Strangeness as a signature of quark gluon plasma

August 12, 2011, CERN-Alice Summer Student Lecture

1) Introduction: Why study high energy nuclear collisions
1) Why study strangeness
2) Strangeness production
3) Hadronization and breakup of QGP
4) Selected references to own work

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Foundations of QGP/RHI Collisions Research

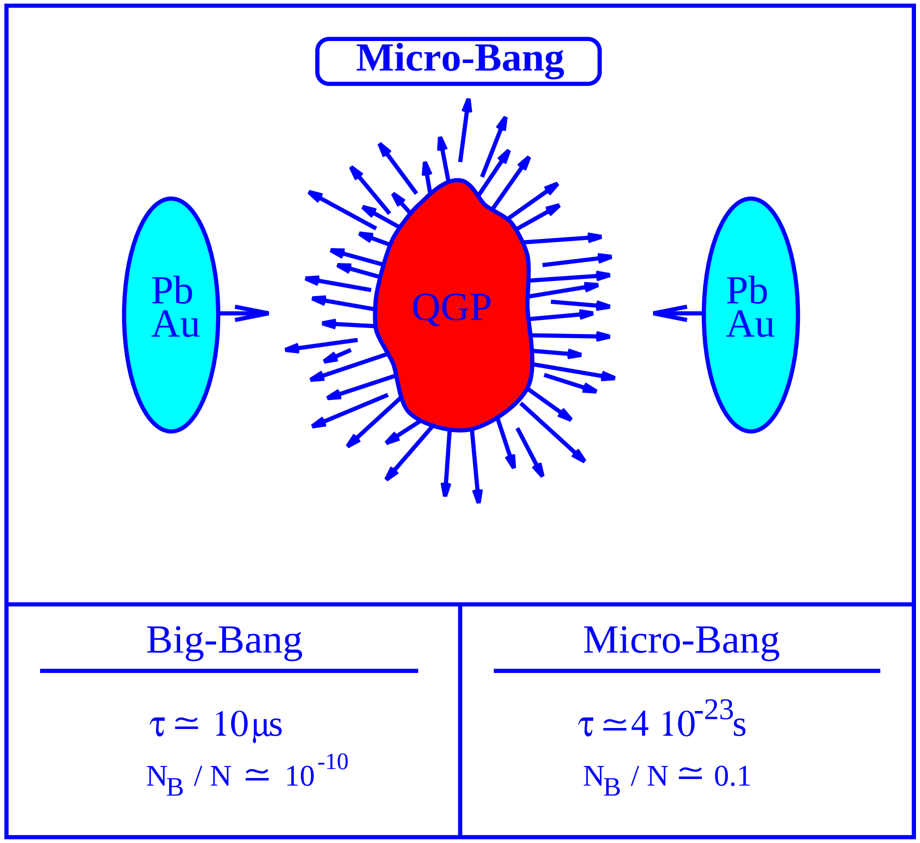
RECREATE THE EARLY UNIVERSE IN LABORATORY:
Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 25 μs after big bang.

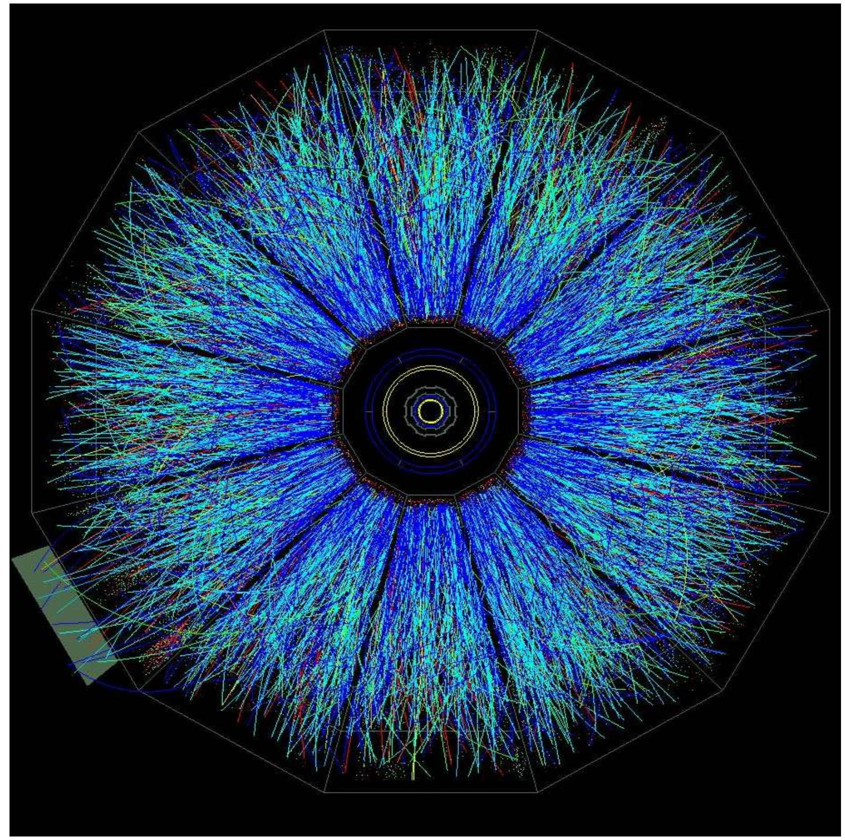
QGP-Universe hadronization led to nearly matter-antimatter symmetric state, ensuing matter-antimatter annihilation yields 10^{-10} *matter asymmetry, the world around us.*

STRUCTURED VACUUM (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 –DECONFINEMENT
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.

RECREATING THE EARLY UNIVERSE IN LABORATORY



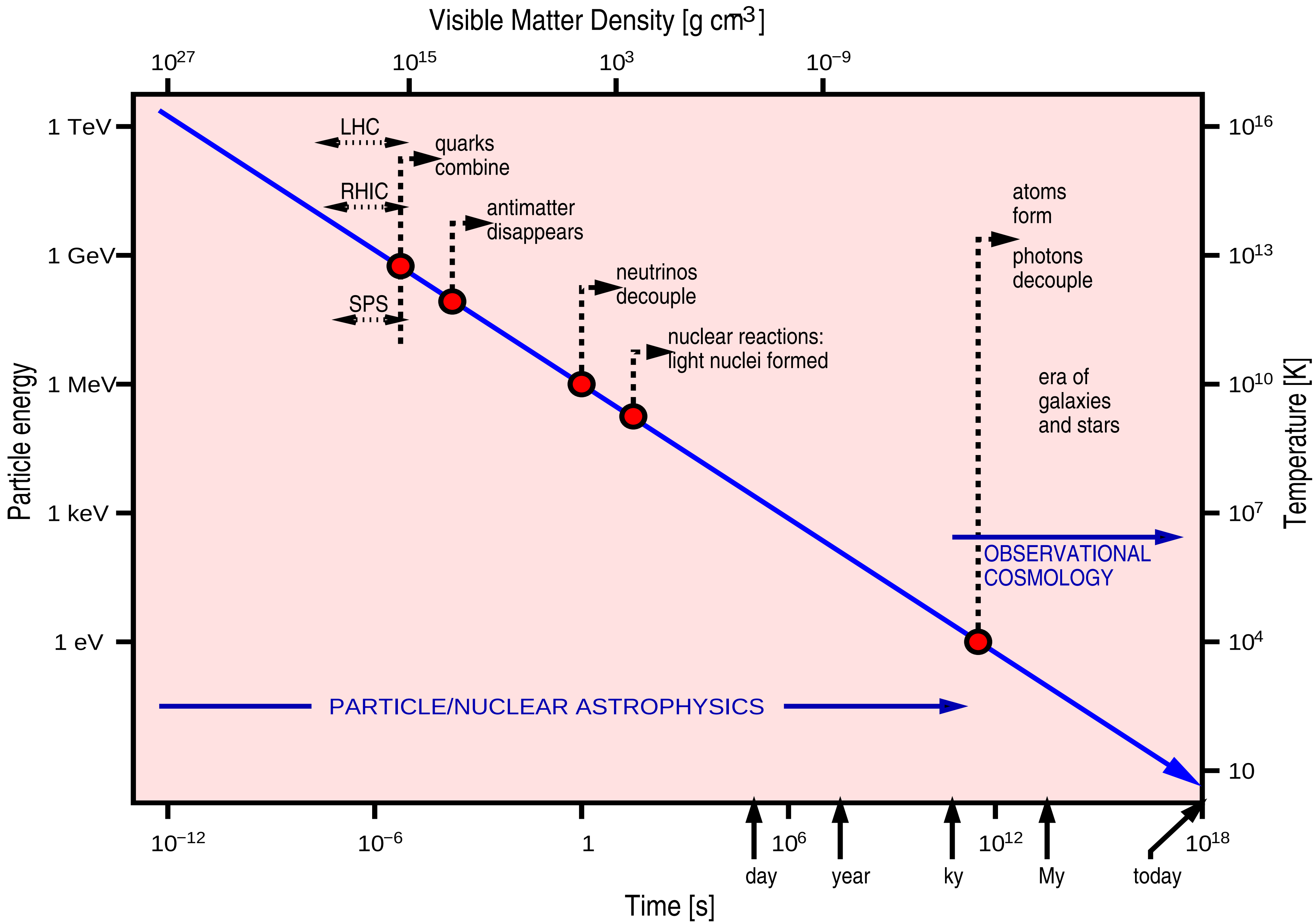


STAR at RHIC

Orders of Magnitude

ENERGY density	ϵ	$\simeq 1$–**50GeV/fm**^{3} $= 0.18$–$9\ 10^{16}$**g/cc**
Latent vacuum heat	B	$\simeq 0.1$–**0.4GeV/fm**^{3} $\simeq (166$–234**MeV**$)^4$
PRESSURE	P	$= \frac{1}{3}\epsilon = (0.52 - 26)\ 10^{30}$ **bar**
TEMPERATURE	T_0, T_f	**700–250, 175–145 MeV;** **300MeV≃3.5** 10^{12}**K**

Stages in the evolution of the Universe



What is deconfinement?

A domain of (space, time) much larger than normal hadron size in which color-charged quarks and gluons are propagating, constrained by external 'frozen vacuum' which abhors color.

We expect a pronounced boundary in temperature and density between confined and deconfined phases of matter: phase diagram. Deconfinement expected at both:

high temperature and at high matter density.

In a finite size system not a singular boundary, a 'transformation'.

THEORY: What we knowledge we need
Hot QCD in equilibrium (QGP from QCD-lattice) and
out of chemical equilibrium

DECONFINEMENT NOT A 'NEW PARTICLE',
there is no good answer to journalists question:

How many new vacuua have you produced today?

Vacuum structure

Quantum vacuum is polarizable: see atomic vac. pol. level shifts
Quantum gluon-quark fluctuations:
Permanent fluctuations in 'space devoid of matter':

$$\begin{aligned}
\textbf{even though} \quad & \langle V|G^a_{\mu\nu}|V\rangle = 0, \quad \langle V|\Psi_{u,d,s,\ldots}|V\rangle = 0, \\
\textbf{we have} \quad & \langle V|\frac{\alpha_s}{\pi}G^2|V\rangle \simeq (2.3 \pm 0.3)10^{-2}\mathrm{GeV}^4 = [390(12)\,\mathrm{MeV}]^4\,, \\
\textbf{and} \quad & \langle V|\bar{u}u + \bar{d}d|V\rangle = -2[225(9)\,\mathrm{MeV}]^3\,.
\end{aligned}$$

Vacuum and Laws of Physics

Vacuum structure controls early Universe properties
Vacuum is thought to generate color charge confinement:
hadron mass originates in QCD vacuum structure.
Vacuum determines inertial mass by confinement 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, etc.....

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 and strongly interacting probes provide image of the last 3fm/c of QGP expansion/hadronization:**
  - **Strangeness enhancement**
  - **Strange antibaryon enhancement**
  - **Strange resonances**
  - **Another time: Heavy flavor (c, b) with strangeness, LHC predictions etc.**

Strangeness: A signature of QGP and Deconfinement

ion to strangeness. Thus, assuming equilibrium in the quark plasma, we find the density of the strange quarks to be (two spins and three colours):

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

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

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

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

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

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

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

When the quark matter dissociates into hadrons, some of the numerous $\bar{s}$ may, instead of being bound in a $q\bar{s}$ kaon, enter into a $(\bar{q}\bar{q}\bar{s})$ antibaryon and, in particular, a $\bar{\Lambda}$ or $\bar{\Xi}^0$. The probability for this process seems to be comparable to the similar one for the production of antinucleons by the antiquarks present in the plasma.

First published literature mention of strange particle production as probe of quark-gluon plasma and as signature of phase transition appears in the preprint CERN-TH-2969 of October 1980 (Rafelski & Hagedorn). Published in "Statistical Mechanics of Quarks and Hadrons", H. Satz, editor, Elsevier 1981. Strangeness enhancement $\bar{s}/\bar{q} \to K^+/\pi^+$, and strange antibaryons $\bar{s}/\bar{q} \to \overline{\Lambda}/p$ are proposed and discussed in qualitative terms as signatures of deconfined QGP phase, matter-antimatter symmetry.

Chemical equilibrium in QGP presumed. A point of considerable later research effort.

1. Strangeness – a popular QGP diagnostic tool

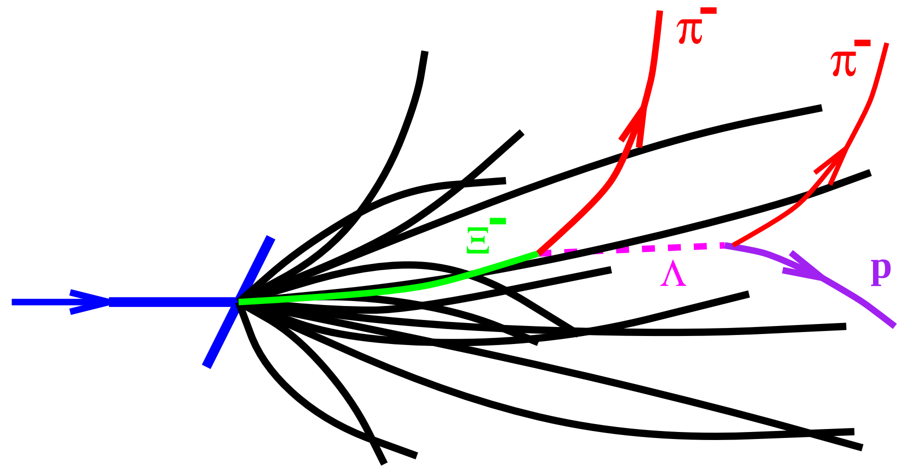
EXPERIMENTAL REASONS

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

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

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

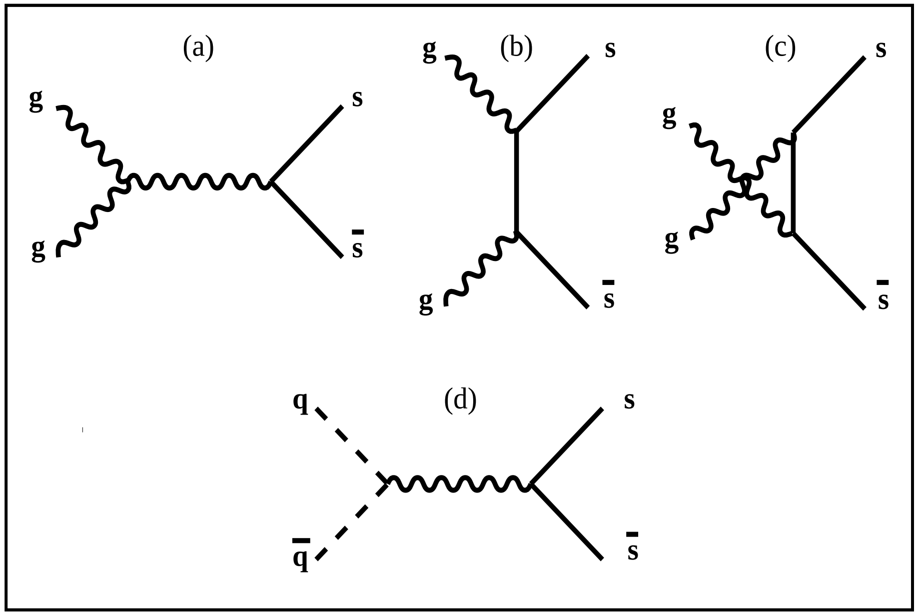
- **Strange hadrons are subject to a self analyzing decay within a few cm from the point of production;**



- **Production rates hence statistical significance is high;**

THEORETICAL CONSIDERATIONS

- **production of strangeness in gluon fusion** $\boxed{GG \to s\bar{s}}$
  strangeness linked to gluons from QGP;



- **coincidence of scales:**
  $\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\rm QGP}} \to$
  strangeness a clock for reaction
- **Often** $\boxed{\bar{s} > \bar{q}} \to$
  strange antibaryon enhancement and
  at RHIC also (anti)hyperon dominance of (anti)baryons.

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)

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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

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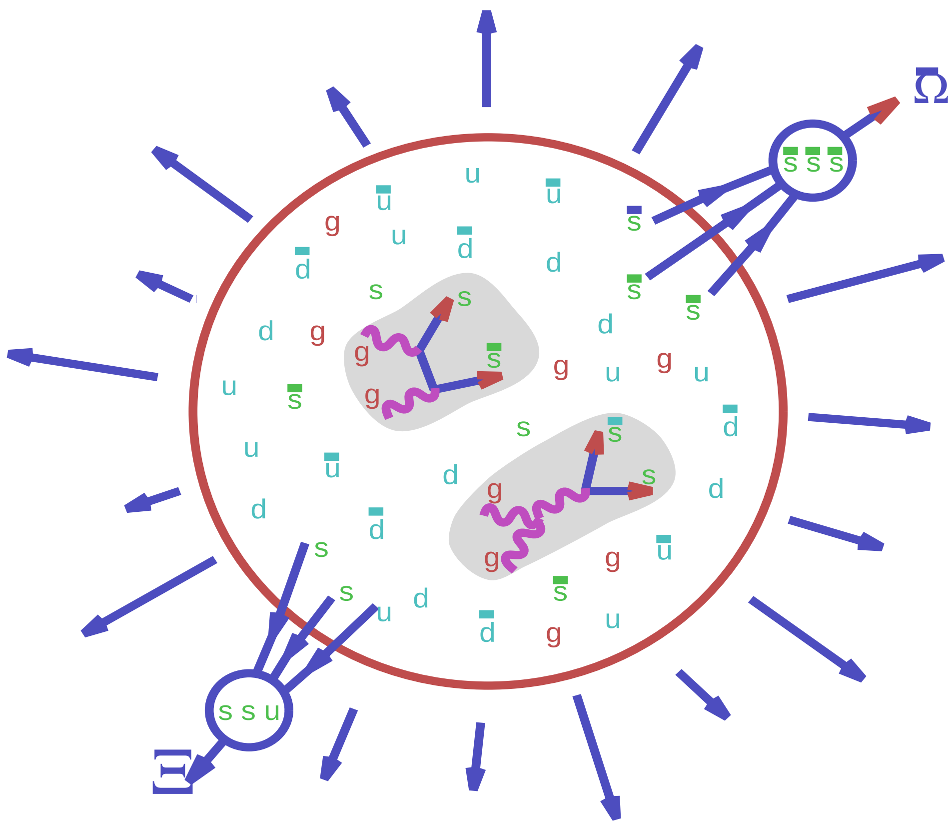
3. STRANGENESS MOBILITY IN QGP IMPLIES
   s–$\bar{s}$ **phase space symmetry, relevant in baryon rich (SPS) environment**
   IMPRINTED ON HADRONS AT HADRONIZATION

TWO STEP HADRON FORMATION MECHANISM IN QGP



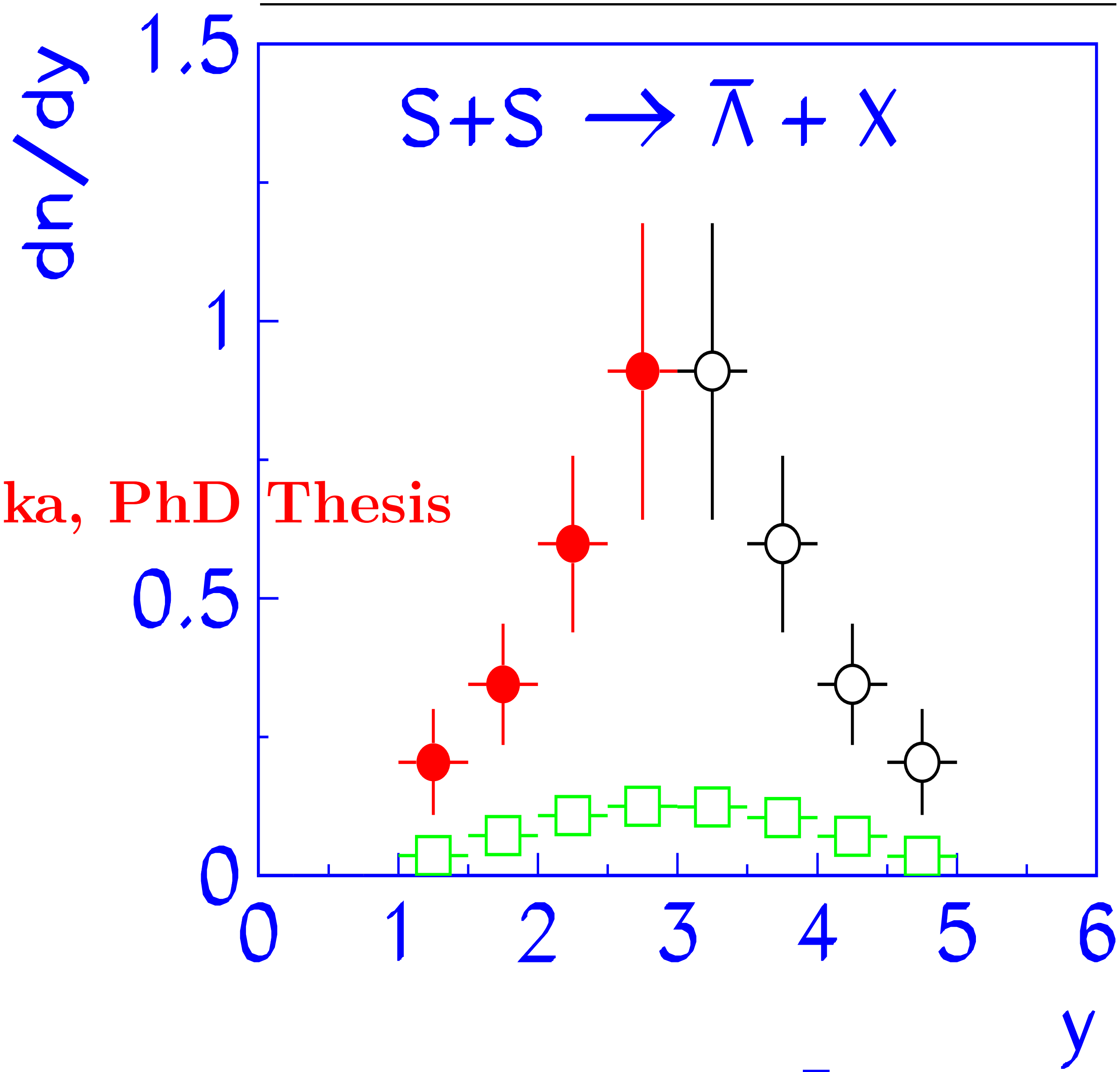
1. $GG \rightarrow s\bar{s}$ **(thermal gluons collide)**
   $GG \rightarrow c\bar{c}$ **(initial parton collision)**
   $GG \rightarrow b\bar{b}$ **(initial parton collision)**
   gluon dominated reactions

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

Formation of complex rarely produced (multi)exotic flavor (anti)particles from QGP 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. Enhancement of flavored (strange, charm,...) antibaryons progressing with 'exotic' flavor content.**

Retrospective: Strangeness Discoveries

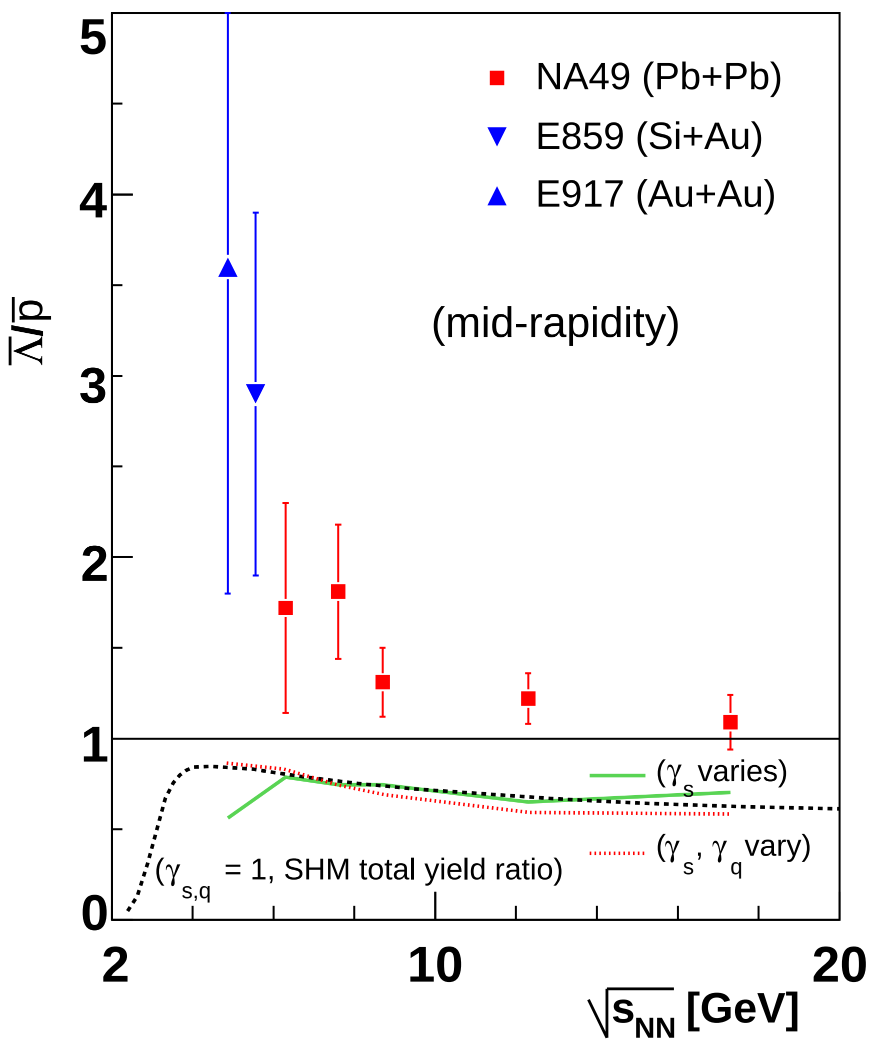
Antibaryon excess at central CM rapidity



Y. Foka, PhD Thesis

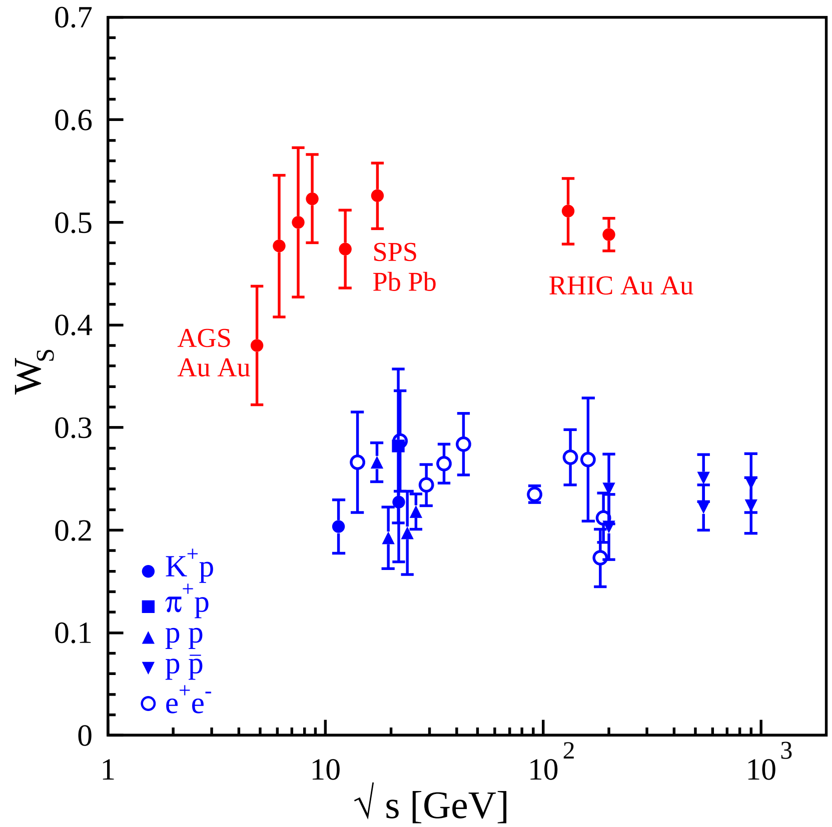
FIRST key result, 1990, SPS-NA35II EXCESS $\bar{\Lambda}$ emitted from a central well localized source. Background (squares) from multiplicity scaled NN reactions

Today systematic confirm of $\overline{\Lambda}/\bar{p} > 1$



Results of CERN NA49 collaboration (M. Mitrovski), SQM2006

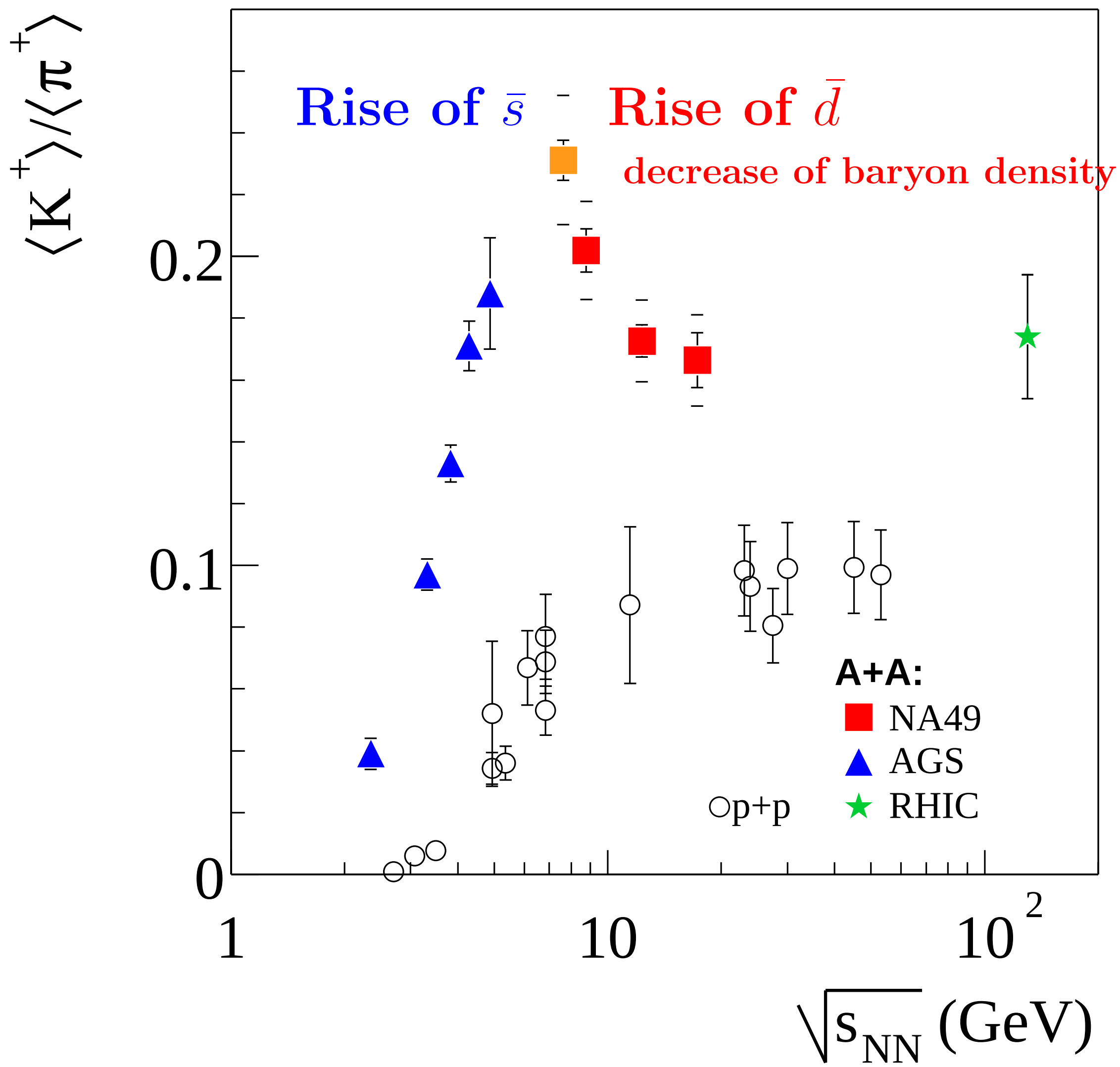
MORE EFFECTIVE CONVERSION OF ENERGY INTO STRANGE MATTER



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:

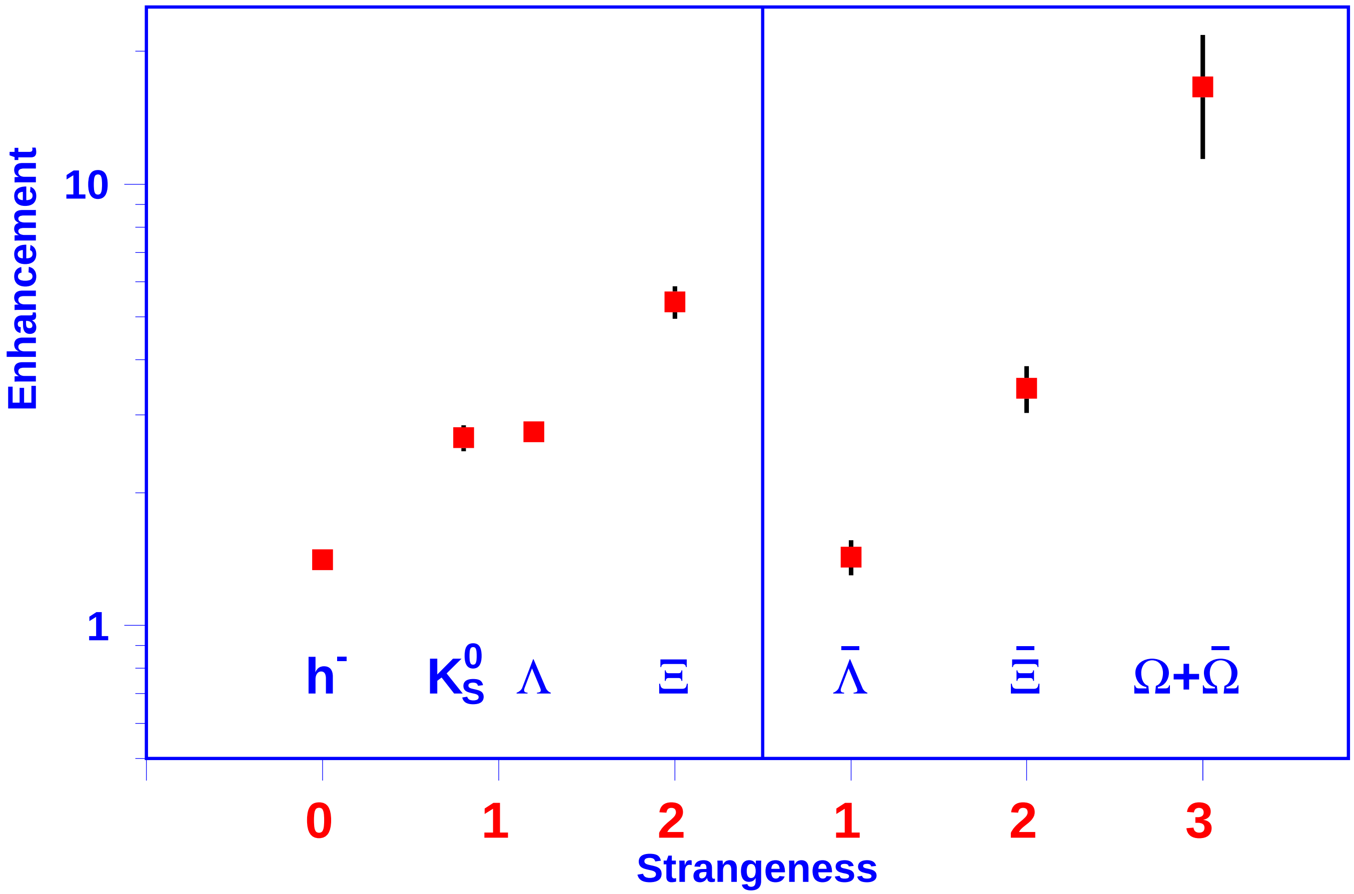
$$W = \frac{2\langle s\bar{s}\rangle}{\langle d\bar{d} + u\bar{u}\rangle}$$

SPECTACULAR HORN



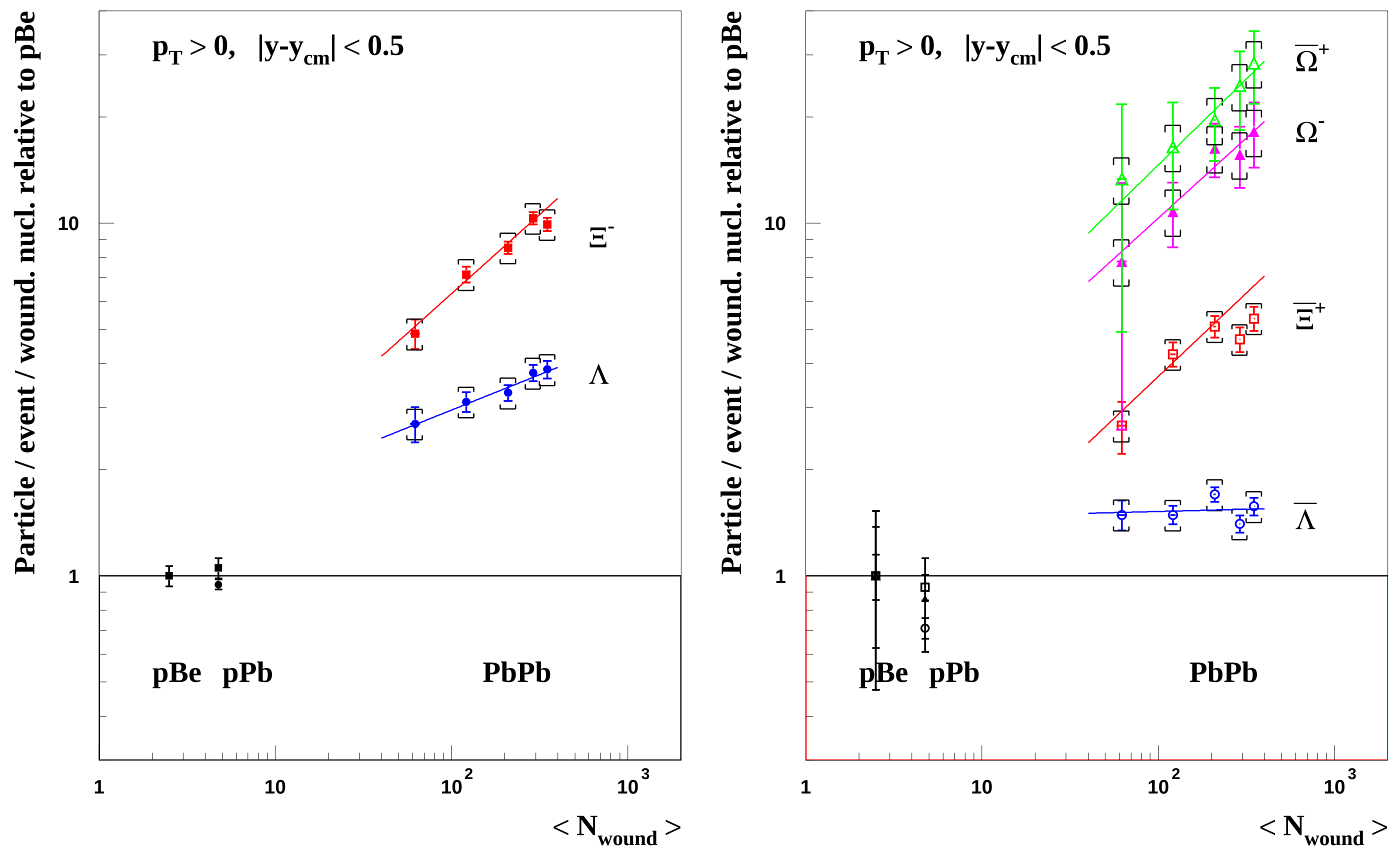
The NA49 (Marek Gaździcki) HORN

MULTI STRANGE HYPERON ENHANCEMENT



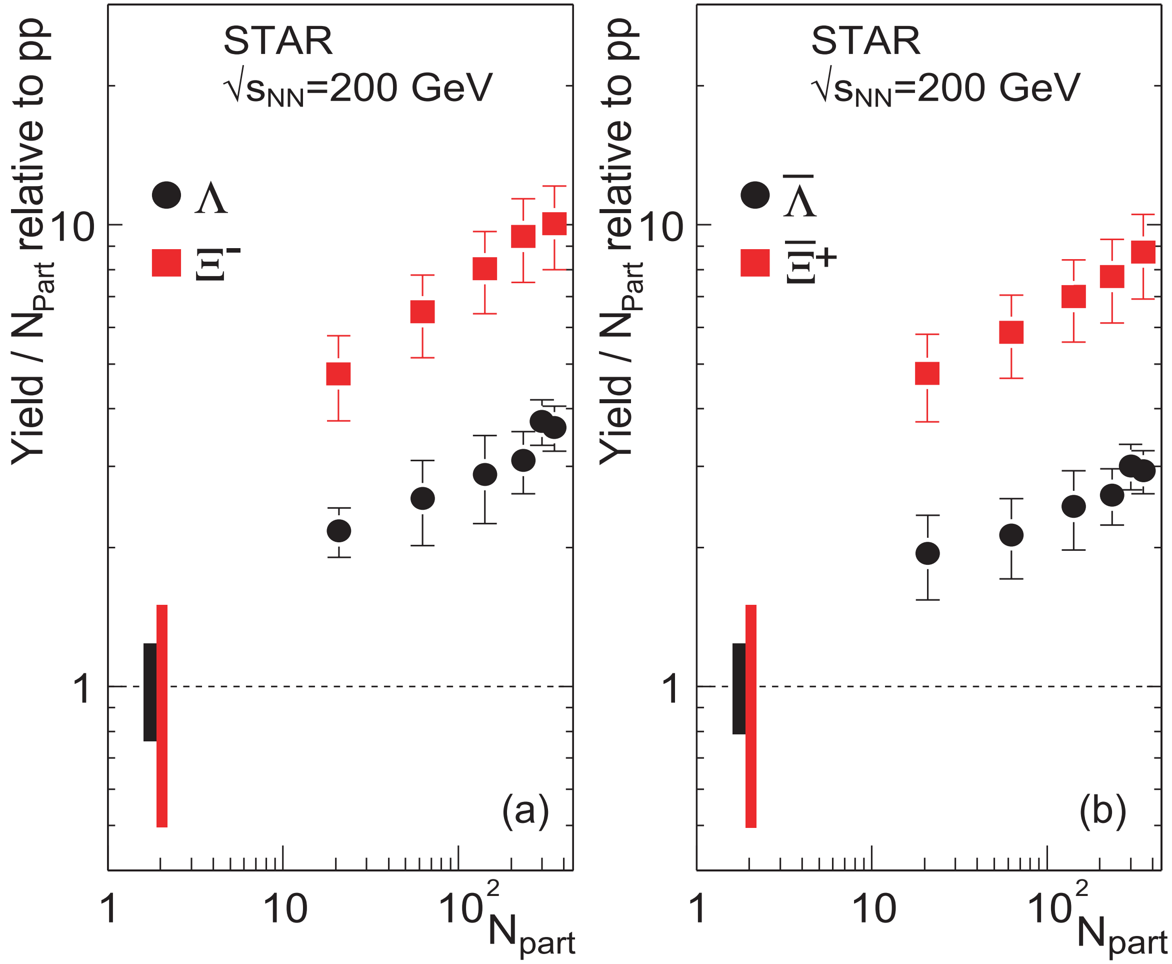
Results of CERN WA97/NA57 collaboration. Enhancement GROWS with a) strangeness b) antiquark content as predicted. Enhancement is defined with respect to yield in p–Be collisions, scaled up with the number of 'wounded' nucleons.

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.

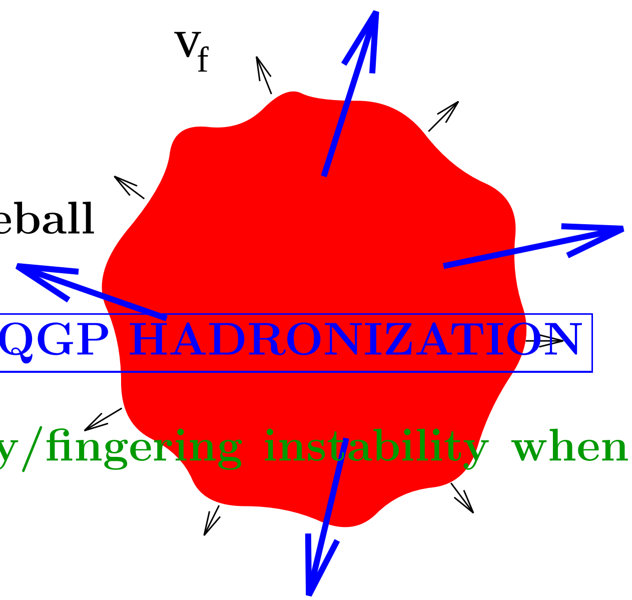
Key feature: MATTER-ANTIMATTER SYMMETRY

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

IF OBSERVED THIS IMPLIES: A common matter-antimatter particle formation mechanism, AND negligible antibaryon re-annihilation/re-equilibration/rescattering

Such a nearly free-streaming particle emission by a quark source into vacuum also required by other observables: e.g. reconstructed yield of hadron resonances and HBT particle correlation analysis

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.

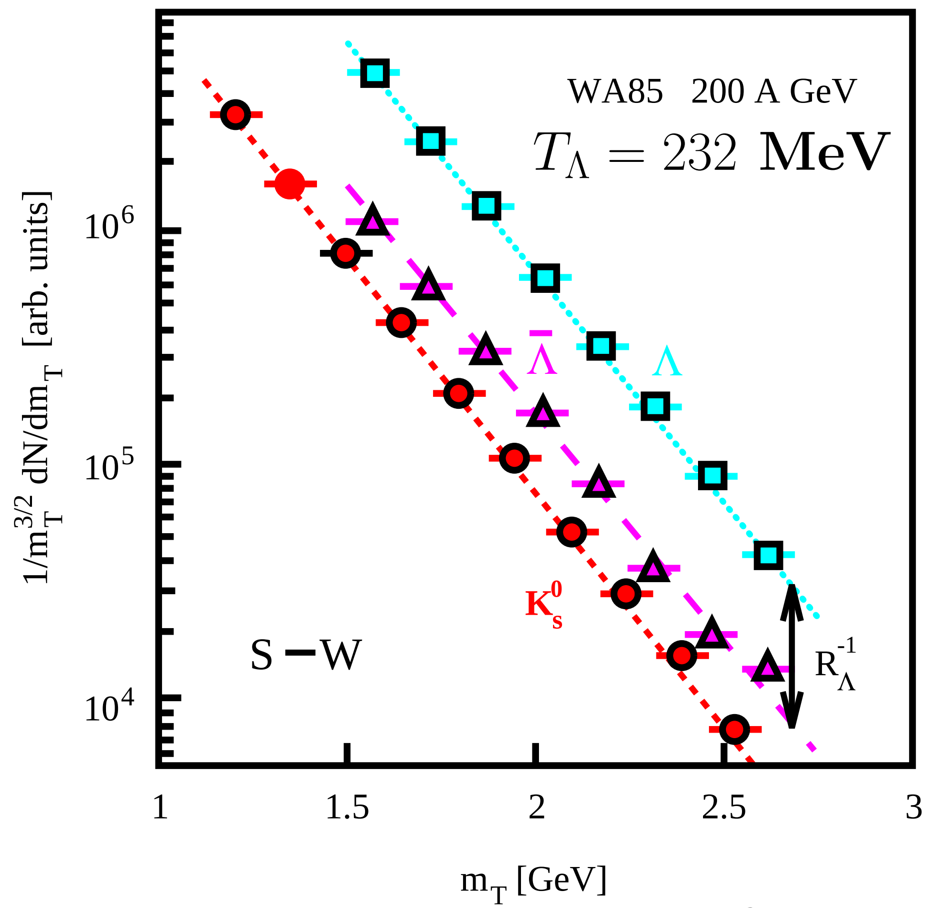
High $m_\perp$ slope universality

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

Why is the slope of baryons and antibaryons precisely the same?

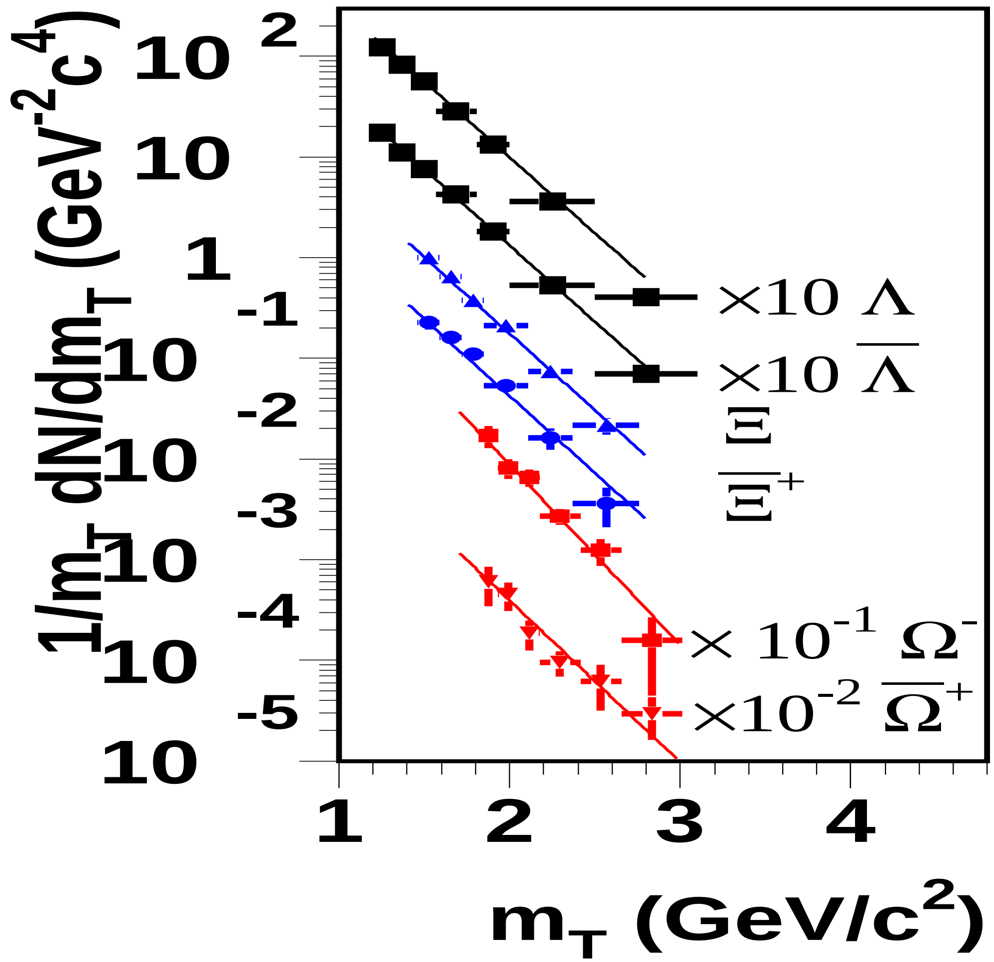
Why is the slope of different particles in same m_t range the same?

Analysis+Hypothesis 1991: QGP quarks coalescing in SUDDEN hadronization



This allows to study ratios of particles measured only in a fraction of phase space

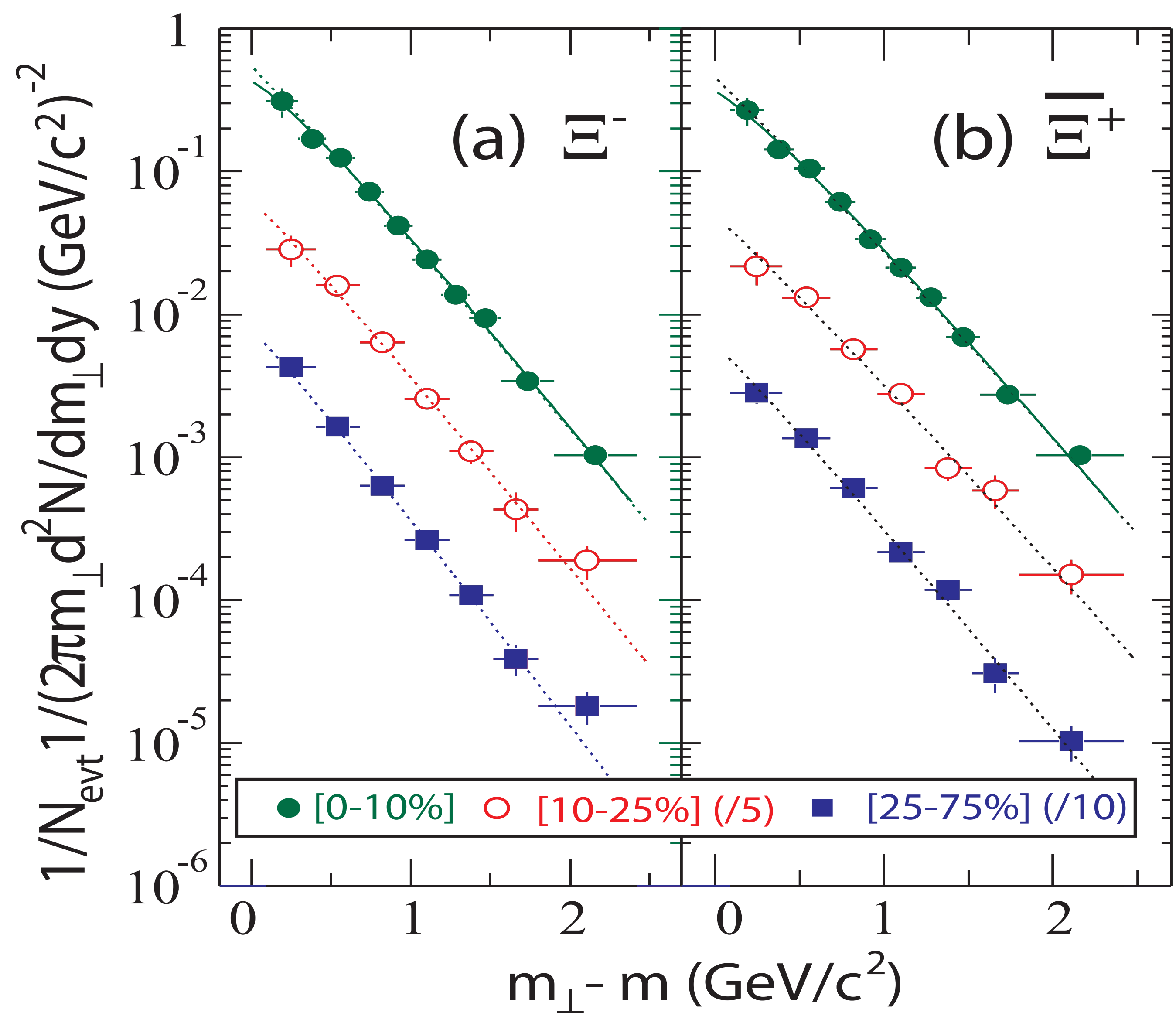
WA97	$T_\perp^{\rm Pb}$ [MeV]
$T^{\rm K^0}$	**230 ± 2**
T^{Λ}	**289 ± 3**
$T^{\overline{\Lambda}}$	**287 ± 4**
T^{Ξ}	**286 ± 9**
$T^{\overline{\Xi}}$	**284 ± 17**
$T^{\Omega+\overline{\Omega}}$	**251 ± 19**



Λ within 1% of $\overline{\Lambda}$

Kaon – hyperon difference:
EXPLOSIVE FLOW effect
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



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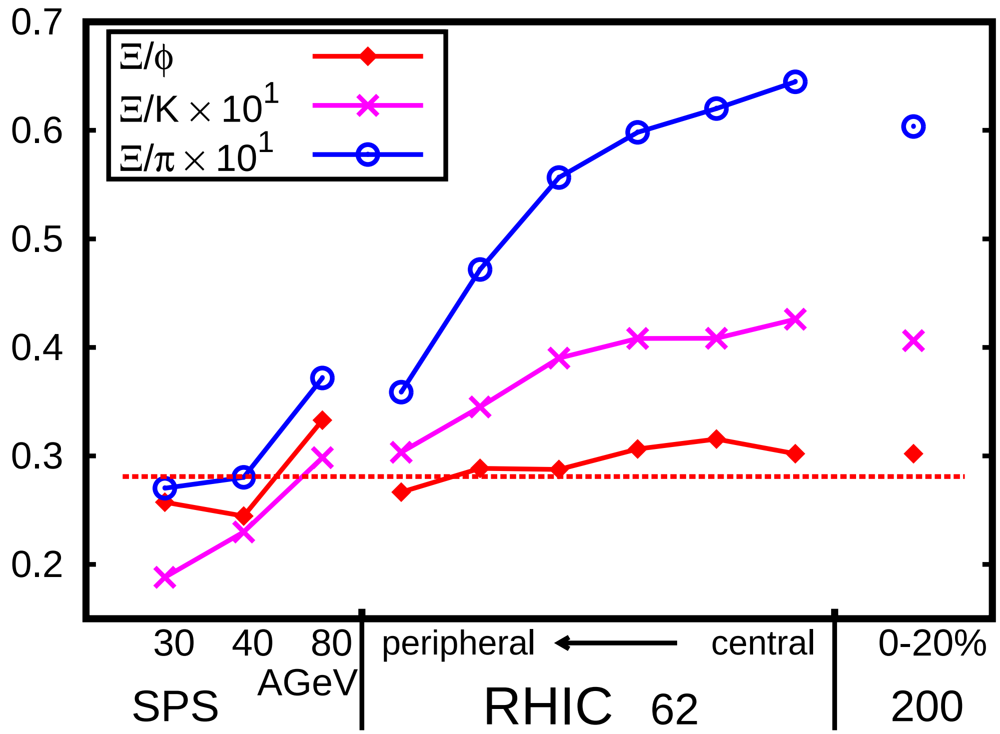
Key Feature: growth of strangeness yield



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.

Key feature: New mechansim of strangeness production

- **production of strangeness in thermal processes in plasma**

dominant processes: JR and BM, December 1981, PRL 1982

$$\langle GG \rangle_T \to s\bar{s}$$

strangeness
abundance due to 'free' gluons =evidence for plasma

10–15% of total rate: $\langle q\bar{q} \rangle_T \to s\bar{s}$

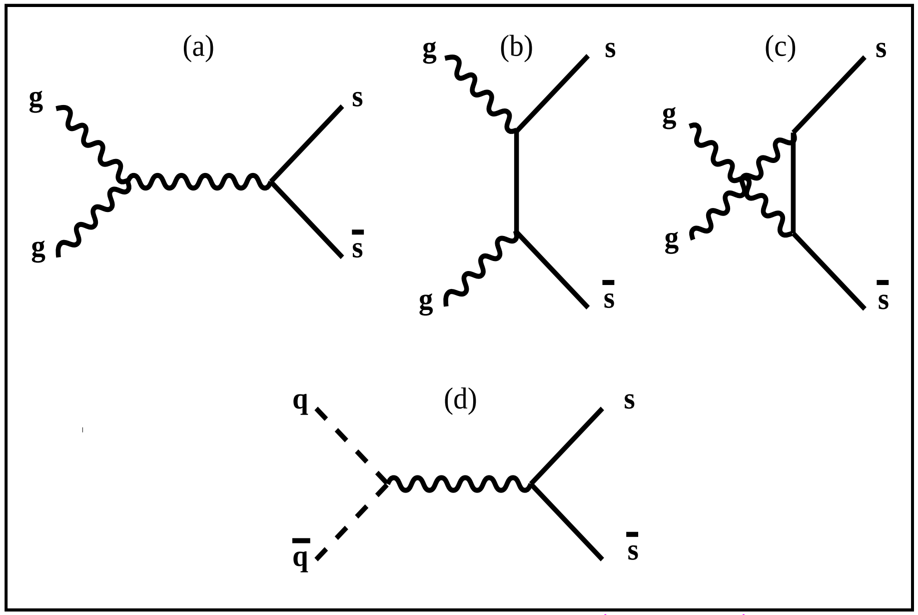
- **coincidence of scales:**

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

clock for QGP phase

strangeness chemical equilibration in QGP possible

- $\boxed{\bar{s} \simeq \bar{q}} \to$ **strange antibaryon enhancement**
  at RHIC (anti)hyperon dominance of (anti)baryons.



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:

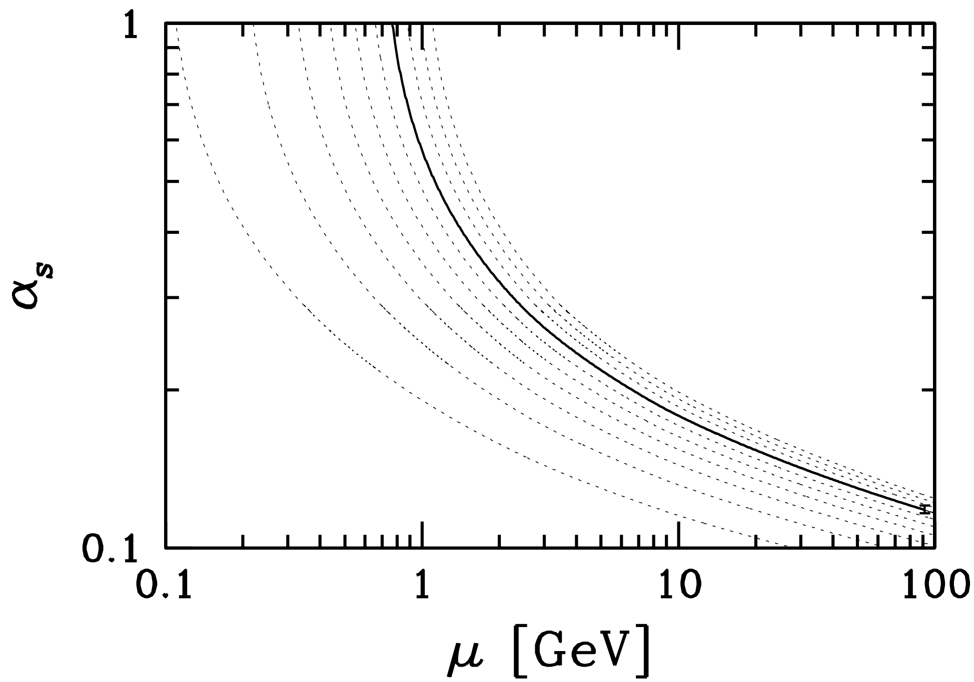
$$\bar{\sigma}_{gg\to s\bar{s}}(s)=\frac{2\pi\alpha_s^2}{3s}\left[\left(1+\frac{4m_s^2}{s}+\frac{m_s^4}{s^2}\right)\tanh^{-1}W(s)-\left(\frac{7}{8}+\frac{31m_s^2}{8s}\right)W(s)\right],$$

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

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 1996 instead of $\alpha_s(M_Z) = 0.118$ than our perturbative strangeness production approach would have been in question.

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

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

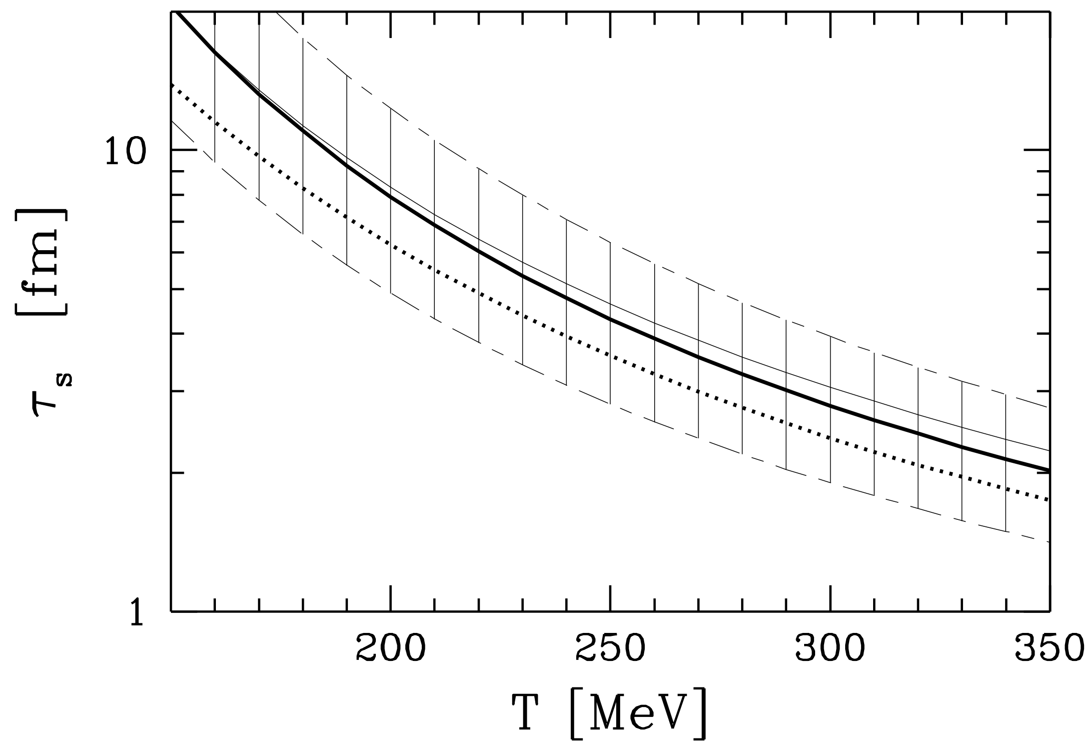
Strangeness relaxation to chemical equilibrium

Strangeness density time evolution in local rest frame:

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

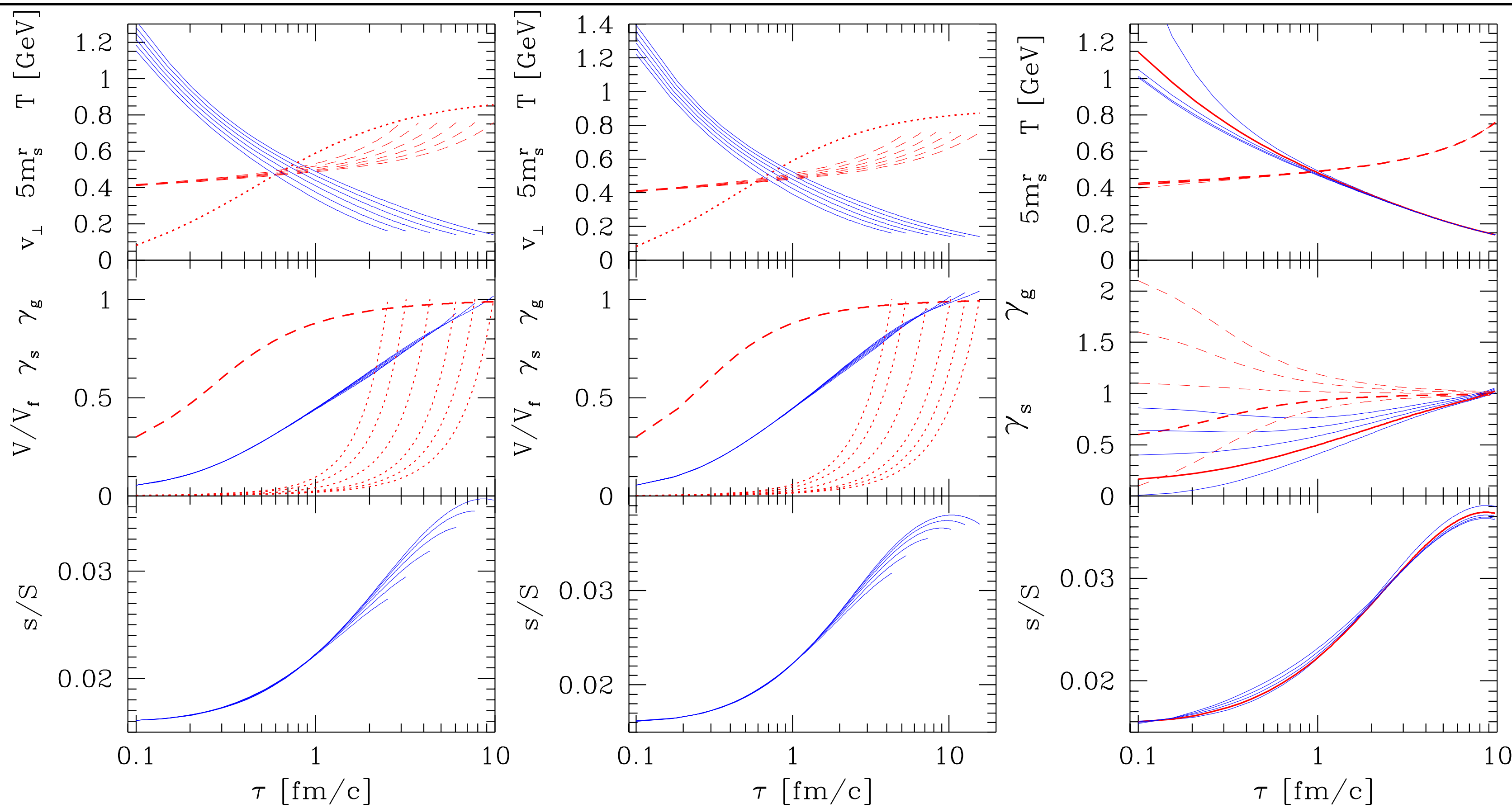
Evolution for s and $\bar{s}$ identical, which allows to set $\rho_s(t) = \rho_{\bar{s}}(t)$.
characteristic time constant τ_s:

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



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

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



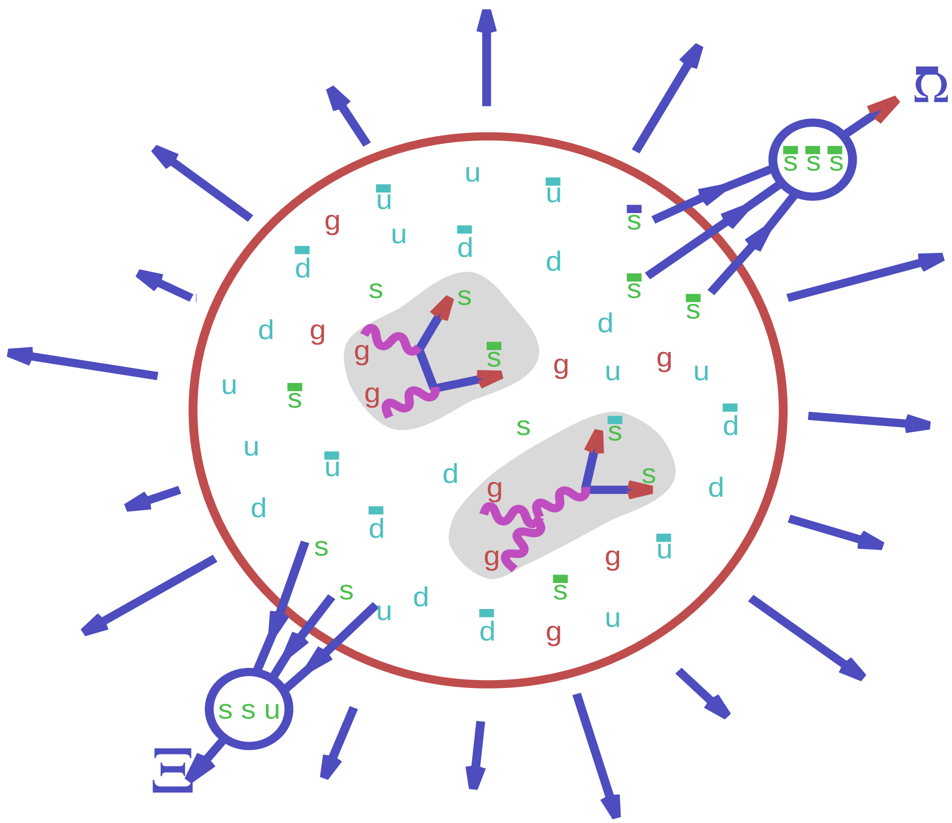
LHC differences to RHIC

- **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 and number of strange to all degrees of freedom. Study as function of centrality to see saturation.

From QGP to Hadrons: Statistical Hadronization Model

= 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 review 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**

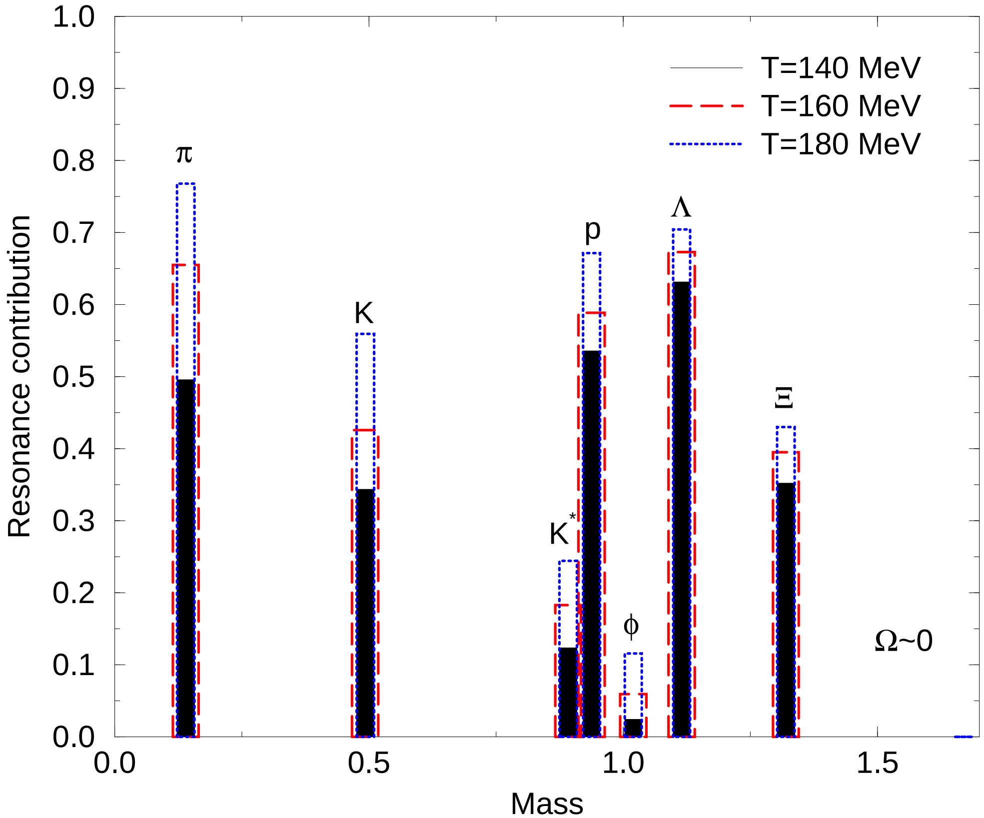
Formation of complex rarely produced multi flavor (exotic) (anti)particles enabled by coalescence between s, $\bar{s}$, c, $\bar{c}$, b, $\bar{b}$ **quarks made in different microscopic reactions; this is signature of quark mobility and independent action, thus of deconfinement. Moreover, strangeness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

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 $T_{\rm H}$:



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

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: $\gamma \equiv \frac{\rho(T,\mu)}{\rho^{\rm eq}(T,\mu)}$

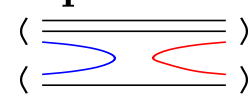
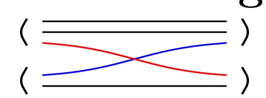
DISTINGUISH: hadron 'h' phase space and QGP phase parameters: micro-canonical variables such as baryon number, strangeness, charm, bottom, etc flavors are continuous, and entropy is almost continuous across phase boundary:

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

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: $s, \bar{s}, q, \bar{q}$ → 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 $(u, d, s, \dots \lambda_q^2 = \lambda_u\lambda_d,\ \lambda_{I3} = \lambda_u/\lambda_d) :$

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

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

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

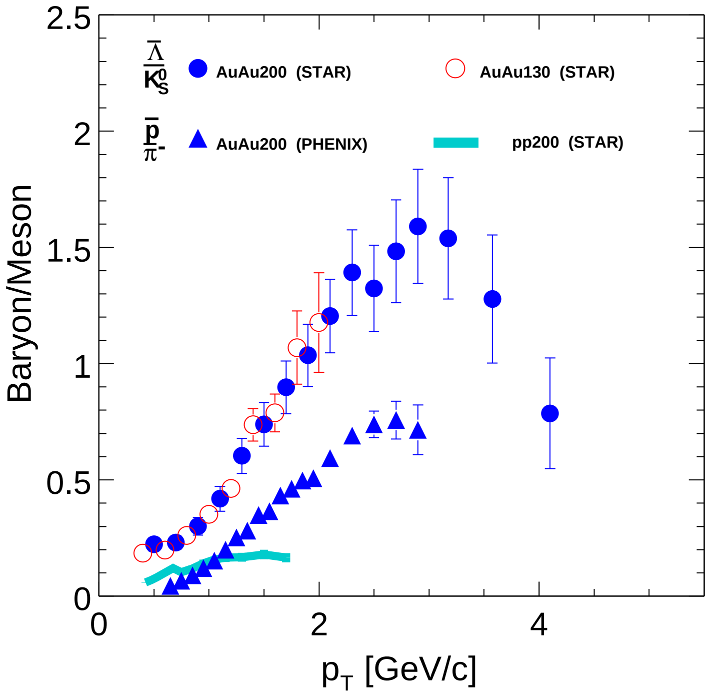
$$\sigma_N \equiv \mu_b + T\ln\gamma_N, \qquad \sigma_{\overline{N}} \equiv -\mu_b + T\ln\gamma_N$$

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

$$\begin{aligned} dE + P\,dV - T\,dS &= \sigma_N\,dN + \sigma_{\overline{N}}\,d\overline{N} \\ &= \mu_b(dN - d\overline{N}) + T\ln\gamma_N(dN + d\overline{N}). \end{aligned}$$

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:

Statistical Hadronization fits of hadron yields

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

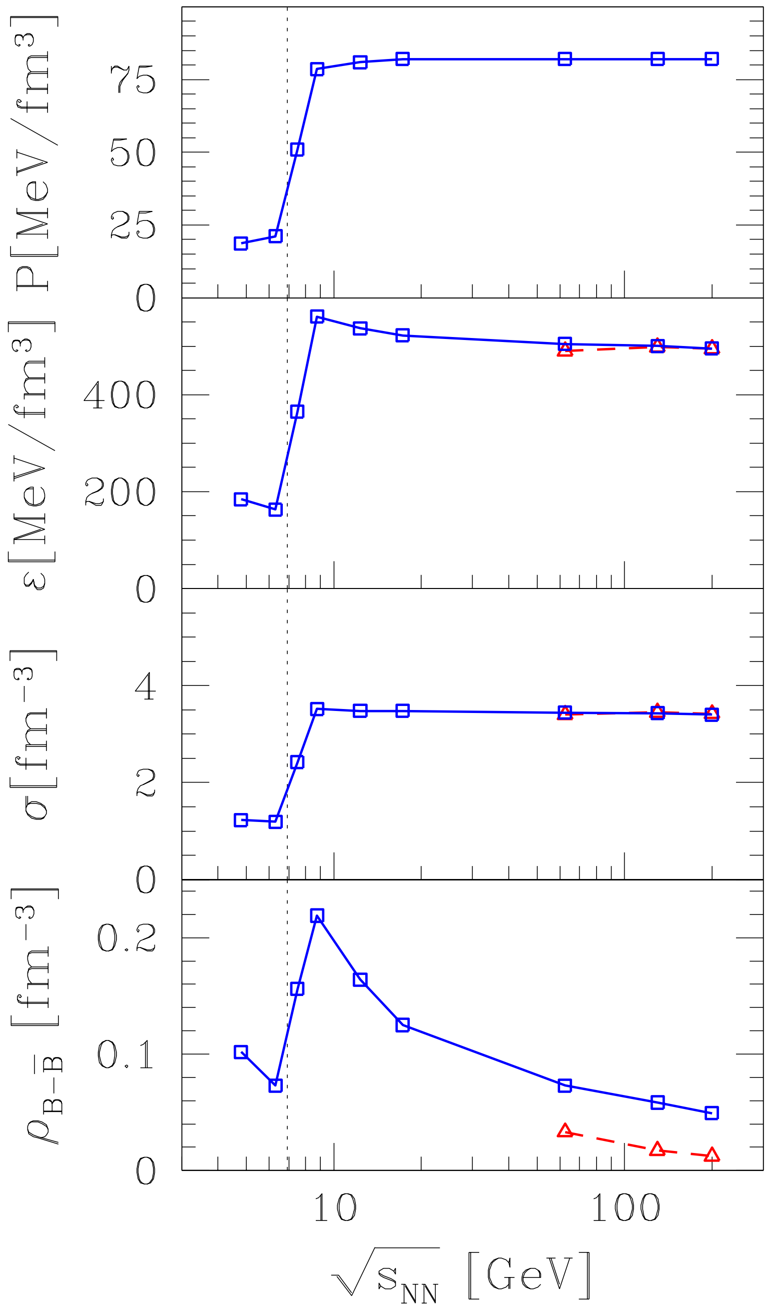
GT, W. Broniowski, W. Florkowski, J. Letessier, S. Steinke, JR nucl–th/0404083 Comp. Phys. Com. 167, 229 (2005)

SHARE 2 with flexible weak decays, fluctuations and chemical flexibility now on line and in review. Involves S.Y. Jeon, Montreal (of fluctuation fame)

SHARE 2.1 in 2006

allows fluctuations and better handling of WI corrections. Comp. Phys. Com. 175, 635 (2006) nucl-th/0603026
Aside of particle yields, also PHYSICAL PROPERTIES of the source are available, both in SHARE and ONLINE.

REMOTE SENSING: CRITICAL PRESSURE

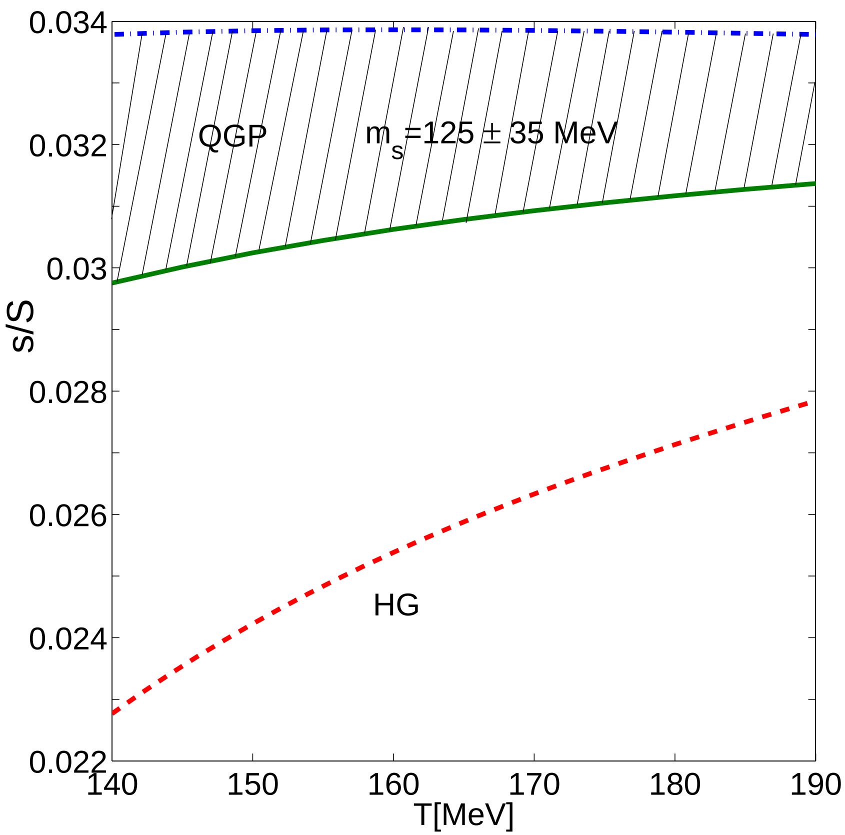


SHARE (Statistical Hadronization with REsonsnces) fit made with SPS and RHIC data as function of energy shows evaluating physical properties of the source (given produced hadron yields) that there is a universal pressure of hadron paroduction for a wide range of reaction energies. The physical properties obtained summing all fractional contributions of different particles.

Physical Properties of bulk at hadronization show a change, from low density and pressure system at low $\sqrt{s}$ to a highly compressed phase just above this, see baryon and energy density. Shift in E/TS consistent with change from adiabatic to fast hadronization. Pressure of hadronization above minimun reaction energy is constant¿

QGP and HG comparison: strangness and entropy

We compare strangeness per entropy (particle multiplicity) in deconfined quark-gluon plasma with hadron gas at a common measured T. This is an enhancement of strangeness governing hadronization process, not an experimental enhancement: we expect that hadron phase spce will 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.

Note that much (30% at LHC!) of HG phase strangeness invisible, in hidden strangeness states η, η', ϕ

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 $s/S \to 1/31 = 0.0323$

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

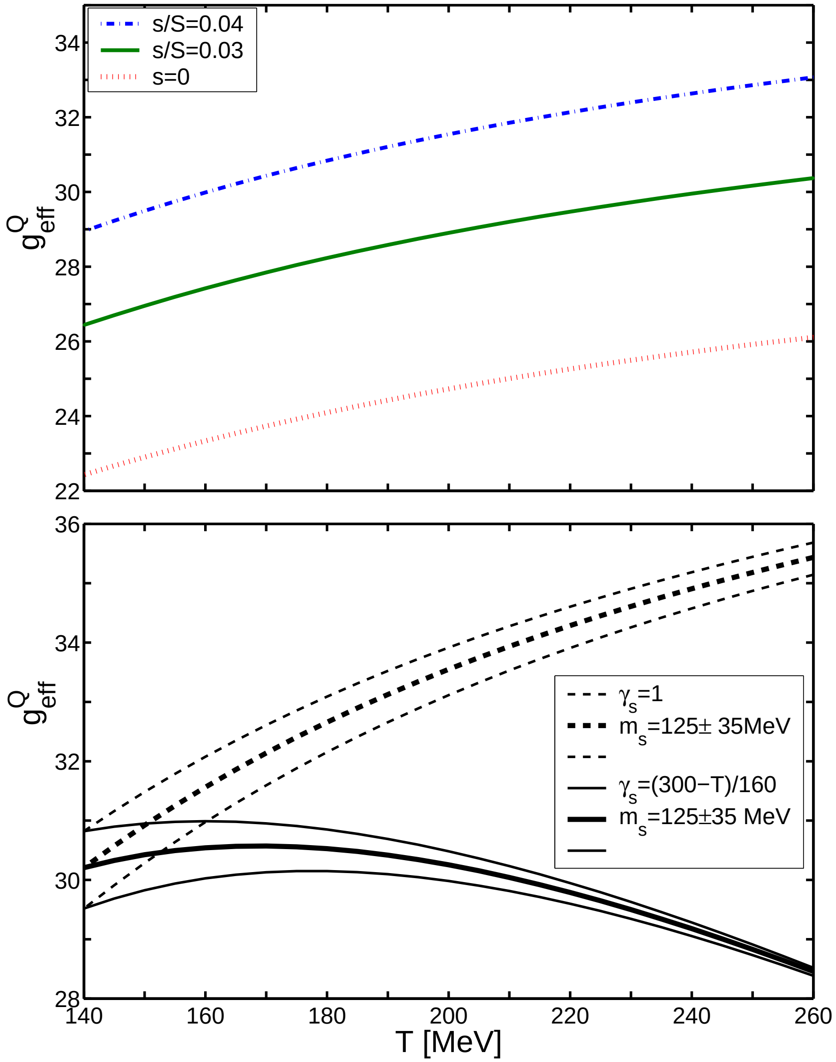
Chemical non-equilibrium occupancy of strangeness $\gamma_s^{\rm Q}$

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

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:

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

Entropy in QGP – degrees of freedom $g_{\rm eff}^Q$?



$g_{\rm eff}^Q$ in QGP

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

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

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 $m_s = 125 \pm 35\,\mathrm{MeV}$
dashed: equilibrated u, d, s, G system
solid lines: strangeness contents increasing with decreasing temperature
$\gamma_s = (300 - T)/160$

We have a rather precise expectation which is seen in the s/S ratio at RHIC. Hence we expect oversaturation of hadron phase space by 30-100% as the excess QGP entropy is accomodated in production of additional hadrons.

Conclusions

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

- **Strangeness experimental results fulfill all our expectations: resounding confirmation of fast hadronization of quark-gluon plasma. – steady rise of s/S with energy and centrality and great enhancement of multistrange hadrons and strange antibaryons**

- **Predicted QGP behavior confirmed by greatly enhanced strangeness and strange antibaryon enhancement, imply 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 QGP at RHIC; but not in final state hadrons which abundances are controlled by prevailing valance quark yields.**

- **We begin to use strange hadron yields to learn about QGP properties – remote 'sensing'**

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