varepsilon$	$C_V = \mathrm{d}\varepsilon/\mathrm{d}T$
1/2	$C/\Delta T^2$	$C/\Delta T^2$	$C/\Delta T^3$	$C + C\Delta T$	$C/\Delta T^4$
1	$C/\Delta T^{3/2}$	$C/\Delta T^{3/2}$	$C/\Delta T^{5/2}$	$C + C\Delta T^{3/4}$	$C/\Delta T^{7/2}$
3/2	$C/\Delta T$	$C/\Delta T$	$C/\Delta T^2$	$C + C\Delta T^{1/2}$	$C/\Delta T^3$
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.

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

Fit experimental mass spectrum

$$\rho(m) = ce^{m/T_\mathrm{H}}/(m_0^2 + m^2)^{a/2}$$



The understanding of critical temperature $T_\mathrm{H} \simeq 140$–160 MeV depends on precise knowledge of the mass spectrum shape at moderate masses.

Hadrons → Quarks → laboratory tests: 1965-82

- 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
- Quark confining vacuum structure dissolved at high T
  A.M.Polyakov, *Phys. Lett. B* **72**, (1978)
  Thermal properties of gauge fields and quark liberation
- Formation of hot quark-gluon matter in RHI collisions:
  conference talks by Rafelski-Hagedorn (CERN) 1978-9
  Chapline-Kerman MIT-CTP 695 unpublished 1978
- First practical experimental signature:
  Strangeness and Strange antibaryons 1980 ff.
  Rafelski (with Danos, Hagedorn, Koch (grad student), B. Müller
- Statistical materialization model (SHM) of QGP: 1982
  Rafelski (with Hagedorn, Koch(grad student), B. Müller

Can we make a fireball of hadron 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

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(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 ☆

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and

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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.

Transparency ⇐ Two opposite views ⇒ SPS-RHIC large stopping
LHC a nice fireball in all cases

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.

Strangeness - a popular QGP diagnostic tool

EXPERIMENTAL REASONS

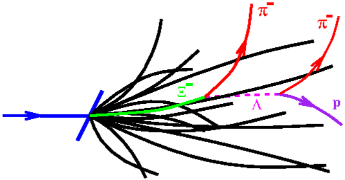
A: There are many strange particles allowing to study different physics questions $(q = u, d)$:

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

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

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

Fledgling strangeness signature 1980: ratio of $\bar{s}/\bar{q}$ in $\overline{\Lambda}/\bar{p}$ triggers immediate interes

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.

FROM HADRON GAS TO QUARK MATTER II

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der Universität Frankfurt

and

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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.

In *Statistical mechanics of quarks and hadrons* proceedings of Bielefeld, August 24-31, 1980 picked up by Marek Gaździcki in Dubna.

REFERENCES

1. G.Chapline et al. Phys.Rev., 1975, D8, p. 4302; R.Hagedorn. Preprint CERN, TH. 3207, Geneva, 1981.
2. J.Rafelski. Preprint UFTP, 1982, 80/82 and 86/82; M.I.Grenstein, G.M.Zinovjev. Preprint ITP-82-109E, Moscow, 1982.
3. J.W.Harris et al. Phys.Rev.Lett., 1981, 47, p. 229.
4. M.Anikina et al. JINR, P1-82-333, Dubna, 1982.
5. N.Akhababian et al. JINR, D1-82-445, Dubna, 1982.
6. M.Anikina et al. International Conference on Nucleus-Nucleus Collisions, Michigan, 1982, (abstract); E.Okonov. JINR, D2-82-568, Dubna, 1982.
7. A.Abdurakhimov et al. Nucl.Phys., 1981, A362, p. 367.
8. M.Anikina et al. Z.Phys., 1981, C9, p. 105.

Received by Publishing Department
on July, 20, 1983.

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Anikina M. et al. E1-83-521

A Study of Λ-Production
in Central Nucleus-Nucleus Interactions
at a Momentum of 4.5 GeV/c Per Incident Nucleon

Transverse momenta and rapidities of Λ's produced in central nucleus-nucleus collisions at 4.5 GeV/c per nucleon /CC, CNe, ONe, CCu, CZr, CPb, OPb/ have been studied and compared with those from inelastic He-Li interactions at the same incident momentum. Polarization of Λ hyperons was found to be consistent /within the errors/ with zero ($\alpha P_\Lambda = -0.06 \pm 0.11$) for 224 Λ's from central collisions. The upper limit of $\bar{\Lambda}/\Lambda$ production ratio was estimated to be less than 10^{-2} at a 90% confidence level.

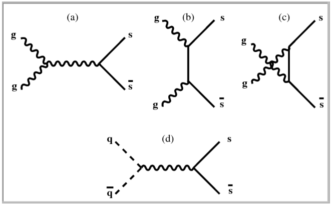
The analyzed experimental data were obtained using the triggered 2 m streamer spectrometer SKM-200.

The investigation has been performed at the Laboratory of High Energies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1983

THEORETICAL CONSIDERATION within QCD followed

A: 1982 Rafelski-Müller PRL48 (1982) 1066 production of strangeness dominated by gluon fusion $\boxed{GG \to s\bar{s}}$
strangeness⇔gluons in QGP;



B: coincidence of scales:
$\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\rm QGP}} \to$
strangeness yield can grow gradually with size of collision system

C: Often as noted in 1980: $\boxed{\bar{s} > \bar{q}} \to$ strange antibaryon enhancement and (anti)hyperon dominance of (anti)baryons growing with strangeness contents Effect preeminent for SPS since baryochemical potential large

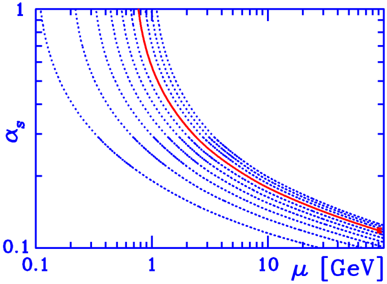
Strangeness cross sections

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:

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

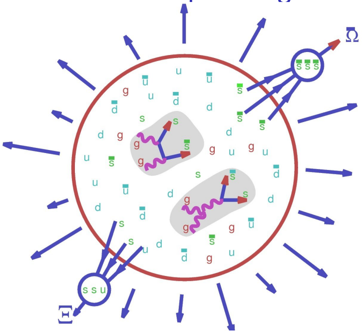
$$\bar{\sigma}_{q\bar{q}\to s\bar{s}}(s) = \frac{8\pi\alpha_s^2}{27s}\left(1+\frac{2m_s^2}{s}\right)W(s). \qquad W(s)=\sqrt{1-4m_s^2/s}$$

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



An essential pre requirement for the perturbative theory to be applicable in domain of interest to us, is the relatively small experimental value; in figure $\alpha_s^{(4)}(\mu)$ as function of energy scale μ for a variety of initial conditions. Solid line: $\alpha_s(M_Z)=0.118$. Were instead $\alpha_s(M_Z)>0.125$ the perturbative strangeness production approach would have been in question.

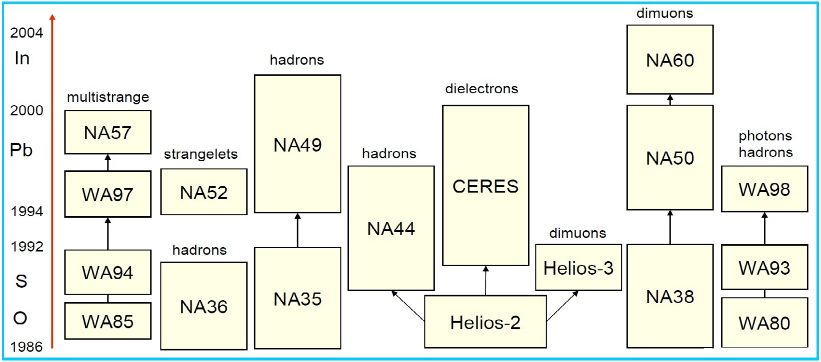
A model of two-step strange hadron formation



1. $GG \to s\bar{s}$ (thermal gluons collide)
   $GG \to c\bar{c}$ (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

CERN RHI experimental SPS program is born 1980-86

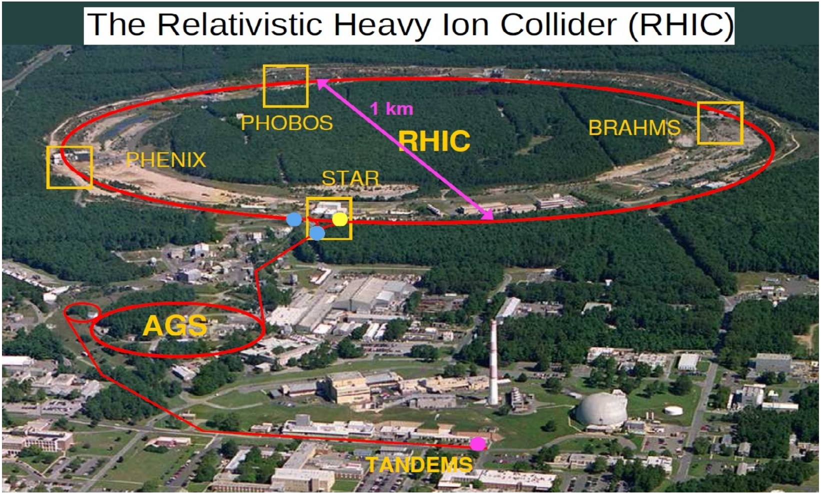


SPS and later LHC for heavy ions

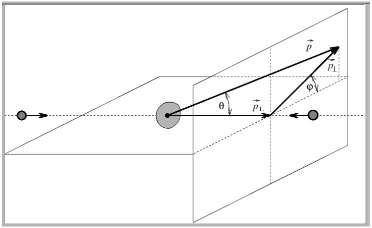
A first meeting September 1988 with RHI data

“Hadronic Matter in Collision,” Tucson, September 1988 – in the picture Wit B., Marek G.,Roy G., Walter G., Hans G., Berndt M., Stanislaw M., Emanuele Q., Chris Q., JR, Gena Z., . . . and some who are in our memory: Mike D., Walter G., Maurice J., Leon VanH, ...

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



ABC of relativistic kinematics ($c = 1$)



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

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

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

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

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

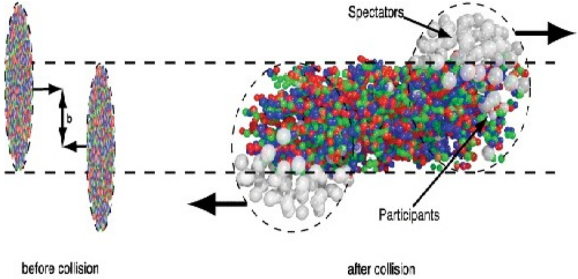
The longitudinal momentum p_L of a particle depends in a nonlinear way on the velocity. The rapidity y is additive under successive Lorentz transformations along the same direction. With

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

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

Use of y allows exploration of the source bulk properties in the co-moving fireball frame

Study particle yields for a given y calling this 'central'=CM domain. Explore collisions as function of centrality=impact parameter as seen in picture



We can study integrated particle $y, p_\perp$ spectra: when integrated in $p_\perp$ this is dN/dy and when also integrated in y this is N_i multiplicity of produced i-particles. N_i is independent from flow of matter. Allows to study bulk thermal properties of the source

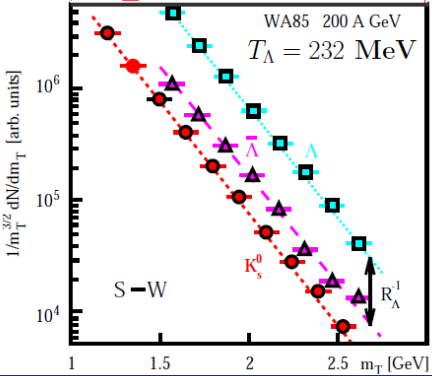
Preproduced quark combination implies matter-antimatter ‘symmetry’

Initial symmetry of $m_\perp$ spectra of (strange) baryons and antibaryons; if present in 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

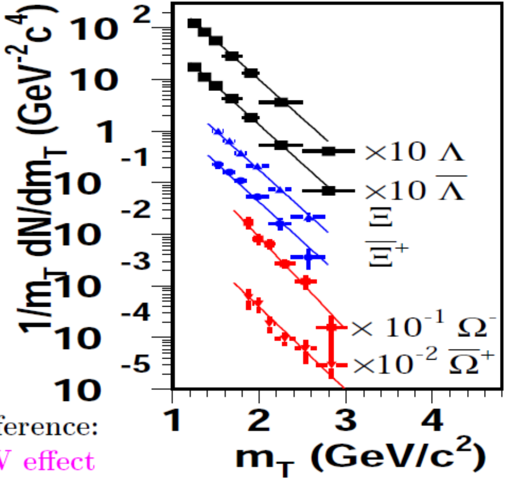
$m_\perp$ slope universality



Pb-Pb SPS collisions also show matter-antimatter symmetry

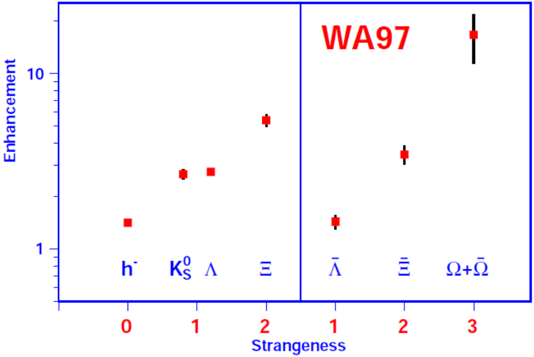
WA97	$T_{\perp}^{\mathrm{Pb}}$ [MeV]
T^{K^0}	230 ± 2
T^{Λ}	289 ± 3
$T^{\overline{\Lambda}}$	287 ± 4
T^{Ξ}	286 ± 9
$T^{\overline{\Xi}}$	284 ± 17
$T^{\Omega+\overline{\Omega}}$	251 ± 19

Λ within 1% of $\overline{\Lambda}$



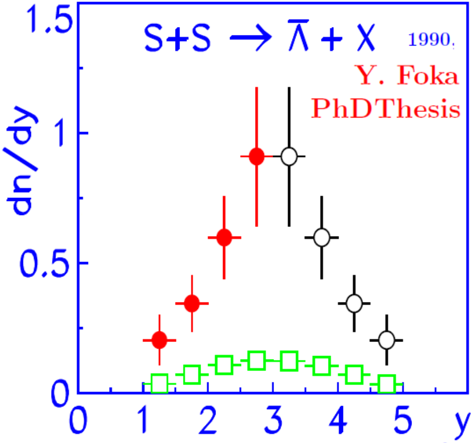
Kaon – hyperon difference:
EXPLOSIVE FLOW effect

WA97 SPS Antihyperons: The largest observed QGP medium effect



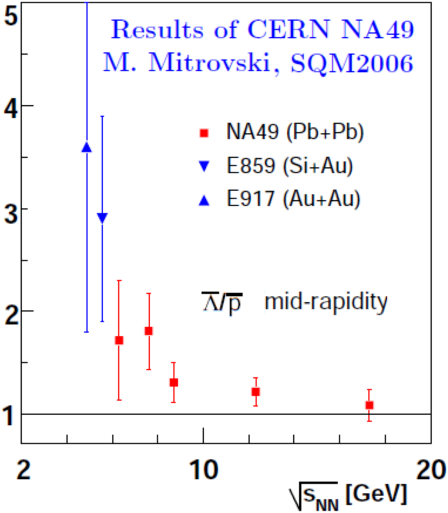
Enhancement GROWS with a) strangeness b) antiquark content as predicted. Enhancement is defined with respect to yield in p–Be collisions, scaled up with the number of ‘wounded’ nucleons.

NA35-SPS: S-S predicted central excess of Antilambdas

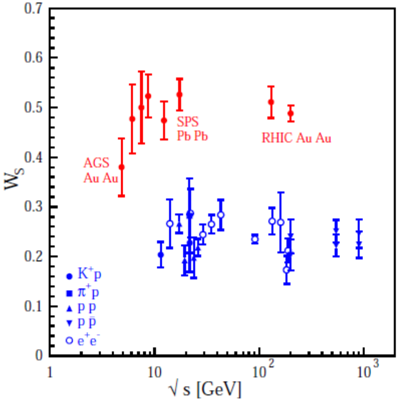


SPS-NA35II EXCESS $\bar{\Lambda}$ emitted from a localized source.

$\overline{\Lambda}/\bar{p} > 1$ (1980 prediction)



Strangeness pair enhancement (1980 prediction)

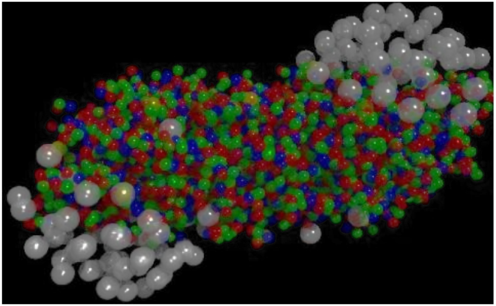


$$\text{Wróblewski ratio } W = \frac{2\langle s\bar{s}\rangle}{\langle d\bar{d} + u\bar{u}\rangle}$$

only newly made s- and q-pairs are counted

CERN press office 10 Feb 2000

New State of Matter created at CERN



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.

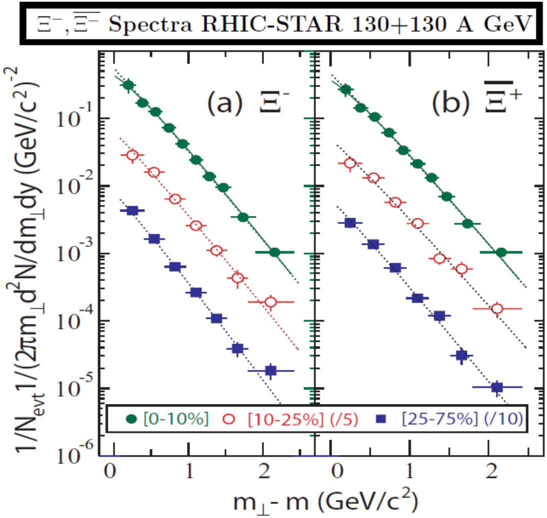
press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

Preeminent signature: Strange antibaryon enhancement

See:*From Strangeness Enhancement to Quark-Gluon Plasma Discovery*

arXiv 1708.0811 P Koch, B Müller, J Rafelski

RHIC collisions also show matter-antimatter symmetry

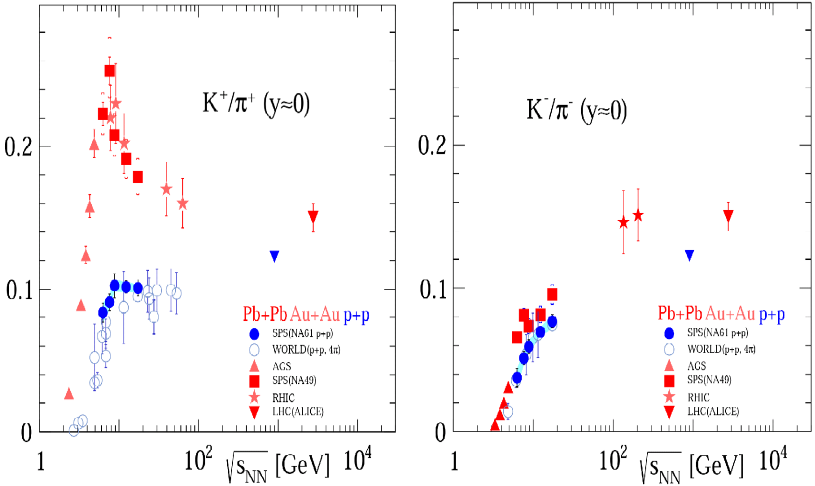


9AM, 18 April 2005; US – RHIC announces QGP Press conference APS Spring Meeting

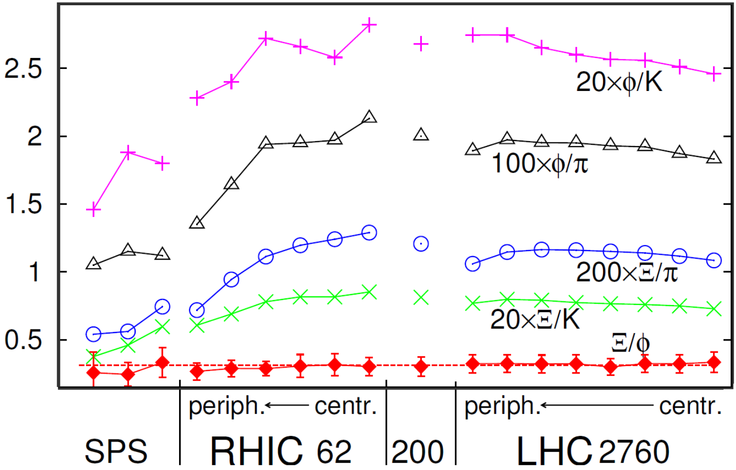
Emphasis on matter flow at quantum limit

AFTER: Energy threshold: horn in baryon rich matter

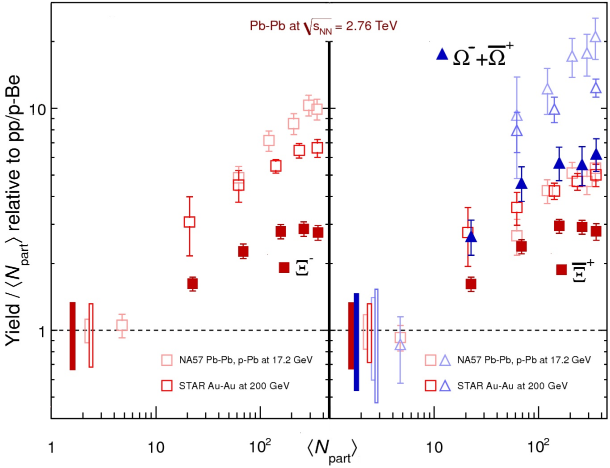
Marek Gaździcki



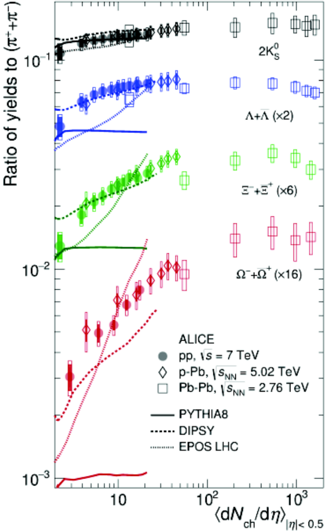
Note $\Xi(ssq)/\phi(s\bar{s})$ constant: competing models killed



LHC Alice antibaryon yields enhanced as a function of participants



. . . and as a function of multiplicity



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)

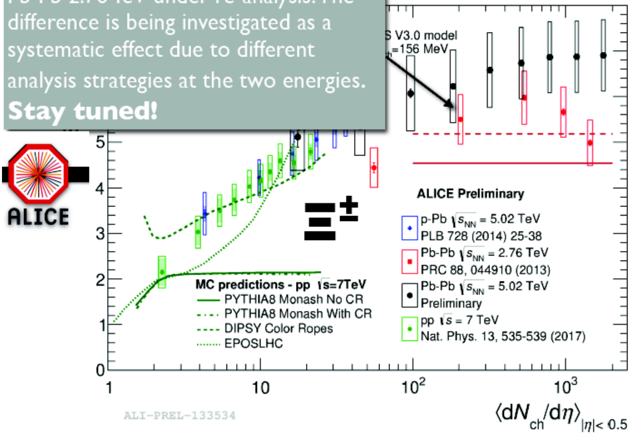
Models fail to riproduce data. Only DIPSY gives a qualitative description.

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

NEW OBJECTIVE: Precision analysis of data

Model relies on:

- Matter-antimatter symmetry implies hadrons emitted directly in breakup of QGP fireball into abundance stable final states.
- Yields are characterized by phase space an not interaction strength which is always at maximum unitarity limit.
- Thermal nature of particle spectra implies that hadrons are born from a source (QGP) that is in kinetic equilibrium but for heavy quarks can deviate from abundance equilibrium.

We will study particle abundances. Thus our model parameters are: Volume V, abundance (chemical) freezeout temperature T, ‘chemical ’ potentials for each particle.

AVERAGE PER COLLISION YIELD OF HADRON i

- Obtained from integral of the distribution over phase space

$$\langle N_i \rangle = g_i V \int \frac{d^3p}{(2\pi)^3} n_i; \qquad n_i(\varepsilon_i; T, \Upsilon_i) = \frac{1}{\Upsilon_i^{-1} e^{\varepsilon_i/T} \pm 1}$$

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

- Degeneracy (spin), $g_i = (2J + 1)$
- Hadron mass (experimental mass spectrum)

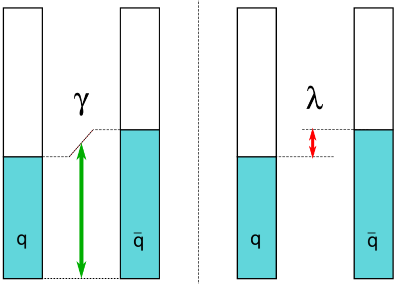
- Overall normalization
- Hadronization temperature
- Fugacity Υ_i (chemical factor, next slides)

CHEMICAL POTENTIAL TUTORIAL: QUARK CHEMISTRY

FUGACITY $\Upsilon = \gamma\lambda$

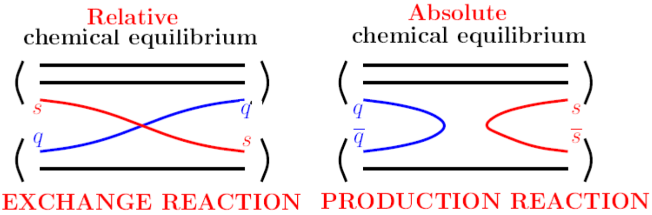
- Chemical factor based on constituent quark flavors
- Relative λ chemical equilibrium controls difference between quarks and antiquarks of same flavor $q - \bar{q}$
- Absolute γ chemical equilibrium controls number of $q\bar{q}$ pairs

- example: $\Lambda(uds)$ $(q = u, d)$
  $\Upsilon_{\Lambda(uds)} = \gamma_q^2 \gamma_s \, \lambda_q^2 \lambda_s$
  $\Upsilon_{\overline{\Lambda}(\bar{u}\bar{d}\bar{s})} = \gamma_q^2 \gamma_s \, \lambda_q^{-2} \lambda_s^{-1}$



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

STANDARDIZED PROGRAM TO FIT MODEL PARAMETERS

Statistical HAdronization with REsonances: (SHARE)

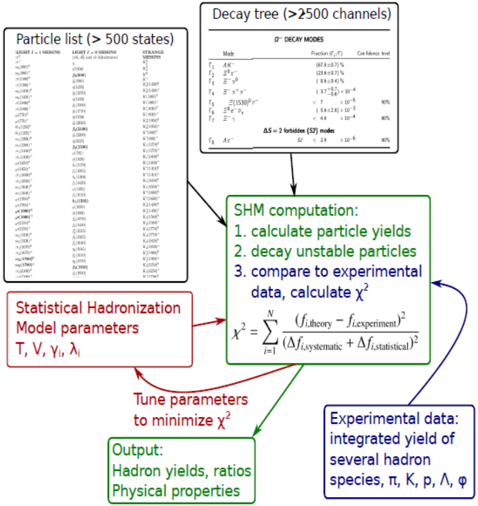
- SHM implementation in publicly available program
  Giorgio Torrieri et al, Arizona + Krakow; SHAREv1 (2004), SHAREv2 + Montreal, added fluctuations (2006)
  Michal Petran SHARE with CHARM: (2013)

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: $Q/B \simeq 0.39$, $\langle s - \bar{s} \rangle = 0$

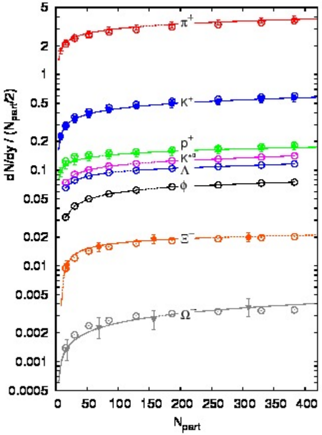
PROCEDURE – FITTING SHM PARAMETERS TO DATA

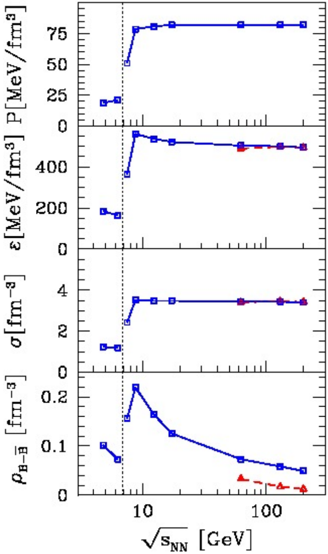
1. Input: T, V, γ_q, γ_s, λ_q, $\lambda_s.\lambda_3$
2. Compute yields of all hadrons
3. Decay feeds – particles experiment observes
4. Compare to exp. data (χ^2)
5. Including bulk properties, constraints
6. Tune parameters to match data (minimize χ^2)



AGS,SPS,RHIC bulk properties⇒

⇓Fit to ALICE data⇓

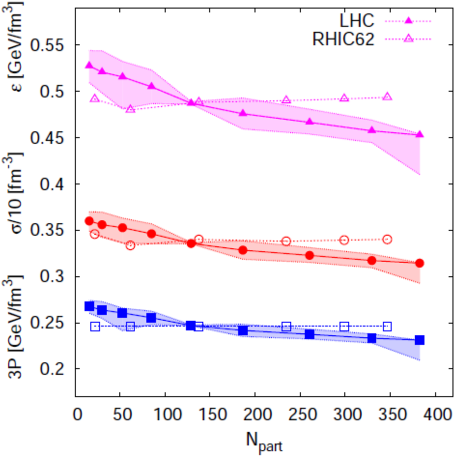




Universality of Hadronization Condition: Bulk intensive properties

FIREBALL PHYSICAL PROPERTIES

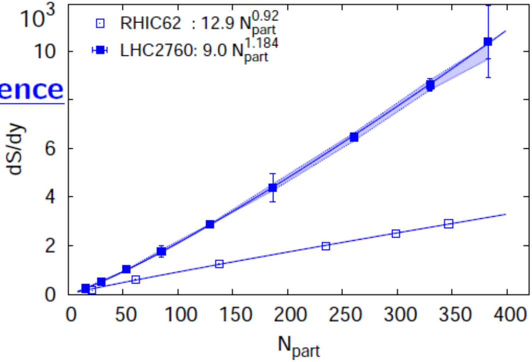
- LHC Compatible with RHIC-62
- Error band is γ_s uncertainty
- Slight decrease with centrality
- Decrease → super–cooling
- Compare $\varepsilon = 0.5$ GeV/fm^3 $\simeq$ $\simeq 3.3\varepsilon_{\rm nucl}$



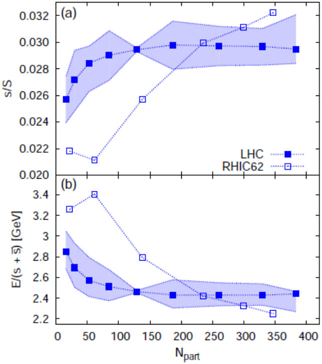
Volume main quantity to change comparing QGP production at RHIC and LHC

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?



Strangeness at LHC grows faster compared to RHIC as function of participant number $N_{\rm part}$ and cost in thermal energy of making strangeness decreases faster QGP value



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.

Interest in strangeness/entropy(=4×particle multiplicity)

s/S: both s and S conserved in QGP→hadrons→detector

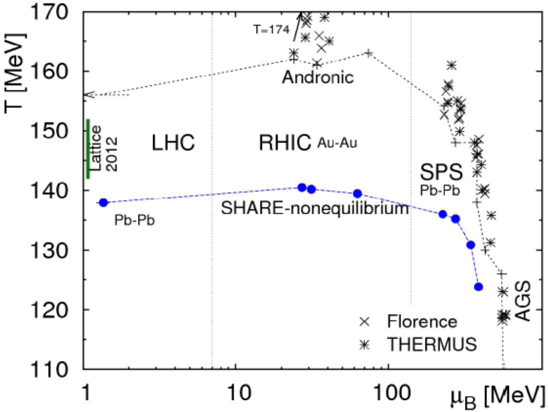
Relative s/S yield measures the number of active degrees of freedom and the degree of relaxation when strangeness production freezes-out in QGP. Perturbative expression in chemical equilibrium:

$$\frac{s}{S}=\frac{\frac{g_s}{2\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{(g2\pi^2/45)T^3+(g_sn_{\rm f}/6)\mu_q^2T}\simeq\frac{1}{35}=0.0286$$

much of $\mathcal{O}(\alpha_s)$ interaction effect cancels out. When considered $s/S\rightarrow 1/31=0.0323$. Now introduce QGP abundance <1nonequilibrium

$$\frac{s}{S}=\frac{0.03{\gamma_{(t)}}_s^{\rm QGP}}{0.4\gamma_{\rm G}+0.1{\gamma_{(t)}}_s^{\rm QGP}+0.5{\gamma_{(t)}}_q^{\rm QGP}+0.05{\gamma_{(t)}}_q^{\rm QGP}(\ln\lambda_q)^2}\rightarrow 0.03{\gamma_{(t)}}_s^{\rm QGP}.$$

Consistency of SHM models with Lattice-QCD

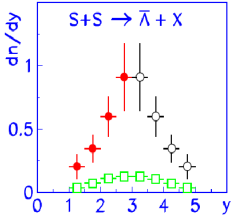


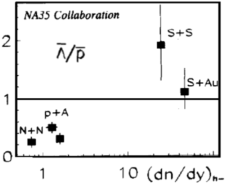
Chemical freeze-out MUST be below lattice results. For direct free-streaming hadron emission from QGP, T-SHM is the QGP source temperature, there cannot be full chemical equilibrium.

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_{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. Mass spectrum of strange hadrons impacts the value of T_{H} .
- 35 years ago we proposed to recreate a new primordial phase of matter smashing heaviest nuclei and developed laboratory observables of this quark-gluon phase of matter: cooking strange quark flavor in the QGP fireball.
- Global effort to discover QGP - followed. 10-15 years ago CERN and BNL Laboratories announced the discovery of new phase, the QGP.
- Today: We understand the properties of QGP. Among key results is the universal hadronization behavior of the QGP formed in vastly different environments of SPS, RHIC, LHC.

QGP discovered/confirmed by 1996: $\bar{\Lambda}/\bar{p}$





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 $\bar{\Lambda}$ 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].

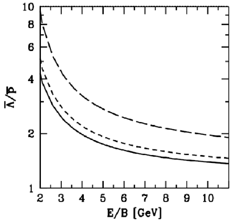
Attempts to describe the antibaryon yields within the RQMD model require the introduction of a new production mechanism beyond hadronic rescattering.

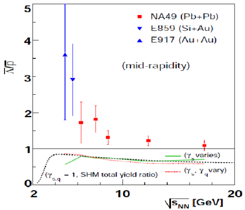
$\bar{\Lambda}/\bar{p}$-ratio near midrapidity in proton-proton, minimum bias proton-nucleus and central nucleus-nucleus collisions at 200 GeV per nucleon as a function of the rapidity density of negatively charged hadrons at midrapidity.

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

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

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





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

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.

EXTRA:Strangeness relaxation to chemical equilibrium

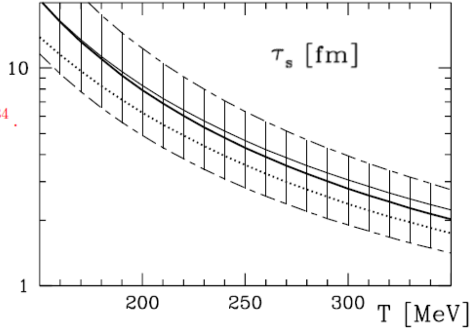
Strangeness density time evolution in local rest frame:

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

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

EXTRA: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

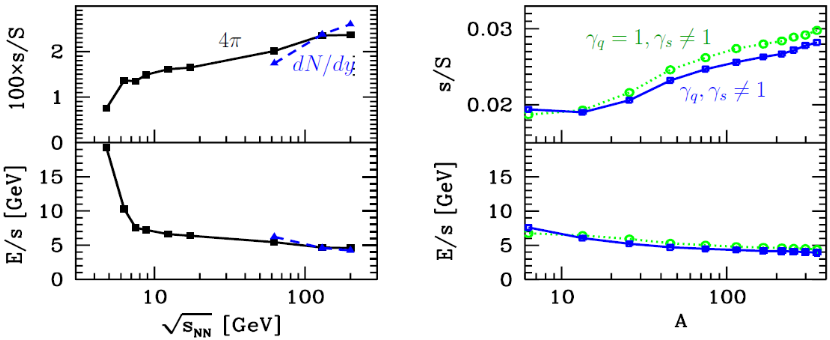
$$\frac{s^Q}{S^Q} = \frac{0.03\gamma_s^Q}{0.4\gamma_G + 0.1\gamma_s^Q + 0.5\gamma_q^Q + 0.05\gamma_q^Q(\ln\lambda_q)^2} \to 0.03\gamma_s^Q.$$

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:

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

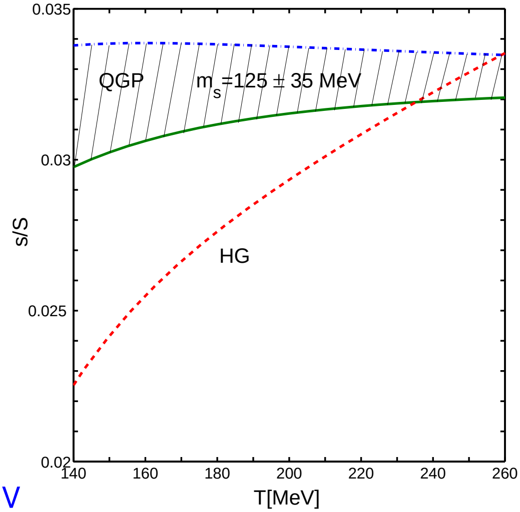
EXTRA: Fits 2003-2008 as a function of $\sqrt{s_{NN}}$ and A

Energy threshold of QGP formation



Interest in energy cost of strangeness pair E/s as it may show change in reaction mechanism.

EXTRA:Two phases: s/S difference of equilibrium condition



Lattice
$T \simeq 145$ MeV

EXTRA: Strangeness as Deconfinement Signatures

A: TOTAL Strangeness YIELD: s strangeness/ S entropy

depends primarily on initial conditions and evolution dynamics

B: Strangeness at QGP break-up:

i: Is QGP near chemical equilibrium?

$$\left.\frac{n_s(t, T(t))}{n_s(\infty, T(t))}\right|_{\text{QGP}} \equiv \gamma_s^{\text{QGP}}(t) \to 1? \qquad \boxed{\gamma_s^{HG} \simeq 3\gamma_s^{\text{QGP}}}$$

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

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.

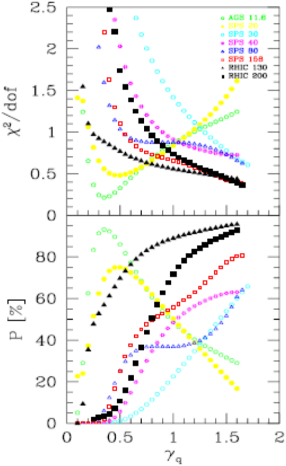
EXTRA: STATISTICAL HADRONIZATION MODEL (SHM)

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: HOWEVER
  Experiments report event-average rapidity particle abundances, model should describe an average event
- Canonical phase space: sharp number of particles
  ensemble average energy $E \to T$ temperature
  T could be, but needs not to be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles: $N \to \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

Our interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated spectra.

EXTRA: The horn and chemical nonequilibrium



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

Looking a the fit χ^2 we see that between 20 and 30GeV results favor that γ_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 $P\%$.