Strangeness and Formation of QGP

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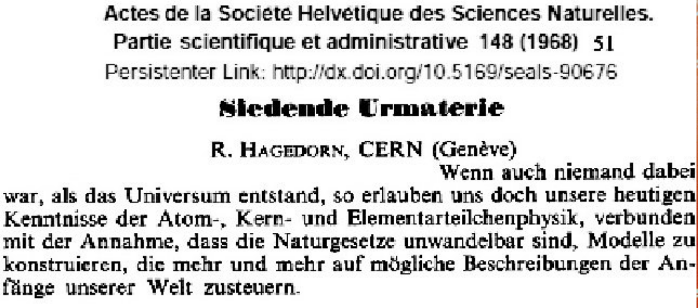
IFJ, Kraków Epiphany January 10, 2019

Relativistic heavy ion collision research program was created to discover and study how hadrons melt into quark gluon plasma (QGP), and QGP turns into matter again. I will survey strangeness as a signature of QGP across past decades and show recent results obtained explaining experimental and lattice data.

1965-7 – Hagedorn's singular Statistical Bootstrap

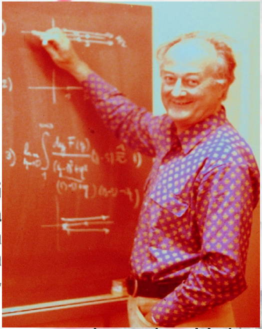
accepted as 'the' initial singular hot Big-Bang theory


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)

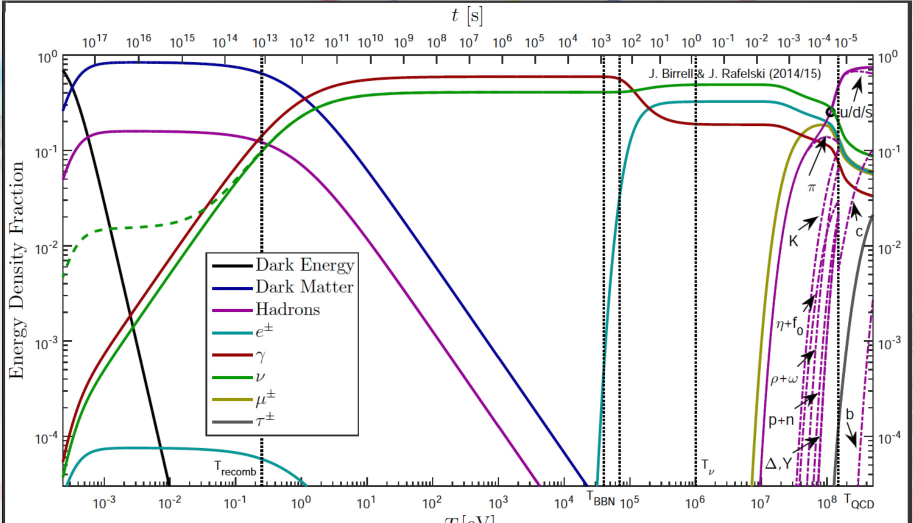
Wenn auch niemand dabei war, als das Universum entstand, so erlauben uns doch unsere heutigen Kenntnisse der Atom-, Kern- und Elementarteilchenphysik, verbunden mit der Annahme, dass die Naturgesetze unwandelbar sind, Modelle zu konstruieren, die mehr und mehr auf mögliche Beschreibungen der Anfänge 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. . . We would have never understood these things if we had not advanced on Earth the fields of atomic and nuclear physics. To understand the great, we must descend into the very small.*

Repeated in S.Weinberg's Cosmology book *about the Big Bang singularity*

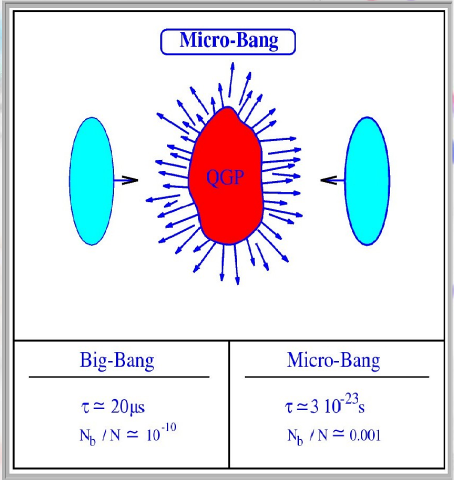
The Universe Composition in Single View 50 y After



dark energy matter radiation ν, γ BBN+leptons hadrons

Different dominance eras: Temperature grows to right

1977/8 JR+RH at CERN: how can we recreate Big-Bang in lab?



Relativistic Heavy Ion Collisions

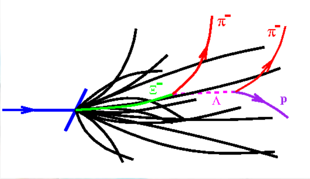
- Universe time scale 18 orders of magnitude longer, hence equilibrium of leptons & photons
- Baryon asymmetry six orders of magnitude larger in Laboratory, hence chemistry different
- Universe: dilution by scale expansion, Laboratory explosive expansion of a fireball

$\Longrightarrow$ Theory connects RHI collision experiments to Universe

Physics of RHI collisions & Quark Gluon Plasma

1. RECREATE THE EARLY UNIVERSE IN LABORATORY
   Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 20 μs after the Big-Bang.
2. PROBING OVER A 'LARGE' DISTANCE THE (DE)CONFINING QUANTUM VACUUM STRUCTURE
   The quantum vacuum, the present day relativistic æther, determines prevailing form of matter and laws of nature.
3. STUDY OF THE ORIGIN OF MATTER & OF MASS
   Matter and antimatter created when QGP 'hadronizes'. Mass of matter originates in the confining vacuum structure
4. PROBE ORIGIN OF FLAVOR
   Normal matter made of first flavor family $(d, u, e, [\nu_e])$. Strangeness-rich quark-gluon plasma the sole laboratory environment filled 'to the rim' with 2nd family matter $(s, c, [\mu, \nu_\mu]))$. and considerable abundance of b and even t.
5. PROBE STRONGEST FORCES IN THE UNIVERSE
   For a short time the relativistic approach and separation of large charges $Ze \leftrightarrow Ze$ generates EM fields 1000's time stronger than those in Magnetars; strongfields=strong force=strong acceleration

Anti-strangeness in QGP: $\bar{s} > \bar{q}$ in SPS experiments



FROM HADRON GAS TO QUARK MATTER II

J. Rafelski
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der Universität Frankfurt

and

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CERN--Geneva

Ref.TH.2969-CERN
13 October 1980

80-12-212

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.

A: Strange hadrons are subject to a self analyzing decay

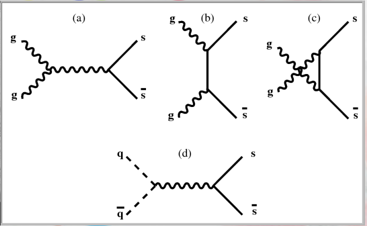
B: There are many strange particles allowing study different physics questions $(q = u, d)$:

$$K(q\bar{s}),\quad \overline{K}(\bar{q}s),\quad K^*(890),\ldots$$
$$\Lambda(qqs),\quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),\quad \Lambda(1520),\ldots$$
$$\phi(s\bar{s}),\quad \Xi(qss),\quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}),\ldots$$
$$\Omega(sss),\quad \overline{\Omega}(\bar{s}\bar{s}\bar{s})$$

C: Production rates hence statistical significance is high.

THEORETICAL CONSIDERATION within QCD

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



B: coincidence of scales:

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

strangeness yield can grow gradually - make models of time/size dep.

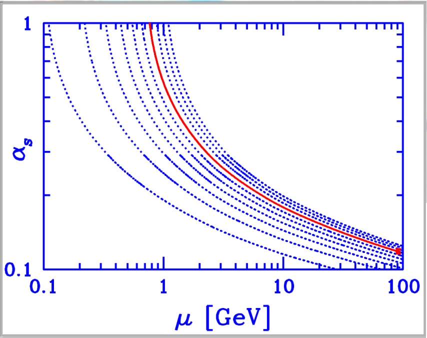
QCD strangeness production cross sections

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.

Hadrons and Quark–Gluon Plasma

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Université de Paris VII (Denis Diderot)

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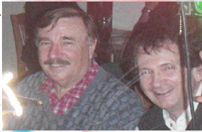
Hardback (ISBN-13: 9780521385367 | ISBN-10: 0521385369) Also available in Paperback | Adobe eBook



Particle abundance N: T, V and Υ

- Overall normalization V (also dV/dy)
- Ambient temperature T
- Fugacity $\Upsilon_\pm = \gamma\, e^{\pm\mu/T}$ where μ Relative" equilibrium chemical potential and phase space occupancy=$\gamma(t)$ is time dependent – creation of strangeness – even if everything is stationary relates to achievement of "Absolute" chemical equilibrium .

- N Obtained from integral of the distribution over phase space

$$\langle N\rangle = gV\int \frac{\mathrm{d}^3p}{(2\pi)^3}\, n; \qquad n\,(\varepsilon; T, \Upsilon) = \frac{1}{\Upsilon_\pm^{-1} e^{\,\varepsilon/T} \pm 1}$$

$$\langle N\rangle = \frac{gVT^3}{2\pi^2}\sum_{n=1}^{\infty}\frac{(\pm 1)^{n-1}\Upsilon_\pm^n}{n^3}\left(\frac{nm}{T}\right)^2 K_2\left(\frac{nm}{T}\right) \qquad \Upsilon_\pm \le e^{m/T}$$

- Particle properties determine:
  degeneracy g (e.g. spin $= (2J+1)$), and Hadron mass m

Strangeness Deconfinement Signatures

A: TOTAL Strangeness: normalized with another conserved yield:

s strangeness/ S entropy s/b baryon # when b measured

depend on evolution dynamics and initial conditions

B: Strangeness at QGP break-up:

i: Is QGP near chemical equilibrium?

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

ii: For consistency we need also to consider $\gamma_q^{\rm HG} > 1$
this over population controls ENTROPY enhancement

C: STRANGENESS MOBILITY IN QGP imprinted at hadronization on greatly enhanced produced multi (anti)strange hadron abundances.

strangeness/entropy s/S: both s and S (almost) 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:

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

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

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

We return to topic at end of lecture

Instant success of strangeness signature proposal

Strangeness in quark–gluon plasma

Johann Rafelski

Based on a lecture given at the Bielefeld Workshop on 'Quark Matter Formation and Heavy Ion Collisions', May 10–14, 1982
S. Afr. J. Phys. 6 (1983) 37–43

Institut für Theoretische Physik der Universität, Frankfurt/Main
and Department of Physics, University of Cape Town, Rondebosch

It is argued that observation of the strange-particle abundance may lead to identification of the quark–gluon plasma and measurement of some of its properties. Approach to chemical equilibrium and competitive processes in the hadronic gas phase are discussed.

picked up by Marek in Dubna . . .

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Received by Publishing Department
on July, 20, 1983.

Anikina M. et al. E1-83-521

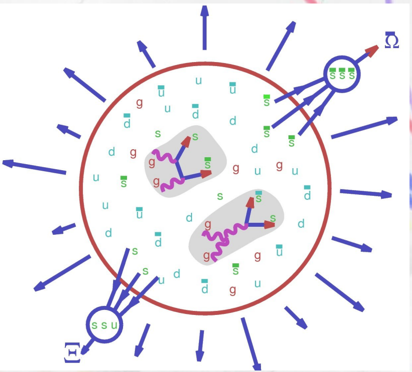
A Study of Λ -Production
in Central Nucleus-Nucleus Interactions
at a Momentum of 4.5 GeV/c Per Incident Nucleon

Transverse momenta and rapidities of Λ's produced in central nucleus-nucleus collisions at 4.5 GeV/c per nucleon /CC, CNe, ONe, OCu, 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



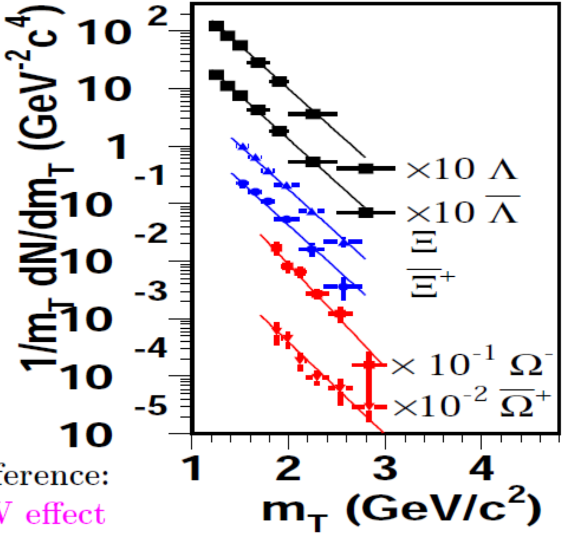
1. $GG \to s\bar{s}$ (thermal gluons collide)
   $GG \to c\bar{c}$ (initial parton collision)
   gluon dominated reactions
2. hadronization of pre-formed
   $s, \bar{s}, c, \bar{c}, b, \bar{b}$ quarks

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. J. Rafelski, *Formation and Observables of the Quark-Gluon Plasma* Phys.Rept. **88** (1982) p331; P. Koch, B. Muller, and J. Rafelski; *Strangeness in Relativistic Heavy Ion Collisions*, Phys.Rept. **142** (1986) p167

Pb-Pb SPS collisions also show matter-antimatter symmetry: Sudden hadronization of QGP

WA97	$T_\perp^{\rm Pb}$ [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

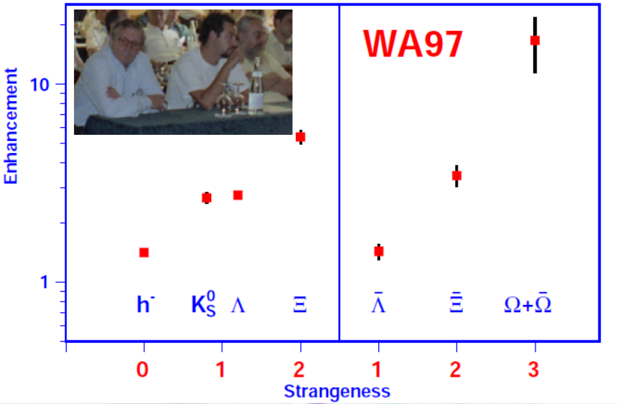
Λ within 1% of $\overline{\Lambda}$



Kaon – hyperon difference:
EXPLOSIVE FLOW effect

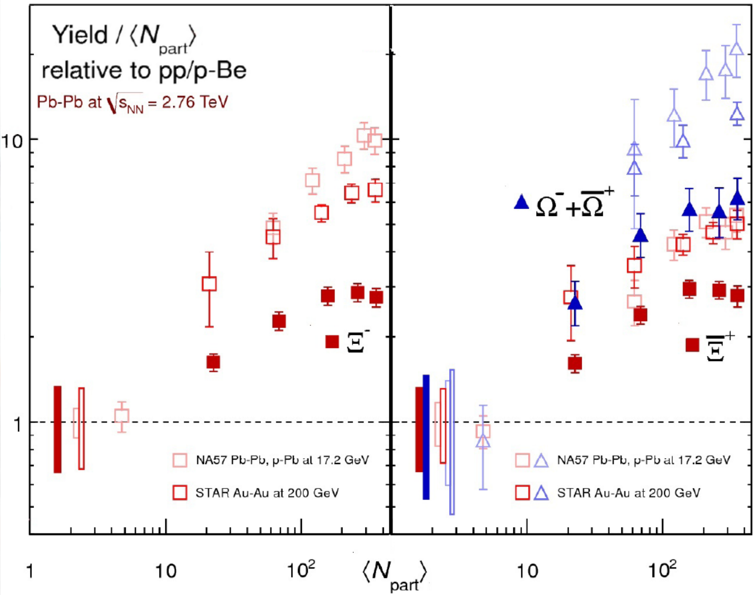
Predicted: Strange antibaryons enhanced

WA97 SPS Antihyperons: The largest observed QGP medium effect



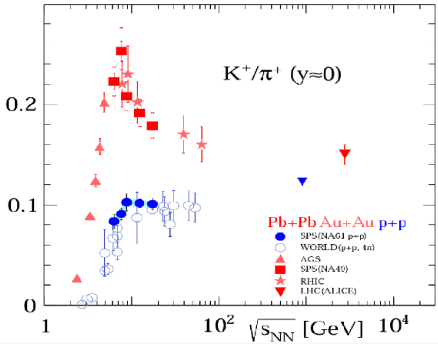
Enhancement GROWS with a) strangeness b) antiquark content as we predicted. Enhancement with respect to yield in p–Be collisions, scaled up with the number of 'wounded' nucleons. Result → CERN QGP discovery announcement in 2000. All other CERN strangeness experimental results agree.

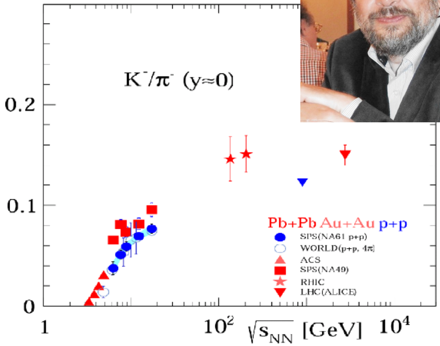
Today: Effect remains largest medium effect in RHI collisions



Onset of Deconfinement: NA49/NA61

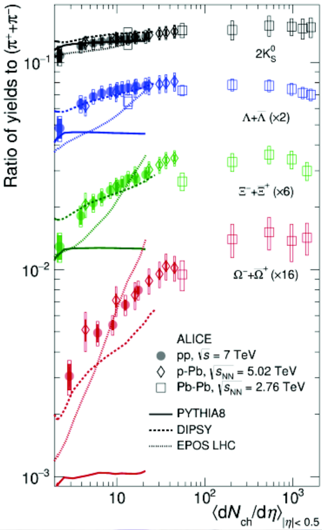
Marek’s Discovery: The HORN





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

Current interest in small systems: Strange antibaryon enhancement smoothly rising with entropy of fireball



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

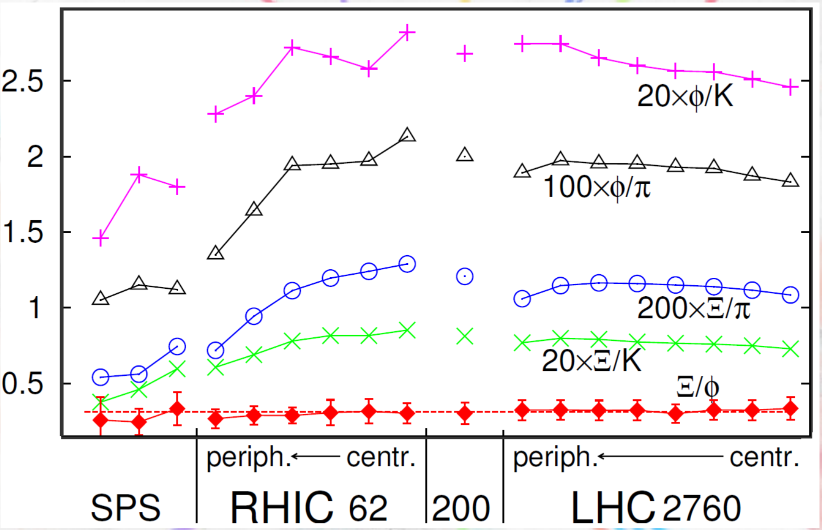
At high mult. pp ratio reaches values similar to the one in Pb-Pb (when ratio saturates)

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

ALI-PUB-106878

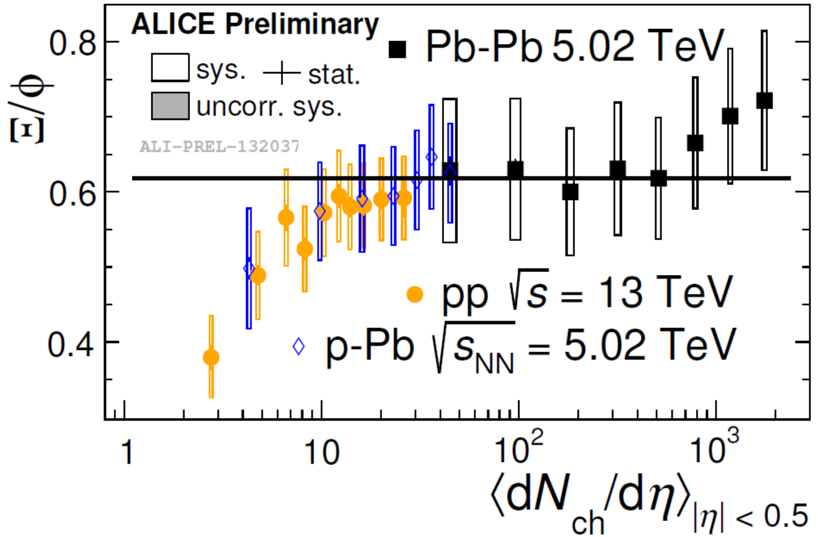
Alessandro Grelli **10/7/2017**

Hadronization: Recombinant $\Xi(ssq)/\phi(s\bar{s})$ (nearly) constant



M. Petran, J. Rafelski, *Multistrange Particle Production and the Statistical Hadronization Model* Phys.Rev. C **82** (2010) 011901

Hadronization: Recombinant $\Xi(ssq)/\phi(s\bar{s})$: Alice



Found in QM2018 Reports, Adapted with one line.....

The chemical hadronization analysis invented

Physics Letters B

Volume 262, Issues 2–3, 20 June 1991, Pages 333-340

open access

Strange anti-baryons from quark-gluon plasma

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Received 5 April 1991, Available online 17 October 2002.

https://doi.org/10.1016/0370-2693(91)91576-H

Abstract

Experimental results on strange anti-baryon production in nuclear S→W collisions at 200 *A* GeV are described in terms of a simple model of an explosively disintegrating quark-lepton plasma (QGP). The importance of the strange anti-baryon signal for the identification of the QGP state and for the diagnosis of its properties is demonstrated.

Chemical nonequilibrium and deconfinement in 200*A* GeV sulphur induced reactions

Jean Letessier and Johann Rafelski

Phys. Rev. C **59**, 947 – Published 1 February 1999 Received 17 June 1998

DOI: https://doi.org/10.1103/PhysRevC.59.947

PHYSICAL REVIEW C
covering nuclear physics

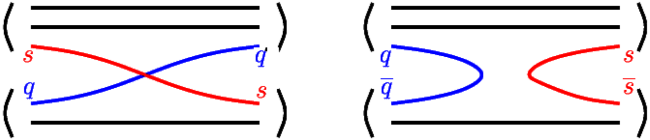
We interpret hadronic particle abundances produced in S-Au/W/Pb $200A$ GeV reactions in terms of the final state hadronic phase space model and determine by a data fit of the chemical hadron freeze-out parameters. Allowing for the flavor abundance nonequilibrium a highly significant fit to experimental particle abundance data emerges, which supports the possibility of strangeness distillation. We find under different strategies stable values for freeze-out temperature $T_f = 143 \pm 3$ MeV, baryochemical potential $\mu_B = 173 \pm 6$ MeV, ratio of strangeness (γ_s) and light quark (γ_q) phase space occupancies $\gamma_s/\gamma_q = 0.60 \pm 0.02$, and $\gamma_q = 1.22 \pm 0.05$ without accounting for collective expansion (radial flow). When introducing flow effects which allow a consistent description of the transverse mass particle spectra, yielding $|v_c| = 0.49 \pm 0.01\ c$, we find $\gamma_s/\gamma_q = 0.69 \pm 0.03$, $\gamma_q = 1.41 \pm 0.08$. The strange quark fugacity is fitted at $\lambda_s = 1.00 \pm 0.02$ suggesting chemical freeze-out directly from the deconfined phase.

Nonequilibrium parameters describe time evolution of fireball system

Hadronization: Chemical reactions involving quarks

EXAMPLE: Strangeness in HG:

Relative chemical equilibrium | **Absolute** chemical equilibrium



EXCHANGE REACTION | **PRODUCTION REACTION**

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

WHY STATISTICAL HADRONIZATION MODEL... (SHM) WORKS

a) Confinement: $\Longrightarrow$ breakup into free quarks not possible;
b) Strong interaction: $\Longrightarrow$ equal hadron production strength irrespective of produced hadron type
$\Longrightarrow$ 'elementary' hadron yields depend only on the available phase space
Historical approaches:

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

Our interest: bulk QGP fireball properties of hadron source evaluated independent of complex explosion dynamics $\Longrightarrow$ analyze integrated hadron spectra.

SHARE Idea/Team: US-Polish NATO collaboration 2002/04

Statistical HAadronization with REsonances

2000-06 Golden age of scientific collaboration Kraków-Arizona

ELSEVIER Computer Physics Communications 167 (2005) 229–251

SHARE: Statistical hadronization with resonances

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Received 27 July 2004; received in revised form 9 November 2004; Available online 19 March 2005

Abstract

SHARE is a collection of programs designed for the statistical analysis of particle production in relativistic heavy-ion collisions. With the physical input of intensive statistical parameters, it generates the ratios of particle abundances. The program includes cascade decays of all confirmed resonances from the Particle Data Tables. The complete treatment of these resonances has been known to be a crucial factor behind the success of the statistical approach. An optional feature implemented is the Breit–Wigner distribution for strong resonances. An interface for fitting the parameters of the model to the experimental data is provided.

ELSEVIER Physics Letters B 633 (2006) 488–491

Balance of baryon number in the quark coalescence model

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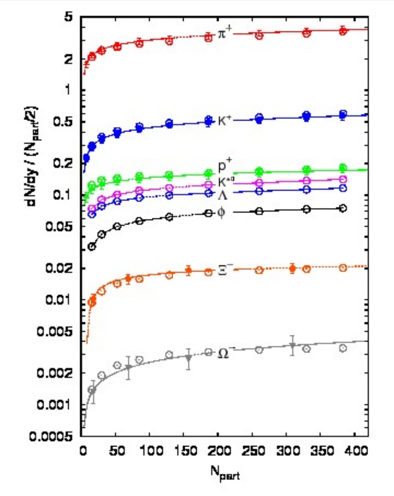
Received 29 August 2005; received in revised form 7 November 2005; Available online 7 December 2005

The charge and baryon balance functions are studied in the coalescence hadronization mechanism of quark–gluon plasma. Assuming that in the plasma phase the $q\bar{q}$ pairs form uncorrelated clusters whose decay is also uncorrelated, one can understand the observed small width of the charge balance function in the Gaussian approximation. The coalescence model predicts even smaller width of the baryon–antibaryon balance function: $\sigma_{B\bar{B}}/\sigma_{+-} = \sqrt{2/3}$

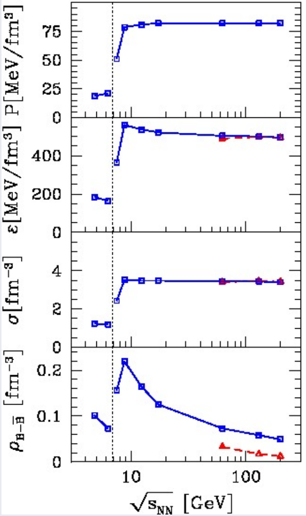
Examples SHM Analysis (Chemical Nonequilibrium)

Particle Yield Example:LHC



M. Petran, J.Letessier, V. Petracek, J. Rafelski Phys.Rev. C **88** (2013) no.3, 034907

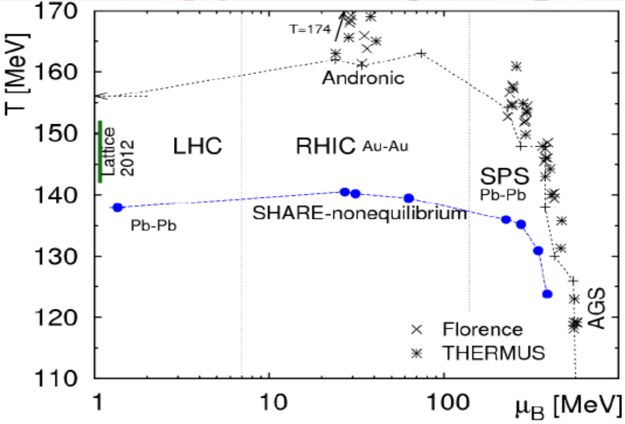
Bulk properties from SHM yields



J. Letessier, J. Rafelski, Eur.Phys.J. A **35** (2008) 221-242

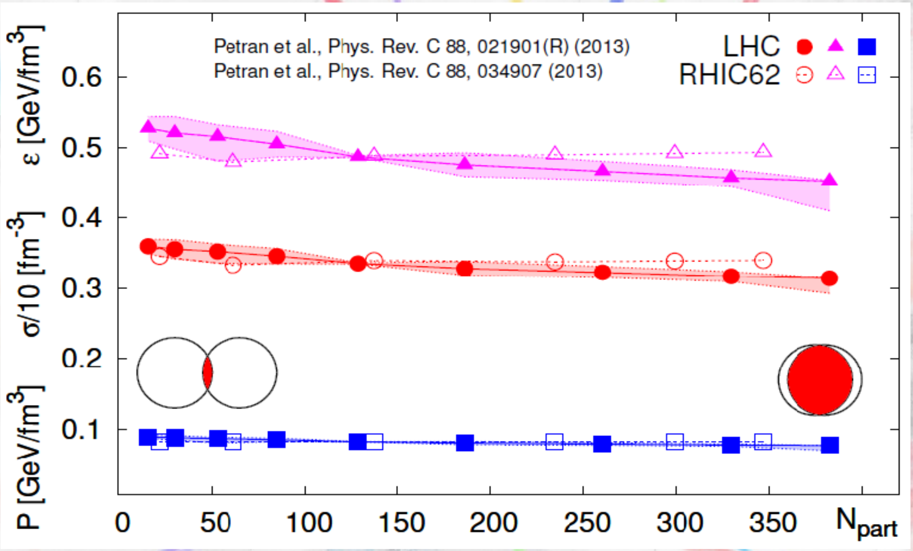
Consistentcy with lattice QCD REQUIRES: Chemical nonequilibrium + supercooling = sudden fireball breakup

Work with Michal Petran



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.

Smaller systems hadronize earlier (more dense fireball)



There are also remaining questions about kinetic process of strangeness production. Today we only look at QCD perturbative model

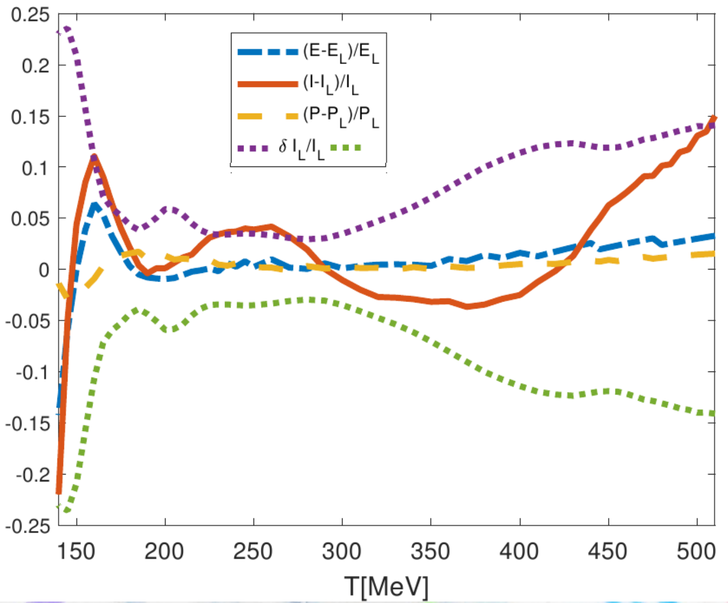
Collaboration/project with Inga Kuznetsova

The problem: the Lattice EOS show that we do not have a simple quark-gluon free gas: QGP is a complicated thermal plasma with effective particles that interact weakly.

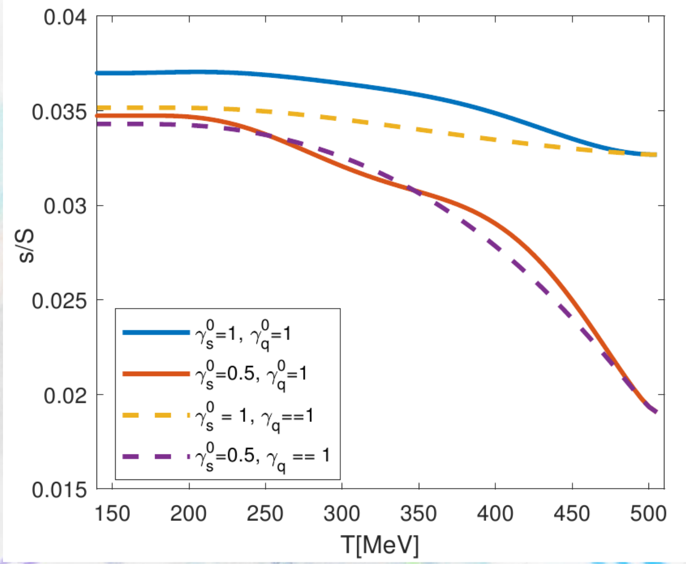
1. Describe the fully thermal and chemical equilibrium state in terms of effective quark and gluone with thermall mass degrees of freedom
2. Use these effective particles to model evolution of strangeness in dynamical fireball to constrain models that were used in step 1

Lesson: A very difficult project: almost always quasiparticles that are easily used to model lattice incompatible with our knowledge about strange particle yields.

Step 1: Level of agreement with Lattice Data



Step 2: Strangeness growth before hadronizatio: Step 1 parameters a big constraint on what works



SPS, RHIC, LHC AA SHM Digest

- Universality of fireball bulk properties across the entire reaction energy domain we express in terms of the invariant measure
- Strange antibaryon signature of QGP leads to discovery of universal properties of QGP at hadronization; differences in: Fireball volume size, and in strangeness saturation
- At SPS, RHIC: Baryon number deposition varies strongly as function of collision energy. This is the chemical potential dependence on collision energy. WHY? To clarify question: why baryons are stopped?
- Advanced models of strangness production consistent with lattice QCD in progress