Strangeness and Universality of QGP Hadronization

October 21, 2011, Columbia U, NYC

Hadron production and HBT volume scaling allow to characterize precisely the bulk matter properties across all energies at SPS, RHIC and now LHC. The properties of quark-gluon plasma at hadronization, such as energy density and pressure are Universal across the entire energy range available; strangeness content is displaying the quark degrees of freedom of QGP.

Supported by a grant from the U.S. Department of Energy, DE-FG02-04ER41318

Key collaborators of past 30years: **M. Danos**, **R. Hagedorn**, **J. Letessier**, **B. Müller**

Ph.D. students P. Koch, I. Kuznetsova, M. Petran, G. Torrieri and others

Johann Rafelski
Department of Physics
University of Arizona
TUCSON, AZ 85718

Four Pillars of QGP/RHI Collisions Research Program

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 30 μs after big bang.

QGP-Universe hadronization led to nearly matter-antimatter symmetric state, the later ensuing matter-antimatter annihilation leaves behind as our world the 10^{-10} *matter asymmetry.*

STRUCTURED VACUUM-AETHER (Einsteins 1920+ Aether/Field/Universe)

The vacuum state determines prevailing fundamental laws of nature. Demonstrate by changing the vacuum from hadronic matter ground state to quark matter ground state, and finding the changes in laws of physics.

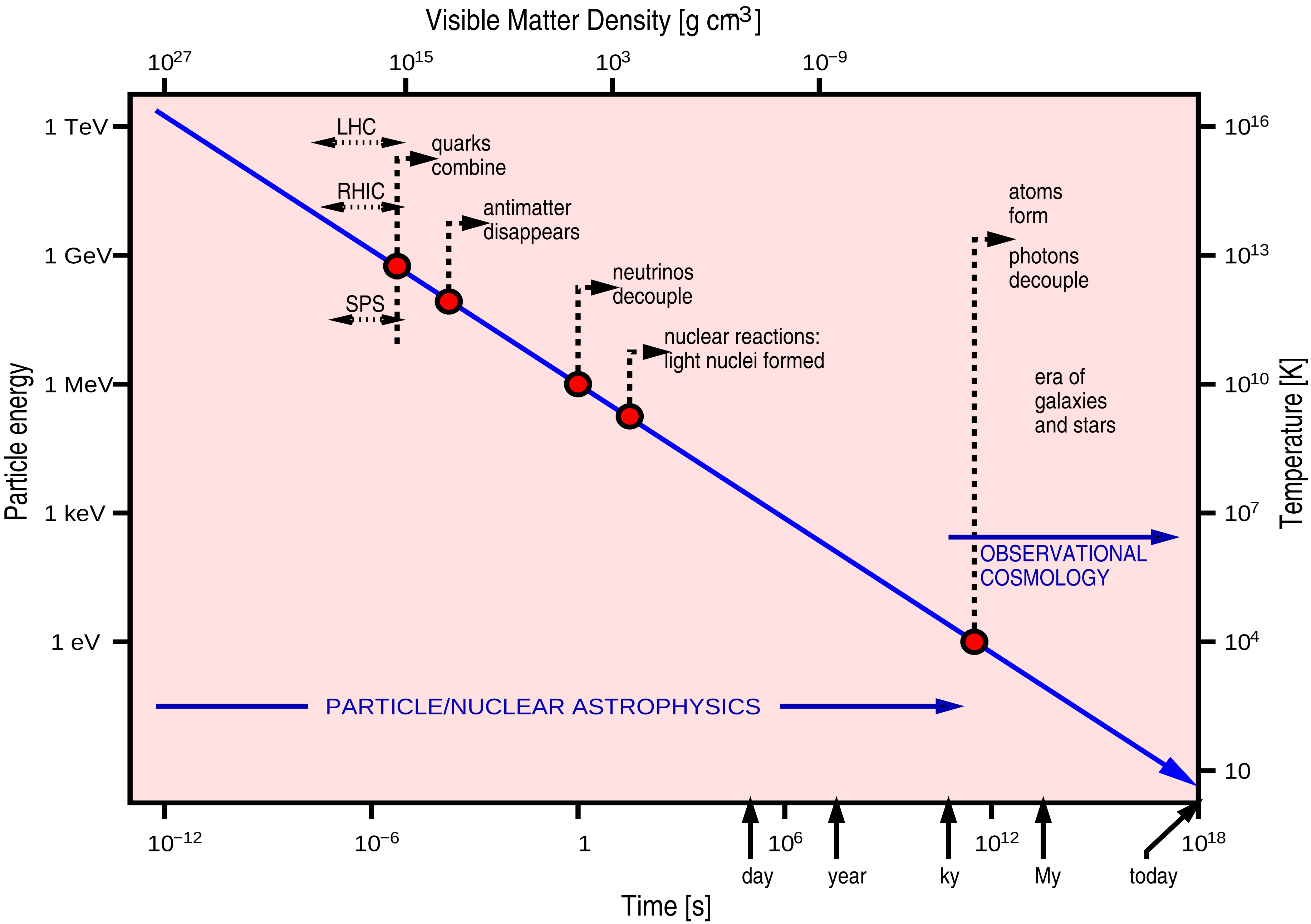
ORIGIN OF MASS OF MATTER –(DE)CONFINEMENT

The confining quark vacuum state is the origin of 99.9% of mass, the Higgs mechanism applies to the remaining 0.1%. We want to show that the quantum zero-point energy of confined quarks is the mass of matter. To demonstrate we 'melt' the vacuum structure setting quarks free.

ORIGIN OF FLAVOR

Normal matter made of first flavor family (u, d, e, ν_e). Strangeness rich quark-gluon plasma the lonly laboratory environment about one-third filled with 2nd family matter (s, c, μ, ν_μ) – potential to unravel the secret of flavor.

Stages in the evolution of the Universe



Aether 1920

Albert Einstein at first rejected æther as unobservable when formulating special relativity, but eventually changed his initial position, re-introducing what is referred to as the 'relativistically invariant' æther. In a letter to H.A. Lorentz of November 15, 1919, see page 2 in *Einstein and the Æther*, **L. Kostro, Apeiron, Montreal (2000). he writes:**

It would have been more correct if I had limited myself, in my earlier publications, to emphasizing only the non-existence of an æther velocity, instead of arguing the total non-existence of the æther, for I can see that with the word æther we say nothing else than that space has to be viewed as a carrier of physical qualities.

In a lecture published in May 1920 (given on 27 October 1920 at Reichs-Universität zu Leiden, addressing H. Lorentz), published in Berlin by Julius Springer, 1920, also in Einstein collected works: In conclusion:

...space is endowed with physical qualities; in this sense, therefore, there exists an æther. According to the general theory of relativity space without æther is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical sense. But this æther may not be thought of as endowed with the quality characteristic of ponderable media, as (NOT) consisting of parts which may be tracked through time. The idea of motion may not be applied to it.

Aether structure and confinement mass

We aim to verify the new paradigm: the Aether (Vacuum) structure a key element for quark confinement and hadron structure:- and

Vacuum structure controls early Universe properties

Vacuum is (QED) polarizable: see atomic vac. pol. level shifts

Vacuum is thought to generate color charge confinement:
hadron mass originates in QCD vacuum structure.

Vacuum determines inertial mass by confinement and/or
for 'elementary' particles, by the way of the Higgs mechanism,

$$m_i = g_i \langle V|h|V\rangle \,,$$

Vacuum determines interactions, symmetry breaking, more.....

What controls INERTIA (resitance to change in velocity)?

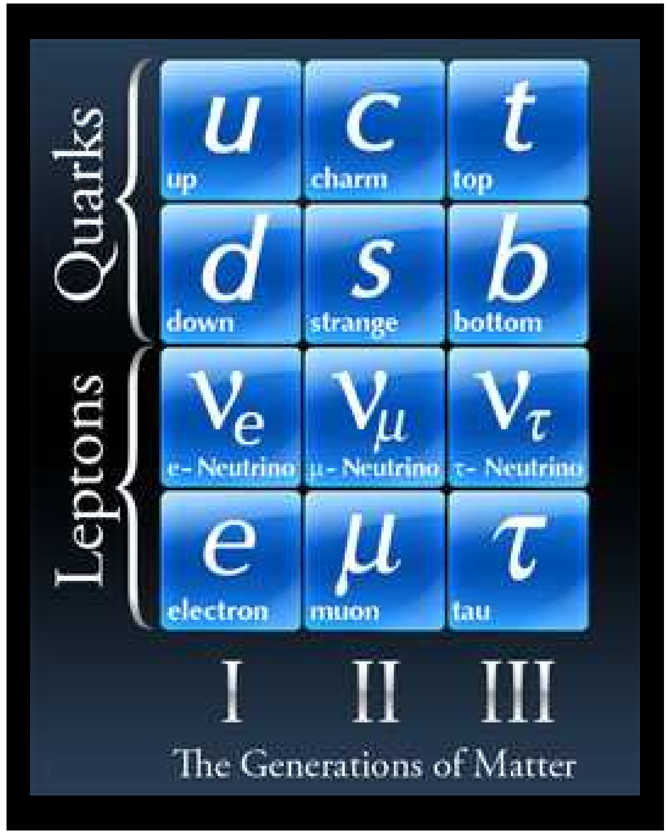
Vacuum of QCD with permanent gluon-quark fluctuations in 'space devoid of matter'

even though $\langle V|G^a_{\mu\nu}|V\rangle = 0, \quad \langle V|\Psi_{u,d,s,\ldots}|V\rangle = 0,$

we have $\langle V|\frac{\alpha_s}{\pi}G^2|V\rangle \simeq (2.3\pm 0.3)10^{-2}\mathrm{GeV}^4 = [390(12)\,\mathrm{MeV}]^4\,,$

and $\langle V|\bar{u}u + \bar{d}d|V\rangle = -2[225(9)\,\mathrm{MeV}]^3\,.$

Reminder: Three Generations of Matter



In QGP we excite a large number of particles of Generation II – this should present an opportunity to explore foundation of flavor physics.

Challenge:QGP has fleeting presence in laboratory
Discover / Diagnosis / Study properties at 10^{-23} s scale

- Diletpons and photons: weakly coupled probes report all of history of collision, including the initial moments (!) – hampred by a large background of decaying hadrons
- J/Ψ suppression: one measurement, ongoing and evolving interpretation
- Jet suppression: in essence demonstration of radiation reaction at critical acceleration.
- Dynamics of quark matter flow: demonstrates presence of collective quark matter dynamics
- **Strange – strongly interacting probes provide image of the last few-fm/c of QGP expansion/hadronization:**
  - **HBT input into size:** dV/dy
  - **Strangeness to entropy ratio enhancement (deeepest probe)**
  - **Bulk Properties and hadronization universality**

Relativistic Heavy Ions - the Beginning I

Developments at CERN

G. Cocconi
Organisation Européenne pour la Recherche Nucléaire, Geneva, Switzerland

At CERN, a group belonging to the Proton Synchrotron Division is preparing a proposal for a two-year study on polarized beam and light-ion acceleration in the PS (the final draft will be ready at the beginning of 1975). Injection into the PS of these particles is becoming compatible with that of ordinary protons because, within a year or so, completion of the new linac will leave free the 50-MeV linac that is now feeding protons into the PS. Another incentive for this project is that at CERN there is the possibility of transferring the particles accelerated in the PS to the intersecting storage rings (ISR) and eventually to the 400-GeV superconducting PS. This enlarges considerably the scope of the experimental program. In Table 1 are given the luminosities at present considered realistic for the PS and the ISR for fully stripped nuclei. No plans have yet been made for the acceleration of heavy ions. If approved soon, the project could lead to usable beams before 1980.

Table 1

Luminosity of Fully Stripped Nuclei in PS and ISR

Accelerated particle	$\sigma_{\rm int}$, cm^2	PS ($\leqslant 28q/e$ GeV) Particles/pulse	ISR [equiv. lab $E \leqslant 2000(q/e)^2/A$ GeV] Luminosity, cm^{-2} sec^{-1}	Interaction rate, sec^{-1}
$p^\dagger$	$10^{-25.5}$	$10^{12.5}$	10^{31}	$10^{5.5}$
$\vec{p}$	$10^{-25.5}$	10^{10}	10^{27}	$10^{1.5}$
α	$10^{-24.5}$	$10^{9.5}$	10^{26}	$10^{1.5}$
^{16}O	10^{-24}	10^{9}	10^{25}	10^{1}

†Present performance.

BNL 50445
(Physics, Nuclear - TID-4500)

Report of the Workshop on
BEV/NUCLEON COLLISIONS OF HEAVY IONS - HOW AND WHY

November 29-December 1, 1974
Bear Mountain, New York

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and
NEVIS LABORATORIES, COLUMBIA UNIVERSITY

Organizing Committee
A. KERMAN, L. LEDERMAN, T.D. LEE, M. RUDERMAN, J. WENESER

Scientific Reporters
LAWRENCE E. PRICE, JAMES P. VARY

CERN attracted the physisists interested in deconfinement and ultimately much of the Relativistic Heavy Ion Program.

Relativistic Heavy Ions - the Beginning II

BNL 50519

ISABELLE

A Proposal for Construction of a Proton-Proton Storage Accelerator Facility

May 1976

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

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INTRODUCTION

This is a description of the Intersecting Storage Accelerator (ISA or affectionately ISABELLE) proposed for construction at Brookhaven National Laboratory. ISABELLE will provide extensive experimental facilities for the study of particle interactions resulting from 200 GeV protons colliding with 200 GeV protons. One ring of magnets carrying protons will be interlaced with a second ring of magnets carrying protons circulating in an opposite sense. The proton beams will collide at eight intersection regions where particle detectors will be arranged for studying the interaction processes.

The advantage of using colliding beams to achieve higher center-of-mass energies than available at conventional accelerators was recognized early in accelerator history by Wideröe.[1] The original work at MURA on the stacking of many pulses[2] in each beam was fundamental for the achievement of adequate luminosity, and laid the foundation for the design of the CERN ISR[3] which is, at present, the only proton-proton colliding beam device in operation.

The construction of proton storage rings at the Brookhaven AGS had been considered previously[4,5] in response to the recommendation made by the Ramsey panel.[6] A summer study was held at Brookhaven in 1963 to discuss the relative merits of accelerators and storage rings.[7] It was concluded that storage rings at AGS energies would be feasible, and a first parameter list for colliding beams was worked out by Jones.[8] At the same time he pointed out that storage rings of two or three times the circumference of the AGS could be used to accelerate the stacked protons to energies of about 100 GeV. However, the choice was eventually made to improve the AGS by increasing the intensity of the proton beam, by adding new experimental areas, and by increasing the number of secondary beams.

With the construction of the CERN ISR nearing completion the idea of building storage rings at Brookhaven was revived in 1970 by Blewett.[9] It soon received the endorsement of the Fitch Committee[10] (a committee of the AUI Board of Trustees) which recommended that BNL apply its pioneering development work in superconducting magnets to build two proton

BNL attracted projects and funding and turned Isabelle into RHIC. Original proposal did not have one word about heavy ions in Isabelle and AGS was absorbed into the project as a proton injector.

Strangeness: A signature of QGP and Deconfinement

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):

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

(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 $\bar{d}$):

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

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:

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

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

J. R. & R. Hagedorn, CERN-TH-2969, Oct.1980 *From Hadron gas to Quark Matter*

$\bar{s}/\bar{q} \to K^+/\pi^+$, **and strange antibaryons** $\bar{s}/\bar{q} \to \overline{\Lambda}/p$ **are proposed as signatures of deconfined QGP phase, matter-antimatter symmetry.**

Chemical equilibrium in QGP is presumed in the argument.

Second Challenge: Biro-Zimanyi

KFKI-1981-69

It is clear from Fig.2 that the possible lifetime of quark-gluon plasma itself is far less than the time necessary for chemical equilibration between strange and non strange quarks.

An interesting feature of the relaxation time, τ, given in eq. (8) is that it does not depend on the density but on the temperature of the quark-gluon plasma ball only.

Finally we want to emphasize again that all of our considerations are based on the applicability of the perturbative QCD for the description of the plasma ball. Even in this case the relaxation time may change appreciably from the value given here if one uses other values for the rest mass of the strange quark and /or for the coupling constant. Here τ is inversely proportional to α^2 and it shows a qualitatively exponential dependence on the strange quark, mass, as exp($-\beta m_s$).

The authours are indebted to J. Kuti and V. Gribov for many enlightening and helpful discussions.

T. BIRÓ
J. ZIMÁNYI

QUARKOCHEMISTRY IN RELATIVISTIC HEAVY ION COLLISIONS

Nearly exactly 30 years ago, in late September 1981, preprint circulates claiming conversion of light quarks to strangeness is much too slow to achieve in QGP the desired chemical equilibrium.

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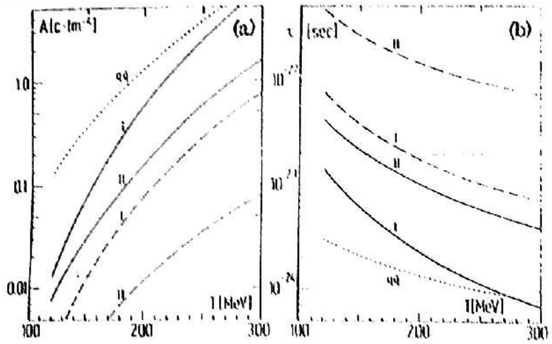


FIG. 2. (a) Rates A. (b) Time constants τ as functions of temperature T. Full lines, $q\bar{q}\to s\bar{s}$ *and* $gg\to s\bar{s}$; dashed lines, $q\bar{q}\to s\bar{s}$; dotted lines, $gg\to q\bar{q}$ ($M = 15$ MeV). Curves marked I are for $\alpha_s = 2.2$ and $M = 280$ MeV; those marked II are for $\alpha_s = 0.6$ and $M = 150$ MeV.

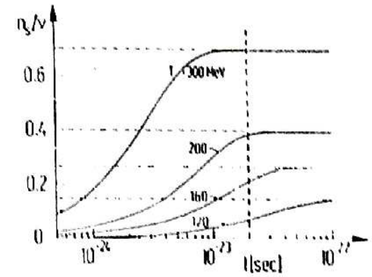


FIG. 3. Time evolution of the relative strange-quark to baryon-number abundance in the plasma for various temperatures

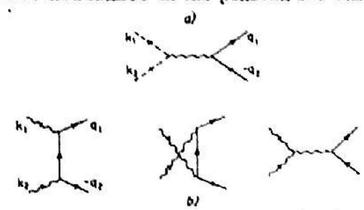


FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q}\to s\bar{s}$, (b) $gg\to s\bar{s}$.

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller

Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany

(Received 11 January 1982)

Rates are calculated for the processes $gg\to s\bar{s}$ and $u\bar{u}, d\bar{d}\to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \gtrsim 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec

Response: in QGP strangeness production by gluon fusion

I shared an office at CERN 1977-79 with Brian Combridge who studied the mechanisms of perturbative QCD charm production, showing glue based process dominated – Berndt Muller and I used Brian's cross sections to compute the thermal invariant rates and prove that equilibration of strangenees in QGP is in experimental reach. This creates the need to introduce approach to chemical equilibrium yield in QGP. Dependent on aspect ratio of quark densities in QGP and streaming hadrons this can result in just about any level of strange hadron abundance in the final hadron count.

Thermal average of (strangeness production) reaction rates

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

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

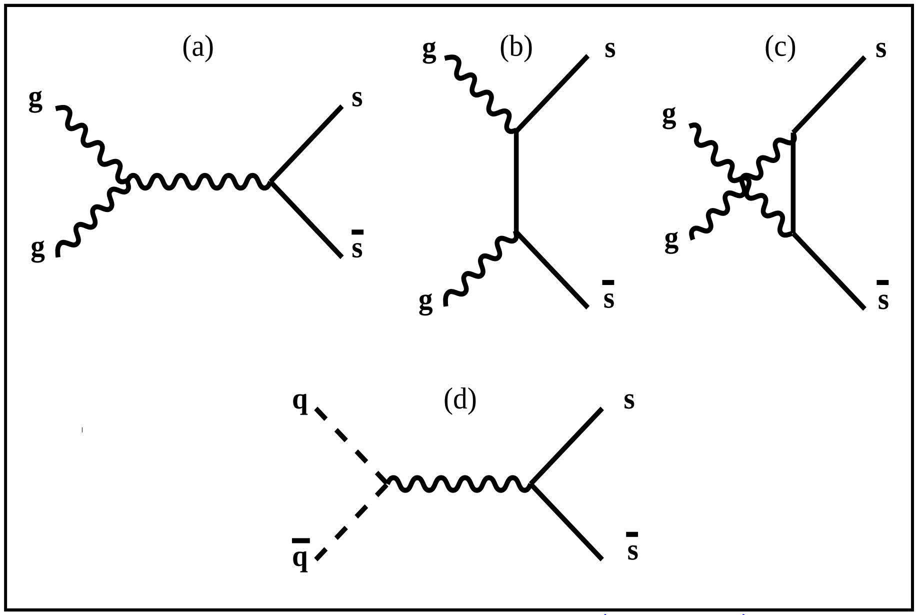
Invariant reaction rate in medium:

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

$1/(1+\delta_{1,2})$ **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

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



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:

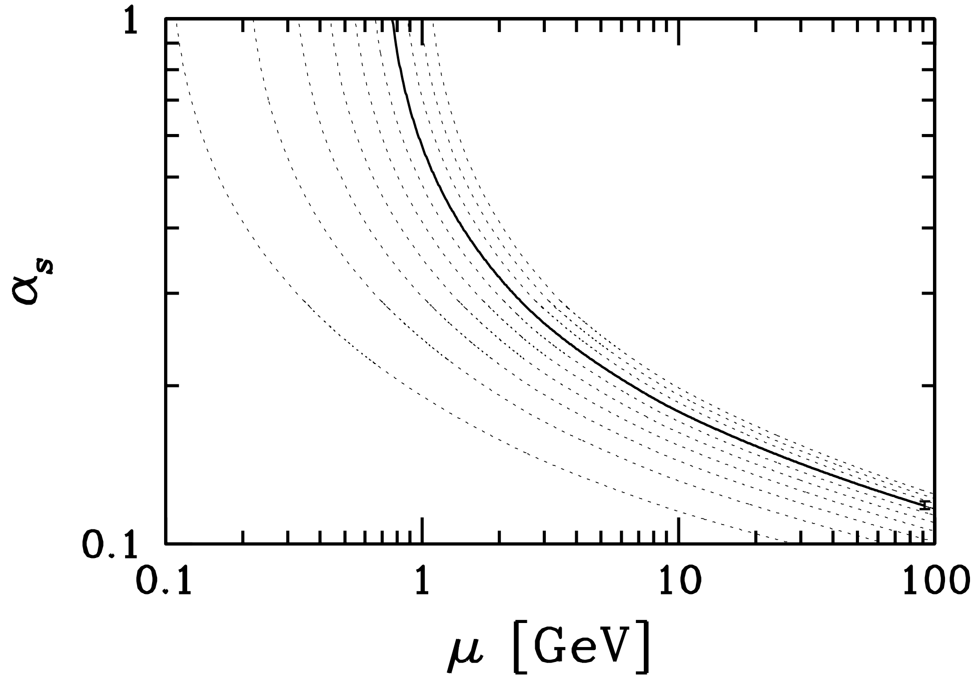
$$\bar{\sigma}_{gg\to s\bar{s}}(s) = \frac{2\pi\alpha_s^2}{3s}\left[\left(1+\frac{4m_s^2}{s}+\frac{m_s^4}{s^2}\right)\tanh^{-1}W(s) - \left(\frac{7}{8}+\frac{31m_s^2}{8s}\right)W(s)\right],$$

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

QCD resummation: running α_s and m_s taken at the energy scale $\mu \equiv \sqrt{s}$. USED: $m_s(M_Z) = 90 \pm 20\%$ MeV (perhaps too large since $m_s(1\mathrm{GeV}) \simeq 2.1 m_s(M_Z) \simeq 200$MeV.

Perturbative production of strangeness works for SMALL enough $\alpha_s^{(4)}(\mu)$

An essential pre-requirement for the perturbative theory of strangeness production in QGP, is the relatively small experimental value $\alpha_s(M_Z) \simeq 0.118$, which has been experimentally established in recent years.



$\alpha_s^{(4)}(\mu)$ as function of energy scale μ for a variety of initial conditions. Solid line: $\alpha_s(M_Z) = 0.1182$ (experimental point, includes the error bar at $\mu = M_Z$).

Had $\alpha_s(M_Z) > 0.125$ been measured instead of $\alpha_s(M_Z) = 0.118$ than our 1981/82 perturbative strangeness production approach would have been in question.

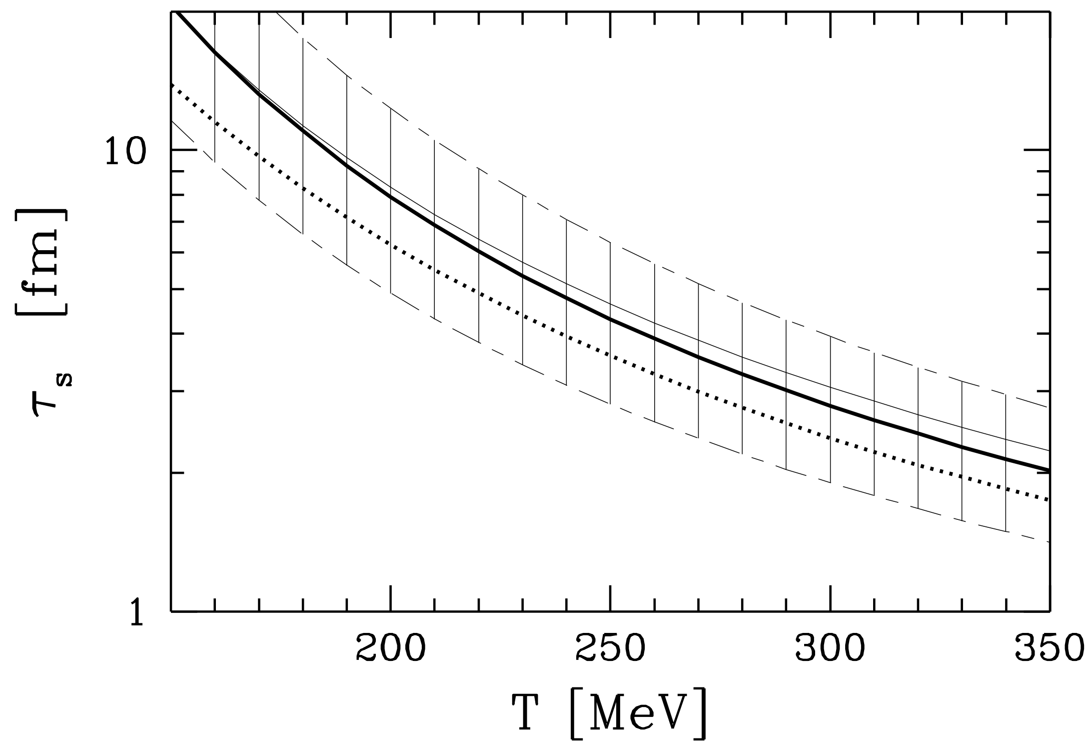
Strangeness relaxation to chemical equilibrium

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:

$$2\tau_s \equiv \frac{\rho_s(\infty)}{A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} + \ldots} \qquad A^{12\to 34} \equiv \frac{1}{1+\delta_{1,2}}\gamma_1\gamma_2\rho_1^\infty\rho_2^\infty\langle\sigma_s v_{12}\rangle_T^{12\to 34}\,.$$



Dominant uncertainty: mass of strange quark (wide range indicated).
Dotted - fixed value $\alpha_s = 0.6$ used in 1981/2

QGP Strangeness / Entropy

s/S: ratio of the number g_s, g of active degrees of freedom in QG plasma,

For chemical equilibrium IN PLASMA:

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

with $\mathcal{O}(\alpha_s)$ interaction $\boxed{s/S \to 1/31 = 0.0323}$ **in QGP chemical equilibrium.**

V=CENTRALITY-A, and ENERGY DEPENDENCE: $\gamma_s^{\rm Q} \to 1$

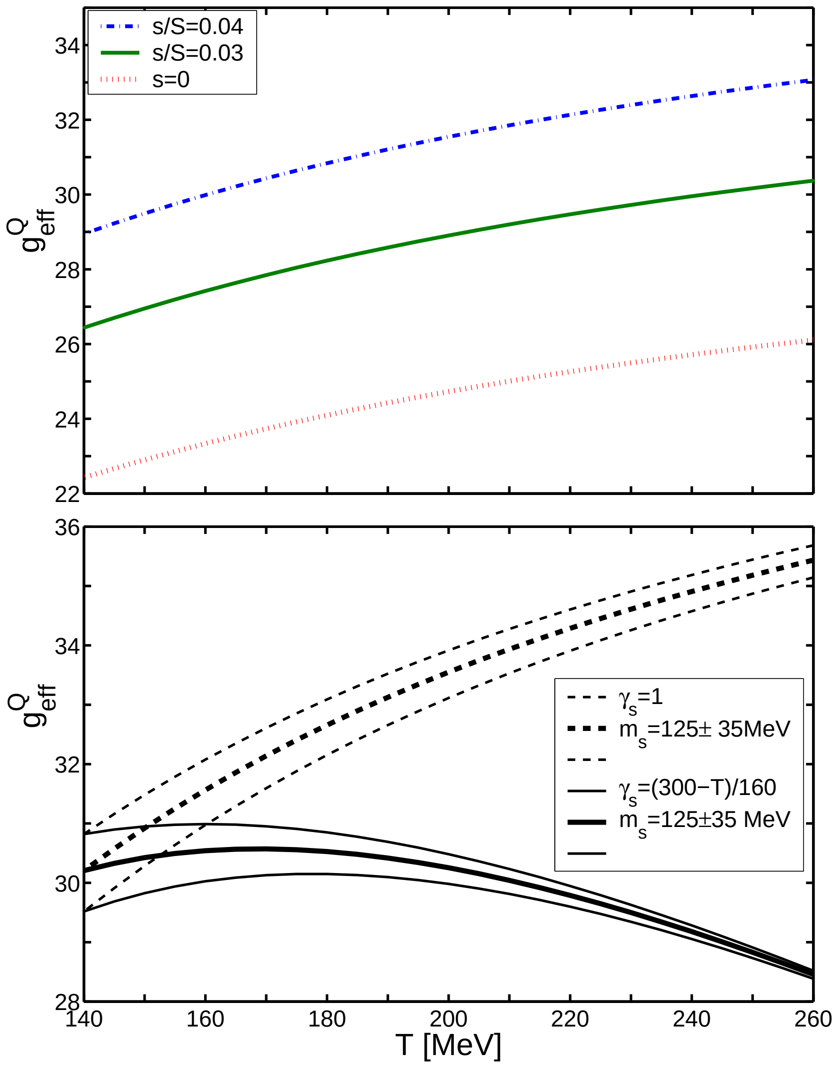
Chemical non-equilibrium occupancy of strangeness $\gamma_s^{\rm Q}$

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

Analysis of experiment: we count all strange/nonstrange hadrons in final state, we use Fermi model (statistical hadronization) to extrapolate to unmeasured particle yields and/or kinematic domains, and evaluate resonance cascading:

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

Entropy in QGP – degrees of freedom $g^Q_{\rm eff}$?



$g^Q_{\rm eff}$ in QGP

$$\sigma = \frac{4\pi^2}{90} g^Q_{\rm eff} T^3,$$

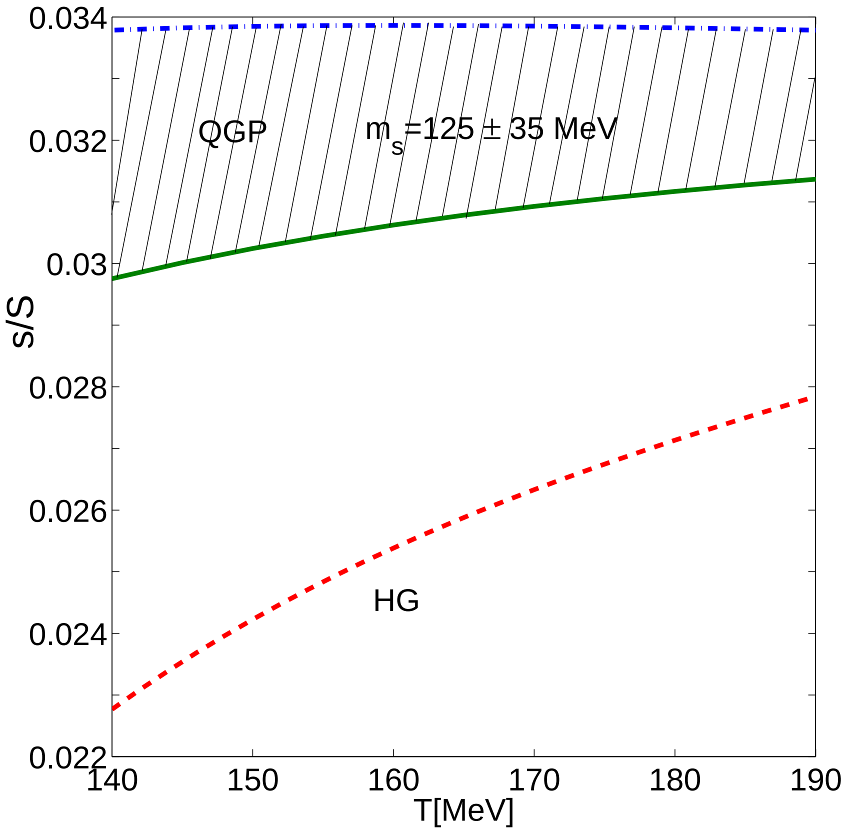
$$g^Q_{\rm eff}(T) = g_g(T) + \frac{7}{4} g_q(T) + 2g_s\frac{90}{\pi^4} + \frac{\mathcal{A}^{\rm pert}}{T^4}\frac{90}{4\pi^2}.$$

Upper frame: fixed s/S
green solid line $s/S = 0.03$
blue dot-dashed $s/S = 0.04$.
red dotted 2-flavor QCD $-u, d, G$;

Bottom:
2+1-flavor QCD with $m_s = 125 \pm 35$ MeV
dashed: equilibrated u, d, s, G system
solid lines: strangeness contents
increasing with decreasing temperature
$\gamma_s = (300 - T)/160$

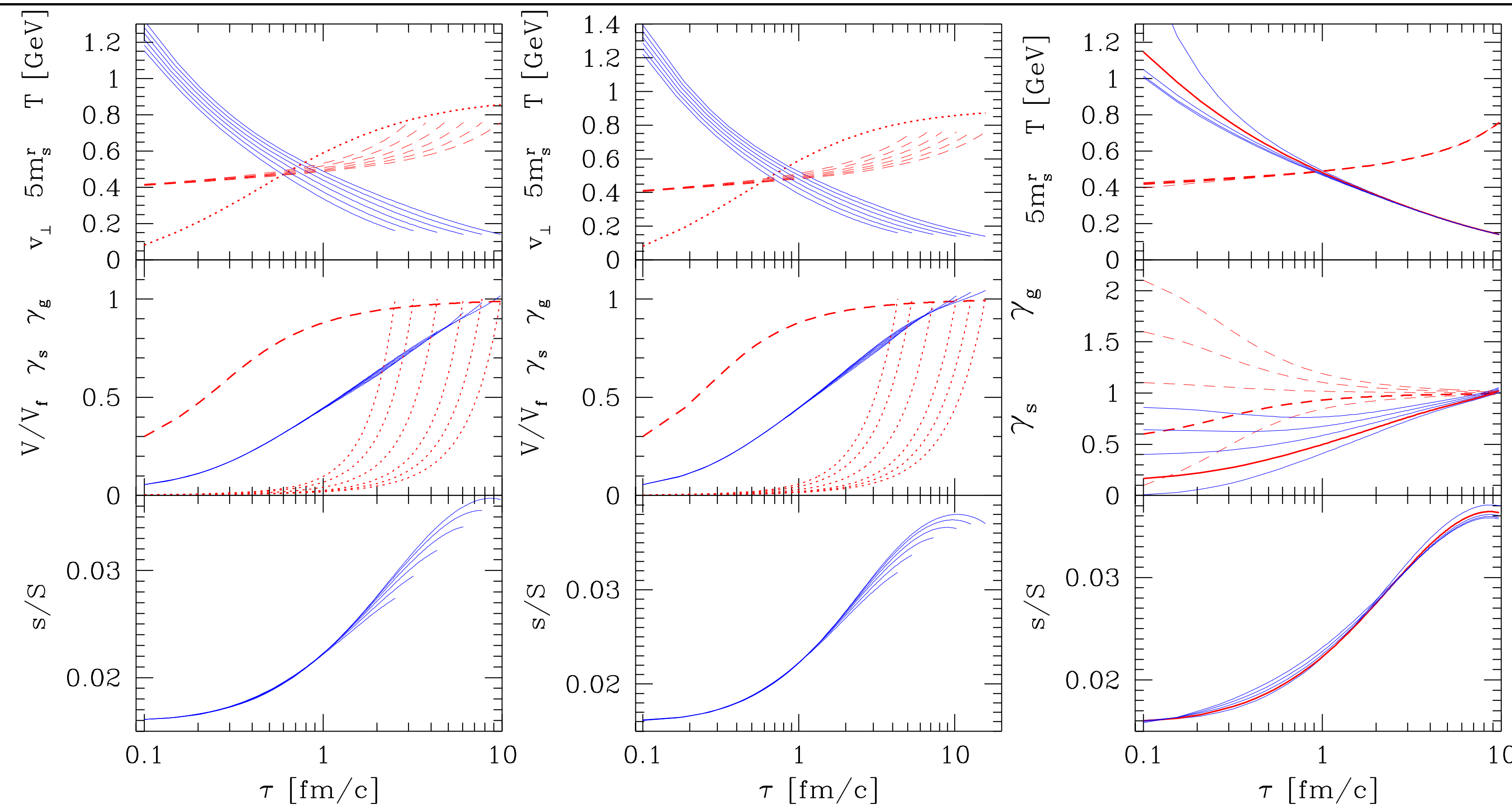
QGP and HG comparison: strangness / entropy

We compare strangeness per entropy (particle multiplicity) in deconfined quark-gluon plasma with hadron gas at a common measured T (Inga Kuznetsova). We expect hadron phase space to be oversaturated if QGP was equilibrated.



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). The excess of SPECIFIC strangeness not assured if QGP not chemically equilibrated. However, since QGP is a high entropy and strangeness density phase, in absolute terms, there is both entropy and strangeness excess ALWAYS when QGP is formed.

Strangeness production at LHC after tuning RHIC, with $dS/dy|_{\rm LHC} = 4dS/dy|_{\rm RHIC}$



"Strangeness chemical equilibration in QGP at RHIC and CERN LHC" Jean Letessier, & Johann Rafelski Phys.Rev.C75:014905,2007. nucl-th/0602047 **LHC differences to RHIC**

- **There is a significant increase in initial temperature and gluon occupancy γ_g to accommodate increased initial pre-thermal evolution entropy.**
- **There is a about twice longer expansion time to the freeze-out condition, since there is 4 times entropy content at similar hadronization T_h.**
- **There is over saturation of $s/S, \gamma_s$ in QGP, and thus a much greater over-saturation in hadron phase space (for $T_h < 240$ MeV)**

NOTE: s/S measures chemical equilibration in QGP.

What happens with antistrange quarks?

PHYSICS REPORTS (Review Section of Physics Letters) 88, No. 5 (1982) 331–347. North-Holland Publishing Company

UFTP-80-1982, Mar 1982. 26pp. Invited lecture given at 17th Rencontre de Moriond on Elementary Particle Physics, Les Arcs, France, Mar 14-26, 1982. Published in Phys.Rept.88:331,1982 (special volume edited by Maurice Jacob).

2. Formation and Observation of the Quark-Gluon Plasma*

J. RAFELSKI

Institut für Theoretische Physik der Universität, Frankfurt, Germany

One can study how much more total strangeness is found in the quark-gluon plasma as compared to the hadronic gas phase. While the total yields are up to 5–7 times higher (again depending on some parameters) it is more appropriate to concentrate attention on those reaction channels which will be particularly strongly populated when the quark plasma dissociates into hadrons. Here in particular, it appears that the presence of quite rare multistrange hadrons will be enhanced, first because of the relative high phase space density of strangeness in the plasma, and second because of the attractive ss-QCD interaction in the $\bar{3}_c$ state and $\bar{s}s$ in the 1_c state. Hence one should search for an increase of the abundances of particles like Ξ, $\bar{\Xi}$, Ω, $\bar{\Omega}$, ϕ and perhaps for highly strange pieces of baryonic matter, rather than in the K-channels. However, it appears that already a large value for the $\bar{\Lambda}/\Lambda$ ratio would be

Strangeness as Deconfinement Signatures

1. **TOTAL Strangeness YIELD:** **$s$strangeness/Sentropy** **depends primarily on initial conditions and evolution dynamics**
(how long the system is at which T)

2. **Strangeness at QGP BREAK-UP:**
   a) $\gamma_s^{\rm QGP} \to 1$ **is QGP near chemical equilibrium?**

$$\gamma_{\rm s,q}^{\rm QGP} = \left.\frac{n_{\rm s,q}(t, T(t))}{n_{\rm s,q}(\infty, T(t))}\right|_{\rm QGP} \to 1?$$

   b) $\gamma_s^{HG} \simeq 3\gamma_s^{\rm QGP}$ **QGP phase space is squeezed into a smaller number of HG phase space cells**

2'. TO BE SENSITIVE WE NEED ALSO TO CONSIDER $\gamma_q^{\rm HG} > 1$
over population of pion phase space is ENTROPY enhancement

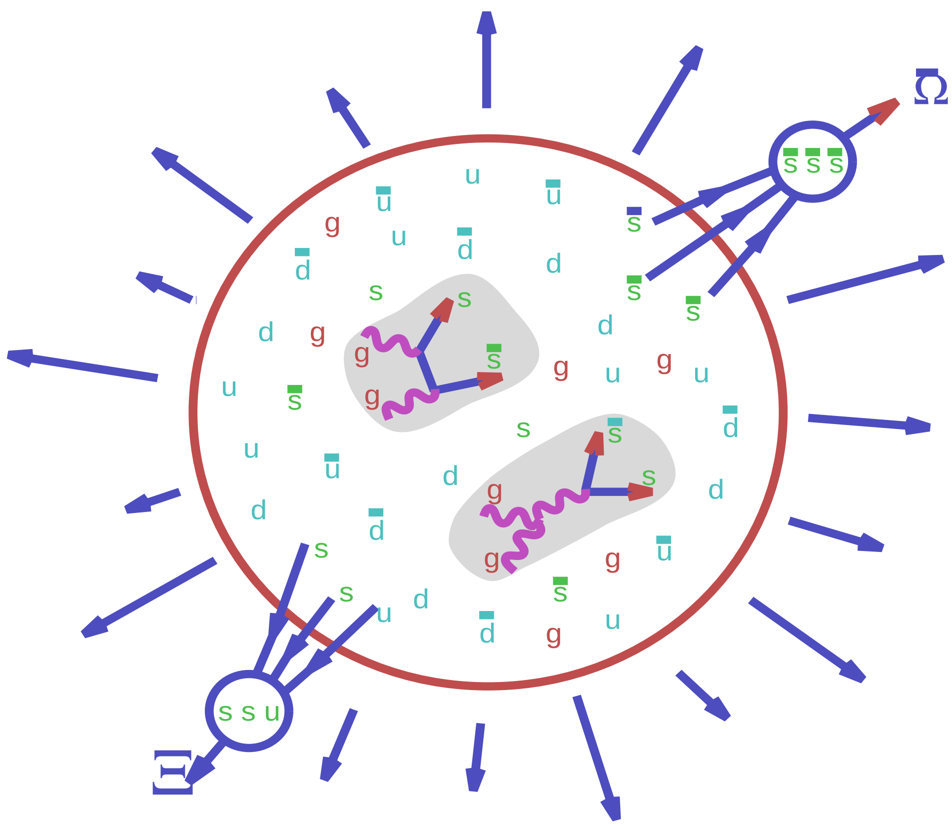
---

3. **STRANGENESS MOBILITY IN QGP IMPLIES**
   s–$\bar{s}$ **phase space symmetry, relevant in baryon rich (SPS) environment**
   IMPRINTED ON HADRONS AT HADRONIZATION

TWO STEP RECOMBINANT HADRON FORMATION FROM QGP

= recombinant quark hadronization, main consequence: enhancement of flavored (strange, charm, bottom) antibaryons progressing with 'exotic' flavor content. Anomalous meson to baryon relative yields. Proposed 25 years ago

See: P. Koch, B. Muller and J. Rafelski, *Strangeness In Relativistic Heavy Ion Collisions,* **Phys. Rept. 142, 167 (1986), and references therein.**

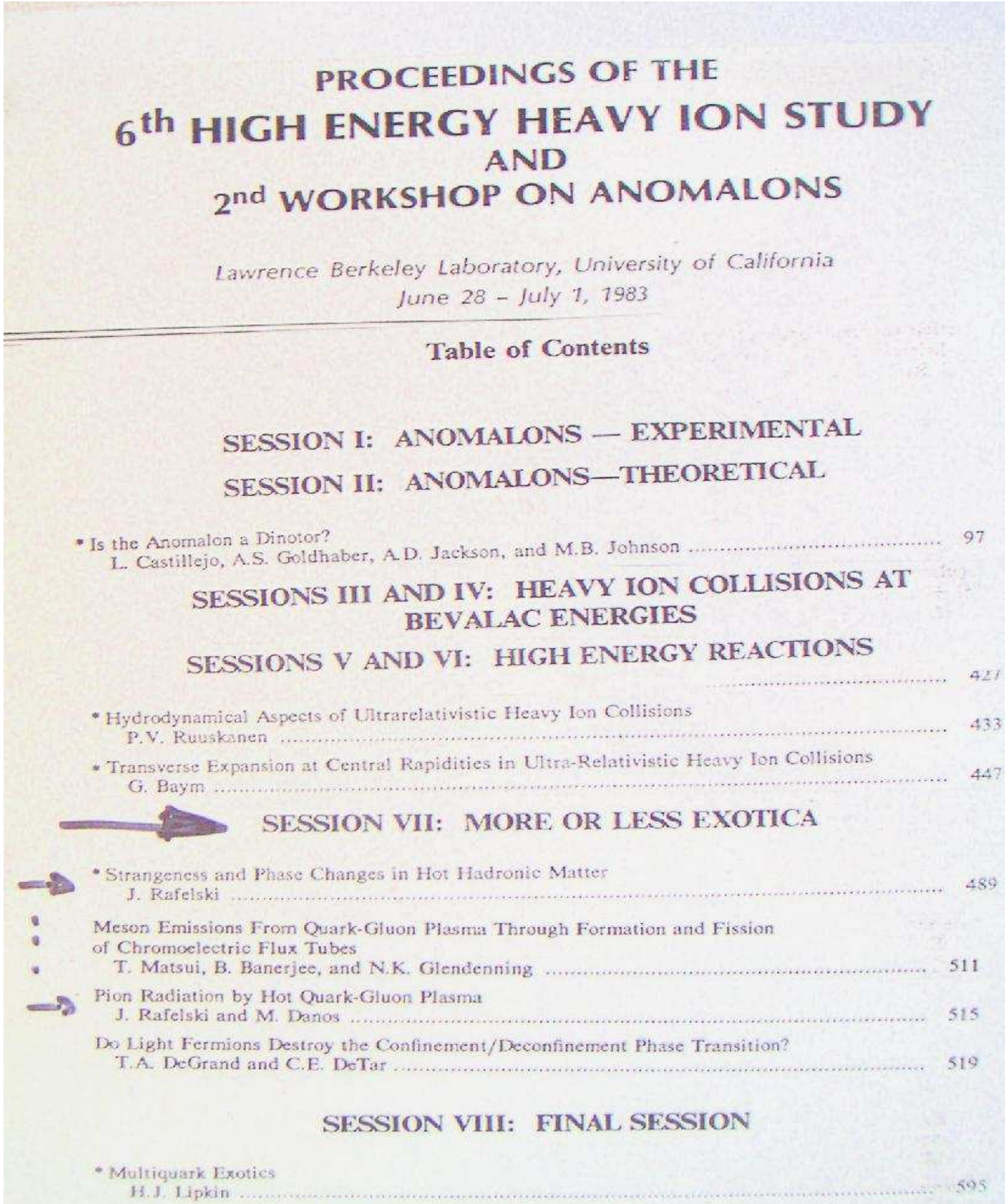


1. $GG \to s\bar{s}$ **(thermal gluons collide)**
   $GG \to c\bar{c}$ **(initial parton collision)**
   $GG \to b\bar{b}$ **(initial parton collision)**
   gluon dominated reactions

2. **RECOMBINATION of pre-formed** s, $\bar{s}$, c, $\bar{c}$, b, $\bar{b}$ **quarks**

Formation of complex rarely produced multi flavor (exotic) (anti)particles enabled by coalescence between s, $\bar{s}$, c, $\bar{c}$, b, $\bar{b}$ **quarks made in different microscopic reactions; this is signature of quark mobility and independent action, thus of deconfinement. Moreover, strangeness enhancement = gluon mobility.**

Exotic Strangeness


PROCEEDINGS OF THE

6th HIGH ENERGY HEAVY ION STUDY
AND
2nd WORKSHOP ON ANOMALONS

Lawrence Berkeley Laboratory, University of California
June 28 – July 1, 1983

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It was difficult to publish in refereed journals on strangeness. Quarks were exotic, QGP was $(\text{exotic})^2$, and strangeness in QGP was $(\text{exotic})^3$. First paper by Peter Koch(-Steinheimer) on statistical hadronization model took two years from submission in one journal to publication in another. In my private archive I keep the transparencies from the LBL 6th Heavy Ion Study where I presented individual particle yields, given the high strange and multistrange anti-baryon yield, Miklos lead there the general laughter, my lecture was termed a 'fantasy' and in proceedings pushed into "Exotica session" of the proceedings far below "anomalons".

Strange Antibaryon CHALLENGE

Around mid 1985 Howell Pugh, in midst of preparation for CERN experiments, called me in Cape Town. Joe Kapusta has shown that hadronization of QGP took 50-100 fm/c. According to Miklos the strange antibaryon enhancement could never happen since strange antibaryons would annihilate in Kapusta's mixed phase. "He (Miklos) thinks the entire strangeness topic was dead". And if so, the bet placed by the LBL nuclear science by Howell on me (both NA35 and NA36 were mainly strangeness experiments) was bad.

I explained that we just completed a Physics Reports(Koch-Müller-Rafelski, 142 (1986) 167) which finds just the opposite. But that work was one drop in an ocean of contrary thaught.

From this challenge was born the realization that
1) spectra of baryons and antibaryons emerging from QGP differ only by normalization, while annihilation in hadron based kinetic models differentiates spectra of baryons and antibaryons, which like in pp reactions woudl be totally different: matter-antimatter spectra distinguish hadronization models (mostly forgotten by chemical equilibrium wishful thinkers.
2) that the production of antibaryons occurs from a central rapidity fireball.

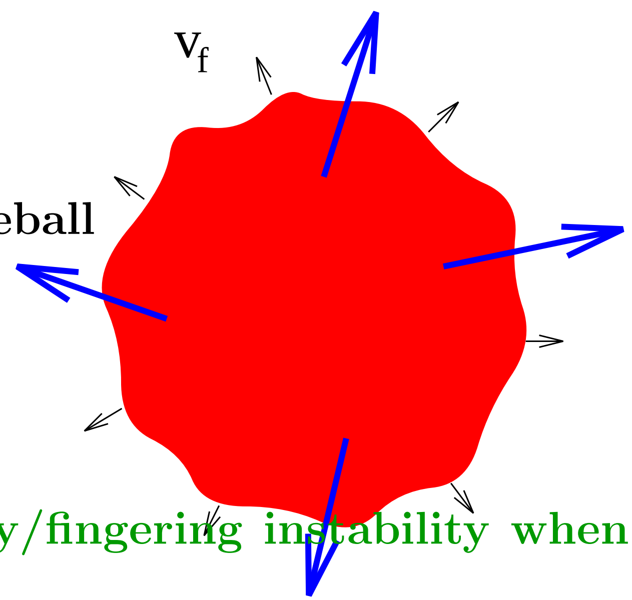
MATTER-ANTIMATTER SPECTRAL SYMMETRY

Recombination hadronization implies symmetry of $m_\perp$ spectra of (strange) baryons and antibaryons also in baryon rich environment.

CONVERSELY: spectral matter-antimatter symmetry implies; A common matter-antimatter particle formation mechanism, AND negligible antibaryon re-annihilation/re-equilibration/rescattering.

Today: a nearly free-streaming particle emission by a quark source into vacuum also required by other observables: e.g. HBT particle correlation analysis pointing to a short emission time and relatively small volume of pion source

Practically no hadronic 'phase'
No 'mixed phase'
Direct emission of free-streaming hadrons from exploding filamentary fireball

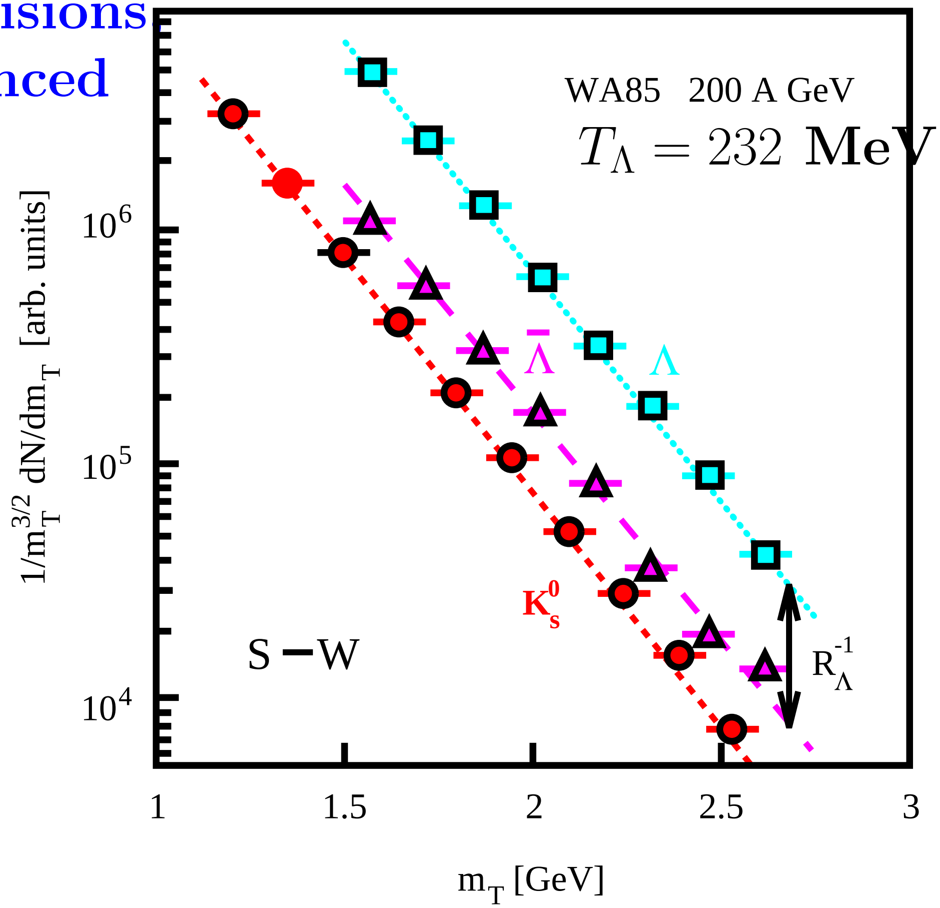


Develop analysis tools viable in SUDDEN QGP HADRONIZATION

Possible reaction mechanism: filamentary/fingering instability when in expansion the pressure reverses.

High $m_\perp$ slope universality

Discovered in S-Pb collisions by WA85, very pronounced in Pb-Pb Interactions.

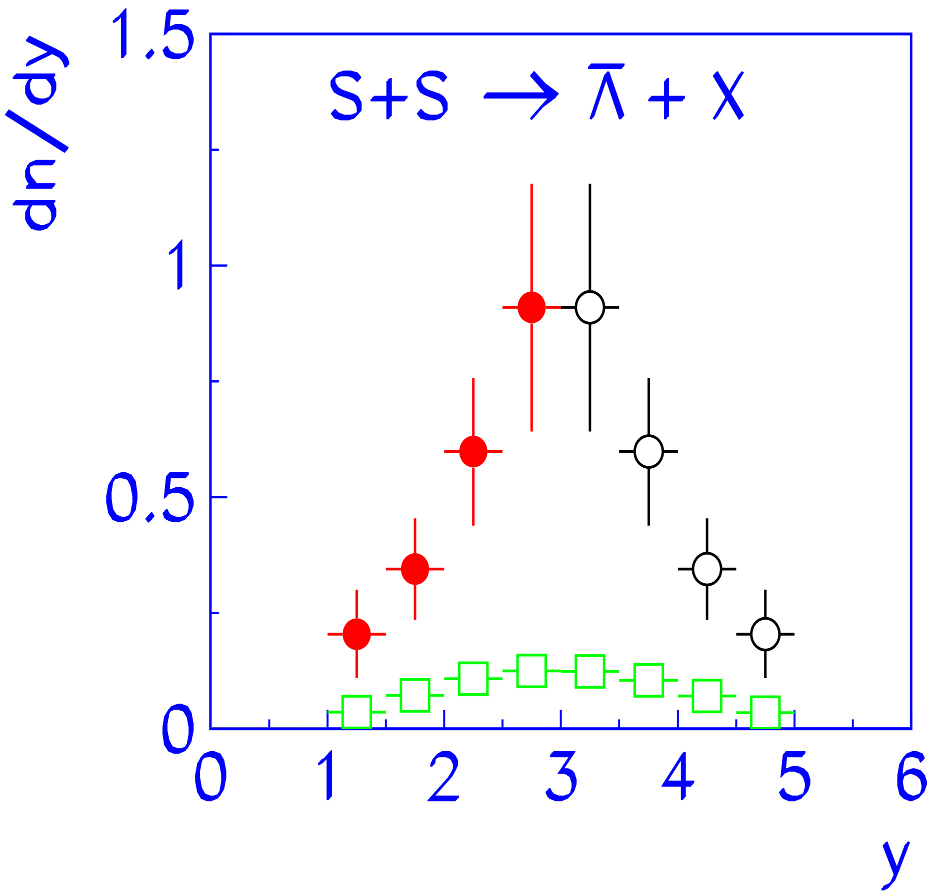


Emanuele Quercigh

Why is the slope of baryons and antibaryons the same?

SUDDEN hadronization without rescattering.

Central Rapidity Fireball and QGP



First antibaryon enhancement result, 1990-94, SPS-NA35II EXCESS $\overline{\Lambda}$ emitted from a central well localized source. Background (squares) from multiplicity scaled NN reactions. From Yiota Foka, PhD Thesis, Geneva University 1994.

Conclusion: by early 1990's we have convincing evidence of QGP formation at SPS energy heavy ion collisions including S-S.

Analysis: 'Statistical Hadronization Model' Invented 1991

Volume 262, number 2,3 PHYSICS LETTERS B 20 June 1991

Strange anti-baryons from quark–gluon plasma

Johann Rafelski

Department of Physics, University of Arizona, Tucson, AZ 85721, USA

Received 5 April 1991

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.

... and similar for $\overline{\Sigma}^0$. Thus comparing *spectra* of particles within overlapping regions of $m_\perp$ we find for their respective ratios

$$R_\Xi = \frac{\overline{\Xi^-}}{\Xi^-} = \frac{\lambda_d^{-1}\lambda_s^{-2}}{\lambda_d\lambda_s^2}$$

$$= \exp(-2\mu_d/T)\exp(-4\mu_s/T)\,. \qquad (4)$$

$$R_\Lambda = \frac{\overline{\Lambda}}{\Lambda} = \frac{\lambda_d^{-1}\lambda_u^{-1}\lambda_s^{-1}}{\lambda_d\lambda_u\lambda_s}$$

$$= \exp[-2(\mu_d+\mu_u)/T]\exp(-2\mu_s/T)\,. \qquad (5)$$

Ignoring isospin differences for the moment, $\lambda_u = \lambda_d \equiv \lambda_q$, we obtain

$$R_\Lambda = (\lambda_s/\lambda_q)^2 R_\Xi\,. \qquad (6)$$

In QGP we have $\lambda_s = 1$, $\lambda_q > 1$, while in equilibrated.

... Which implies

$$\mu_q/T = 0.46 \pm 0.08\,, \quad \delta\mu_q/T = 0.041 \pm 0.007\,.$$

We can use this result, together with $\mu_s = 0$ and eq. (8), to predict the key strange anti-baryon ratios expected from primordial QGP (where as discussed above, $0 < \gamma \leq 1$ characterizes the approach to absolute chemical equilibrium of strangeness):

$$\overline{\Xi^-}/\overline{\Lambda} = \overline{\Lambda}/\bar{p} = \gamma_s 1.55 \pm 0.13\,,$$

$$\Xi^-/\Lambda = \Lambda/p = \gamma_s 0.64 \pm 0.05\,,$$

$$\overline{\Omega^-}/\overline{\Xi^-} = \gamma_s 1.61 \pm 0.13\,,$$

$$\Omega^-/\Xi^- = \gamma_s 0.62 \pm 0.05\,.$$

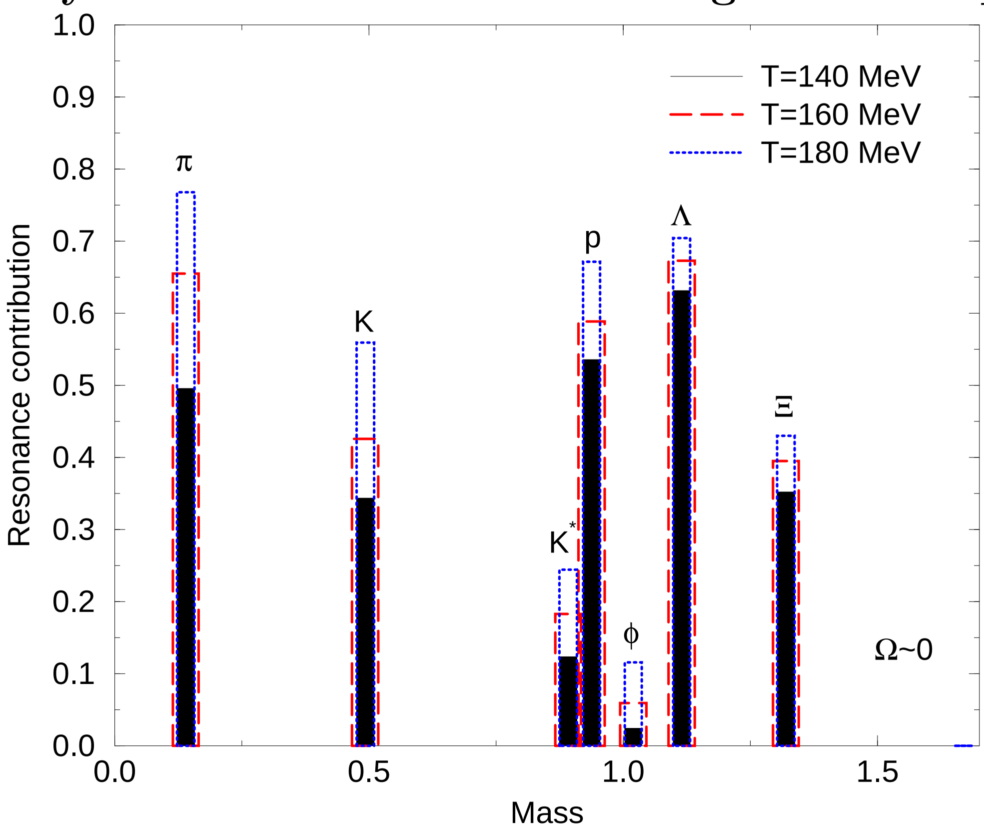
Comparing with the first results on these ratios eq. (3), we can extract a first estimate of strange phase space saturation: $\frac{1}{2}\gamma = 0.4 \pm 0.2$. Here we used the strange anti-baryon ratio, to avoid the systematic

STATISTICAL HADRONIZATION

Hypothesis (Fermi, Hagedorn): particle production can be described by evaluating the accessible phase space.

Verification of statistical hadronization:

Particle yields with same valance quark content are in relative chemical equilibrium, e.g. the relative yield of $\Delta(1230)/N$ as of K^*/K, $\Sigma^*(1385)/\Lambda$, etc, is controlled by chemical freeze-out i.e. Hagedorn Temperature $T_{\rm H}$:



$$\frac{N^*}{N} = \frac{g^*(m^* T_{\rm H})^{3/2} e^{-m^*/T_{\rm H}}}{g(m T_{\rm H})^{3/2} e^{-m/T_{\rm H}}}$$

Resonances decay rapidly into 'stable' hadrons and dominate the yield of most stable hadronic particles.

Resonance yields test statistical hadronization principles.

Resonances reconstructed by invariant mass; important to consider potential for loss of observability.

HADRONIZATION GLOBAL FIT:→

SHM is FERMI MODEL with QUARK CHEMISTRY

If QGP near/at chemical equilibrium prior to fast hadronization we expect that emerging hadron multiplicites to be governed by parameters of ABSOLUTE chemical non-equilibrium described by phase spae occupancy γ; Boltzmann gas: $\gamma \equiv \frac{\rho(T,\mu)}{\rho^{\rm eq}(T,\mu)}$

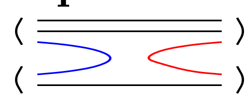
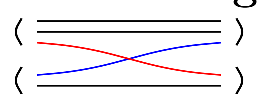
DISTINGUISH: hadron 'h' phase space and QGP phase parameters: micro-canonical variables such as baryon number, strangeness, charm, bottom, etc flavors are continuous, and entropy is almost continuous across phase boundary:

$$\gamma_s^{\rm QGP}\rho_{\rm eq}^{\rm QGP}V^{\rm QGP} = \gamma_s^{\rm h}\rho_{\rm eq}^{\rm h}V^{\rm h}$$

Equilibrium distributions are different in two phases and hence are densities:

$$\rho_{\rm eq}^{\rm QGP} = \int f_{\rm eq}^{\rm QGP}(p)dp \neq \rho_{\rm eq}^{\rm h} = \int f_{\rm eq}^{\rm h}(p)dp$$

Another RELATIVE equilibrium: **FOUR QUARKS:** $s, \bar{s}, q, \bar{q} \to$ **FOUR CHEMICA**

γ_i	**controls overall abundance of quark** $(i = q, s)$ **pairs**	**Absolute chemical equilibrium**	**HG production** 
λ_i	$=e^{\mu_i/T}$**controls difference between strange and light quarks** $(i = q, s)$	**Relative chemical equilibrium**	**HG exchange** 

See Physics Reports 1986 Koch, Müller, JR

Example of counting hadronic particles

The counting of hadrons is conveniently done by counting the valence quark content $(u, d, s, \ldots \lambda_q^2 = \lambda_u \lambda_d,\ \lambda_{I3} = \lambda_u/\lambda_d)$:

$$\Upsilon_i \equiv \Pi_i \gamma_i^{n_i} \lambda_i^{k_i} = e^{\sigma_i/T}; \quad \lambda_q \equiv e^{\frac{\mu_q}{T}} = e^{\frac{\mu_b}{3T}}, \quad \lambda_s \equiv e^{\frac{\mu_s}{T}} = e^{\frac{[\mu_b/3-\mu_S]}{T}}$$

Example of NUCLEONS $\gamma_N = \gamma_q^3$**:**

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

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

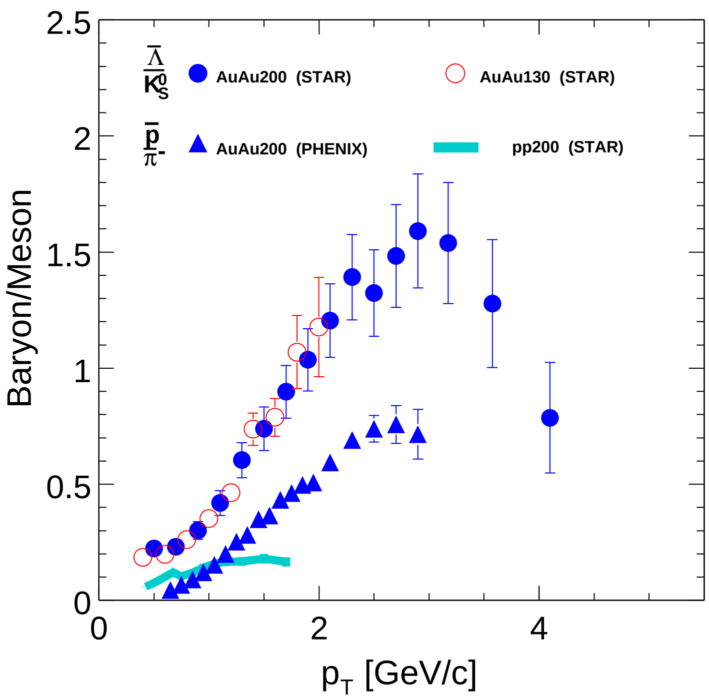
Meaning of parameters from e.g. the first law of thermodynamics:

$$dE + P\,dV - T\,dS = \sigma_N\, dN + \sigma_{\overline{N}}\, d\overline{N}$$

$$= \mu_b(dN - d\overline{N}) + T \ln \gamma_N (dN + d\overline{N}).$$

NOTE: For $\gamma_N \to 1$ **the pair terms vanishes, the** μ_b **term remains, it costs** $dE = \mu_B$ **to add to baryon number.**

Indeed, a 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:**

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

GROUND LAID FOR MORE FORMAL AND DETAILED APPROACH:

1993 – Paris-Period

In early 90's Hagedorn urges me to team up with his Paris friends Letessier and Tounsi to manage the rapidly rising data flow. Today, after many years with about 100 papers, one Book-monograph, several proceedings, this was my longest running engagement! Viva Jean Letessier! We build togather analysis tools and models.

Many competitors emerged, both competant and less so: Francesco Becattini, Jean Cleymans, Krzysztof Redlich. This collaboration widened with arrival of PhD student Giorgio Torrieri, and we embraced Krakow (Wojtek)^2 and got SHARE.

18 Years after: Statistical Hadronization

Full analysis of experimental hadron yield results requires a significant numerical effort in order to allow for resonances, particle widths, full decay trees, isospin multiplet sub-states.

Kraków-Tucson (and SHARE 2 Montreal) collaboration produced a public package SHARE Statistical Hadronization with Resonances which is available e.g. at

http://www.physics.arizona.edu/˜torrieri/SHARE/share.html

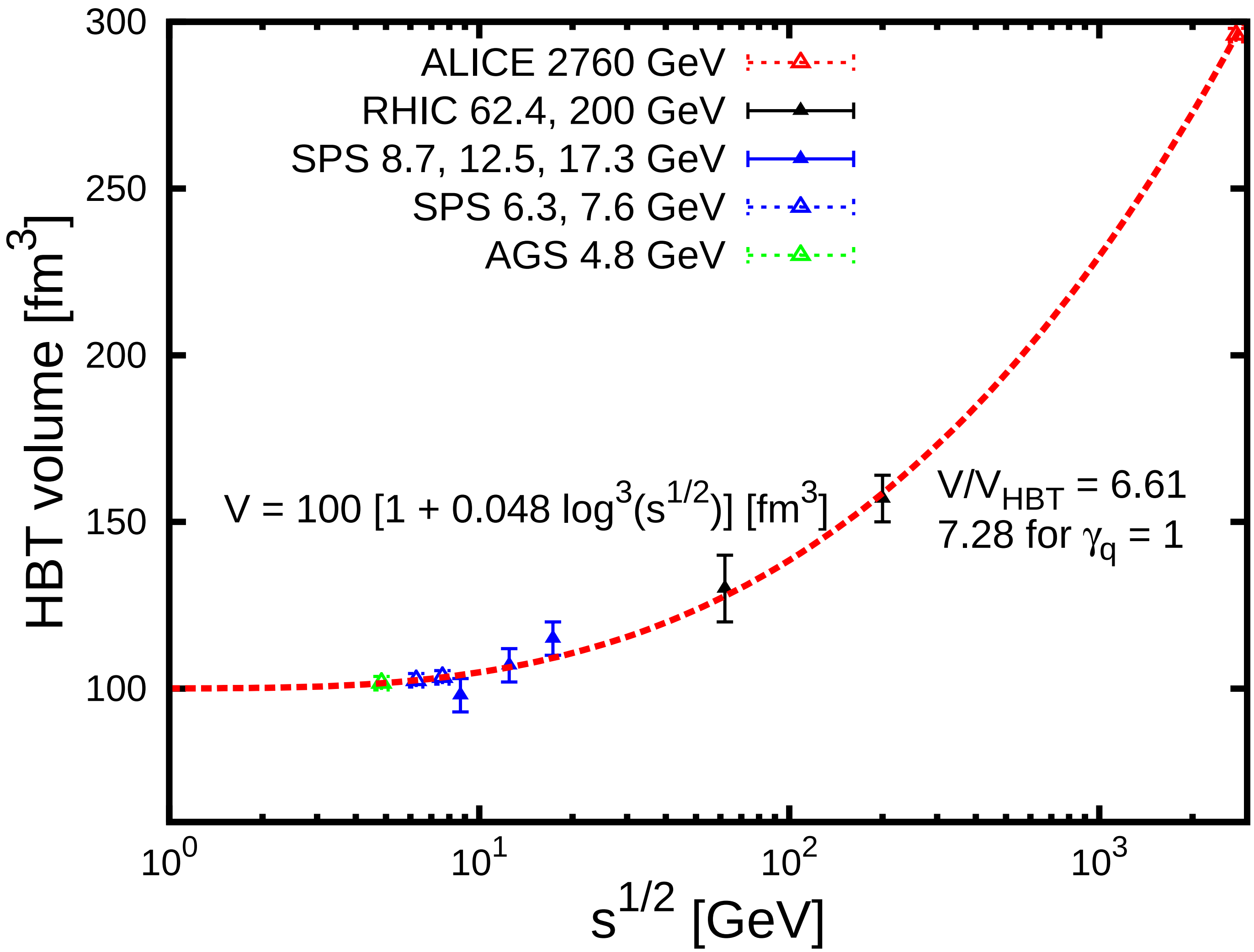
Lead author: Giorgio Torrieri

nucl–th/0404083 Comp. Phys. Com. 167, 229 (2005)
nucl-th/0603026 Comp. Phys. Com. 175, 635 (2006)

Wojtek Broniowski JR Wojtek Florkowski Giorgio Torrieri

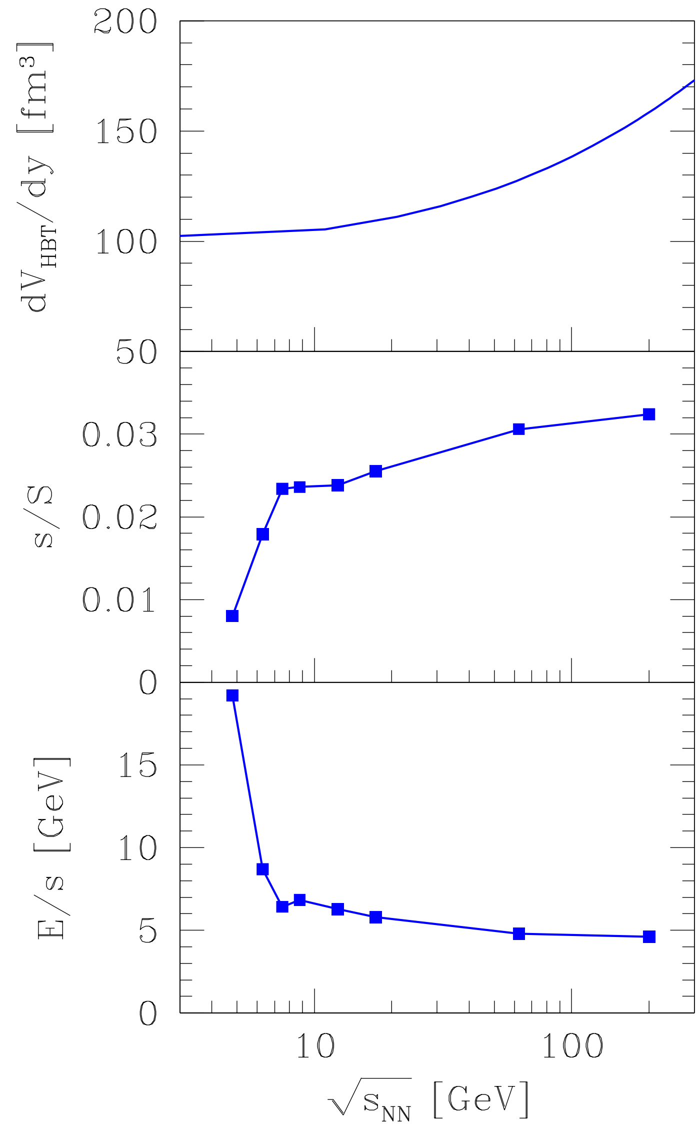
FITS ACROSS ALL ENERGY RANGE

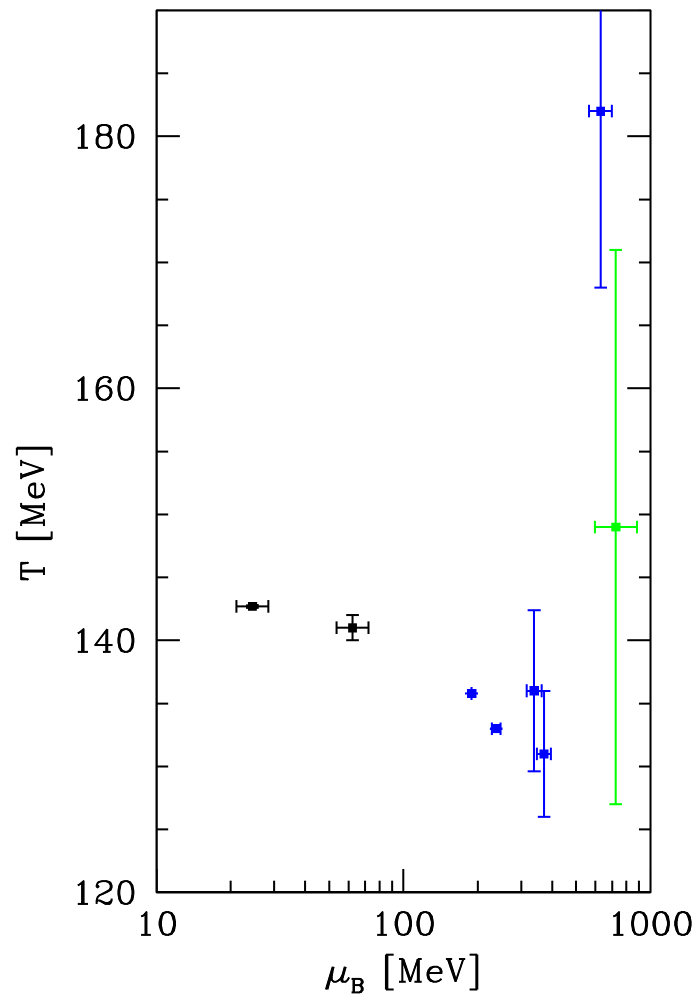
A fit to data should be consistent across reaction energies. In addition we seek consistency with the HBT results - that is if sudden hadronization occurs the chemical freeze-out volume shouls be proportional to the pion HBT volume, $dV/dy \simeq (6.5 \pm 0.5)V_{\rm HBT} = (6.5 \pm 0.5)\, R_1 R_2 R_3$



Fit function arbitrary. We obtain normalization factor at RHIC-200 where the outcome of the fit is equally good for to different scenarios: a "semi-equilibrium" where light quarks are just as many as HG needs and "non-equilibrium" where both $\gamma_s, \gamma_q \neq 1$ **Only nonequilibrium fits across SPS, RHIC and LHC have high confidence level. Only AGS and SPS-20 are 'different'**

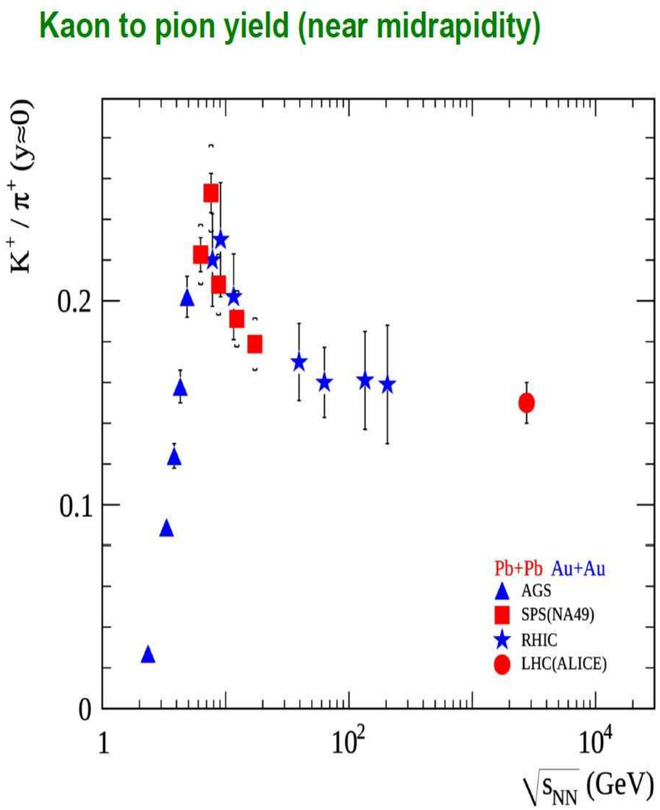
Strangeness production and hadronization line $T - \mu_B$

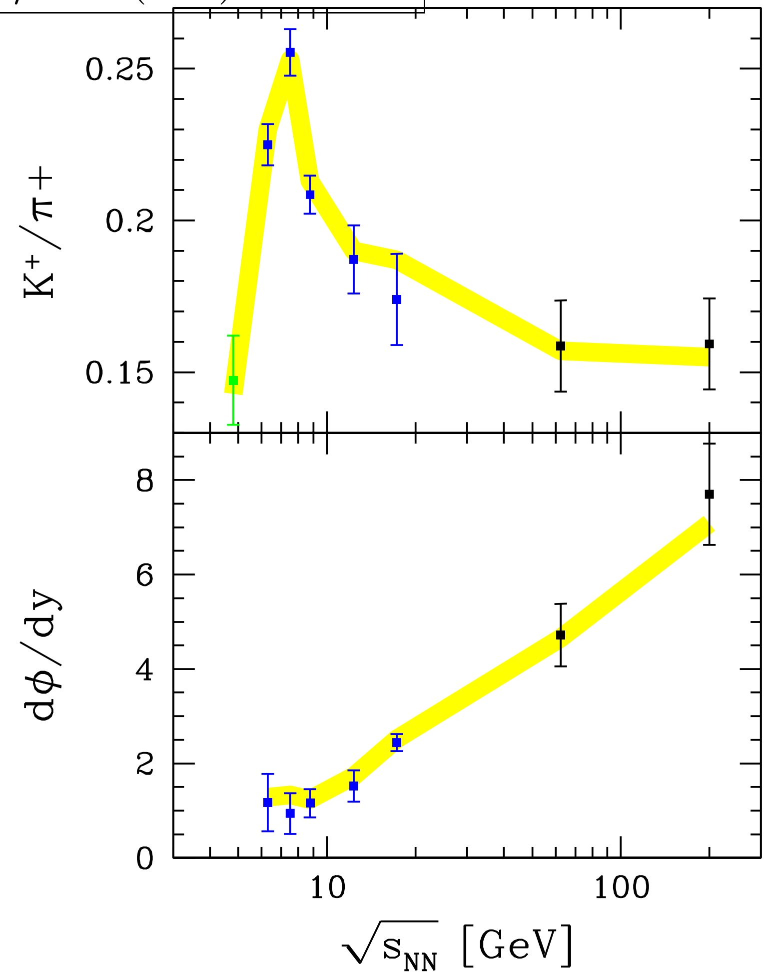




Strangeness production in all measures grows continously with increasing energy and volume and cost of making a strange quark pair decreases reaching a minimum.

The $K^+(u\bar{s})/\pi^+(u\bar{d})$ horn

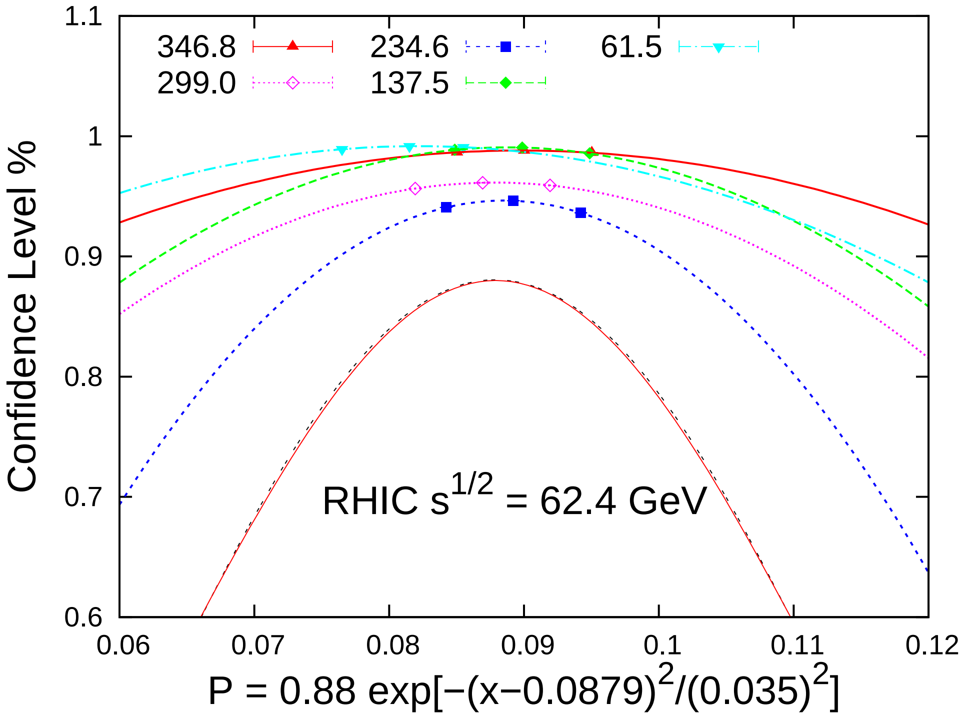




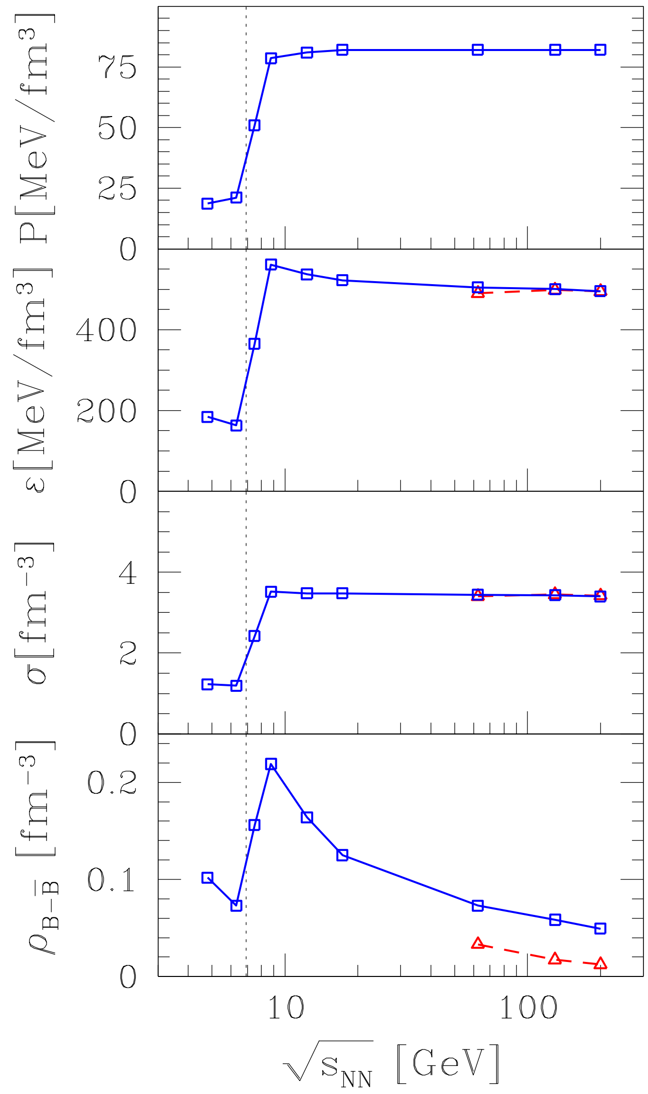
Formation of the Horn in $K^+(u\bar{s})/\pi^+(u\bar{d})$ is understood as being due to competing strangeness hadronization into $\eta, \Phi(s\bar{s})$, and also (anti)strange baryons. The nonequilibrium hadronization is only way to describe correctly both the horn and Φ-yield. The yellow band is our result.

CRITICAL PRESSURE

Example: We obtained Pressure profiles of confidence level prescribing the hadronization pressure for centrality bins of RHIC 62.4 GeV results. The product of each bin confidence level results in a nice Gaussian.



CRITICAL PRESSURE II



Conclusions

- **Strangeness fingerprints properties of QGP and demonstrates deconfinement**

- **Strangeness experimental results (I skipped most of the plots, supplemental material) fulfill all our expectations: resounding confirmation of fast hadronization of quark-gluon plasma. – steady rise of s/S with energy and centrality, expected enhancement of multistrange hadrons and strange antibaryons**

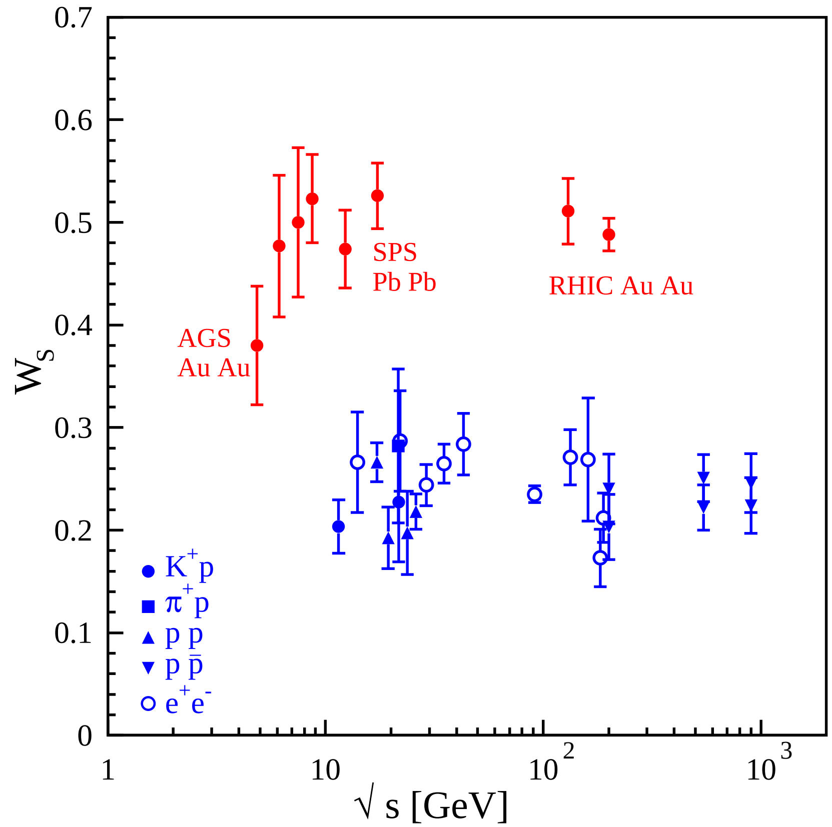
- **This requires strange quark mobility. Enhanced source of entropy content consistent with initial state thermal gluon degrees of freedom, expected given strangeness enhancement. Chemical properties consistent with sudden hadron production in fast breakup of QGP.**

- **Evidence for CHEMICAL equilibration of the QUARK-GLUON phase at RHIC**

- **We can use (strange) hadron yields to learn about QGP properties at hadronization – remote 'sensing'**

SUPPLEMENTAL SLIDES

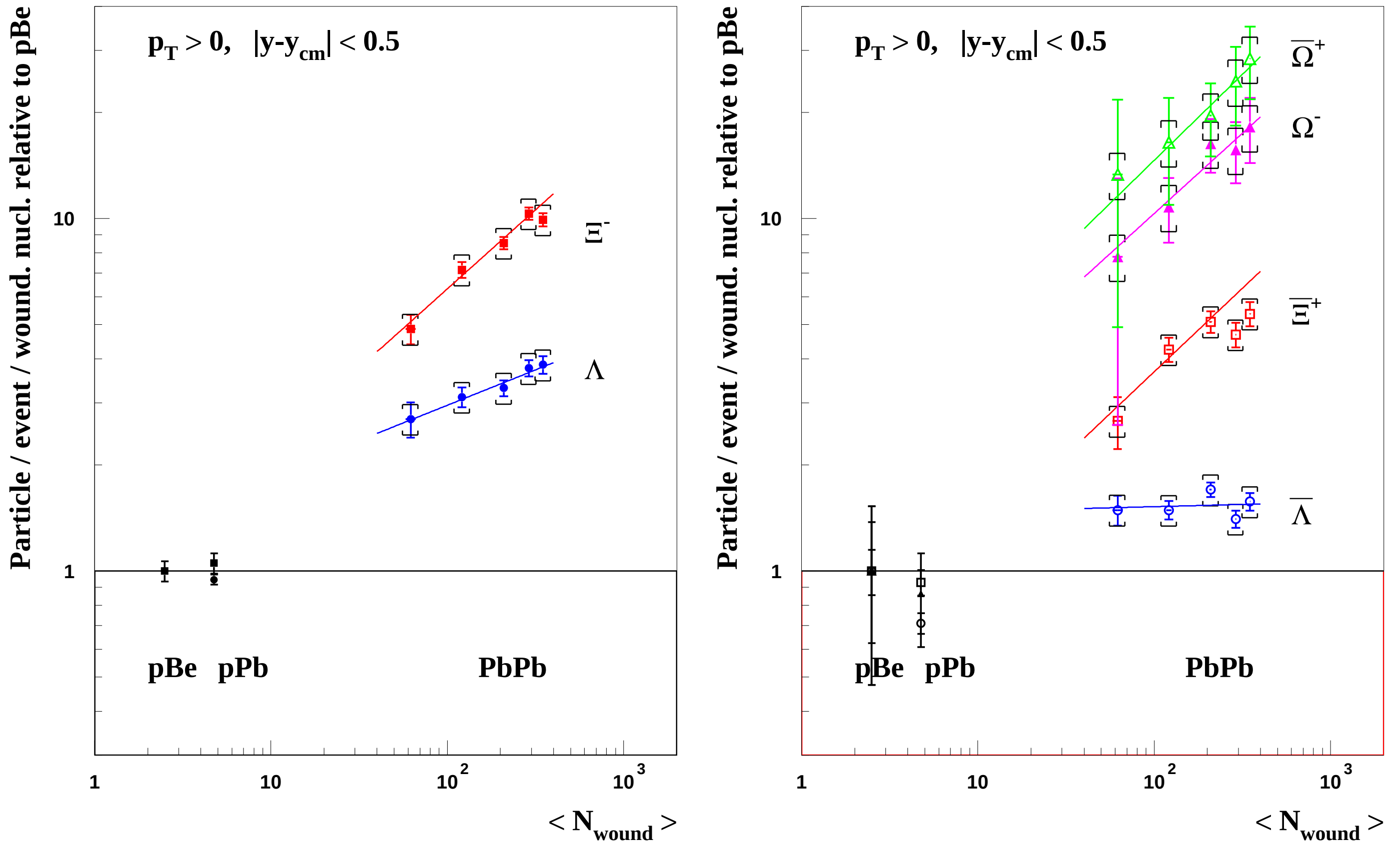
MORE EFFECTIVE CONVERSION OF ENERGY INTO STRANGE MATTER



Enhancement of strangeness pair production compared to light quarks due to onset of thermal glue fusion processes – seen most clearly in Wróblewski ratio in which only newly made s- and q-pairs are counted:

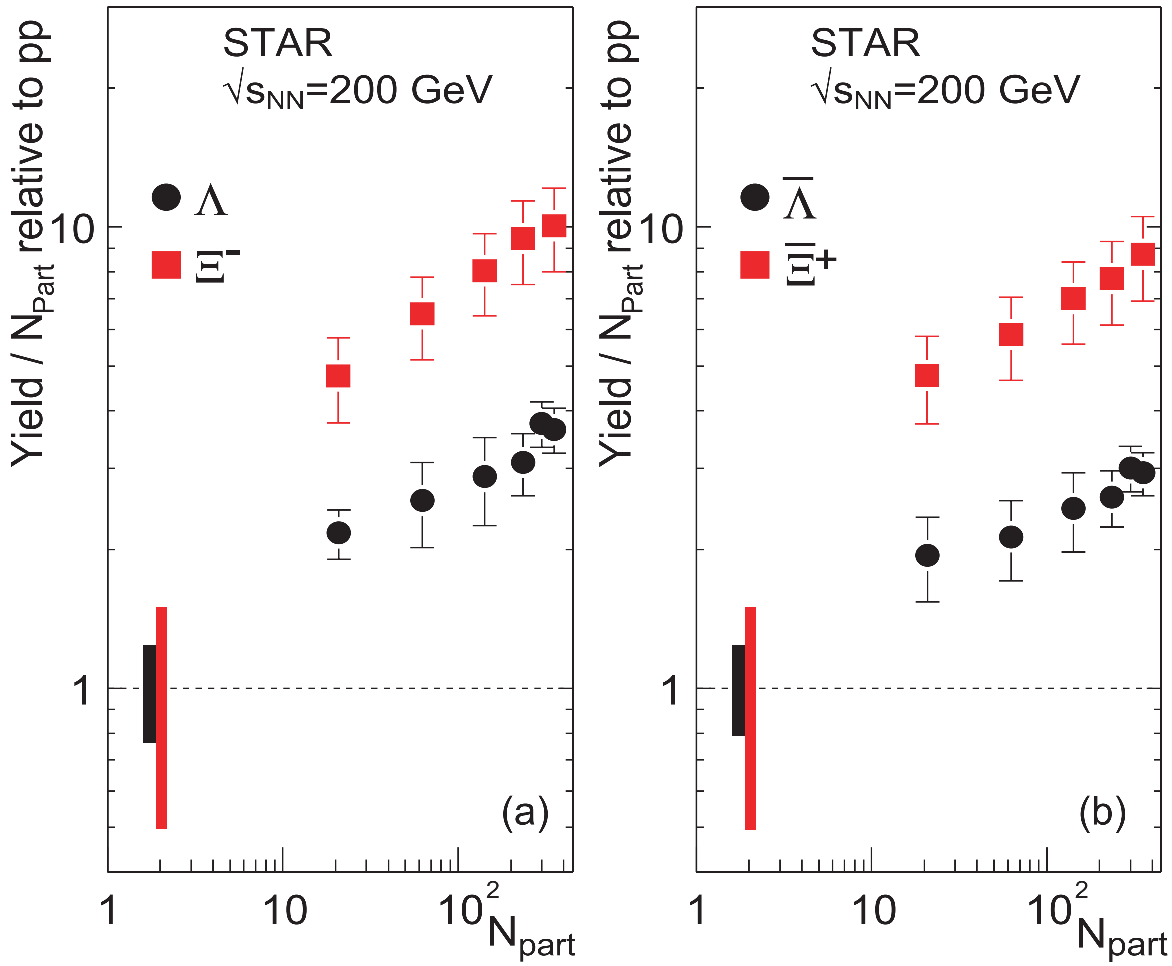
$$W = \frac{2\langle s\bar{s}\rangle}{\langle d\bar{d} + u\bar{u}\rangle}$$

SPS MULTI STRANGE HYPERON ENHANCEMENT



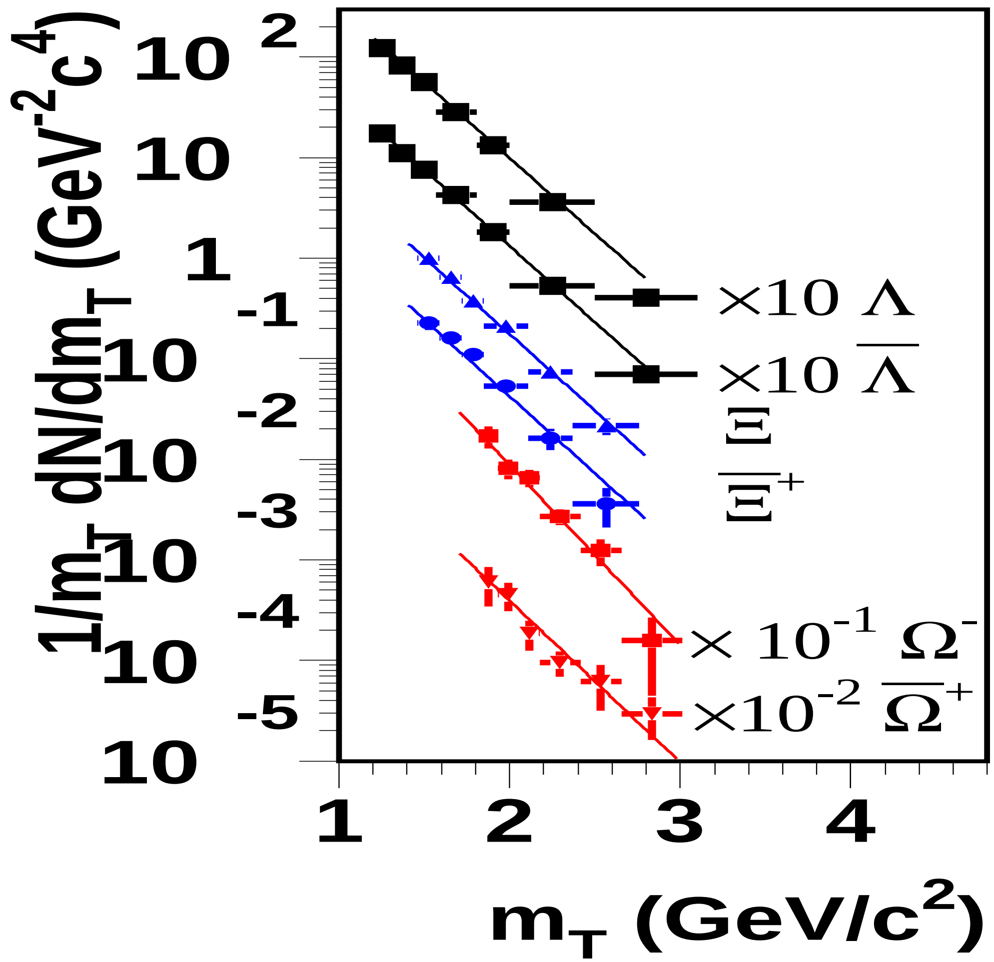
Results of NA57 collaboration as function of centrality.

RHIC MULTI STRANGE HYPERON ENHANCEMENT



Results of the STAR collaboration. More available.

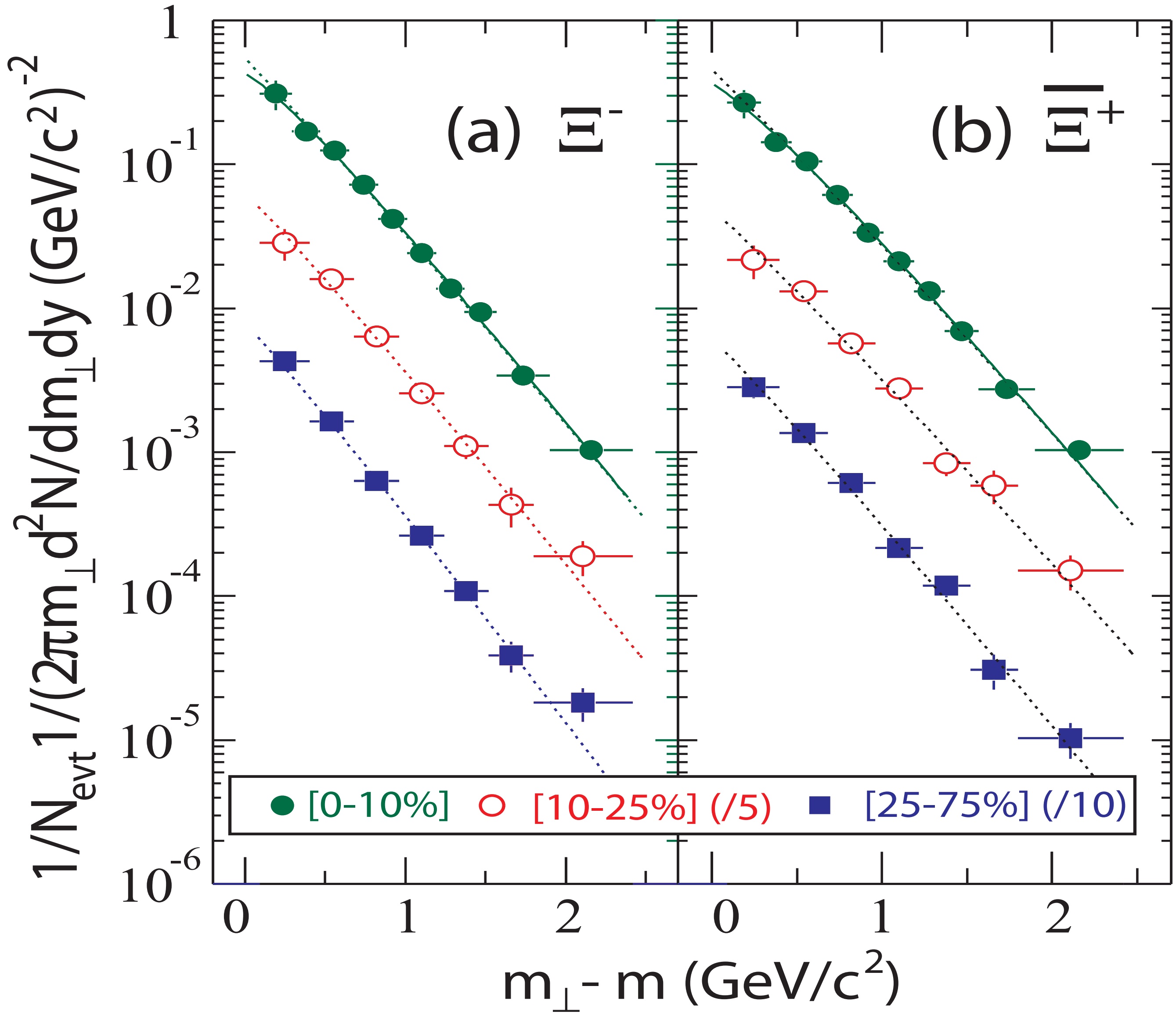
WA97	$T_\perp^{\rm Pb}$ [MeV]
$T^{\rm K^0}$	**230 ± 2**
T^{Λ}	**289 ± 3**
$T^{\overline{\Lambda}}$	**287 ± 4**
T^{Ξ}	**286 ± 9**
$T^{\overline{\Xi}}$	**284 ± 17**
$T^{\Omega+\overline{\Omega}}$	**251 ± 19**



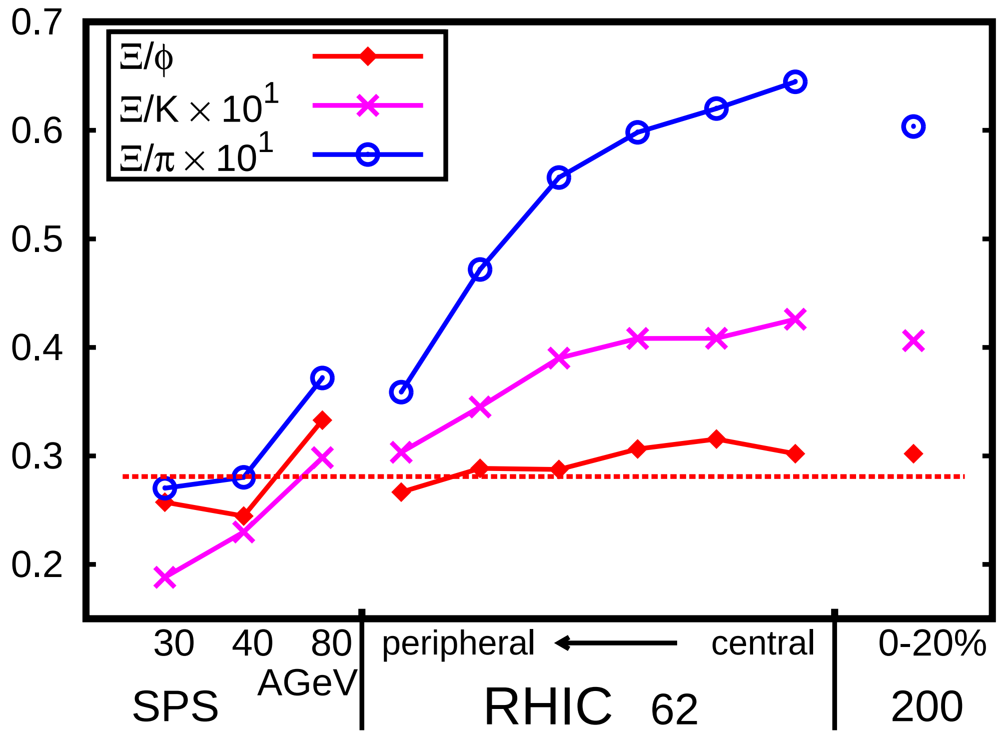
<u>**Λ within 1% of $\overline{\Lambda}$**</u>

Kaon – hyperon difference:
EXPLOSIVE FLOW effect
Difference between $\Omega + \overline{\Omega}$:
presence of an excess of low $p_\perp$ particles
we will return to study this in spectral analysis

$\Xi^-, \overline{\Xi^-}$ Spectra RHIC-STAR 130+130 A GeV



Key Feature: growth of strangeness yield



Baseline (red) comparison of two double strange hadrons. No change in yield.indicates similar mechanism of production of multistrange baryons and mesons. Violett: Comparison of double-strange to single strange hadrons and of double-strange to non-strange hadron; → prepondarance of strangeness grows with reaction energy.