

THERMAL STRANGENESS PRODUCTION AND STRANGE RESONANCES

Shanghai, August 19, 2004

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STRANGENESS s AND ENTROPY S
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Johann Rafelski
Department of Physics
University of Arizona
TUCSON, AZ, USA

What is QGP, and how we go about to find it

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 finite size systems always a 'transformation', not a sharp boundary.

What we need as background knowledge:

- 1) QGP equilibrium properties from QCD-lattice,
- 2) Understanding how to adapt these to the environment of heavy ion reactions,
- 3) Model of QGP hadronization into final particles,
- 4) Sensitive signatures of deconfinement: final particles always hadrons.

NOT A SINGLE SMOKING GUN type observation, NOT a 'new' particle.

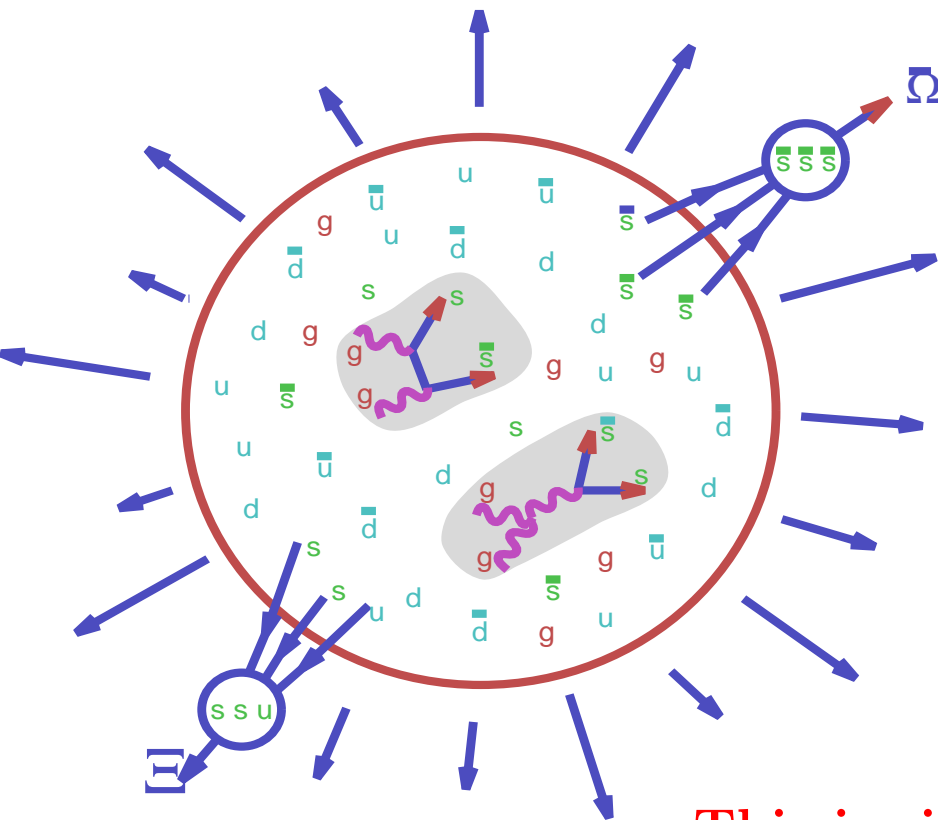
We need to pursue global, systematic and physics-consistent understanding of all experimental results. Where we are not able (yet) to evaluate results in detail, at least in principle interpretation should be available.

When reaching a consensus about discoveries, we are also remembering the difference between: **verified predictions**, accompanied by expected global behavior, and **inventive/clever often negative post-dictions**, limited in scope to punctual experimental data interpretation.

QGP is FULL OF STRANGENESS AND ENTROPY

Observables: STRANGENESS s AND ENTROPY S

Stable matter is made of only up and down quarks, strange flavor is always almost all newly made.



In the QGP hadrons are dissolved into an entropy rich partonic liquid. TWO STEP MECHANISM of (strange) hadron formation from QGP:

1. $GG \rightarrow s\bar{s}$ in QG-plasma
2. hadronization of pre-formed s, \bar{s} quarks

Excess of strangeness and even more of complex rarely produced multi strange (anti)particles from QGP **enabled by coalescence** between s, \bar{s} quarks made earlier in QCD based microscopic reactions.

This is signature of quark mobility in the source.

Experimental observable: **Enhanced production of strange anti-baryons**, progresses strongly with strangeness content of the particle, increases gradually with reaction volume and energy. First seen at SPS at CERN by WA97, recent work by NA57, NA49, and STAR at RHIC collaborations. Predictions developed in detail 1981–1991 prior to experimental results.

Why Strangeness is a diagnostic tool

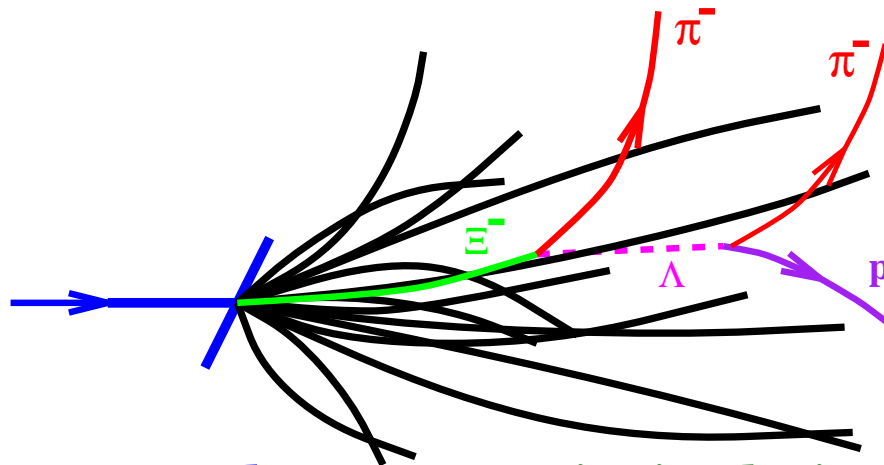
EXPERIMENTAL REASONS

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

$$\phi(s\bar{s}), \quad K(q\bar{s}), \quad \bar{K}(\bar{q}s), \quad \Lambda(qqs), \quad \bar{\Lambda}(\bar{q}\bar{q}\bar{s}),$$

$$\Xi(qss), \quad \bar{\Xi}(\bar{q}\bar{s}\bar{s}), \quad \Omega(sss), \quad \bar{\Omega}(\bar{s}\bar{s}\bar{s}) \quad \dots \text{resonances} \dots$$

- 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; (strong interaction reaction cross sections)

THEORETICAL CONSIDERATIONS

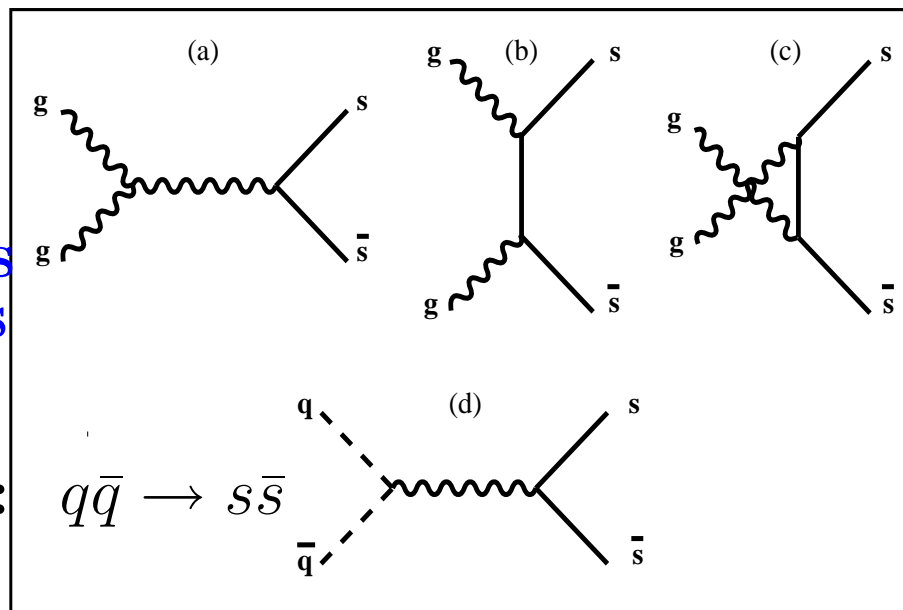
- production of strangeness in gluon fusion $GG \rightarrow s\bar{s}$
strangeness linked to gluons from QGP;

dominant processes:

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

abundant strangeness
=evidence for gluons

10–15% of total rate:



- coincidence of scales:

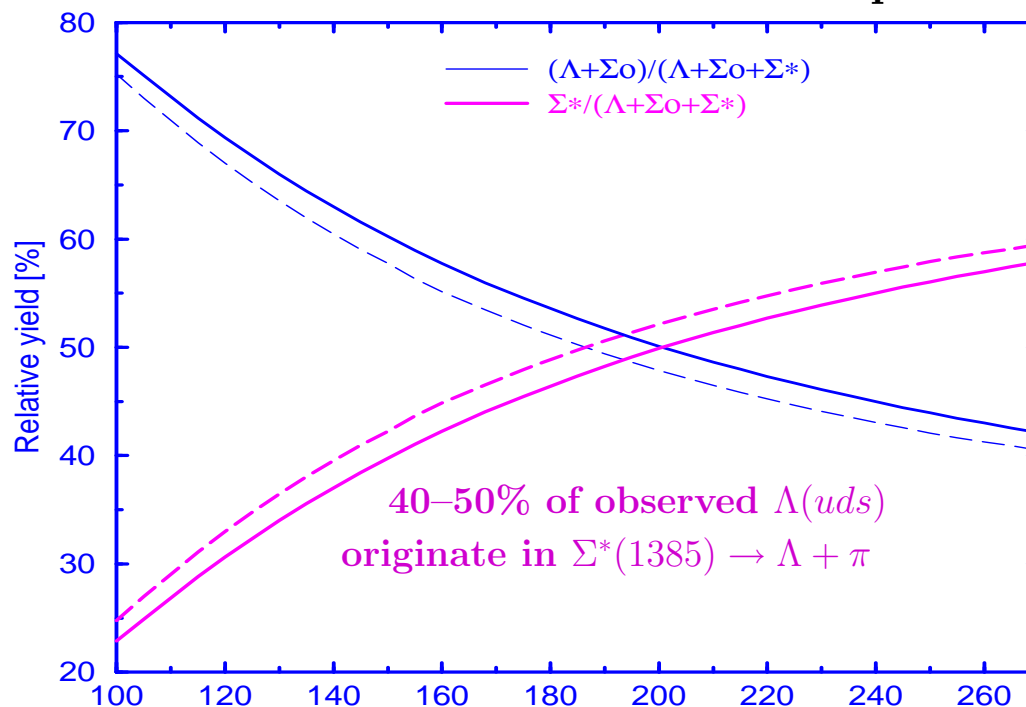
$$m_s \simeq T_c \rightarrow \tau_s \simeq \tau_{\text{QGP}} \rightarrow$$

strangeness a clock for QGP phase

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

II: Strange hadron resonances: A PROBE OF hadronization dynamics

direct experimental measurement!

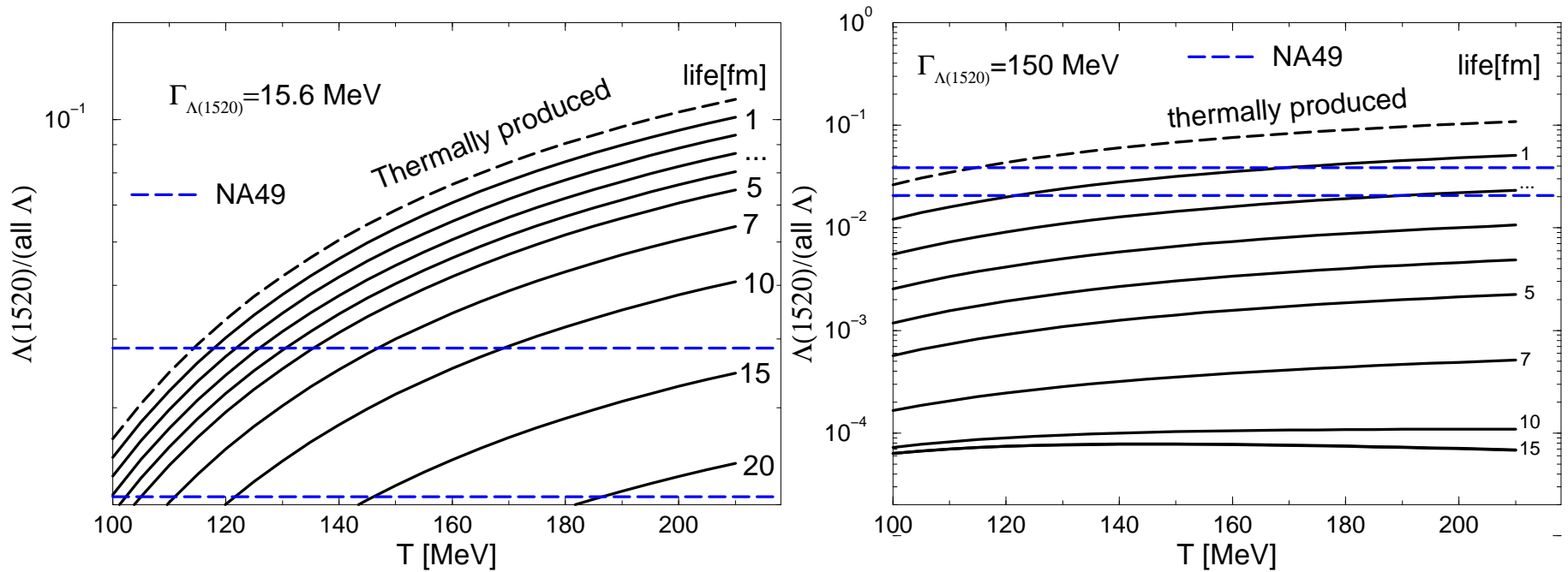


$\Sigma^*(1385) \rightarrow \Lambda + \pi$ decay width of $\Gamma_{\Sigma^*} = 35 \text{ MeV} = 1/(5.6 \text{ fm})$ assures that some decays occur within, and some outside the hadron matter – large fraction of decays within matter would be unreconstructable due to scattering of decay products. Same is true for observed $\Gamma_{K^*(892)} = 50 \text{ MeV} = 1/(4 \text{ fm})$.

Measured yields of $\Sigma^*(1385)$, $K^*(892)$ are IN GENERAL NOT the chemical freeze-out yields. Reduction by factor 2 for K^* probable.

Other candidates for study $\Gamma_{\Lambda(1520)} = 15.6 \text{ MeV} = 1/(12.6 \text{ fm})$. **Complication:** QUENCHING, metastable resonances such as $\Lambda(1520)$ may disappear.

Yields as function of t and T

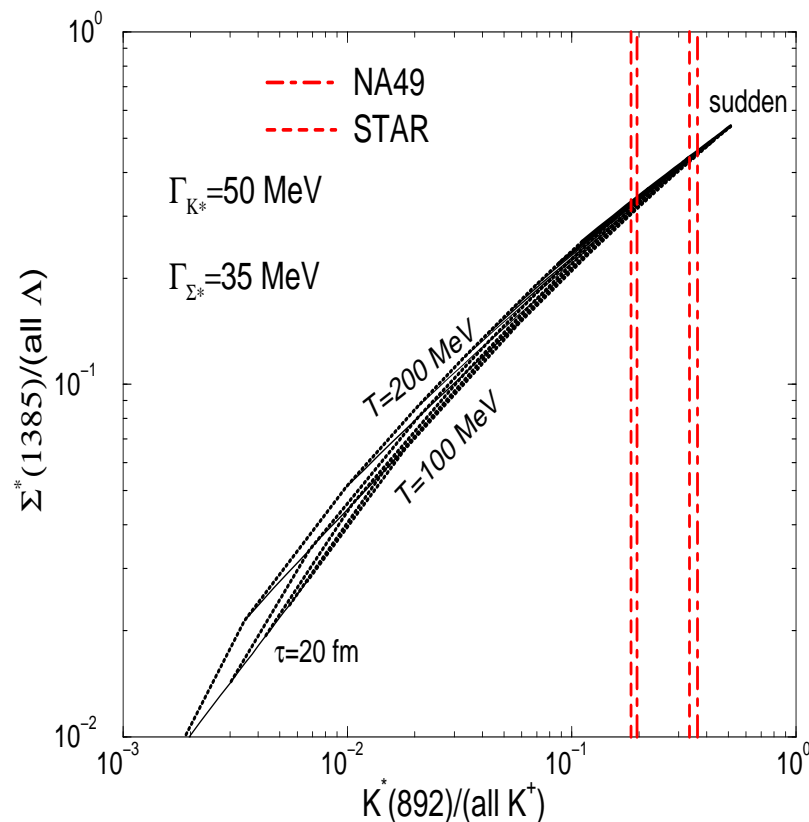
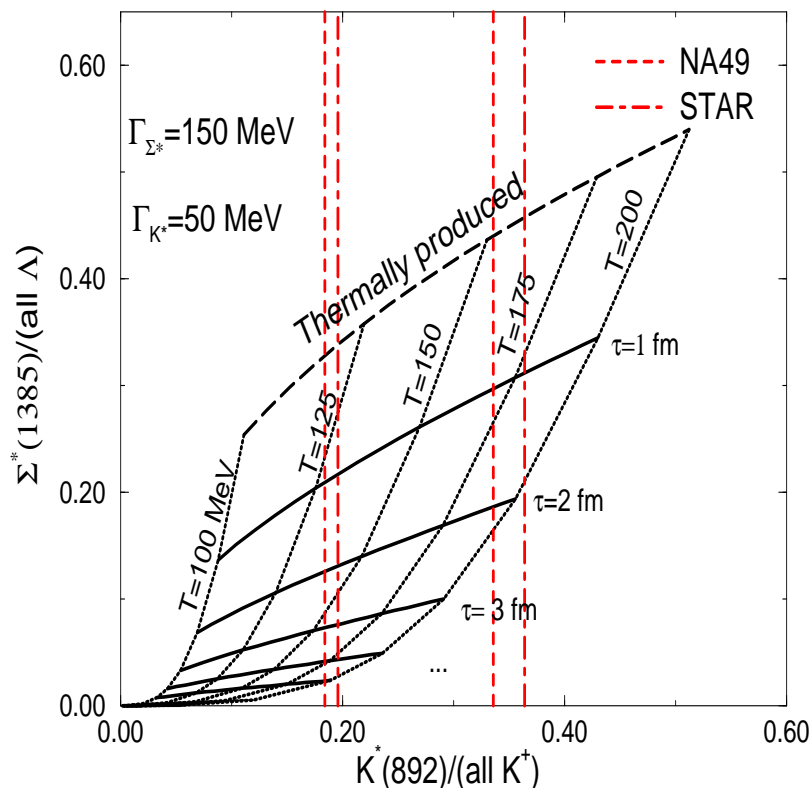


Relative $\Lambda(1520)/(\text{all } \Lambda)$ yield as function of freeze-out temperature T . Dashed - thermal yield, solid lines: observable yield for evolution lasting the time shown (1....20 fm) in an opaque medium.

LEFT: natural $\Gamma_{\Lambda(1520)} = 15.6 \text{ MeV}$, **RIGHT:** quenched $\Gamma_{\Lambda(1520)}^* = 150 \text{ MeV}$. **NA49 measures** in $pp \simeq 0.11 \pm 0.02$, in $Pb-Pb \simeq 0.025 \pm 0.008$ (horizontal lines).

HOW TO FIX value of Γ^* ?

Evaluate TWO resonances; EXAMPLE



Dependence of the combined $\Sigma^*/(\text{all } \Lambda)$ with $K^*(892)/(\text{all } K)$ signals on the chemical freeze-out temperature and HG phase lifetime.

LEFT: quenched $\Gamma_{\Sigma^*} = 150$

RIGHT natural widths

J.R., J. Letessier and G. Torrieri, Phys. Rev. C64, 054907 (2001) and C65, 069902(E) (2002).

III: Sudden Hadronization

Since 1982 we assumed sudden breakup of QGP into hadrons and thus preservation of hadronic signatures of deconfinement. Other workers explored a range of alternate models, and there were speculations that there would be an extremely long lived transformation stage. **HOW CAN ONE DECIDE THIS EXPERIMENTALLY??**

Experiments since 1991 (WA85, WA97) see identical shape of m_{\perp} spectra of strange baryons and antibaryons, obtained in central reactions at CM rapidity, also observed by NA49, and very precisely at RHIC.

Interpretation: **Common matter-antimatter formation mechanism, little reannihilation in sequel evolution.**

Appears to be **DIRECT** emission by a quark source into vacuum. Fast hadronization confirmed today by HBT particle correlation analysis, which yields a nearly energy independent size of hadron fireball with short lifespan of pion production.

High m_{\perp} slope universality

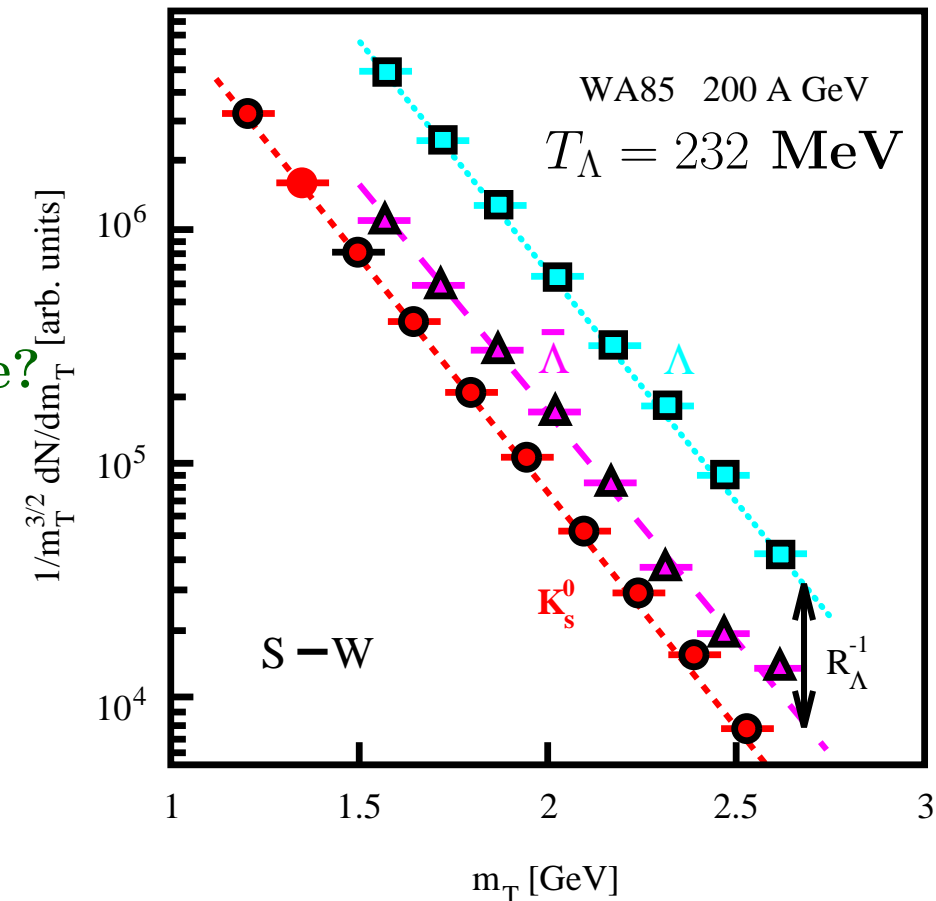
Discovered in S-induced collisions, pronounced in Pb-Pb Interactions.

Why is the slope of baryons and antibaryons in baryon-rich environment precisely the same?

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

Analysis+our hypothesis 1991:
QGP quarks coalescing in
SUDDEN hadronization

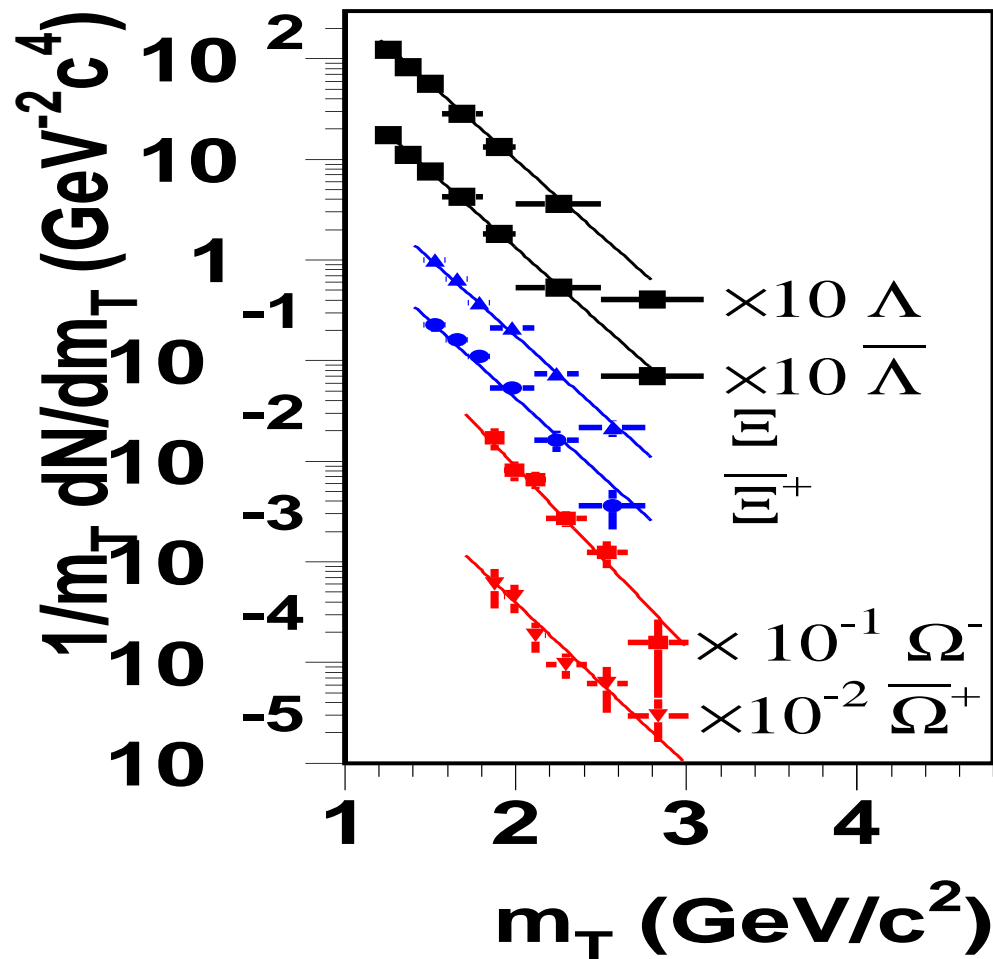
This allowed the study of ratios of particles measured only in a fraction of phase space



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

Λ within 1% of $\bar{\Lambda}$

Kaon – hyperon difference: **EXPLOSIVE FLOW** effect

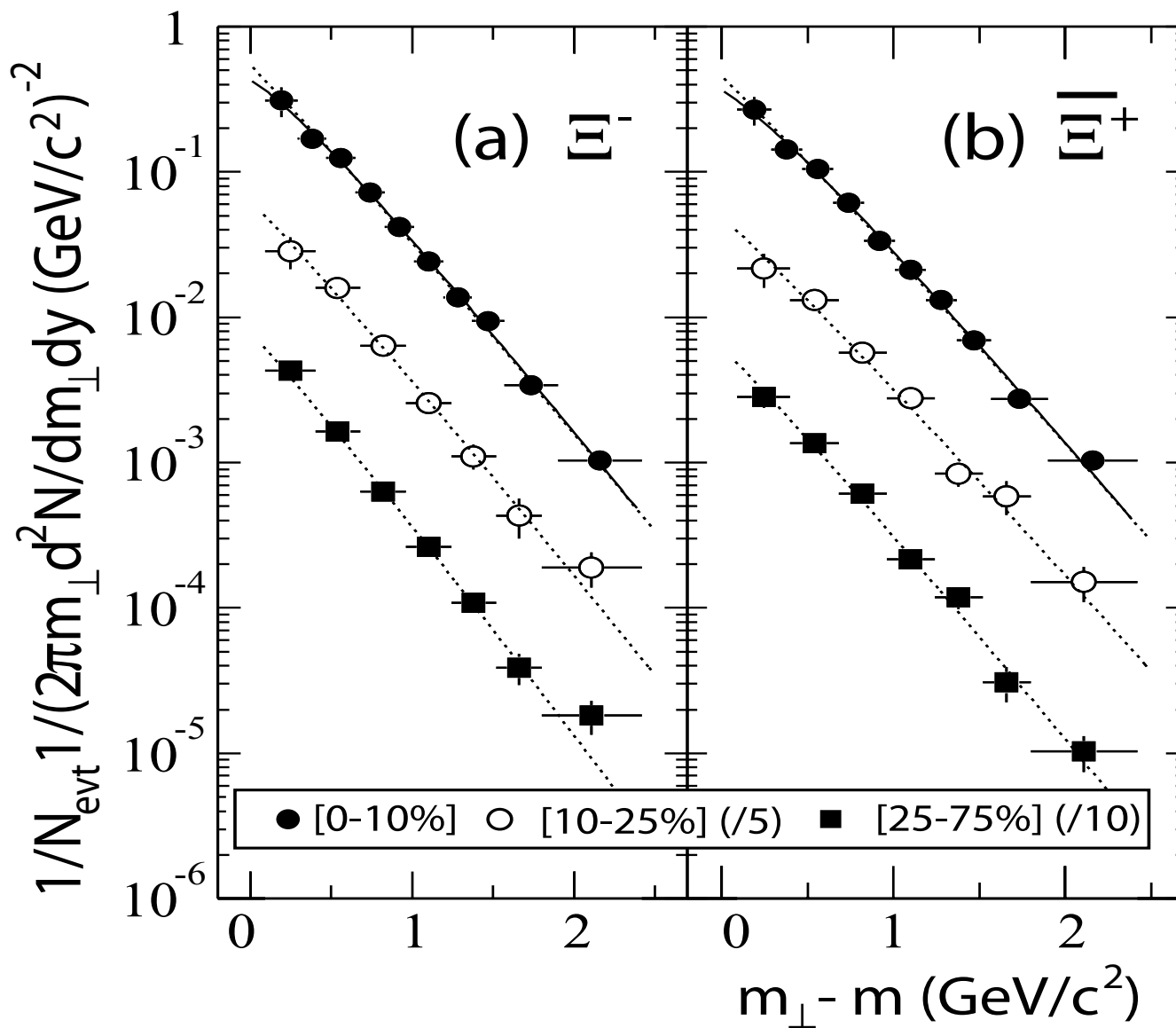


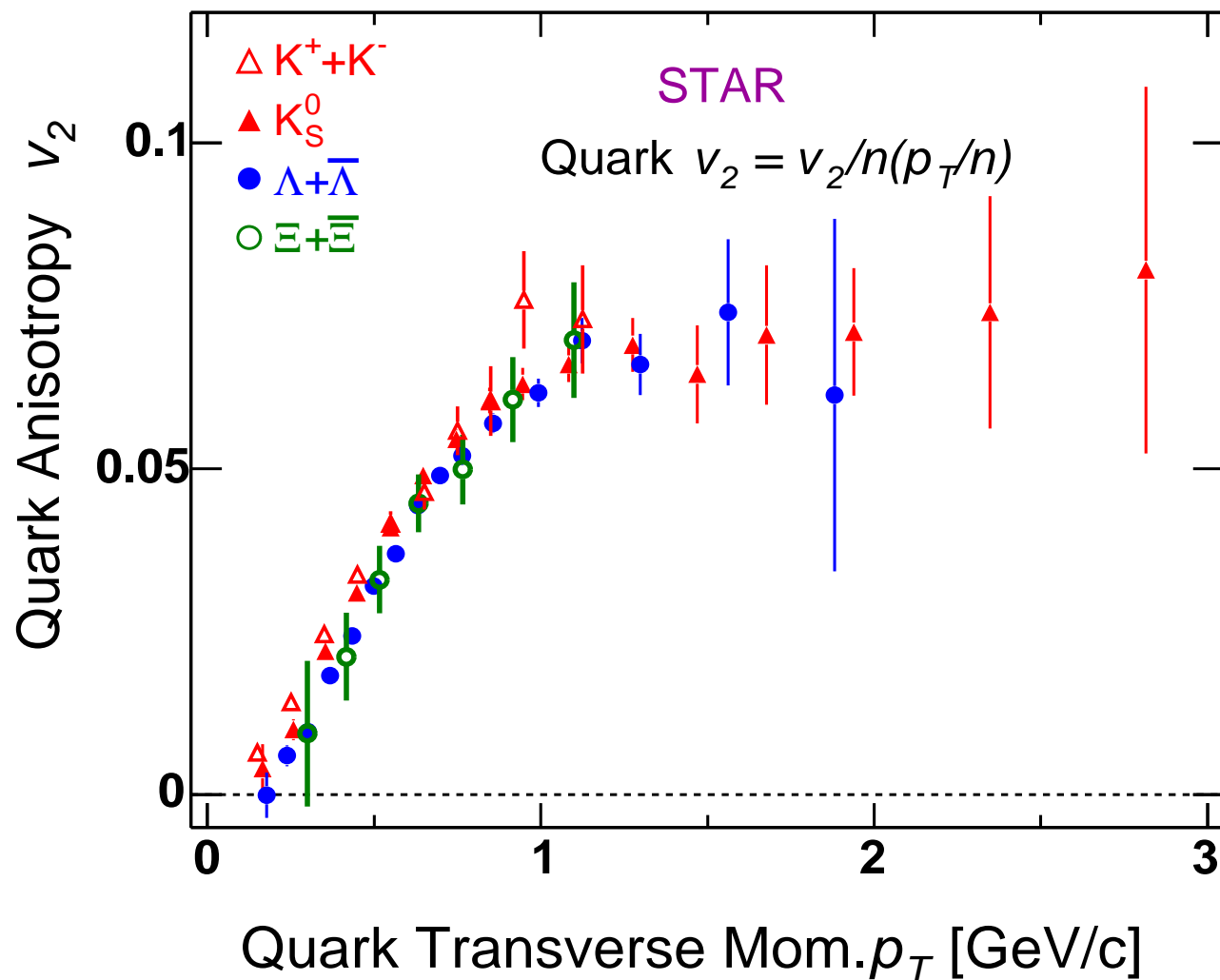
Spectra at RHIC-STAR 130+130 A GeV show the same effect

h^-	centrality	Exponential Fit		Boltzmann Fit	
		dN/dy	$T_E(\text{MeV})$	dN/dy	$T_B(\text{MeV})$
Ξ^-	260.3 ± 7.5	2.16 ± 0.09	338 ± 6	2.06 ± 0.09	296 ± 5
	$\bar{\Xi}^+$	1.81 ± 0.08	339 ± 7	1.73 ± 0.08	297 ± 5
Ξ^-	163.6 ± 5.2	1.22 ± 0.11	335 ± 16	1.18 ± 0.11	291 ± 13
	$\bar{\Xi}^+$	1.00 ± 0.10	349 ± 17	0.97 ± 0.10	302 ± 13
Ξ^-	42.5 ± 3.0	0.28 ± 0.02	312 ± 12	0.27 ± 0.02	273 ± 10
	$\bar{\Xi}^+$	0.23 ± 0.02	320 ± 11	0.22 ± 0.02	280 ± 9

m_\perp spectra of Ξ^- , $\bar{\Xi}^-$, for three centrality bins 0-10%, 10-25% and 25-75% with $h^- = dN_{h^-}/d\eta|_{|\eta|<0.5}$. Statistical and p_\perp dependent systematic uncertainties are presented. The p_\perp independent systematic uncertainties are 10%. (STAR Collaboration, PRL92 (2004) 182301)

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



Early Quark Thermalization and COMMON COLLECTIVE FLOW

A superb confirmation that dynamics of the fireball is in partonic degrees of freedom, UCLA, P. Sorenson and Huan-Zhong Huang

DIRECT PARTICLE PRODUCTION

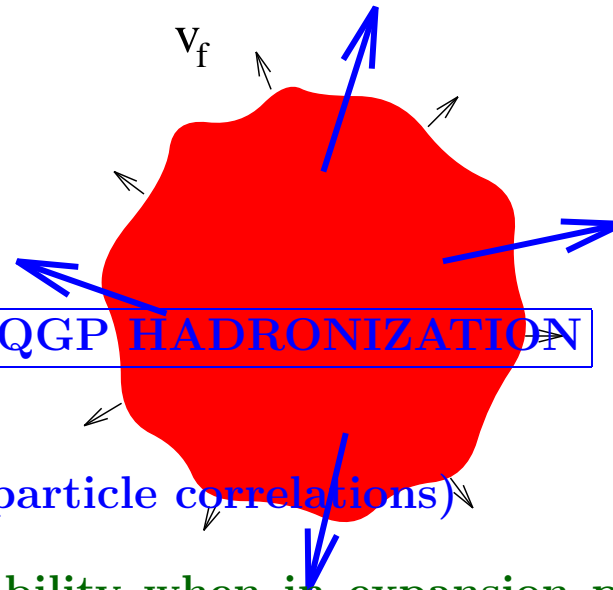
Common formation mechanism for all particles, for antimatter little reannihilation in sequel evolution.

Appears to be direct emission by a quark source into vacuum.

Practically no hadronic 'phase'!

No 'mixed phase' either!

Direct emission of free-streaming hadrons from **exploding QGP**



Develop analysis tools viable in SUDDEN QGP HADRONIZATION

SLOW transformation is in contradiction to experiment (single particle spectra, 2-particle correlations)

Reaction mechanism: filamentation instability when in expansion pressure reverses (L. Csernai, Bergen et al, JR et al).

NEXT:

1) Flow of matter and supercooling

2) Production of final state particles in **Statistical Hadronization**

Super-cooling WIND of a fast expanding fireball

P and ε : local in QGP particle pressure, energy density, \vec{v} local flow velocity. The pressure component in the energy-momentum tensor:

$$T^{ij} = P\delta_{ij} + (P + \varepsilon)\frac{v_i v_j}{1 - \vec{v}^2}.$$

The rate of momentum flow vector $\vec{\mathcal{P}}$ at the surface of the fireball is obtained from the energy-stress tensor T_{kl} :

$$\vec{\mathcal{P}} \equiv \hat{T} \cdot \vec{n} = P\vec{n} + (P + \varepsilon)\frac{\vec{v}_c \vec{v}_c \cdot \vec{n}}{1 - \vec{v}_c^2}.$$

The pressure and energy comprise particle and the vacuum properties: $P = P_p - \mathcal{B}$, $\varepsilon = \varepsilon_p + \mathcal{B}$. Condition $\vec{\mathcal{P}} = 0$ reads:

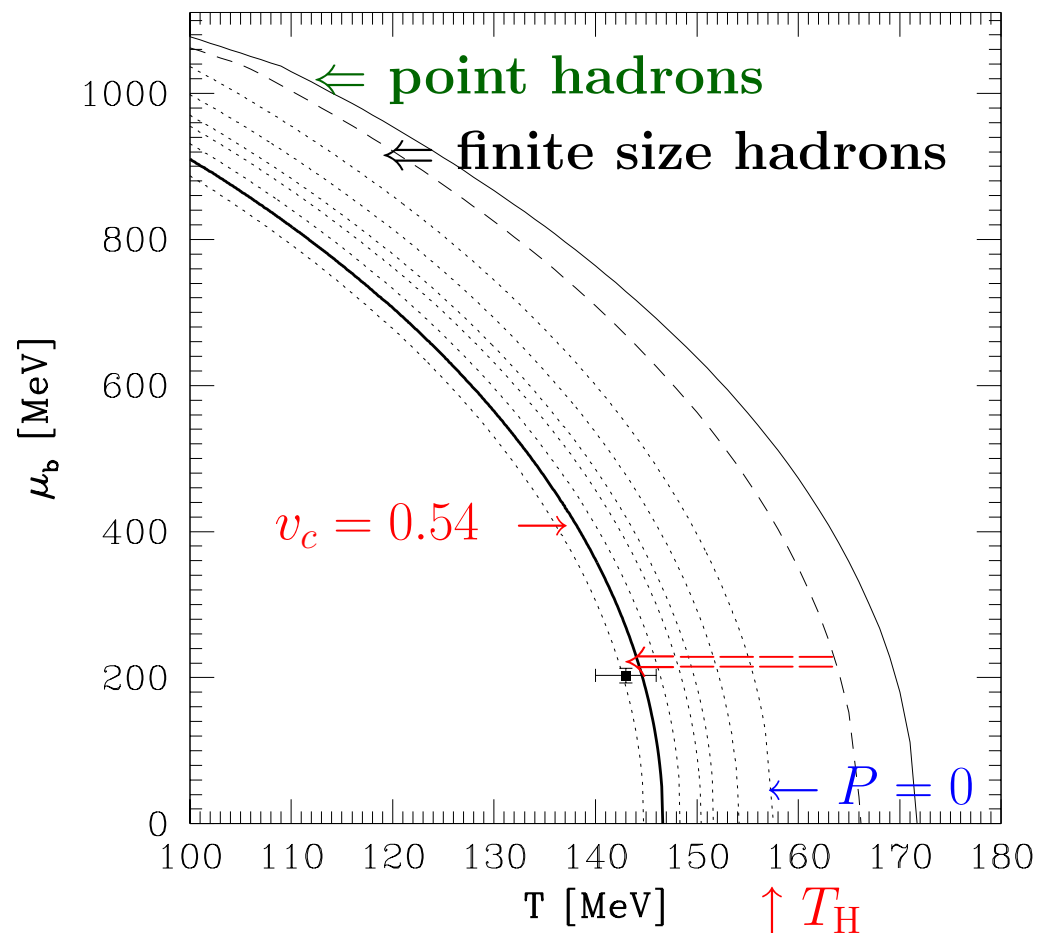
$$\mathcal{B}\vec{n} = P_p\vec{n} + (P_p + \varepsilon_p)\frac{\vec{v}_c \vec{v}_c \cdot \vec{n}}{1 - v_c^2},$$

Multiplying with \vec{n} , we find,

$$\mathcal{B} = P_p + (P_p + \varepsilon_p)\frac{\kappa v_c^2}{1 - v_c^2}, \quad \kappa = \frac{(\vec{v}_c \cdot \vec{n})^2}{v_c^2}.$$

This requires $P_p < \mathcal{B}$: QGP phase pressure P must be NEGATIVE. A fireball surface region which reaches $\mathcal{P} \rightarrow 0$ and continues to flow outward is torn apart in a rapid instability. This can ONLY arise since matter presses against the vacuum which is not subject to collective dynamics.

Phase boundary and ‘wind’ of flow of matter



Solid: point hadrons T_p

Dashed: finite size

Dotted: $T_c(\mu_b)|_{P_{eff}-B=0}$ for $v^2 = 0, 1/10, 1/6, 1/5, 1/4, 1/3$.

Thick solid: breakup with $v = 0.54$ ($\kappa = 0.6$)

PRL 85 (2000) 4695

**DEEP SUPERCOOLING
by 20 MeV**

$T_H = 158$ MeV Hagedorn temperature where $P = 0$, no hadron P
 $T_f \simeq 0.9T_H \simeq 143$ MeV is where supercooled QGP fireball breaks up
 equilibrium phase transformation is at $\simeq 166$.

IV: Strangeness in QGP

1. TOTAL STRANGENESS YIELD: strangeness/*b*aryon depends primarily on **initial** conditions and (less) on **evolution** dynamics
(how long the system is at which *T*)

γ_s^{QGP} :

is QGP near chemical equilibrium?

$$\gamma_{s,q}^{\text{QGP}} = \frac{n_{s,q}(t, T(t))}{n_{s,q}(\infty, T(t))} \Big|_{\text{QGP}} \rightarrow 1?$$

2. Strangeness overpopulation at QGP BREAK-UP:

QGP phase space is squeezed into

a smaller number of HG phase space cells: $\gamma_s^{\text{HG}} \simeq (2\dots 5)\gamma_s^{\text{QGP}}$

3. WE NEED ALSO TO CONSIDER QGP ENTROPY enhancement expressed

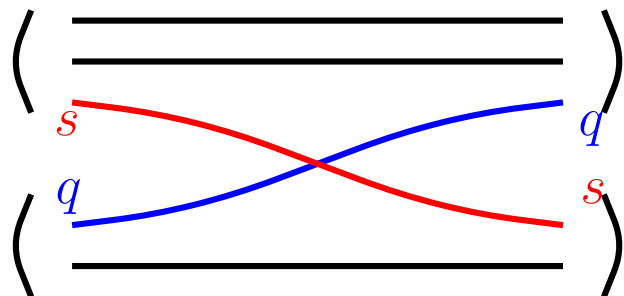
in $e^{m_\pi/(2T)} > \gamma_q^{\text{HG}} > 1$

over population of pion phase space is **ENTROPY** enhancement

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
λ_i controls difference between strange and non-strange quarks ($i = q, s$)	Relative chemical equilibrium

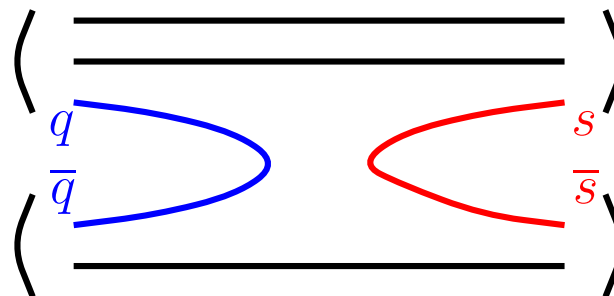
HG-EXAMPLE: redistribution,
Relative chemical equilibrium



EXCHANGE REACTION

λ_i

production of strangeness
Absolute chemical equilibrium



PAIR PRODUCTION REACTION

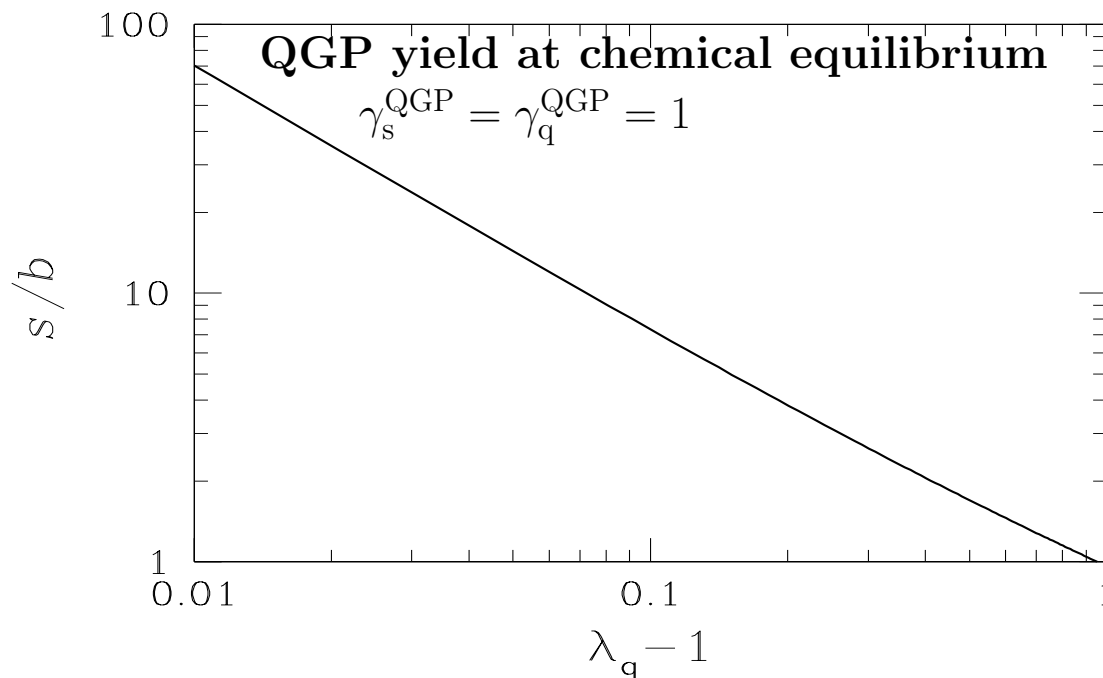
γ_i

STRANGENESS YIELD IN QGP and $\gamma_s^{\text{QGP}}/\gamma_q^{\text{QGP}}$

$$\frac{\rho_s}{\rho_b} = \frac{s}{q/3} = \frac{\gamma_s^{\text{QGP}} \frac{3}{\pi^2} T^3 (m_s/T)^2 K_2(m_s/T)}{\gamma_q^{\text{QGP}} \frac{2}{3} (\mu_q T^2 + \mu_q^3/\pi^2)}, \rightarrow \frac{s}{b} \simeq \frac{\gamma_s^{\text{QGP}}}{\gamma_q^{\text{QGP}}} \frac{0.7}{\ln \lambda_q + (\ln \lambda_q)^3/\pi^2}.$$

assumption: $\mathcal{O}(\alpha_s)$ interaction effects cancel out between b, s

We consider $m_s = 200$ MeV and hadronization $T = 150$ MeV,



At SPS $\lambda_q=1.5-1.6$, implies $s/b \simeq 1.5$.

Observation: $s/b \simeq 0.75 \rightarrow \gamma_s^{\text{QGP}}/\gamma_q^{\text{QGP}} = 0.5$ at SPS

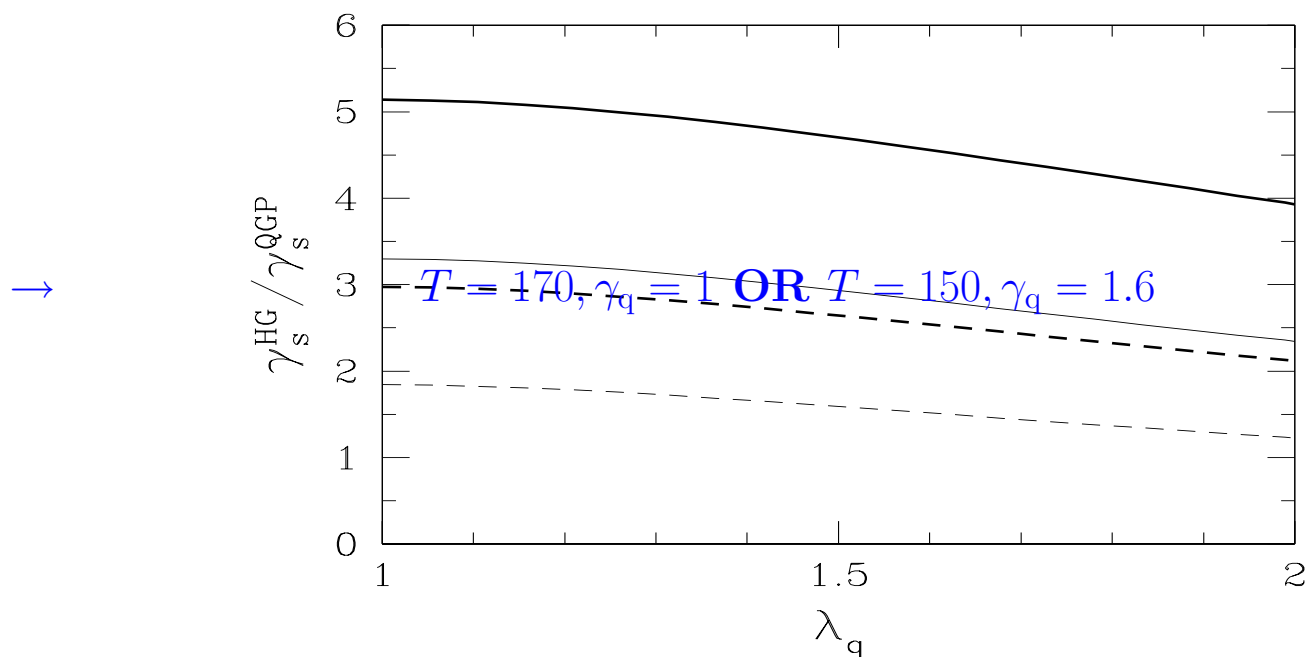
Similarly for RHIC at $\sqrt{s_{\text{NN}}} \geq 130$ GeV we have $1 \leq \lambda_q \leq 1.1$ and a comparison of the actual s/b yield allows to estimate $\gamma_s^{\text{QGP}}/\gamma_q^{\text{QGP}} = 0.7-0.8$ at RHIC-130.

CAN WE ESTIMATE THE EXPECTED γ_s^{HG} ?

COMPUTE EXPECTED RATIO OF $\gamma_s^{\text{HG}}/\gamma_s^{\text{QGP}}$

In sudden hadronization, $V^{\text{HG}} \simeq V^{\text{QGP}}$, $T^{\text{QGP}} \simeq T^{\text{HG}}$,

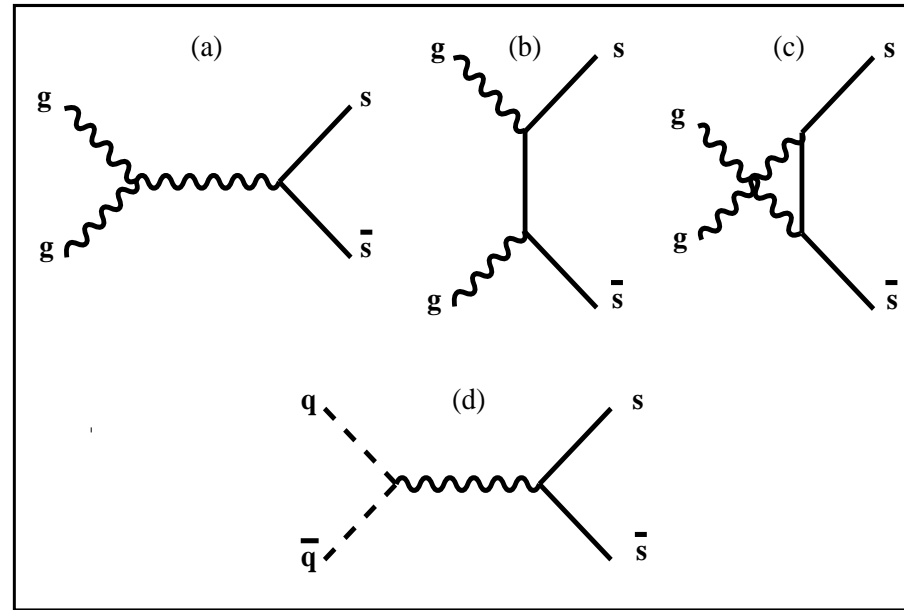
the chemical occupancy factors accommodate the different magnitude of particle phase space.



$\gamma_s^{\text{HG}}/\gamma_s^{\text{QGP}}$ in sudden hadronization as function of λ_q . Solid lines $\gamma_q = 1$, and short dashed $\gamma_q = 1.6$. Thin lines for $T = 170$ and thick lines $T = 150$ MeV, common to both phases.

$$\gamma_s^{\text{HG}} \simeq 2 \dots 5 \gamma_s^{\text{QGP}}$$

Kinetic description of strangeness production



The generic angle averaged cross sections for (heavy) flavor s , \bar{s} production processes $g + g \rightarrow s + \bar{s}$ and $q + \bar{q} \rightarrow s + \bar{s}$, are:

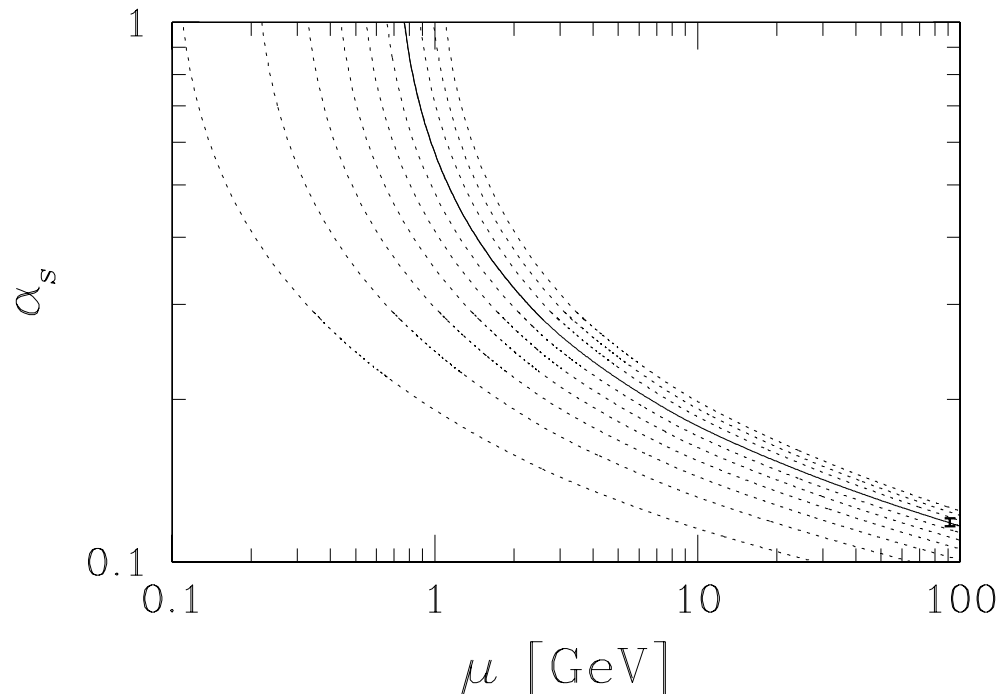
$$\bar{\sigma}_{gg \rightarrow s\bar{s}}(s) = \frac{2\pi\alpha_s^2}{3s} \left[\left(1 + \frac{4m_s^2}{s} + \frac{m_s^4}{s^2} \right) \tanh^{-1}W(s) - \left(\frac{7}{8} + \frac{31m_s^2}{8s} \right) W(s) \right],$$

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

Infinite 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 $m_s(1\text{GeV}) \simeq 2.1m_s(M_Z) \simeq 200\text{MeV}$.

WHY PERTURBATIVE STRANGENESS WORKS

An essential prerequisite 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 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:

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

Invariant reaction rate in medium:

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

$1/(1 + \delta_{1,2})$ introduced for two gluon processes compensates 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

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

Strangeness density time evolution

in local restframe (\vec{v}) we have :

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

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

Use detailed balance to simplify

$$\frac{d\rho_s}{dt} = A \left(1 - \frac{\rho_s^2(t)}{\rho_s^2(\infty)} \right), \quad A = A^{gg \rightarrow s\bar{s}} + A^{q\bar{q} \rightarrow s\bar{s}}$$

The generic solution at fixed T ($\rho \propto \tanh$) implies that in all general cases there is an exponential approach to chemical equilibrium

$$\frac{\rho_s(t)}{\rho_s^\infty} \rightarrow 1 - e^{-t/\tau_s}$$

with the characteristic time constant τ_s :

$$\tau_s \equiv \frac{1}{2} \frac{\rho_s(\infty)}{(A^{gg \rightarrow s\bar{s}} + A^{q\bar{q} \rightarrow s\bar{s}} + \dots)}$$

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

Characteristic time constant and γ_s -evolution



$\sigma_{\text{QCD}}^{\rightarrow s\bar{s}}$ gives τ_s similar to lifespan of the plasma phase!

Strange quark pair production dominated by gluon fusion: $G + G \rightarrow s\bar{s}$, also some (10%) $q\bar{q} \rightarrow s\bar{s}$, present; this is due to gluon collision rate.

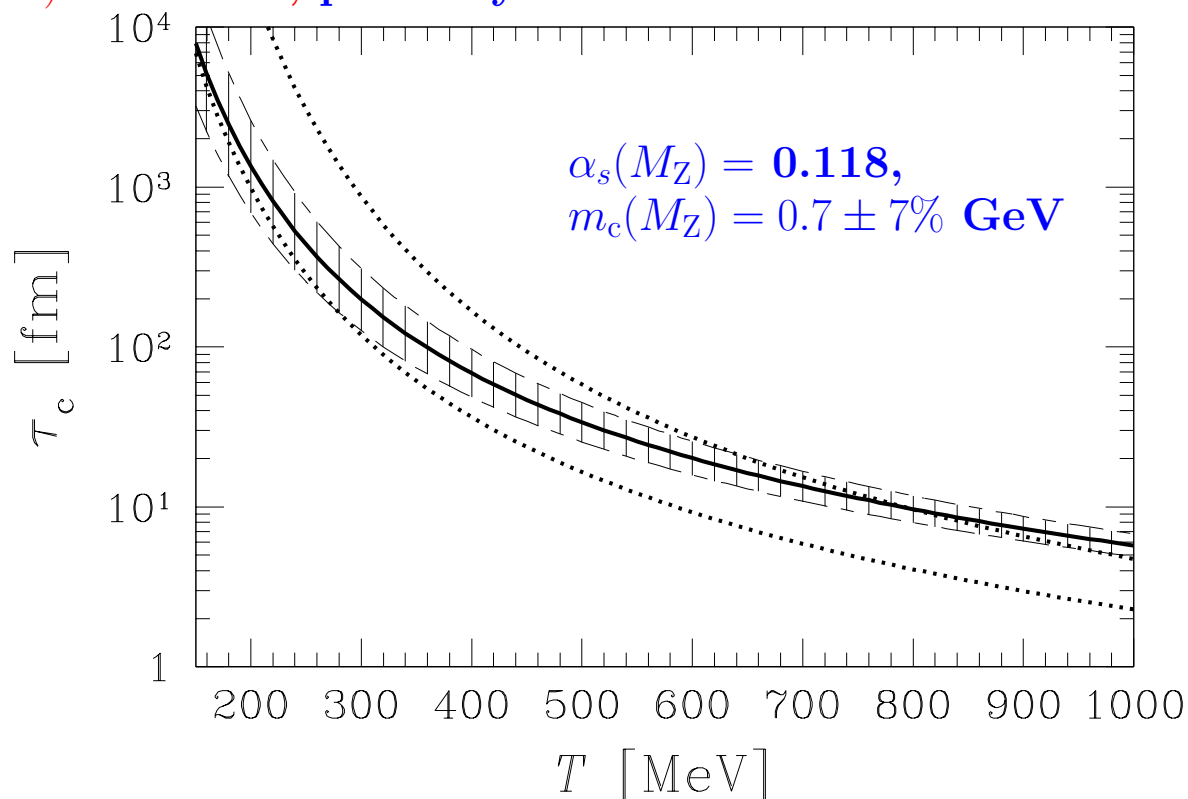
ENTROPY CONSERVING expansion i.e. at SPS $T^3V = \text{Const.}$ (not yet long scaling):

$$2\tau_s \frac{dT}{dt} \left(\frac{d\gamma_s}{dT} + \frac{\gamma_s}{T} z \frac{K_1(z)}{K_2(z)} \right) = 1 - \gamma_s^2, \quad \gamma_s(t) \equiv n_s(t)/n_s^\infty, \quad z = \frac{m_s}{T}, \quad K_i : \text{Besself.}$$

Once γ_s known, $\langle \rho_s(t) \rangle = \langle \bar{\rho}_s(t) \rangle = \int dx^3 \rho_s^\infty(T(t, x)) \gamma_s(T(t, x), \dot{T}(t, x))$;
evolution till $t \rightarrow t_f$, but effectively production stops for $T < 180$ MeV.

What about charm? $m_s \rightarrow m_c$

We expect that thermal charm production is of relevance only for $T \rightarrow m_c (1 \text{ GeV}) \simeq 1.5 \text{ GeV}$, probably not accessible.



Lower dotted line: for fixed $m_c = 0.9 \text{ GeV}$, $\alpha_s = 0.35$;

upper dotted line: for fixed $m_c = 1.5 \text{ GeV}$, $\alpha_s = 0.4$.

Equilibrium density for $\rho_c^\infty(m_c \simeq 1.5 \text{ GeV})$.

Charm is produced relatively abundantly in first parton collisions. **Benchmark:** 10 $c\bar{c}$ pairs in central Au–Au at RHIC-200. This yield is greater than the expected thermal equilibrium yield at hadronization of QGP. Charmonium enhancement by recombination.

OBJECTIVE: Physical properties of the source at hadronization NEED the phase space of hadronic particles in great precision.

V: SHARE – FERMI STATISTICAL HADRONIZATION MODEL

The thermal emitted particles production yield dN_i within the time

T_f	Local rest frame chemical freeze-out temperature
v_h, v_f	Hadronization, Local flow speed of emitting source
λ_s, λ_q	Chemical fugacities describe conserved quantum number
γ_s, γ_q	Phase space occupancies describe quark pair yield

dt from a locally at rest surface element dS :

$$dN_i = \frac{dS d^3p}{(2\pi)^3} A_i v_i dt .$$

$v_i = dz/dt$ is the particle velocity normal to the surface element dS .

In a thermal quark-gluon source, phase space factor A_i is:

$$A_i = g_i \lambda_i \gamma_i e^{-E_i/T}, \quad \lambda_i = \prod_{j \in i} \lambda_j, \quad \gamma_i = \prod_{j \in i} \gamma_j, \quad E_i = \sum_{j \in i} E_j,$$

RATIOS OF PARTICLE YIELDS FIX CHEMICAL PARAMETERS

$$R_\Lambda = \frac{\bar{\Lambda}}{\Lambda} = \frac{\bar{\Lambda} + \bar{\Sigma}^0 + \bar{\Sigma}^* + \dots}{\Lambda + \Sigma^0 + \Sigma^* + \dots} = \frac{\bar{s}\bar{q}\bar{q}}{sqq} = \lambda_s^{-2}\lambda_q^{-4} = e^{2\mu_s/T} e^{-2\mu_b/T}.$$

$$R_\Xi = \frac{\bar{\Xi}^-}{\Xi^-} = \frac{\bar{\Xi}^- + \bar{\Xi}^* + \dots}{\Xi^- + \Xi^* + \dots} = \frac{\bar{s}\bar{s}\bar{q}}{ssq} = \lambda_s^{-4}\lambda_q^{-2} = e^{4\mu_s/T} e^{-2\mu_b/T}.$$

Sensitivity to **nonequilibrium** occupancy factors γ_i derives from comparison of hadron yields with differing q, s quark content e.g.:

$$\frac{\Xi^-(dss) + \Xi^* + \dots}{\Lambda(dd)s + \Lambda^* + \dots} \propto \frac{\gamma_d \gamma_s^2}{\gamma_d^2 \gamma_s} \frac{g_\Xi \lambda_d \lambda_s^2}{g_\Lambda \lambda_d^2 \lambda_s}.$$

note: $\gamma_q^2 \equiv \gamma_u \gamma_d$, $\gamma_u \simeq \gamma_d$. Observation of $\gamma_q > 1, \gamma_s > 1$ implies rapid expansion of near equilibrium QGP, with final hadrons emitted directly from deconfined state.

Complete description of all hadron yields

We note above the presence of resonance decays. Full analysis requires a significant effort with 1000's of decaying states. A public package **SHARE** Statistical Hadronization with Resonances is available at <http://www.physics.arizona.edu/~torrieri/SHARE/share.html> developed by Kraków-Tucson collaboration.

Lead author: **Giorgio Torrieri.**

The **complete** statistical hadronization model allows precise description of all hadron yields, including resonances at all energies. The myth that resonances are not described within the same scheme is due to the limited model applied by some other groups which omits one or more key properties required. We find that Single freeze-out model as proposed in 1991 suffices when we consider:

1. Complete tree of resonance decays please note:
not only for yields but also most important for **spectra.**
2. **WIDTH** of the resonances (needed to describe resonance yields)
3. Chemical off-equilibrium in hadron yields (if QGP near equilibrium, it is not present in the hadron sector, as the transformation is sudden).

Look for a few publications using the SHARE package on line.

PARTICLE ABUNDANCES

$$\pi(q\bar{q}) \sim \gamma_q^2 \quad N(qqq) \sim \gamma_q^3 \lambda_q^3; \quad \bar{N}(\bar{q}\bar{q}\bar{q}) \sim \gamma_q^3 \lambda_q^{-3}$$

QUANTUM STATISTICS

$$\frac{N_\pi}{V} = g_\pi \int \frac{d^3p}{(2\pi)^3} \frac{1}{\gamma_q^{-2} e^{\sqrt{m_\pi^2 + p^2}/T} - 1}, \quad \gamma_q^2 < e^{m_\pi/T} \simeq (1.6)^2$$

$$\frac{N}{V} = g_N \int \frac{d^3p}{(2\pi)^3} \frac{1}{1 + \gamma_q^{-3} \lambda_q^{-3} e^{E/T}} \quad \frac{\bar{N}}{V} = g_N \int \frac{d^3p}{(2\pi)^3} \frac{1}{1 + \gamma_q^{-3} \lambda_q^{+3} e^{E/T}}$$

$$\mu_N^{\text{eff}} = 3T(\ln \lambda_q + \ln \gamma_q); \quad \mu_{\bar{N}}^{\text{eff}} = -3T(\ln \lambda_q - \ln \gamma_q)$$

presence of γ, λ is simply allowing to assign different potentials for particles and antiparticles else $\bar{\mu} = -\mu$

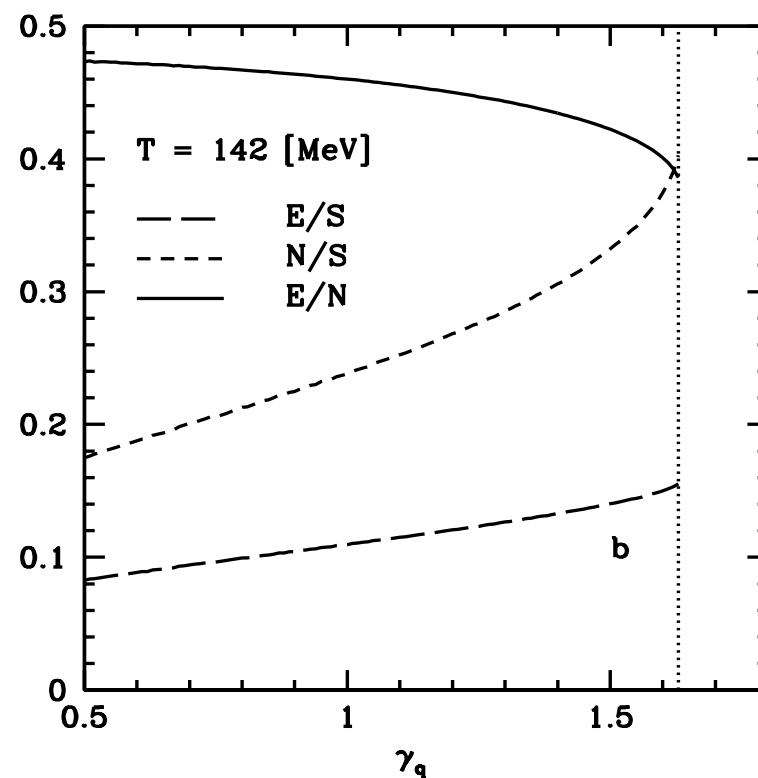
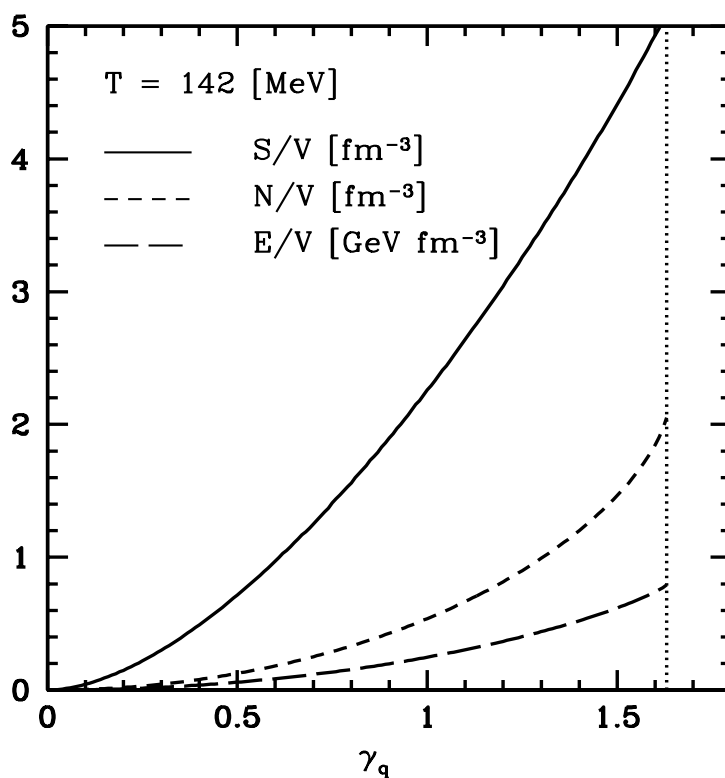
$\gamma_q^2 \rightarrow e^{m_\pi/T}$: A way to 'consume' excess of QGP entropy

Maximization of entropy density in pion: gas.

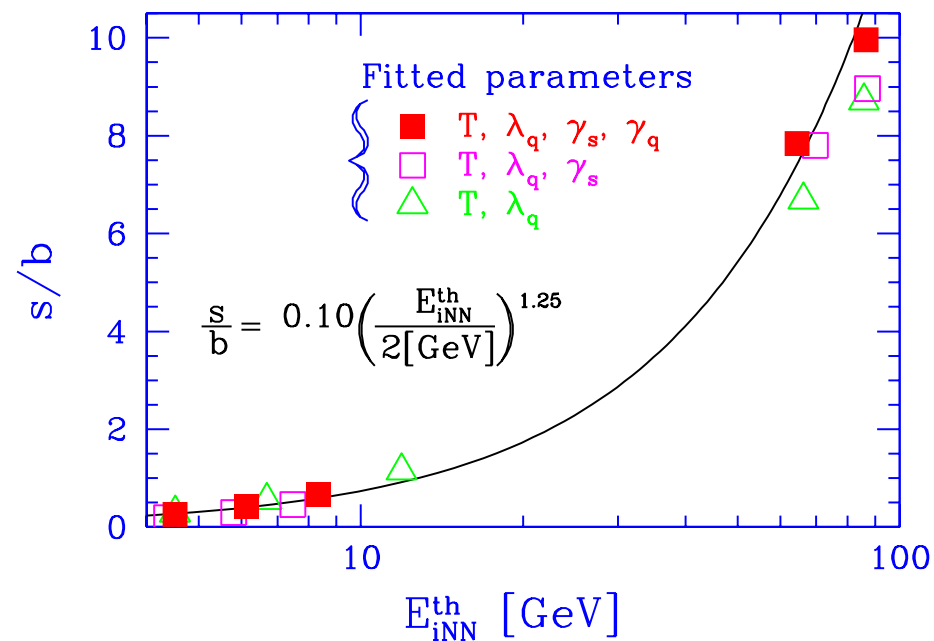
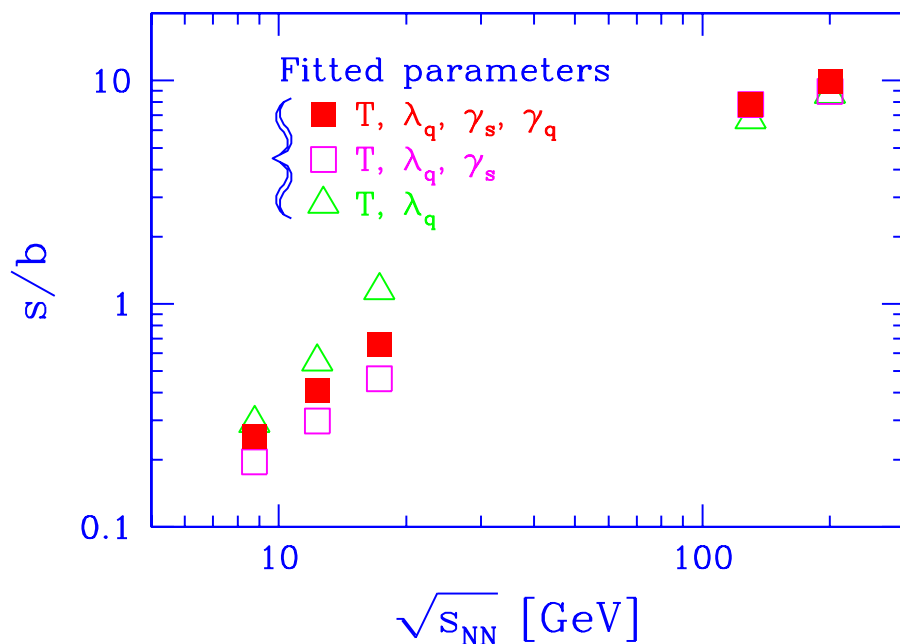
$$E_\pi = \sqrt{m_\pi^2 + p^2}$$

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

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



FROM SPS to RHIC: STRANGENESS vs NET BARYON CONTENT



Strangeness per thermal baryon participating in the reaction grows rapidly and continuously. **Glue based thermal production mechanism UNDERSTOOD.**

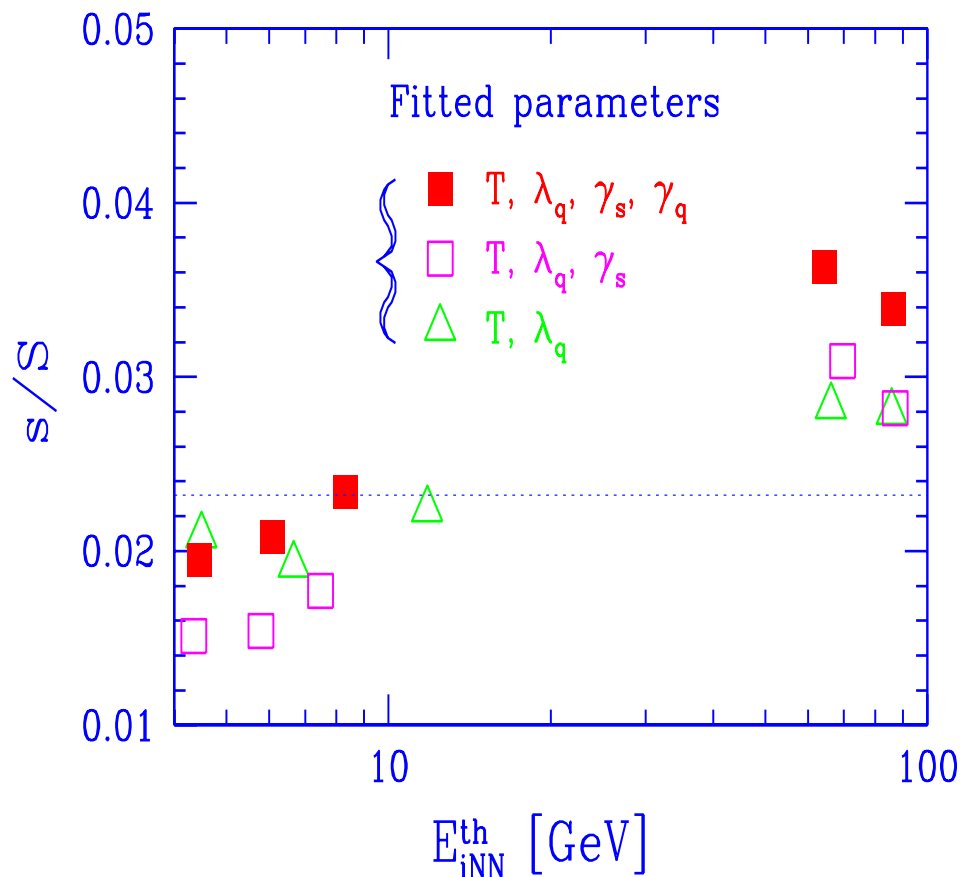
Strangeness production rises faster than entropy.

YIELD MUCH GREATER THAN IN NN-REACTIONS

OUTLOOK:

Soon at LHC – charm takes over from strangeness – an experimental challenge

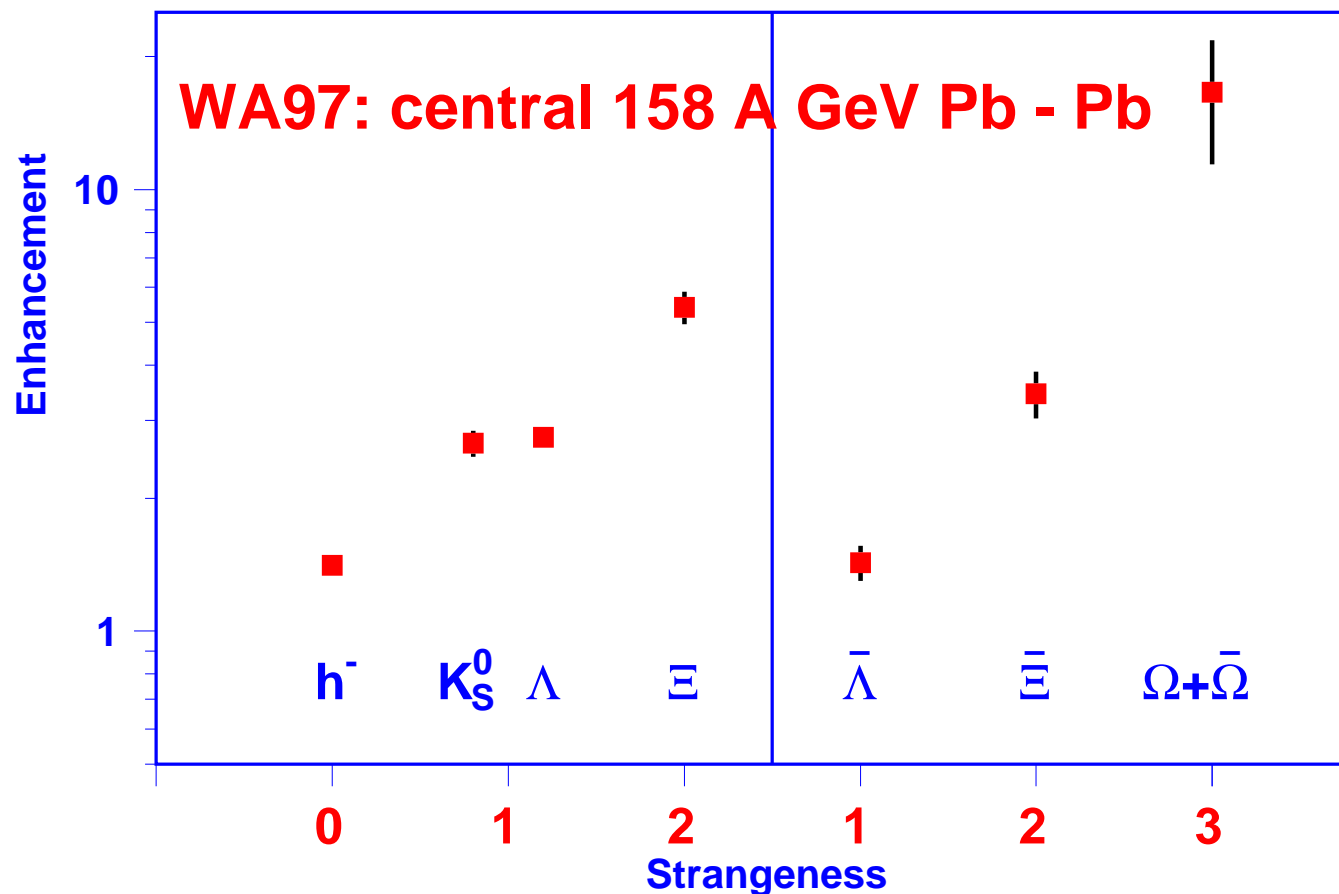
YET MORE INTERESTING: STRANGENESS/ENTROPY CONTENT



From AGS to SPS: step up by 50% (not shown) and second step-up by 50% in strangeness per entropy between SPS and RHIC
 Strangeness production rises with energy faster than production of entropy.

New physics at RHIC compared to SPS
 New physics at SPS compared to AGS.

VI: (MULTI)STRANGE (ANTI)HYPERON ENHANCEMENT



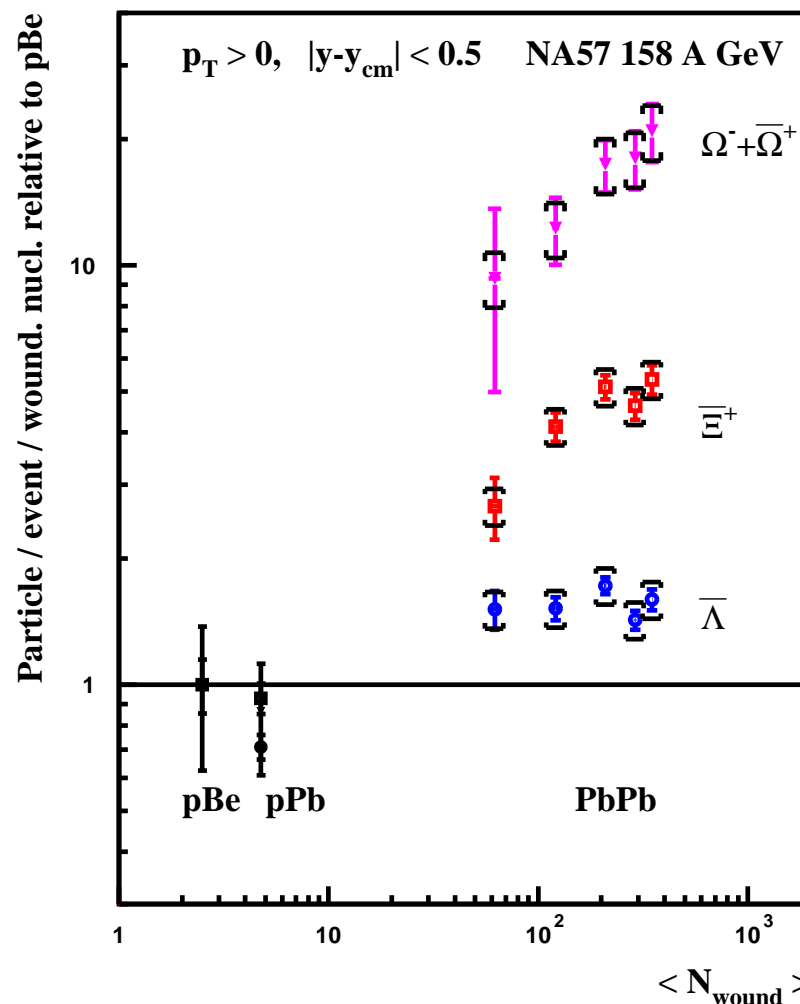
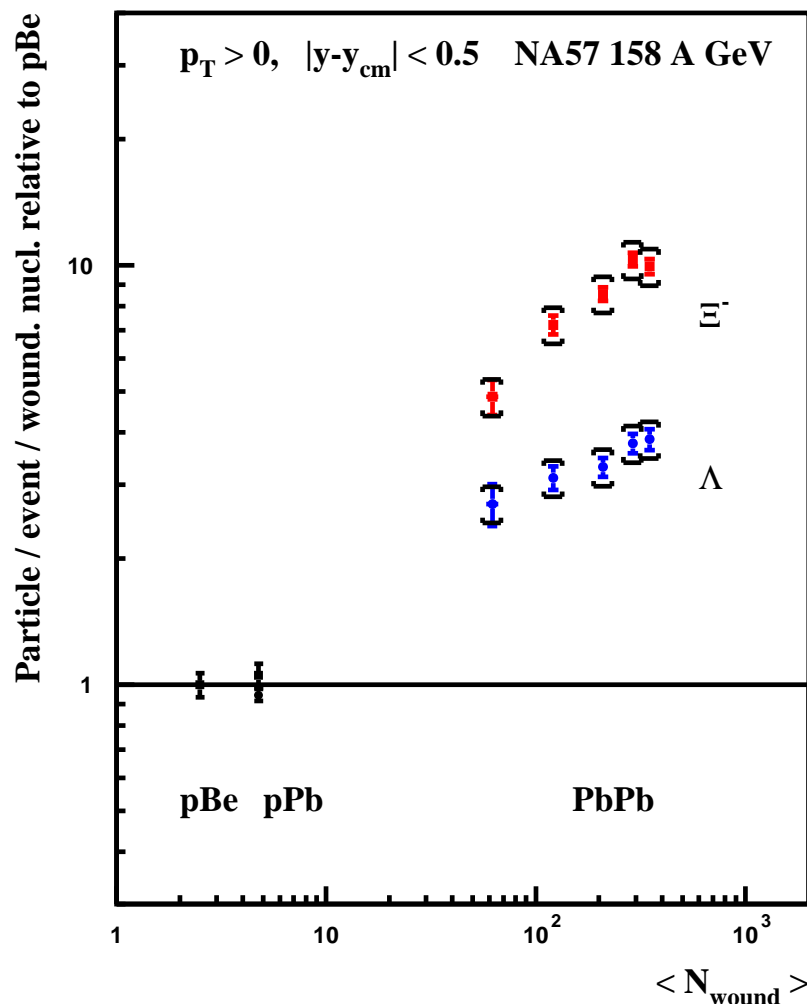
Enhancement GROWTH with

strangeness

antiquark content.

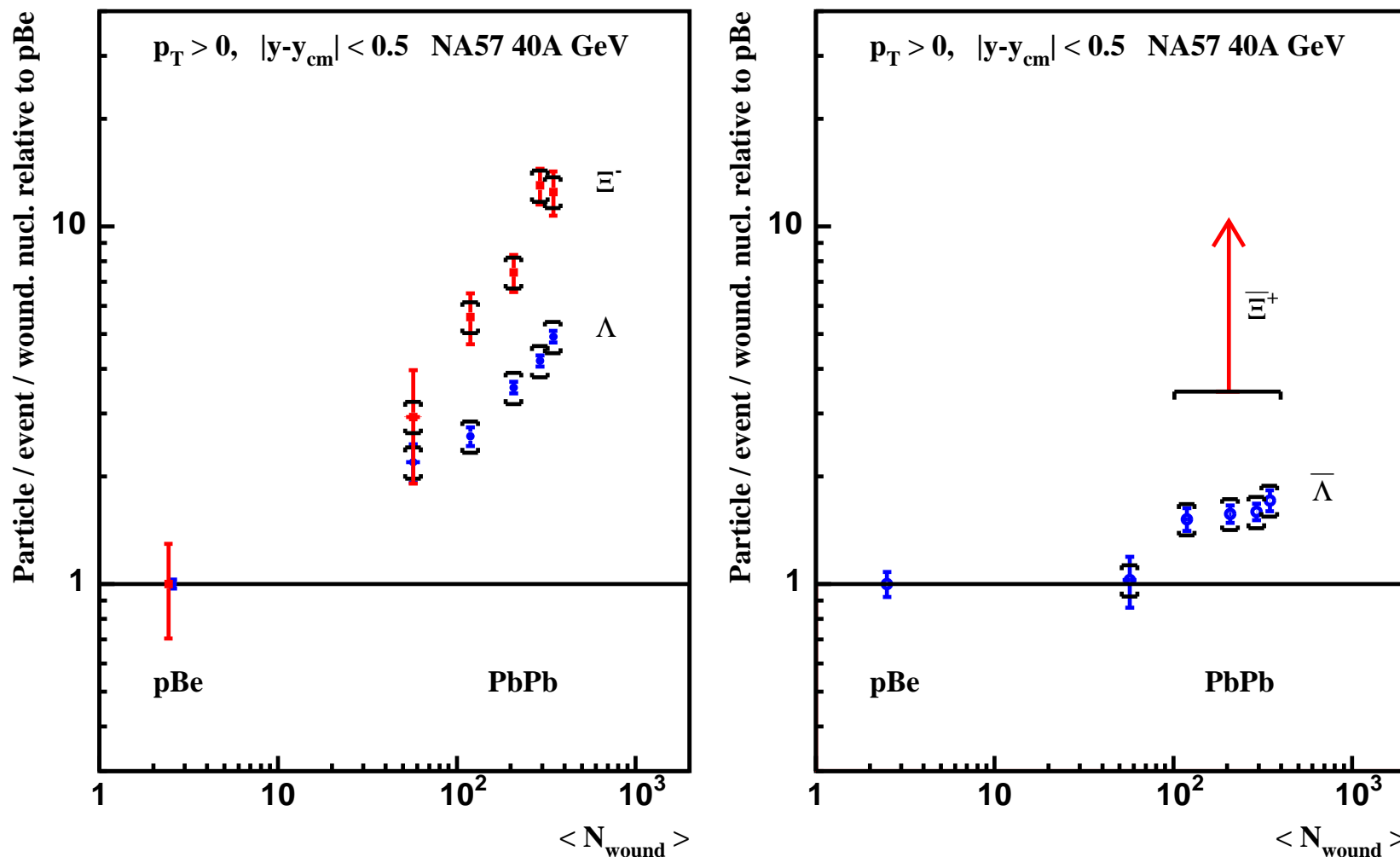
Enhancement is here defined with respect to the yield in p-Be collisions, scaled up with the number of collision 'wounded' nucleons.

ENHANCEMENT AS FUNCTION OF REACTION VOLUME



Note the gradual onset of enhancement with reaction volume. “Canonical enhancement” (a hadronic equilibrium model) is grossly inconsistent with these results. Gradual enhancement shown predicted by kinetic strangeness production.

ENHANCEMENT at low SPS Energy



At 40A GeV we still see a strong volume dependent hyperon enhancement, in agreement with expectations for deconfined state formation.

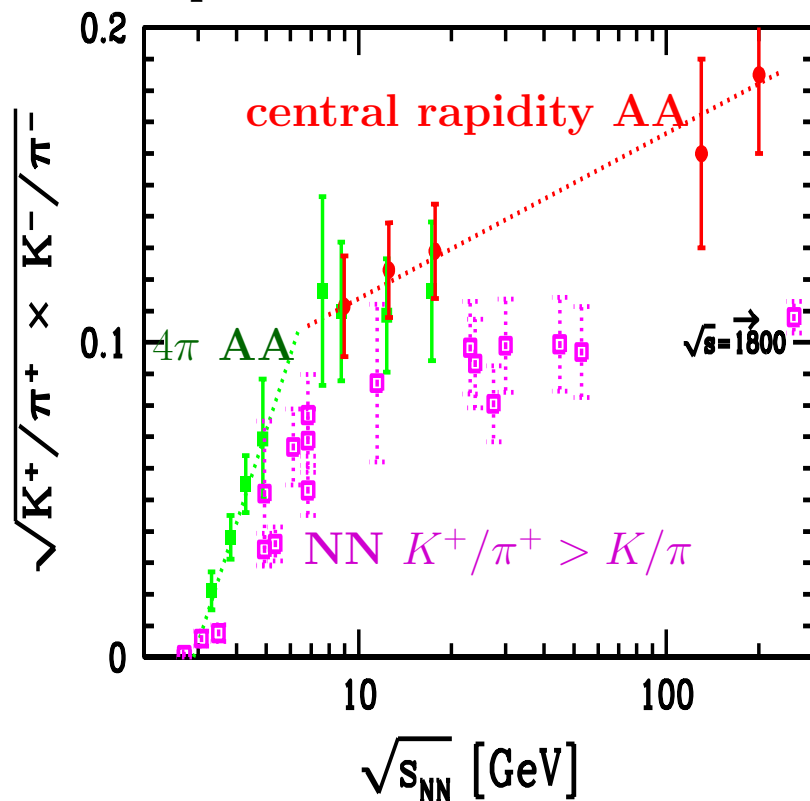
Probing strangeness excitation by ratio K/π

The particle yield products

$$K \equiv \sqrt{K^+(u\bar{s})K^-(\bar{u}s)} \propto \sqrt{\lambda_u/\lambda_s \lambda_s/\lambda_u}$$

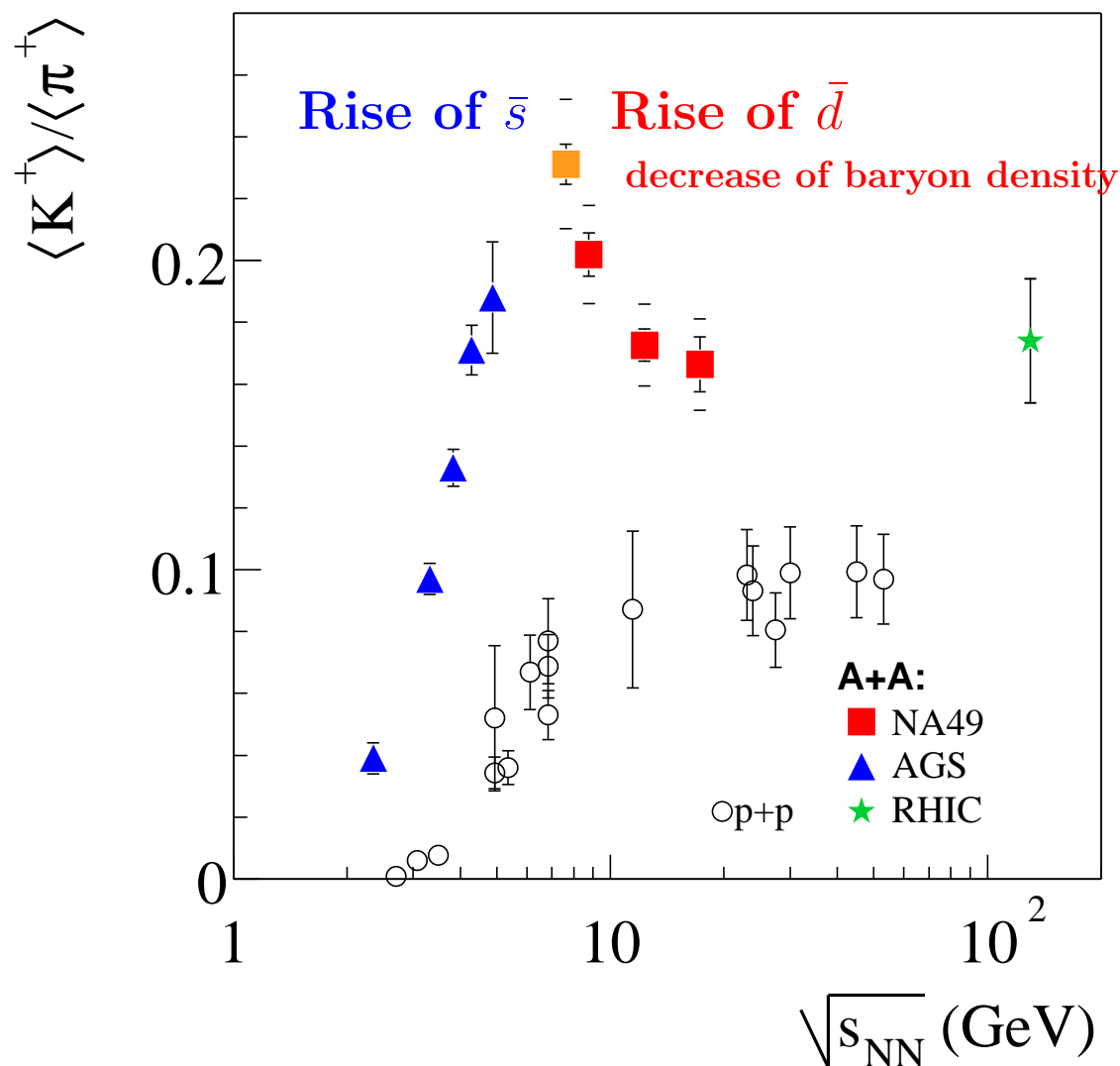
$$\pi \equiv \sqrt{\pi^+(u\bar{d})\pi^-(\bar{u}d)} \propto \sqrt{\lambda_u/\lambda_d \lambda_d/\lambda_u}$$

are less dependent on chemical conditions including baryon density.



There is a notable enhancement in K/π above the K^+/π^+ ratio recorded in pp reactions, which provides an upper limit on K/π . There is a clear change in the speed of rise in the K/π ratio at the lower energy limit at SPS; This combined with change in nuclear compression results in a peak in the K^+/π^+ .

NA49/Marek Gaździcki STUDY \bar{s}/\bar{d} ENHANCEMENT



The 'peak' is result of two effects: approach to saturation of strangeness, followed by increased baryon transparency signaling a change in reaction mechanism. Possibly, deconfinement!

Is QGP discovered??

Predicted QGP behavior confirmed by strangeness and strange antibaryon enhancement experiments, verifies strange quark mobility. Enhanced source entropy content consistent with gluon degrees of freedom, expected given strangeness enhancement. Chemical properties consistent with sudden hadron production in fast breakup of QGP.

Furthermore: quark coalescence explains features of non-azimuthally symmetric strange particle production. Early thermalization and strange quark participation in matter flow.

Strangeness excitation function fingerprints QGP as the new state of matter:
Probable onset of 'valon' quark deconfinement at AGS;
between SPS and RHIC entropy and strangeness change 2nd time

SO WHAT??

This is not the end of the story, but its beginning. We will soon know how did the quark-gluon Universe hadronizes and how did the antimatter component disappear.