Strangeness as a signature of quark gluon plasma

September 16, 2010, Washington Univerity, St.Louis

1) Introduction: Why study high energy nuclear collisions
1) Why study strangeness
2) Strangeness production
3) Hadronization and breakup of QGP
4) Strangeness evolution in dynamic QGP drop

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Foundations of QGP/RHI Collisions Research

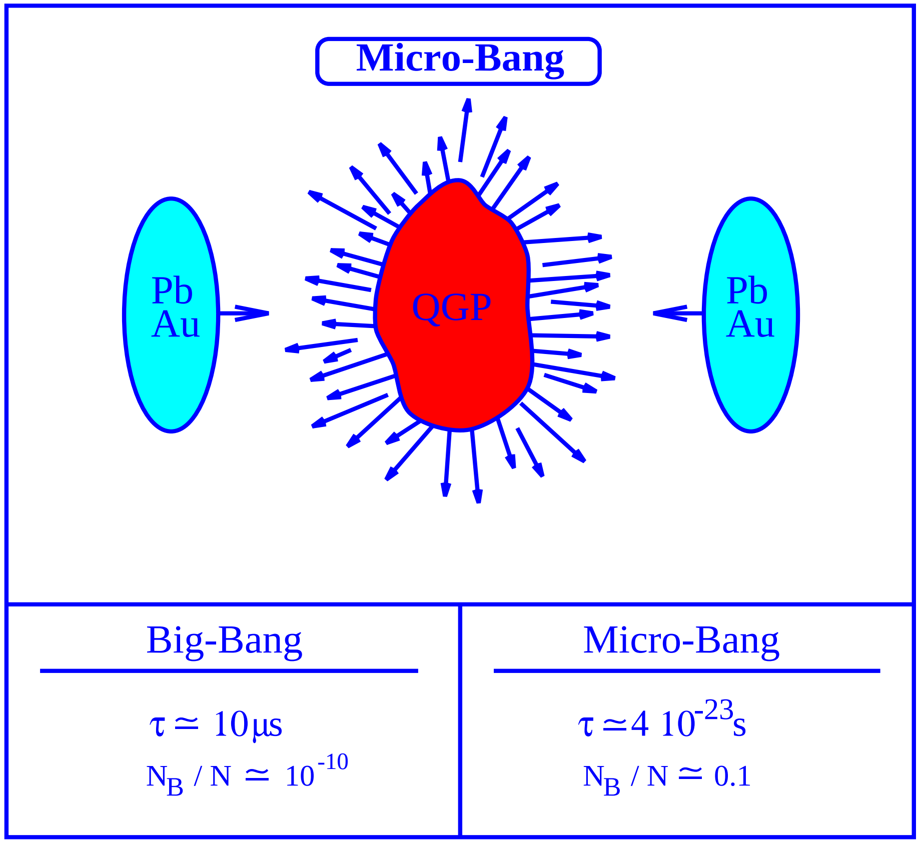
RECREATE THE EARLY UNIVERSE IN LABORATORY:
Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 25 μs after big bang.

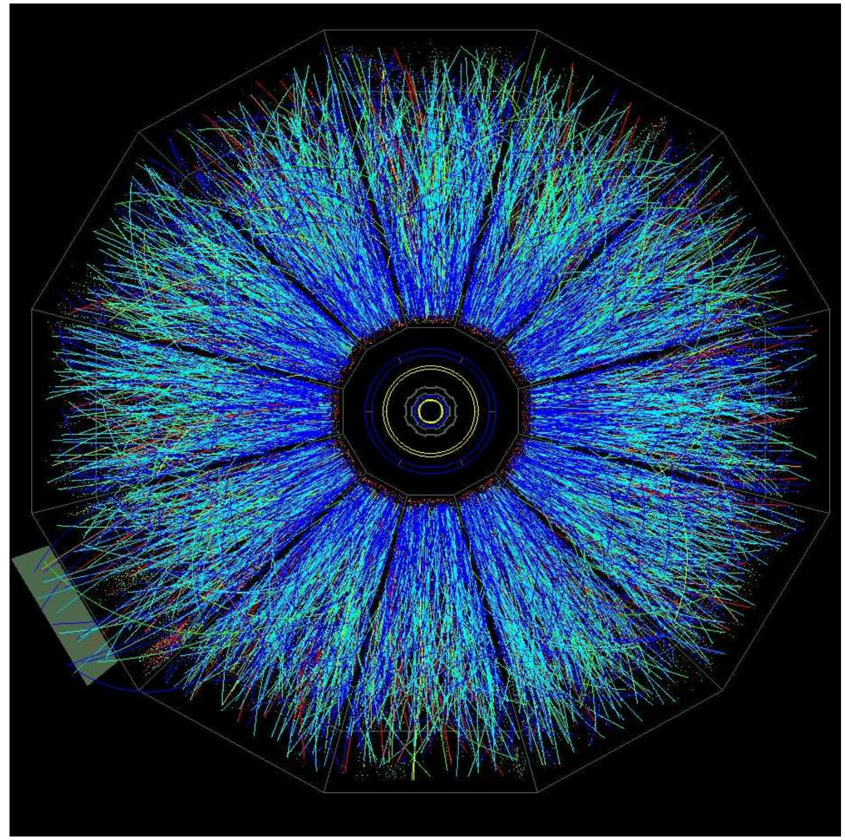
QGP-Universe hadronization led to nearly matter-antimatter symmetric state, ensuing matter-antimatter annihilation yields 10^{-10} *matter asymmetry, the world around us.*

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



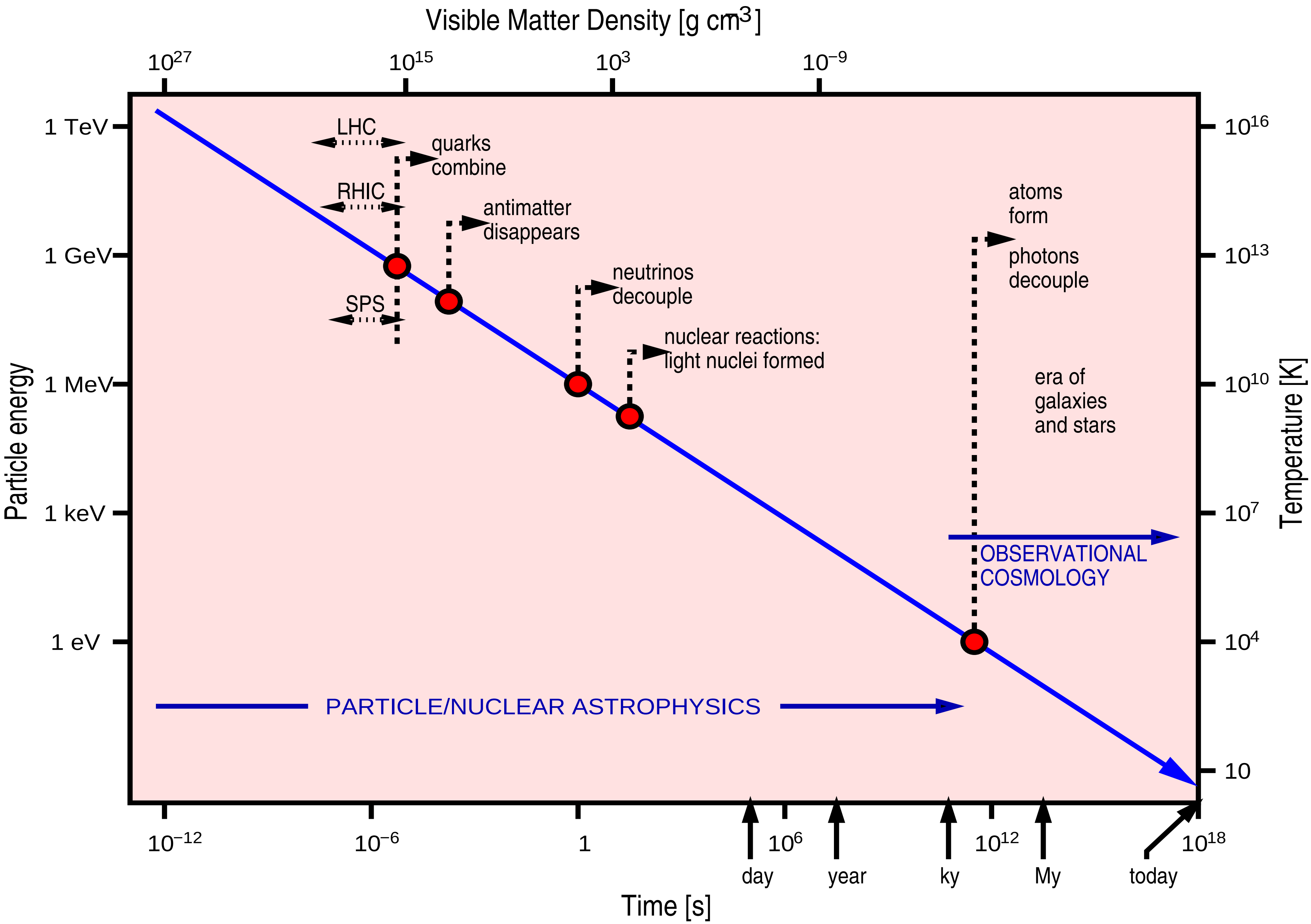


STAR at RHIC

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':

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

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

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

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

- Deep probes (diletpons and photons), weakly coupled probes of all history of collision, including the initial moments (!) – large background of decaying hadrons
- J/Ψ suppression: one measurement, ongoing and evolving interpretation
- Jet suppression: spectacular measurements, theoretical postdictions
- Dynamics of quark matter flow: demonstrates presence of collective quark matter dynamics

Strange and strongly interacting probes of 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):

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

(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 $\bar{d}$):

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

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.

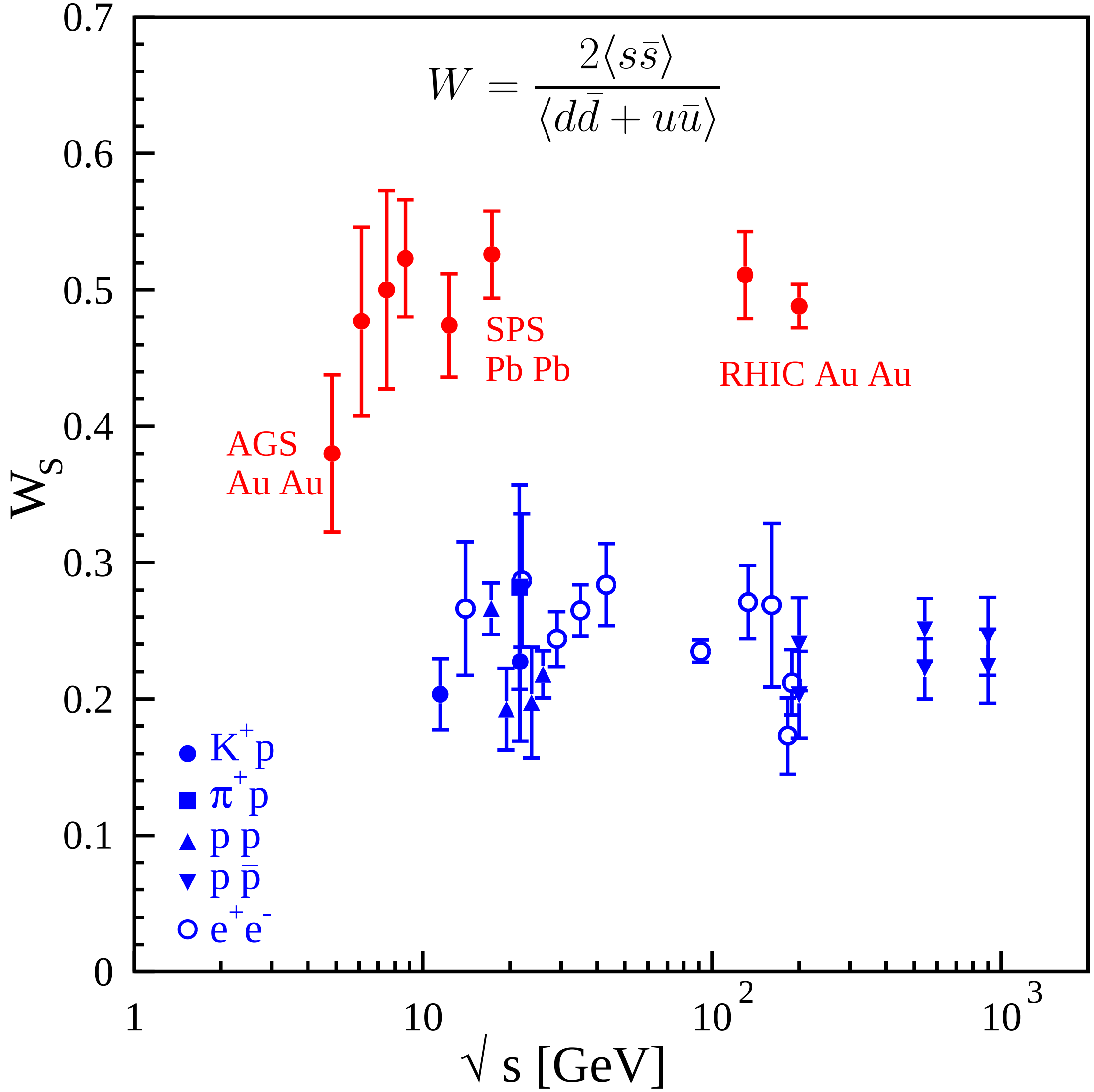
When the quark matter dissociates into hadrons, some of the numerous $\bar{s}$ may, instead of being bound in a $q\bar{s}$ Kaon, enter into a $(\bar{q}\bar{q}\bar{s})$ antibaryon and, in particular, a $\bar{\Lambda}$ or $\bar{\Sigma}^0$. The probability for this process seems to be comparable to the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

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.

MORE EFFECTIVE CONVERSION OF ENERGY INTO STRANGENESS

Wróblewski ratio: counting newly made s- and q-pairs:



Enhancement of strangeness pair production compared to light quarks due to onset of thermal glue fusion processes.

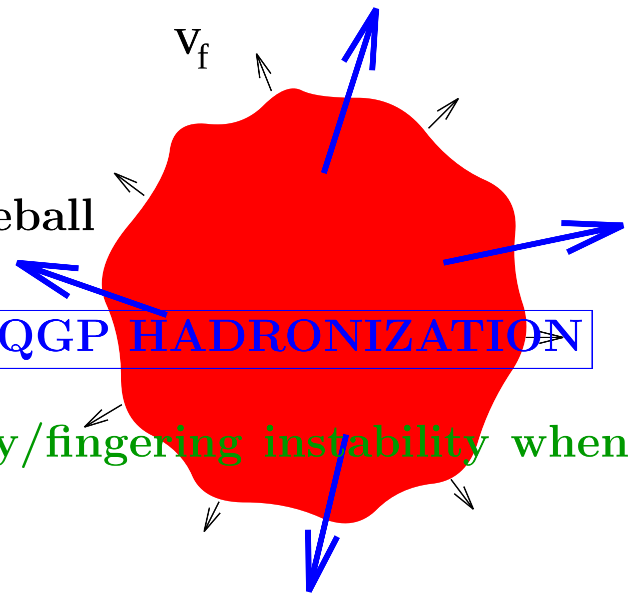
Key features: PREDICTED MATTER-ANTIMATTER SYMMETRY

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.

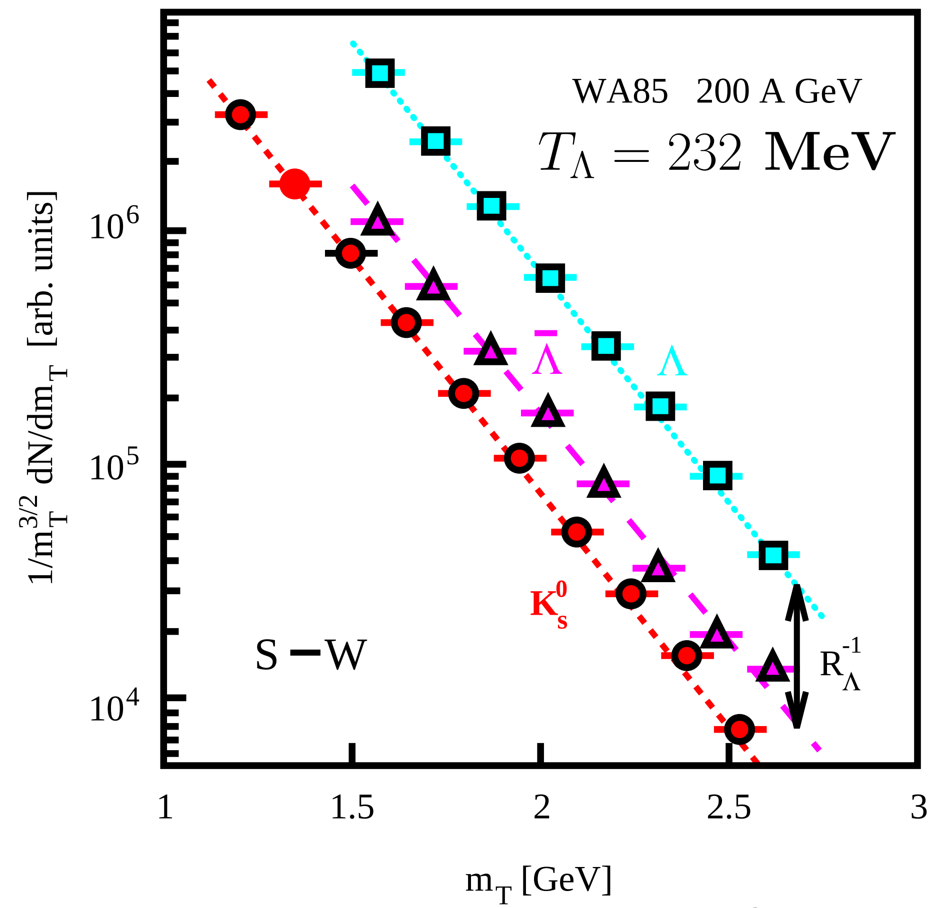
High $m_\perp$ slope universality

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

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

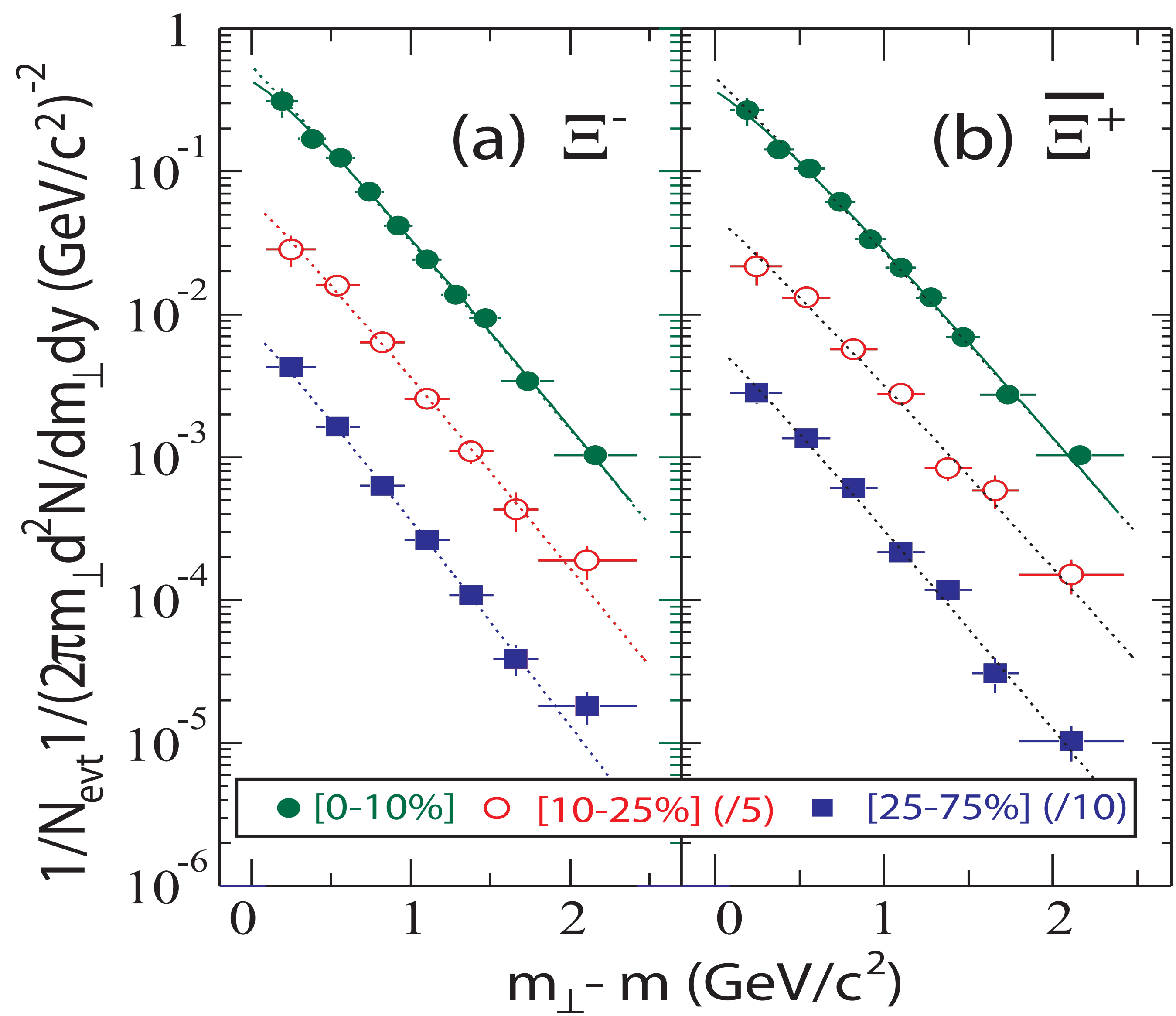
Why is the slope of different particles in same m_t range the same?

Analysis+Hypothesis 1991: QGP quarks coalescing in SUDDEN hadronization



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

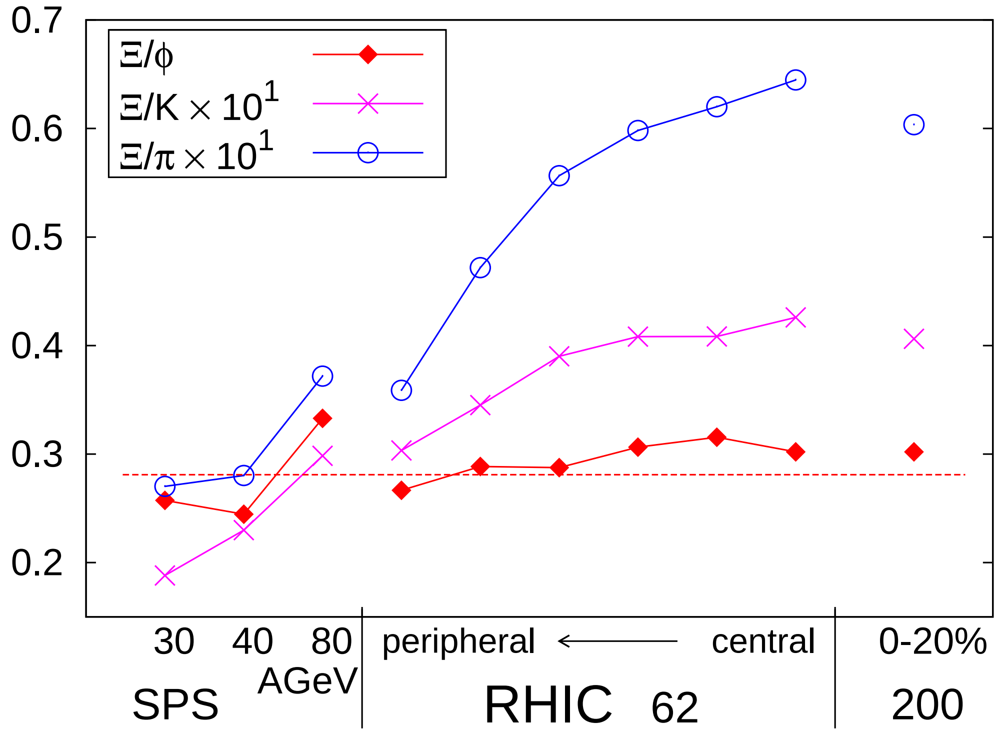
$\Xi^-, \overline{\Xi^-}$ Spectra RHIC-STAR 130+130 A GeV



+

KEy Features: growth of strangeness yield

$$\frac{\Xi}{\phi} \equiv \sqrt{\frac{\overline{\Xi}(\bar{s}\bar{s}\bar{d})^{+}\Xi(ssd)^{-}}{\phi(s\bar{s})\phi(s\bar{s})}} \simeq \gamma_q f(T) \simeq 0.277 \pm 10\%,$$



Key feature: New mechansim of strangeness production

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

dominant processes:

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

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

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

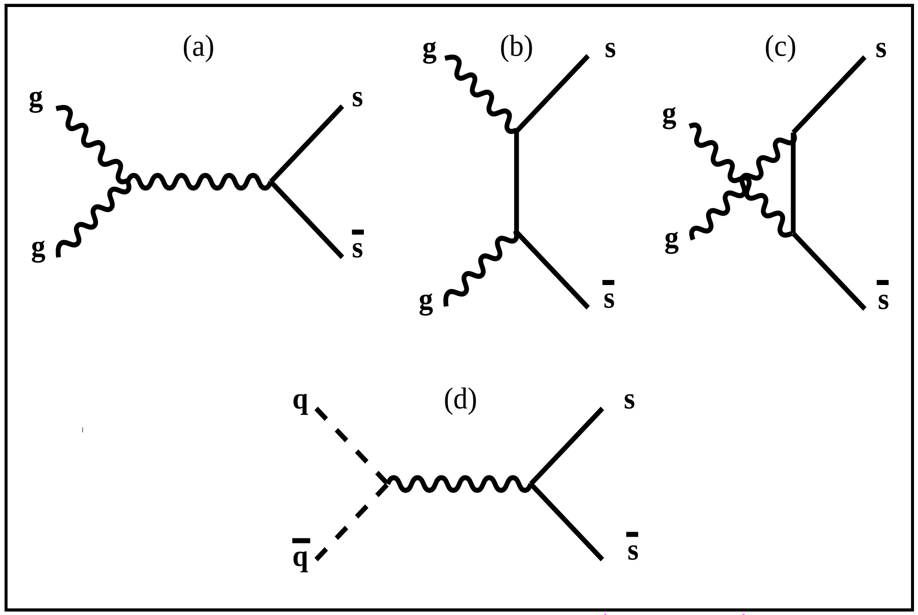
- **coincidence of scales:**

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

clock for QGP phase

strangeness chemical equilibration in QGP possible

- $\boxed{\bar{s} \simeq \bar{q}} \rightarrow$ **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:

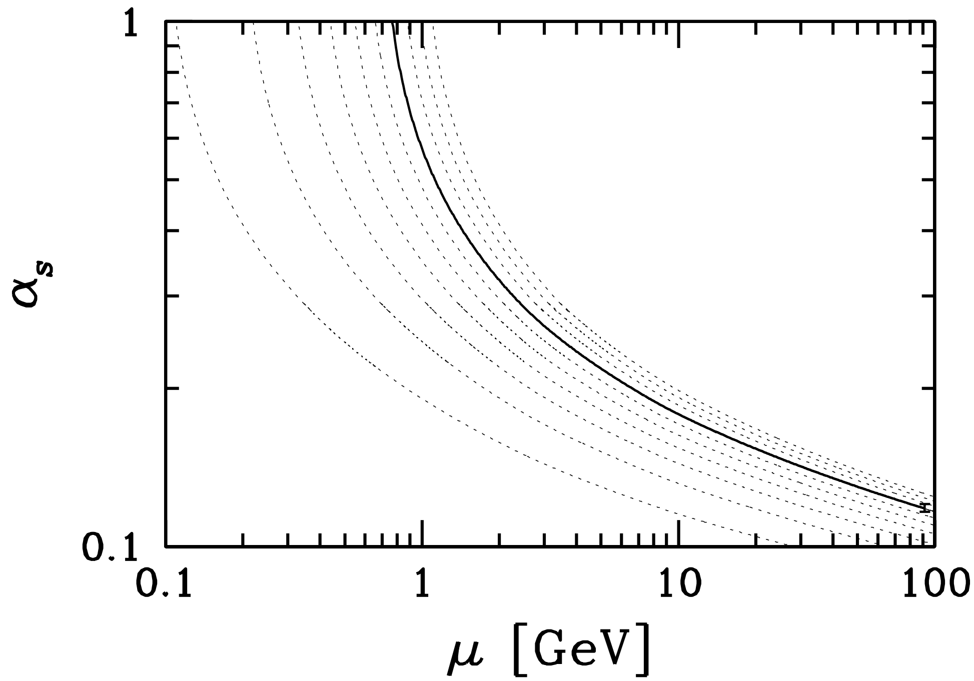
$$\bar{\sigma}_{gg\to s\bar{s}}(s)=\frac{2\pi\alpha_{\rm s}^2}{3s}\left[\left(1+\frac{4m_{\rm s}^2}{s}+\frac{m_{\rm s}^4}{s^2}\right)\tanh^{-1}W(s)-\left(\frac{7}{8}+\frac{31m_{\rm s}^2}{8s}\right)W(s)\right],$$

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

Infinite QCD resummation: running $\alpha_{\rm s}$ and $m_{\rm s}$ taken at the energy scale $\mu\equiv\sqrt{s}$.
USED: $m_s(M_Z)=90\pm20\%$ MeV $m_s(1\,\textbf{GeV})\simeq 2.1 m_s(M_Z)\simeq 200\,$**MeV.**

WHY PERTURBATIVE STRANGENESS WORKS

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 $\mu = M_Z$).

At the scale of just above 1 GeV where typically thermal strangeness production in RHIC QGP occurs, perturbative theory makes good sense but is not completely reliable. Had $\alpha_s(M_Z) > 0.125$ been measured 1996 than our perturbative strangeness production approach from 1982 would have been invalid.

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

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

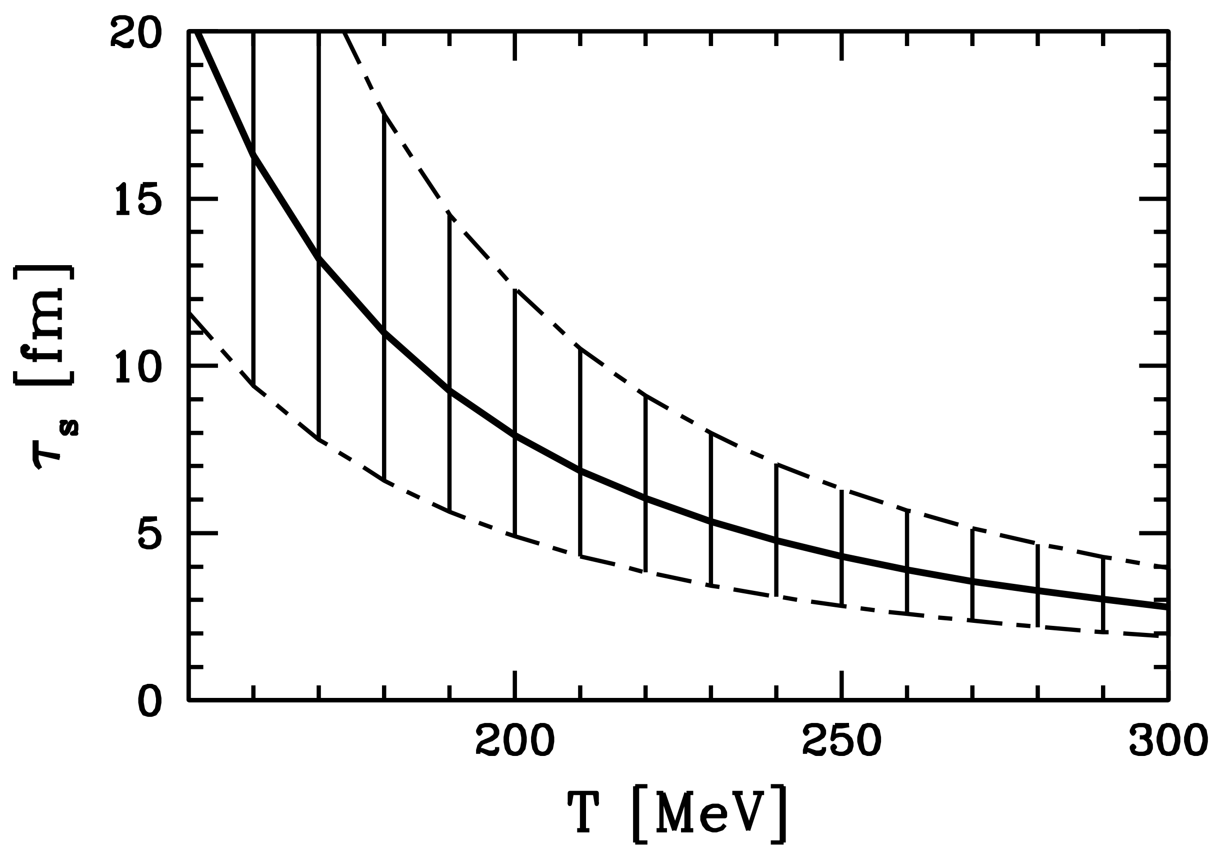
Strangeness relaxation to chemical equilibrium

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:

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

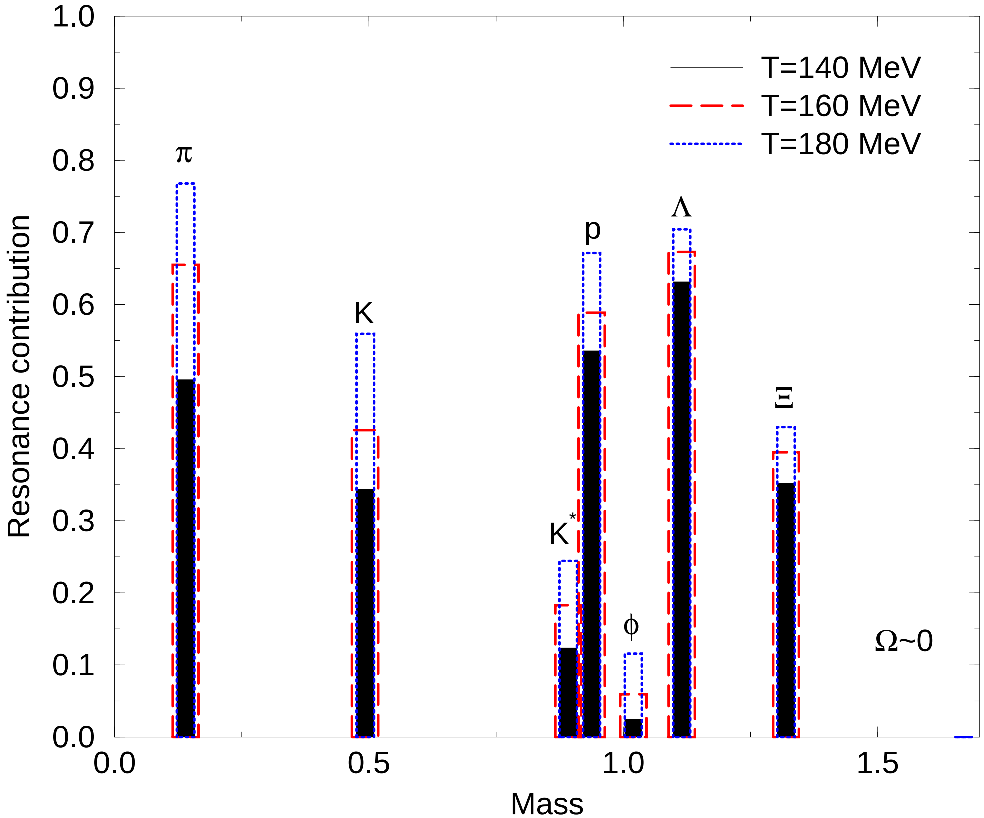


STATISTICAL HADRONIZATION

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:→

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

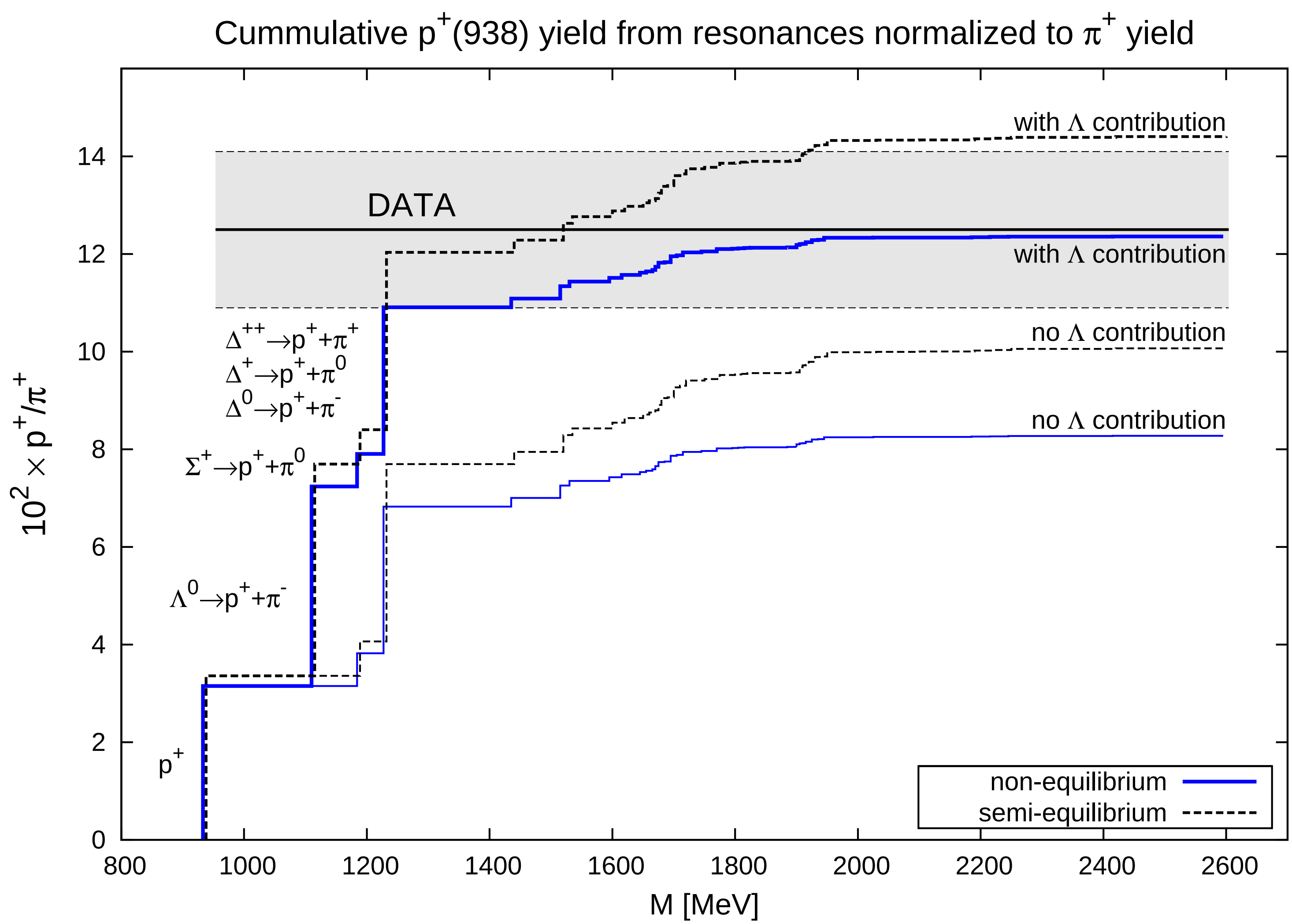
GT, W. Broniowski, W. Florkowski, J. Letessier, S. Steinke, JR nucl–th/0404083 Comp. Phys. Com. 167, 229 (2005)

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

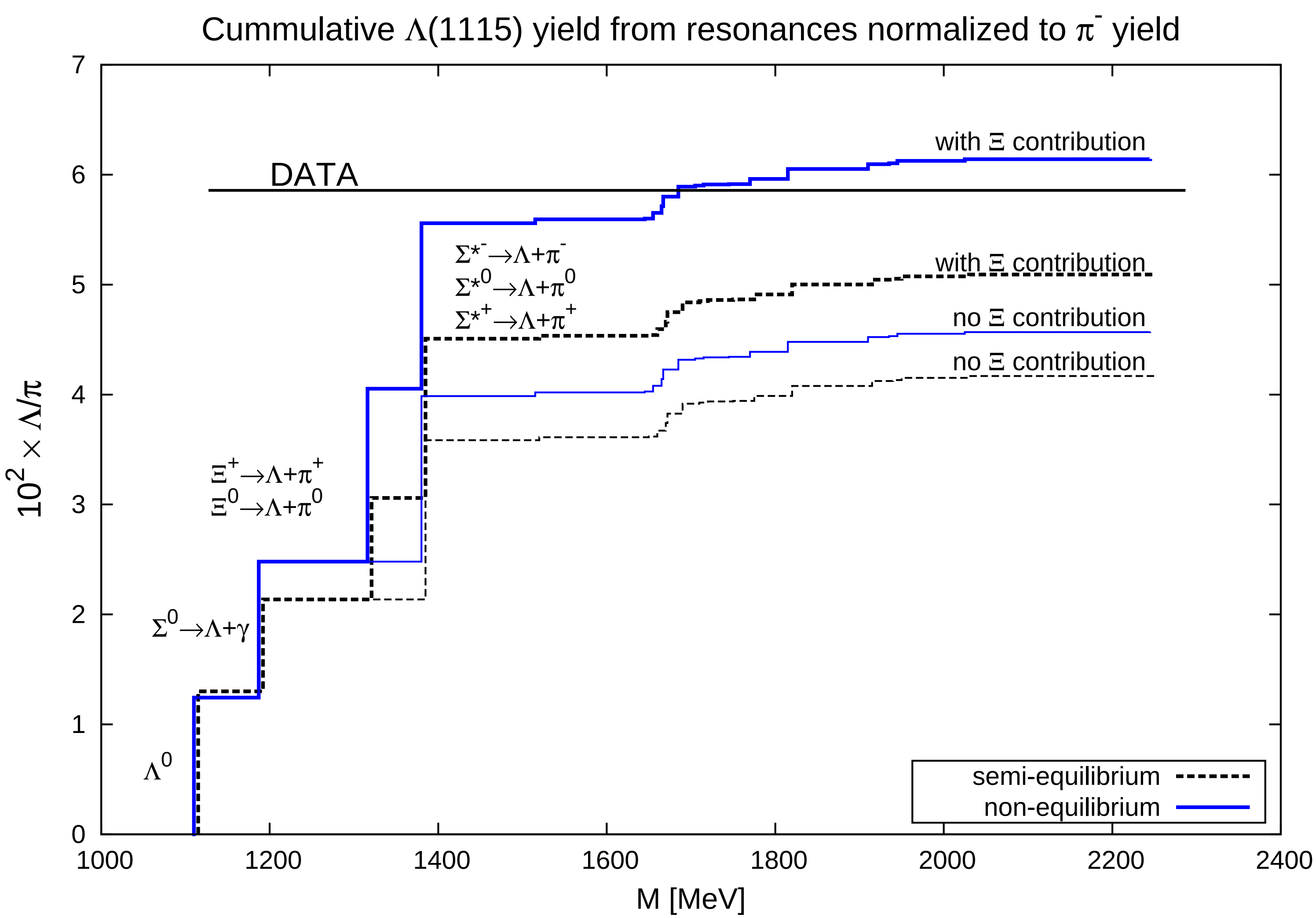
SHARE 2.1 in 2006

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.

Resonances and Weak Decays Create Final p/π^+ 62GeV Yield

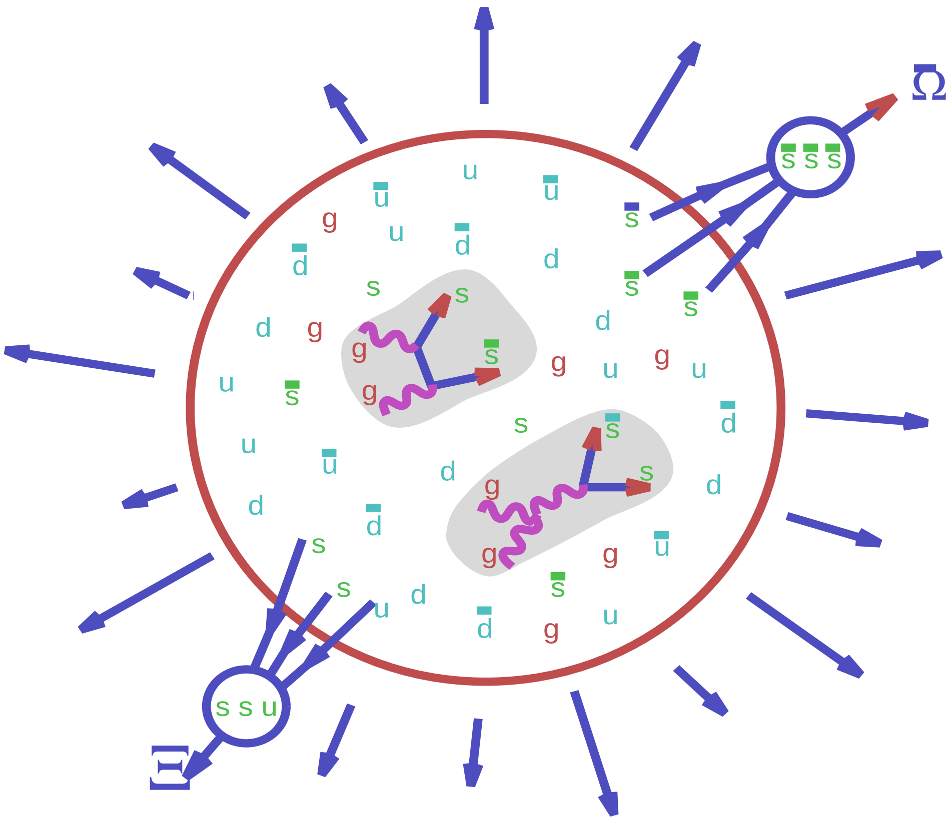


Resonances and Weak Decays Create Final Λ/π^- 62GeV Yield



SHM: recombinant quark hadronization

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.**

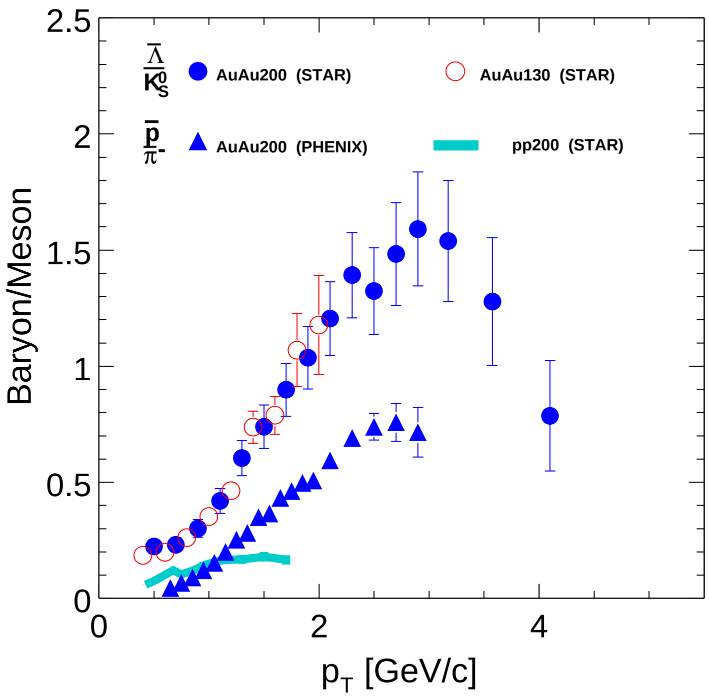


1. $GG \to s\bar{s}$ **(thermal gluons collide)**
$GG \to c\bar{c}$ **(initial parton collision)**
$GG \to b\bar{b}$ **(initial parton collision)**
gluon dominated reactions

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.**

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:**

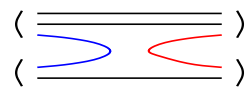
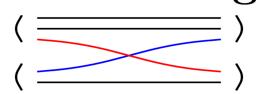
$$\frac{\overline{\Lambda}(\bar{u}\bar{d}\bar{s})}{\bar{p}(\bar{u}\bar{u}\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \qquad \frac{\mathrm{K}^+(u\bar{s})}{\pi^+(u\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \qquad \frac{\phi}{h} \propto \frac{\gamma_s^2}{\gamma_q^2}, \qquad \frac{\Omega(sss)}{\Lambda(sud)}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

WHAT IS THIS γ ?

FERMI MODEL — QUARK CHEMISTRY

If QGP near/at chemical equilibrium prior to SUDDEN hadronization we must expect that a different phase, the hadron matter, will be in ABSOLUTE chemical non-equilibrium.

In general: FOUR QUARKS: $s, \bar{s}, q, \bar{q} \rightarrow$ **FOUR CHEMICAL PARAMETERS**

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

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:

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

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:

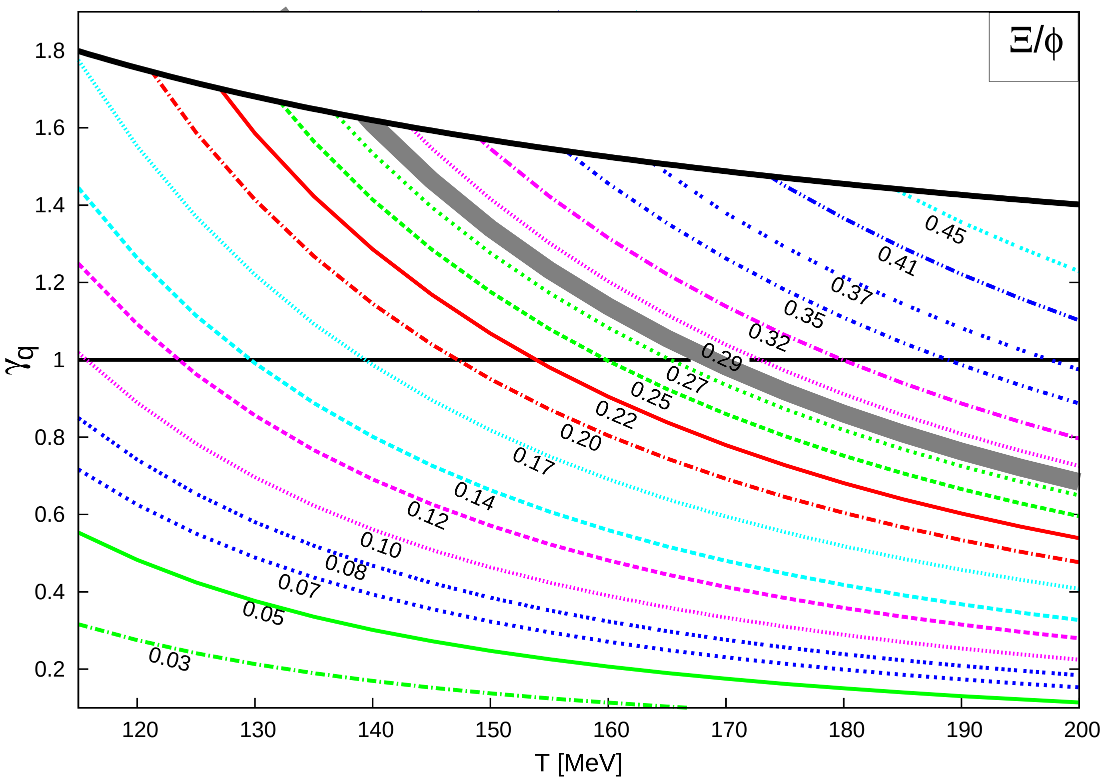
$$\begin{aligned} dE + P\,dV - T\,dS &= \sigma_N\,dN + \sigma_{\overline{N}}\,d\overline{N} \\ &= \mu_b(dN - d\overline{N}) + T \ln \gamma_N (dN + d\overline{N}). \end{aligned}$$

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.**

Multistrange Hadrons

We consider the ratio

$$\frac{\Xi}{\phi} \equiv \sqrt{\frac{\overline{\Xi}(\bar{s}\bar{s}\bar{d})^{+}\Xi(ssd)^{-}}{\phi(s\bar{s})\phi(s\bar{s})}} \simeq \gamma_q f(T) \simeq 0.277 \pm 10\%,$$



SINCE

- **By taking the product of particle and antiparticle, we eliminate baryo-chemical potential μ_B as well as strange chemical potential μ_S.**
- **We also eliminate the strange quark phase space occupancy γ_s, because the strange and anti-strange quark content in the numerator and denominator is the same.**
- **The overall normalization V is eliminated by the fact that we have the same number of hadrons in the ratio numerator and denominator.**

All world data (SPS,RHIC) yield same constraint between γ_q and T.

- **$T \simeq 140$ MeV, $\gamma_q \simeq 1.6$ (Chemical Nonequilibrium Model) and**
- **$T \simeq 170$ MeV and $\gamma_q = 1$ (Chemical Equilibrium Model).**

Large $T > 170$-option disfavored.

Measure of s-enhancement at RHIC and LHC: Strangeness / Entropy

s/S: ratio of the number 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: $\gamma_s^{\rm Q} \to 1$

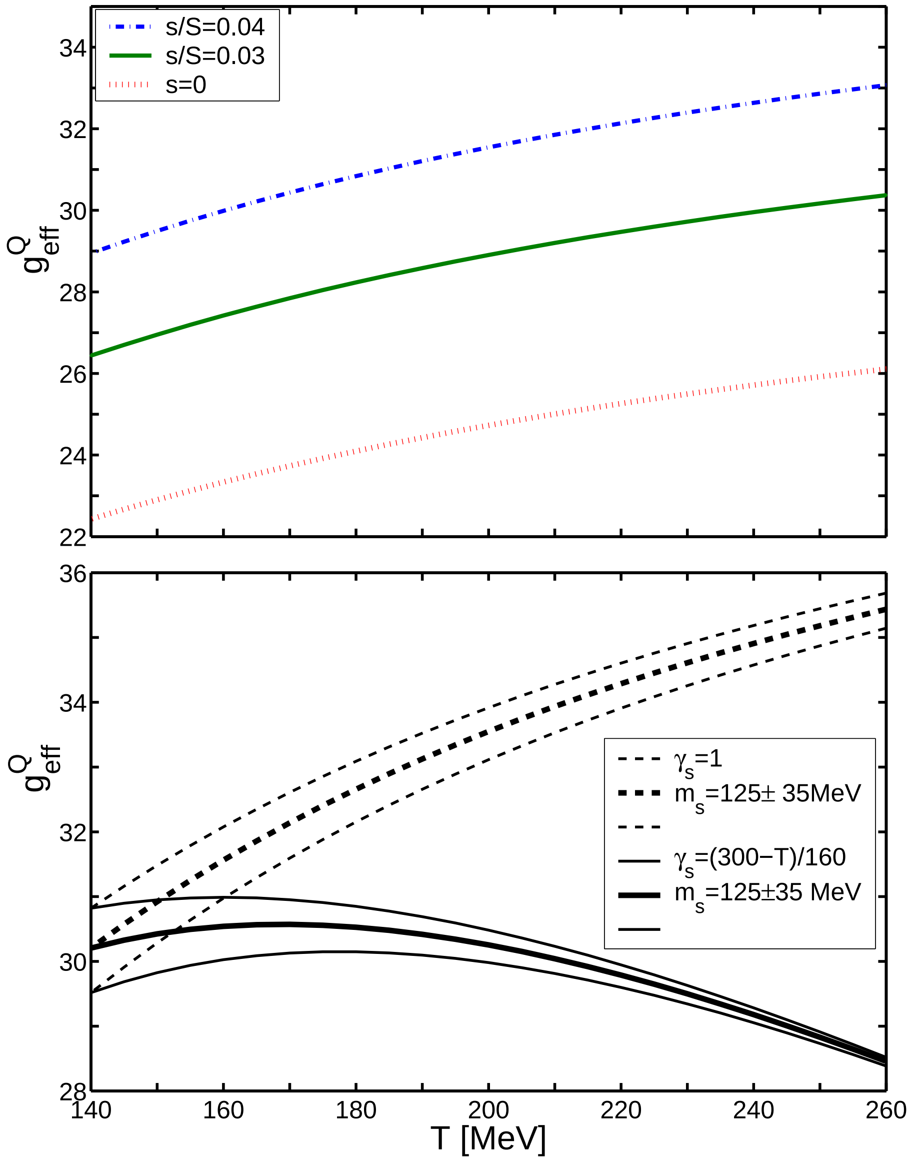
Chemical non-equilibrium occupancy of strangeness $\gamma_s^{\rm Q}$

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

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:

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

How much entropy is in QGP – how many degrees of freedom $g^Q_{\rm eff}$?



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

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

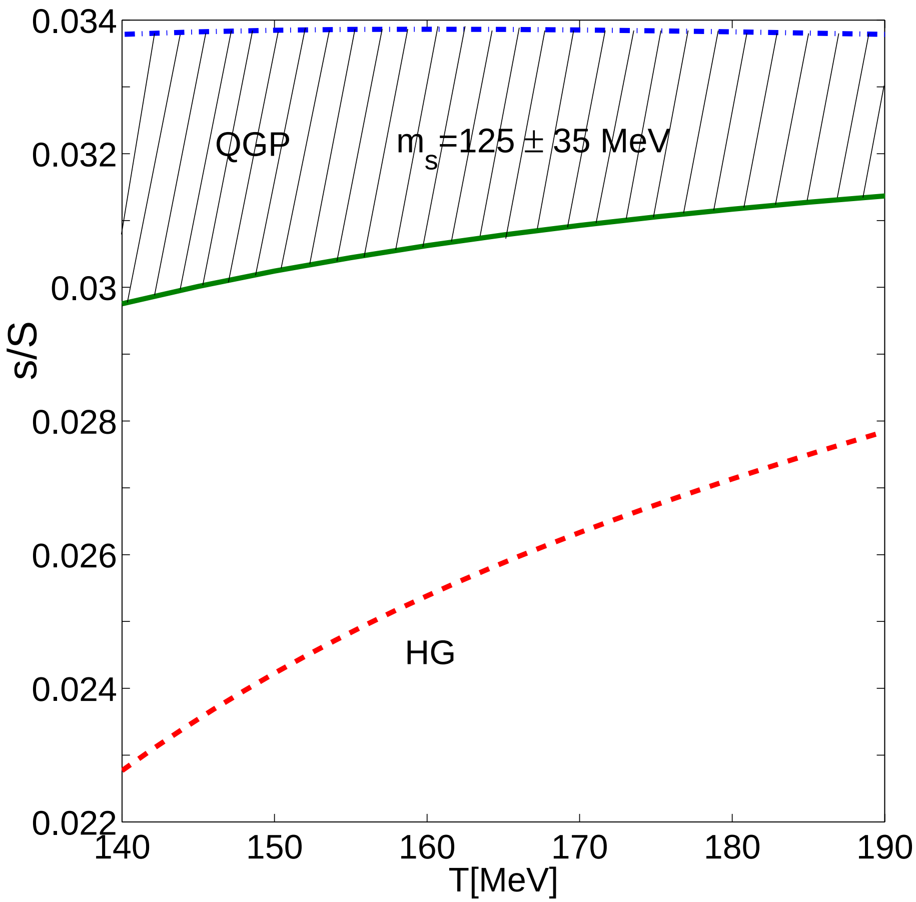
$$g^Q_{\rm eff}(T) = g_g(T) + \frac{7}{4} g_q(T) + 2g_s \frac{90}{\pi^4} + \frac{\mathcal{A}^{\rm pert}}{T^4}\frac{90}{4\pi^2}.$$

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
$\gamma_s = (300 - T)/160$

s/S QGP and HG comparison in chem. equilibrium

We compare deconfined quark-gluon plasma with hadron gas at a common measured T. This is a phase enhancement of strangeness needed to understand hadronization, not an experimental enhancement.



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

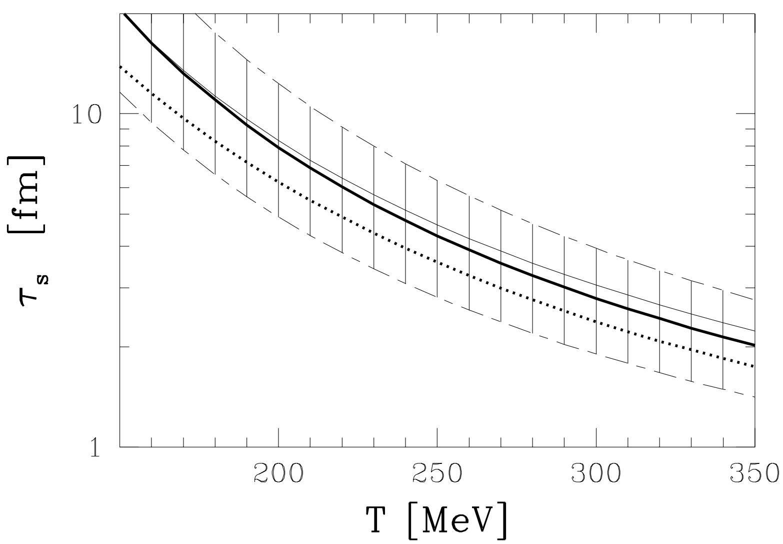
Time evolution of $s^{\rm Q}/S^{\rm Q}$, $\gamma_s^{\rm Q}$ (*drop henceforth superscript Q*)

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

Kinetic equations for time evolution of s/S and γ_s

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

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



pQCD invariant production rate A:

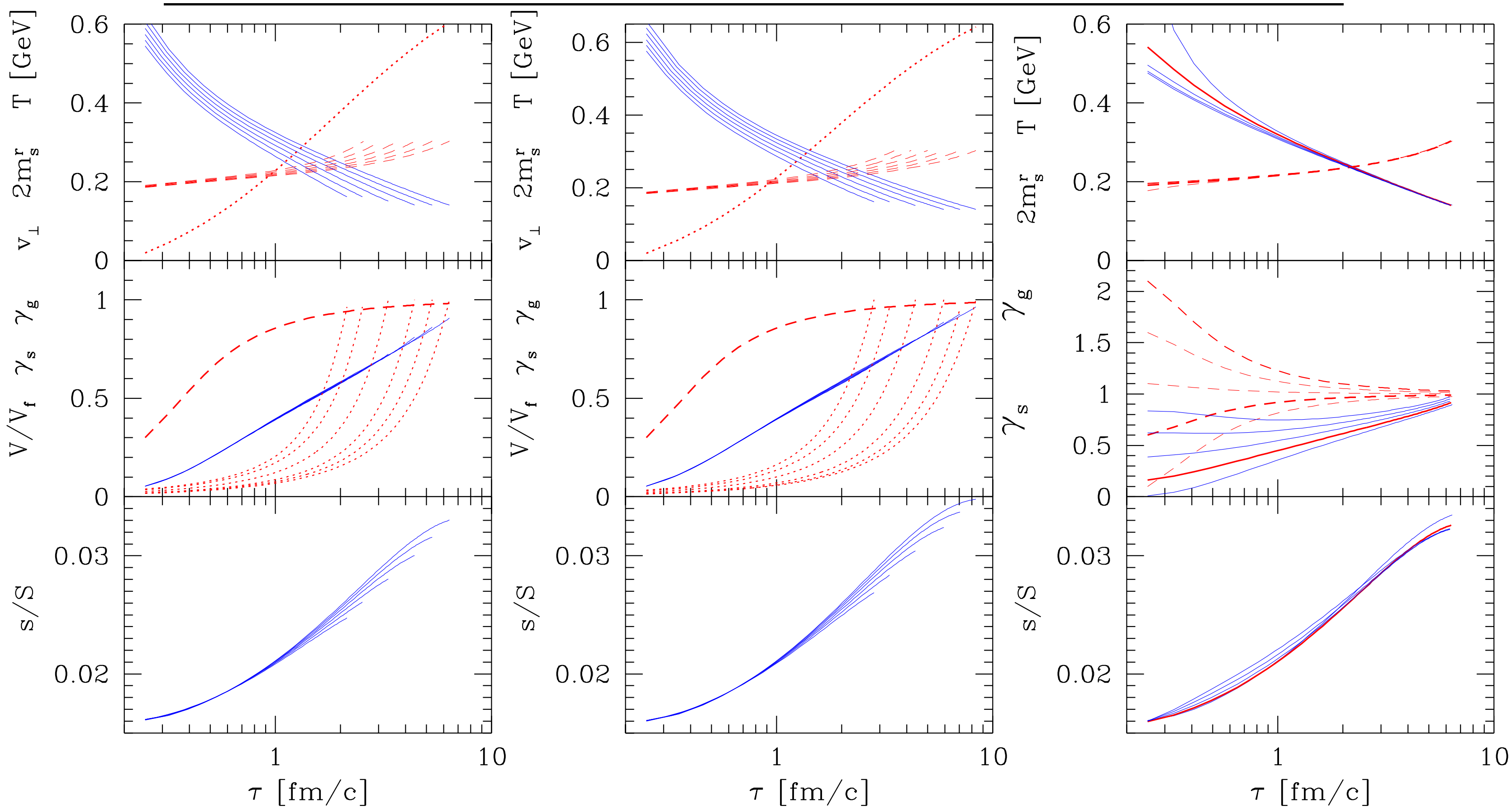
$$A^{12\to 34} \equiv \frac{1}{1+\delta_{1,2}} \rho_1^\infty \rho_2^\infty \langle \sigma_s v_{12} \rangle_T^{12\to 34}.$$

and the related characteristic time constant τ_s:

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

To integrate the equation for s/S we need to understand $T(\tau)$. Hydrodynamic expansion with Bjørken scaling motivates simple model assumptions.

s/S and γ_s at RHIC: centrality & initial state dependence

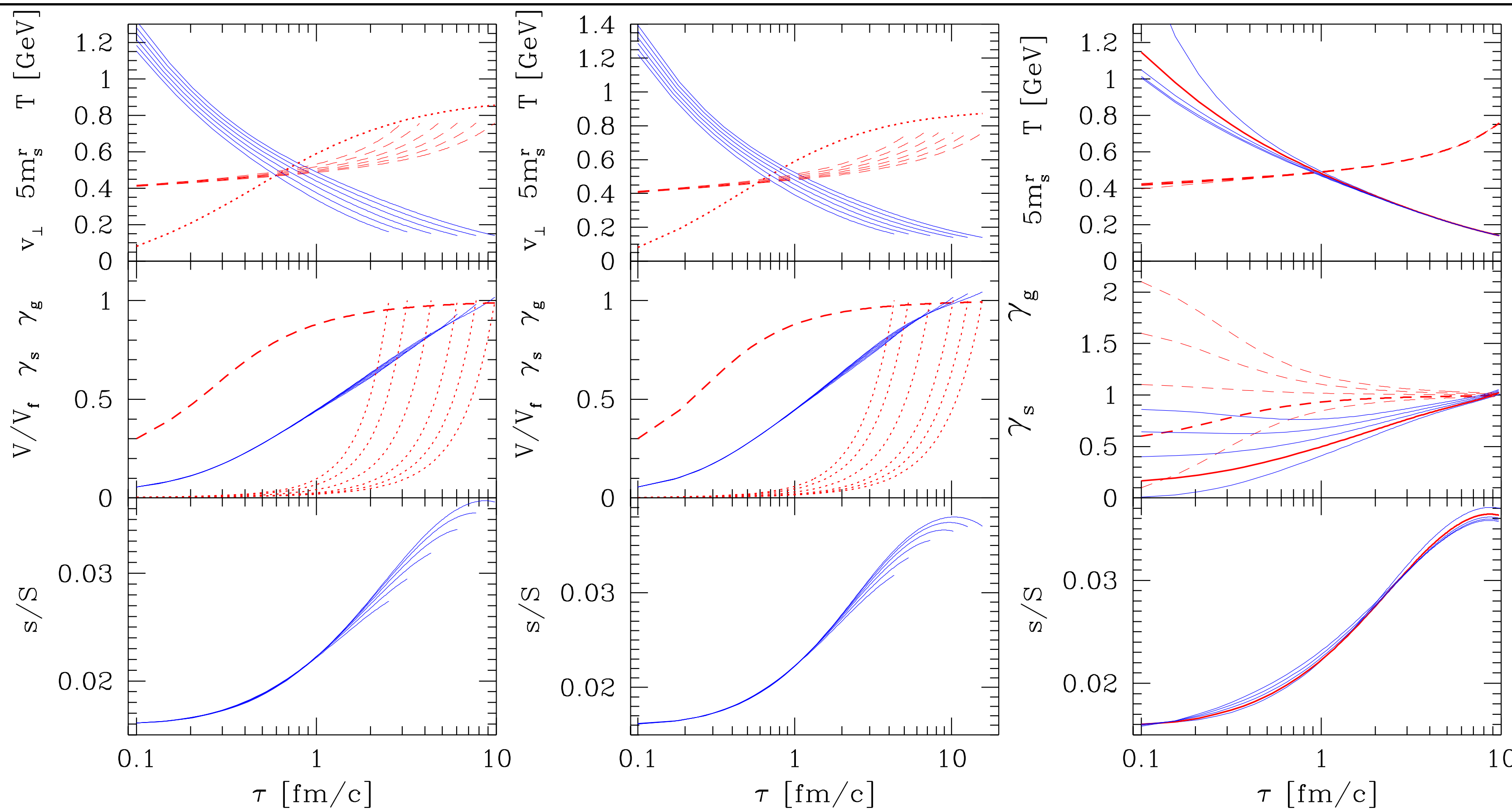


The two left panels: **Comparison of the two transverse expansion models, bulk expansion (left), and wedge expansion. Different lines correspond to different centralities. On right: study of the influence of the initial density of partons.**

Top: T, middle γ_s and bottom s/S

Assumptions:
dotted top panel: profile of $v_\perp(\tau)$, the transverse expansion velocity; middle panel: dashed $\gamma_g(\tau)$,(which determines slower equilibrating γ_q dotted: normalized $dV/dy(\tau)$ normalized by the freeze-out value.

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



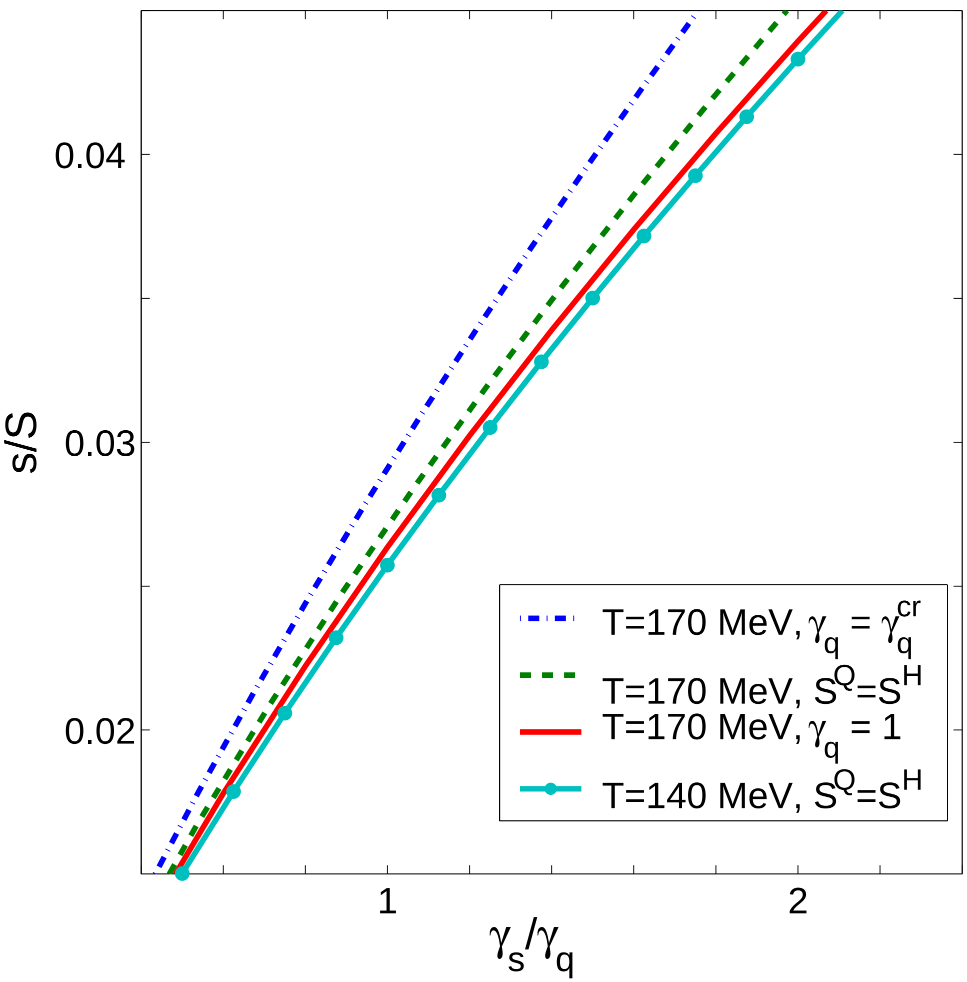
LHC differences to RHIC

- **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.

STRANGENESS ENHANCEMENT CONSEQUENCE

Hadronizing QGP leads to chemical nonequilibrium HG phase space.



Strangeness to entropy ratio s/S at $\lambda_q = \lambda_s = 1$, as function of γ_s^H/γ_q^H, the final state hadron occupancy in chemically NON-equilibrated HG. Strangeness excess in QGP leads to over-occupancy observable in particle yield analysis.

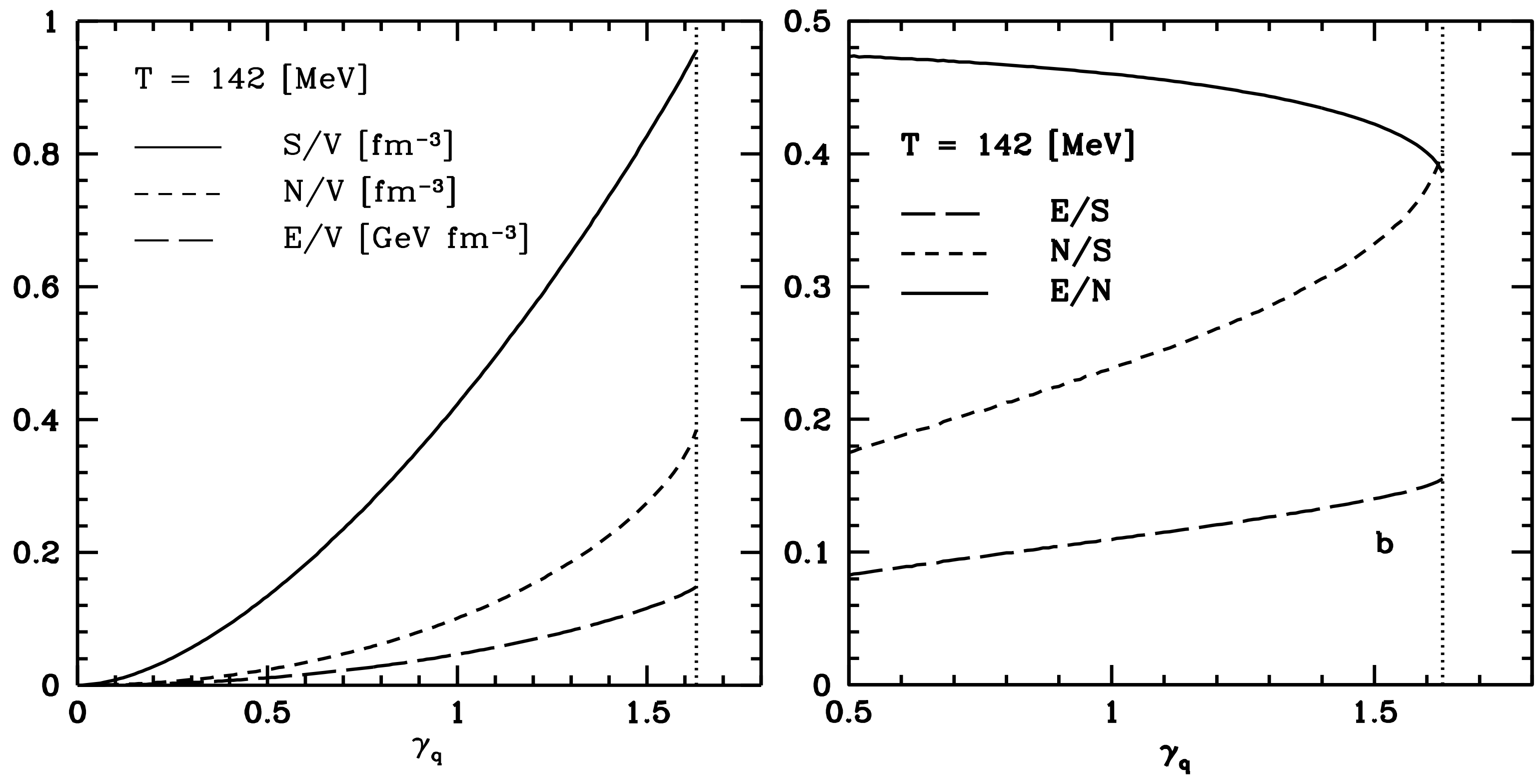
ENTROPY ENHANCEMENT CONSEQUENCE: $\gamma_q^{\rm H} > 1$ at breakup

To maximize entropy density in hadron phase space at hadronization $\gamma_q^2 \to e^{m_\pi/T}$:

Example:maximization of entropy density in pion gas $E_\pi = \sqrt{m_\pi^2 + p^2}$

$$S_{\rm B,F} = \int \frac{d^3p\, d^3x}{(2\pi\hbar)^3} \left[\pm(1\pm f)\ln(1\pm f) - f\ln f\right], \qquad f_\pi(E) = \frac{1}{\gamma_q^{-2} e^{E_\pi/T} - 1}.$$

Pion gas properties:
N-particle,
E-energy,
S-entropy,
V-volume
as function of γ_q.



WHAT THAT MEANS FOR LHC HADRONIZATION

For computation of soft hadron production at LHC we need:

1) the entropy content: $dS/dy \equiv$ multiplicity,

not (yet) predictable, use extrapolation.

2) strangeness content ds/dy and/or s/S

strangeness computable within pQCD given entropy

3) charm, bottom content dc/dy, db/dy

computable with considerable uncertainty within pQCD

4) nett baryon stopping $\frac{d(b-\bar{b})}{dy}$, $\frac{b-\bar{b}}{b+\bar{b}} \simeq 0$

unknown, very difficult to measure, not relevant

Other Constraints and Inputs

a) Flavor balance $\langle s \rangle = \langle \bar{s} \rangle$ and c, b at any rapidity

b) Net charge per net baryon ratio $Q/b = 0.4$

c1) $T = 140$ for hadronization at fixed V, T (Chemical non-equilibrium approach) and

c2) $T = 162$ for final hadron chemical equilibrium requiring re-heating/inflation (change in V, T).

Conclusions

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

- **At SPS and RHIC: 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.**

- **At RHIC: clear evidence for quark coalescence, Early thermalization and strange quark participation in matter flow.**

- **Strangeness yield and density enhancement – steady rise of s/S with energy and centrality and great enhancement of multistrange hadrons**