Strangeness and Statistical Hadronization of Quark-Gluon Plasma

Kraków School of Theoretical Physics, June 1, 2003, Zakopane

[I] **Strangeness – a popular QGP diagnostic tool**

[II] **Statistical Hadronization**

[III] **Strangeness at SPS and at RHIC**

[IV] **Onset of QGP**

[V] **Future: strangeness at LHC**

J. Rafelski, Arizona
Department of Physics
with Jean Letessier, Paris 7

Supported by a grant from the U.S. Department of Energy, DE-FG03-95ER40937.

I Strangeness – a popular QGP diagnostic tool

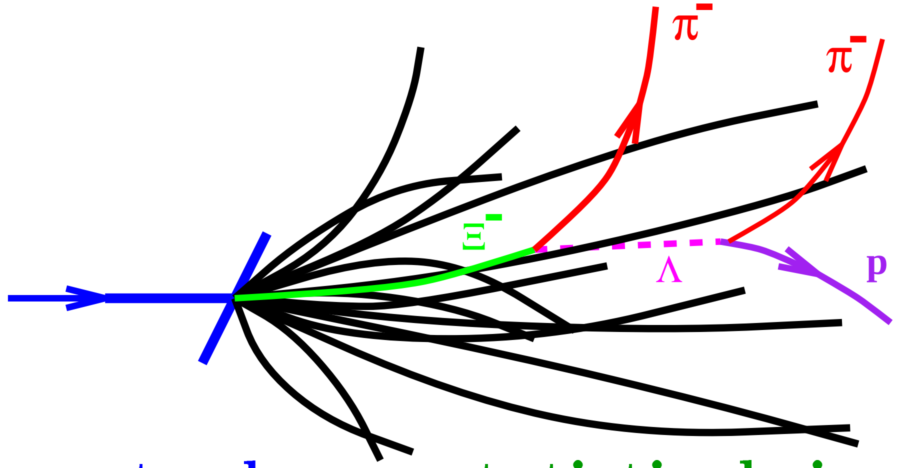
EXPERIMENTAL REASONS

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

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

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

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



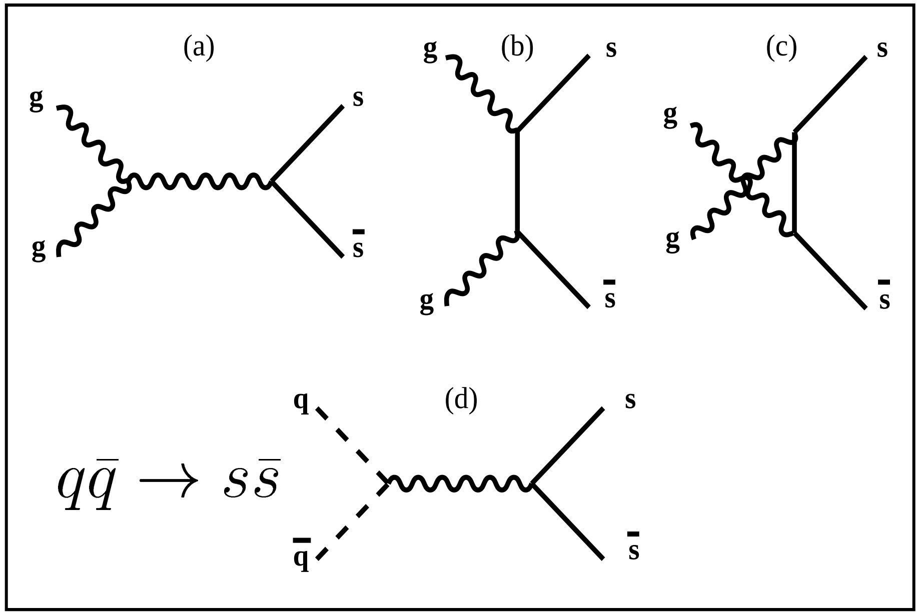
- **Production rates hence statistical significance is high;**

THEORETICAL CONSIDERATIONS

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

dominant processes:
$GG \to s\bar{s}$

10–15% of total rate:



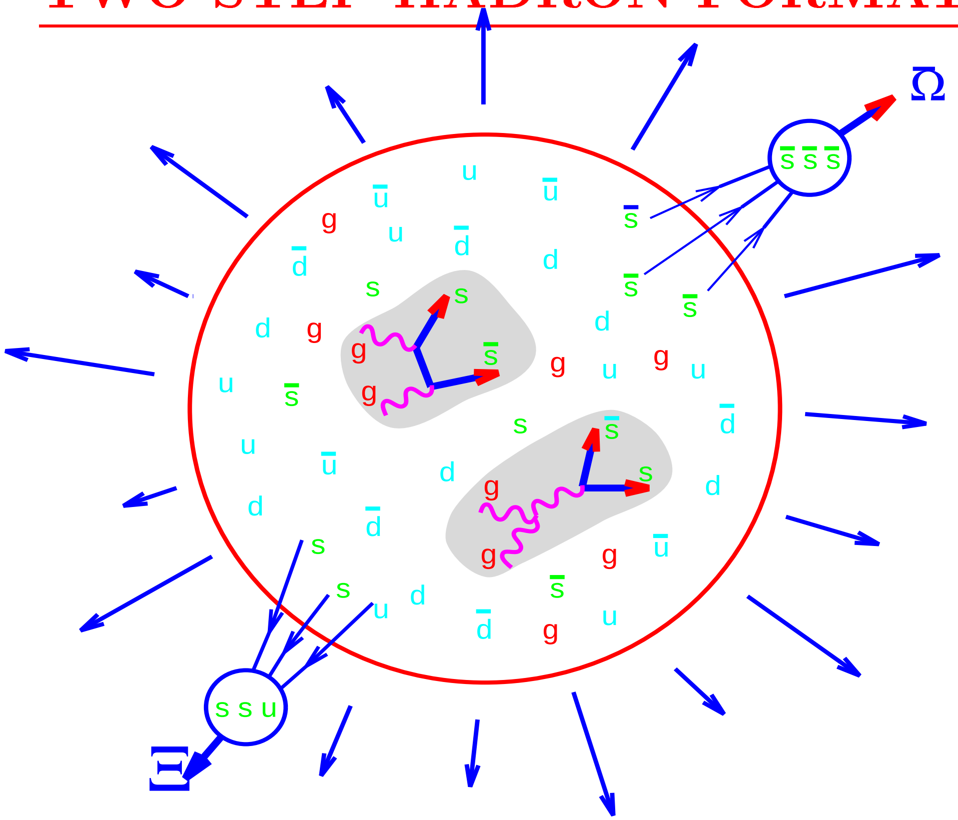
- **coincidence of scales:**

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

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.**

TWO STEP HADRON FORMATION MECHANISM IN QGP



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

Formation of complex rarely produced multi strange (anti)particles form QGP enabled by 'cross talk' between $s, \bar{s}$ **quarks made in different microscopic reactions; this is signature of deconfinement. Enhancement of strange antibaryons progressing with strangeness content.**

II STATISTICAL HADRONIZATION

Objective: Obtain a valid description of particle production yields and spectra in order to understand both intensive (T_h, . . .), and extensive (energy, baryon, strangeness, entropy content) properties of the fireball.

This requires the knowledge of the phase space of hadronic particles in great precision.

Statistical hadronization implies

Within a 'family', particle yields with same valance quark content are in relation to each other thermally equilibrated, e.g. the relative yield of $\Delta(1230)(qqq)$ and $N(qqq)$ completely controlled by ratios m_N/T, m_Δ/T e.g statistical weights (Hagedorn):

$$\frac{n_\Delta}{n_N} = \frac{g_\Delta (m_\Delta/T)^{3/2} e^{-m_\Delta/T}}{g_N (m_N/T)^{3/2} e^{-m_N/T}}$$

Comprehensive test still outstanding.

Chemical Potentials and fugacities

particle fugacity: $\Upsilon_i \equiv e^{\sigma_i/T} \Longleftrightarrow \sigma_i$ **particle 'i' chemical potential**

Example of NUCLEONS:

two particles $N, \overline{N} \rightarrow$ **two chemical factors, convenient choice:**

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

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

The (baryo)chemical potential μ_b, controls the particle difference = baryon number. This can be seen looking at the first law of thermodynamics:

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

γ **regulates the number of nucleon-antinucleon pairs present.**

RATIOS OF PARTICLE YIELDS

We follow the flavor quark content $(u, d, s, \ldots)$:

$$R_\Lambda = \frac{\overline{\Lambda}}{\Lambda} = \frac{\overline{\Lambda} + \overline{\Sigma}^0 + \overline{\Sigma}^* + \cdots}{\Lambda + \Sigma^0 + \Sigma^* + \cdots} = \frac{\bar{s}\bar{q}\bar{q}}{sqq} = \lambda_{\mathrm{s}}^{-2}\lambda_{\mathrm{q}}^{-4} = e^{2\mu_{\mathrm{S}}/T} e^{-2\mu_b/T}\,.$$

$$R_\Xi = \frac{\overline{\Xi^-}}{\Xi^-} = \frac{\overline{\Xi^-} + \overline{\Xi^*} + \cdots}{\Xi^- + \Xi^* + \cdots} = \frac{\bar{s}\bar{s}\bar{q}}{ssq} = \lambda_{\mathrm{s}}^{-4}\lambda_{\mathrm{q}}^{-2} = e^{4\mu_{\mathrm{S}}/T} e^{-2\mu_b/T}\,.$$

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

$$\frac{\Xi^-(dss)}{\Lambda(dds)} \propto \frac{\gamma_d \gamma_s^2}{\gamma_d^2 \gamma_s}\, \frac{g_\Xi \lambda_d \lambda_s^2}{g_\Lambda \lambda_d^2 \lambda_s}\,.$$

note: $\gamma_q^2 \equiv \gamma_u \gamma_d, \quad \gamma_u \simeq \gamma_d$

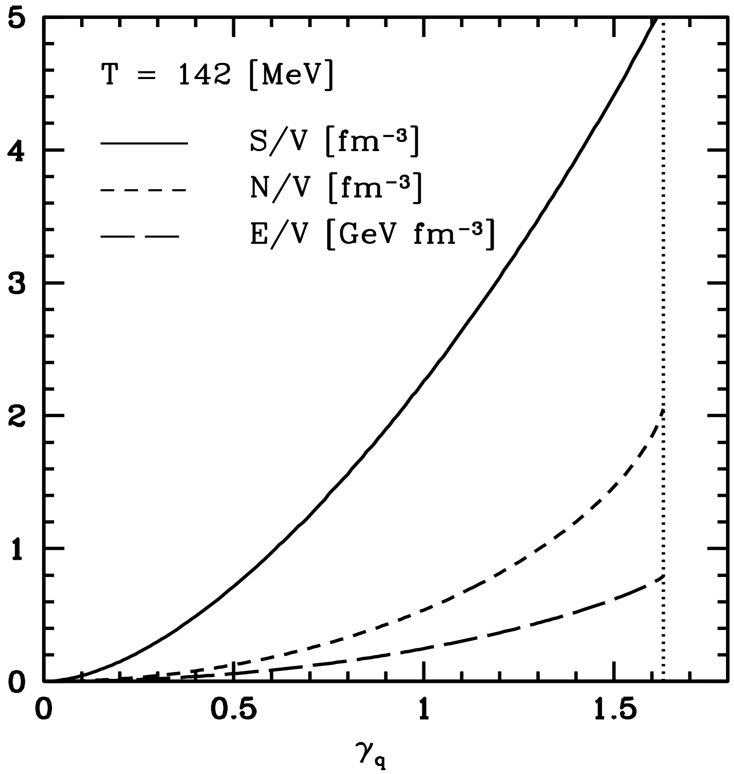
SPECIAL ROLE OF $\gamma_q^2 \to e^{m_\pi/T}$

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

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

More generally, the phase space density is:

$$\frac{d^6N_i}{d^3p d^3x} = g_i \frac{\Upsilon_i}{(2\pi)^3} e^{-E_i/T}, \qquad \frac{d^6N_i^{\mathrm{F/B}}}{d^3p d^3x} = \frac{g_i}{(2\pi)^3} \frac{1}{\Upsilon_i^{-1} e^{E_i/T} \pm 1}, \qquad \Upsilon_i^{\mathrm{bosons}} \le e^{m_i/2T},$$



Pion gas properties as function of γ_q. Note increase of entropy density. This is a way to 'consume' excess of QGP entropy in sudden hadronization (no volume expansion).

Particle abundances

The 4π particle yields the particle abundance is proportional to phase space integrals – no influence of matter flow dynamics.

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

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

Integrals easily computed. Proportionality constant C NOT A VOLUME for a dynamically evolving system.

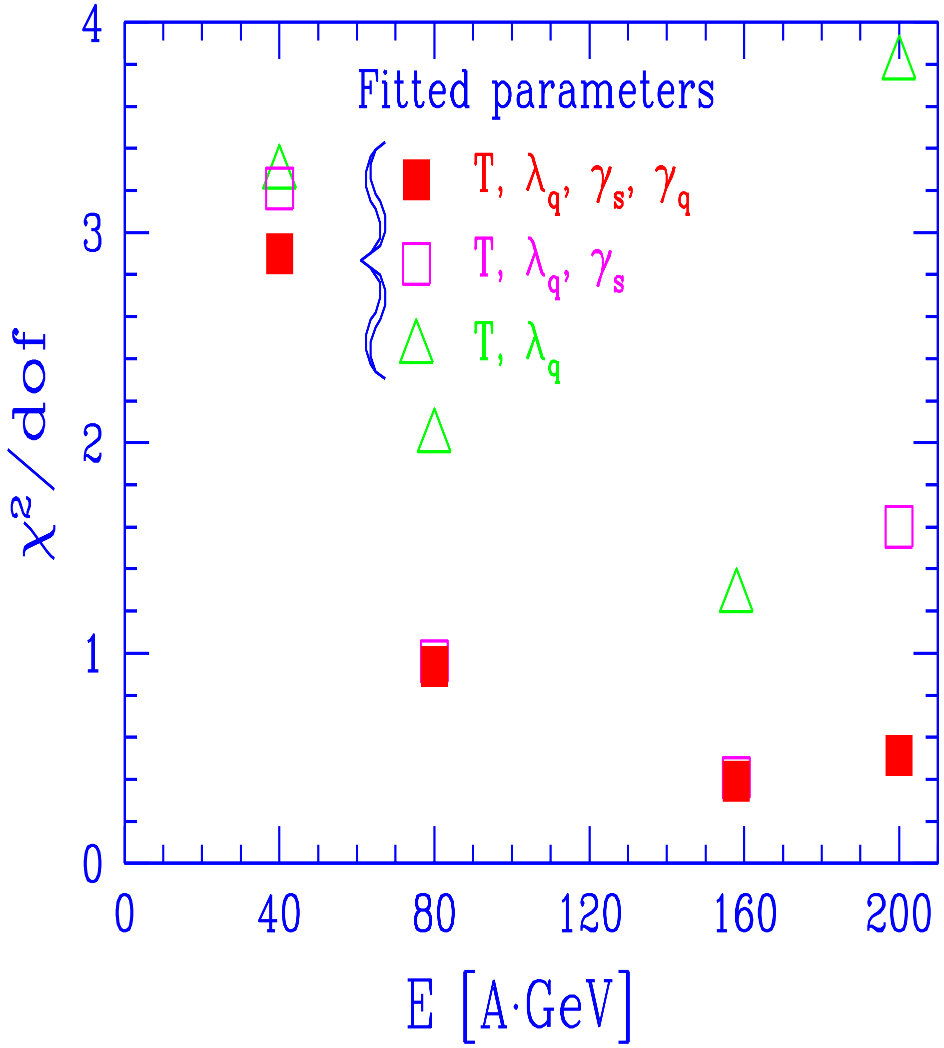
Consideration valid at RHIC/LHC with Bjorken-y-scaling equivalent infinite series of fireballs at all rapidities (Hagedorn).

Hadronization Analysis at SPS, RHIC

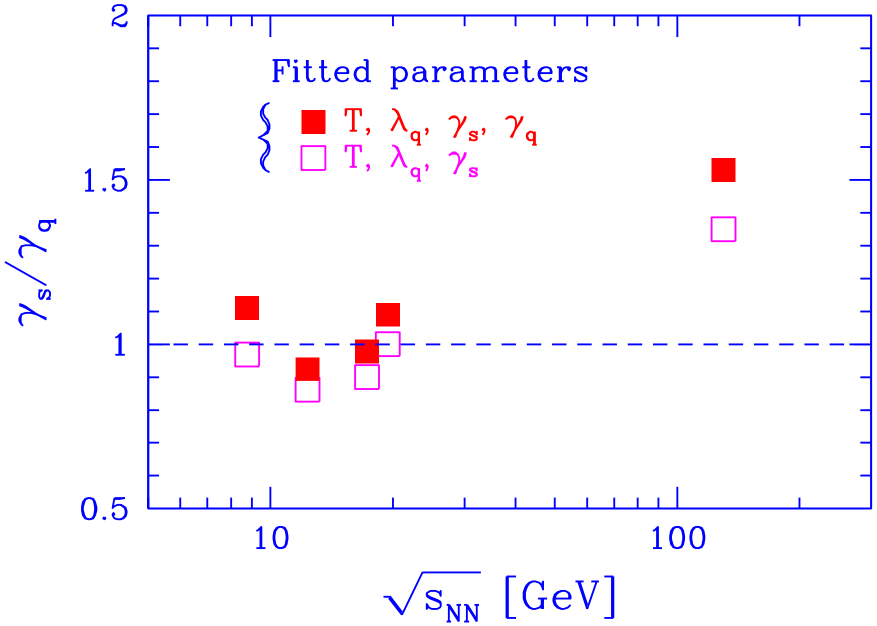
METHOD OF COMPARISON

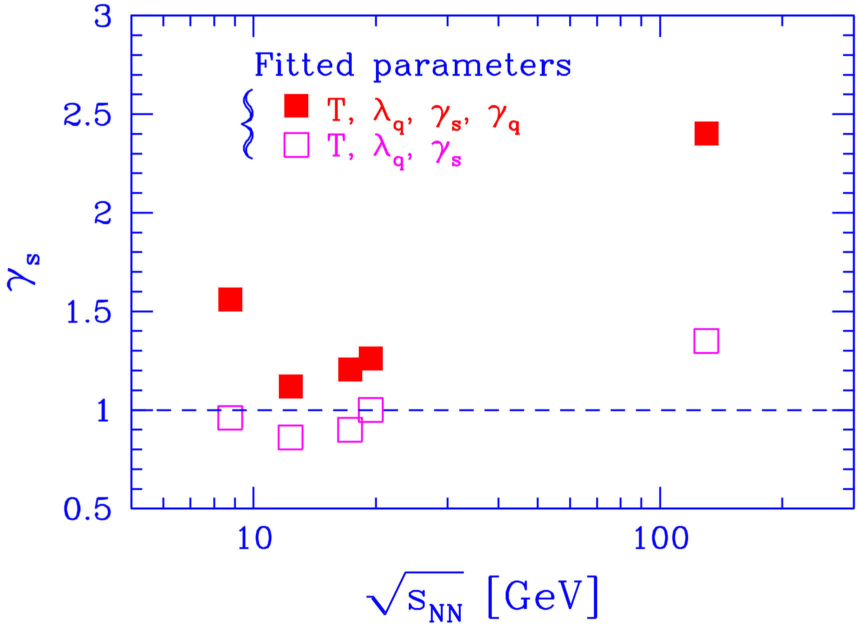
Apply statistical hadronization method to SPS energy scan results $\pi^{\pm}, \mathbf{K}^{\pm}, \Lambda, \overline{\Lambda}, \Phi$ of Pb-Pb NA49[1] **at (30AGeV), 40AGeV, 80AGeV, 158AGeV include for comparison WA85 S-W 200AGeV results, and compare to global study of QM2002 STAR/PHOENIX RHIC130 results. Generally, good statistical significance found allowing chemical non equilibrium, except at 40AGeV. Note results using chemical equilibrium, and semi-chemical equilibrium.**

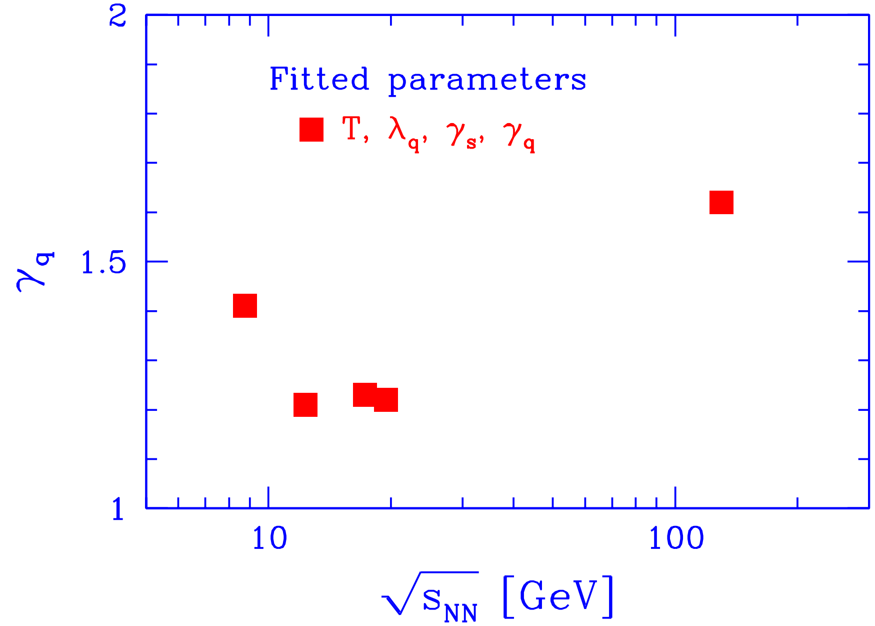
[1] We thank M. Gazdzicki for a very useful compilation of NA49 results



Hadronization phase space occupancy

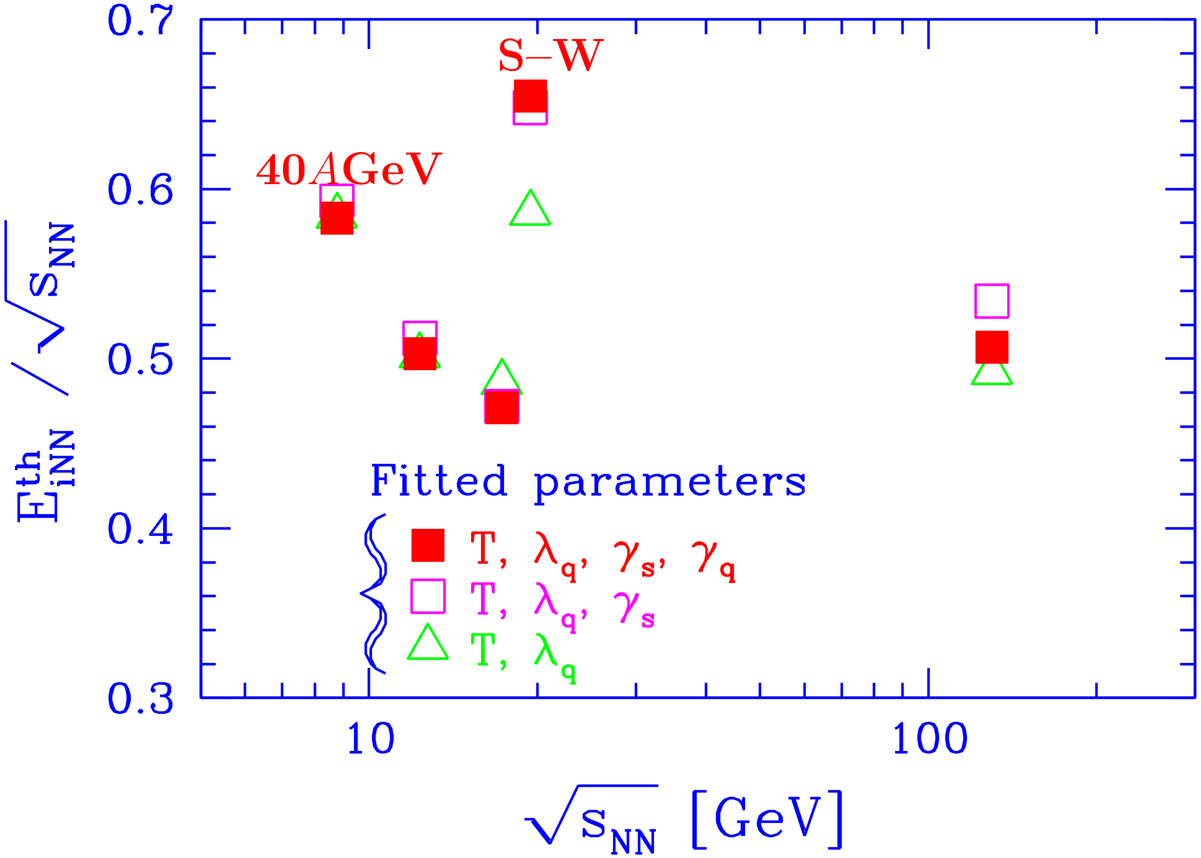






Allowing $\gamma_q^{\rm HG} \neq 1$ fits are statistically significant. We find, most clearly so at RHIC, that hadronization is accompanied by $\gamma_s^{\rm HG} > 1$. Recall: we used NA49 results for $K, \overline{K}, \Lambda, \overline{\Lambda}, \phi$ at 40,80,160 AGeV and find at top SPS energy using this data sample a $\gamma_q^{\rm HG} > 1$, but a bit smaller than cited earlier.

Behavior of energy stopping



Enhanced yield of fireball intrinsic (at rest) thermal energy $E^{\rm th}_{\rm i\,NN}$ (greater stopping) for 40*A*GeV and for the asymmetric S–W collision system.
NOTE very high RHIC result.
DATA shown is: SPS for 40,80,158 *A*GeV Pb and 200*A*GeV S-W/Pb, RHIC for 65+65*A*GeV Au

III STRANGENESS at SPS and RHIC

STRANGENESS / FINAL STATE LIGHT QUARK PAIRS

Wróblewski ratio: In 'color string snapping' strangeness pairs $s\bar{s}$ are 4 times fewer compared to light quark pairs $q\bar{q}$. Thermal production of strangeness changes expectations.

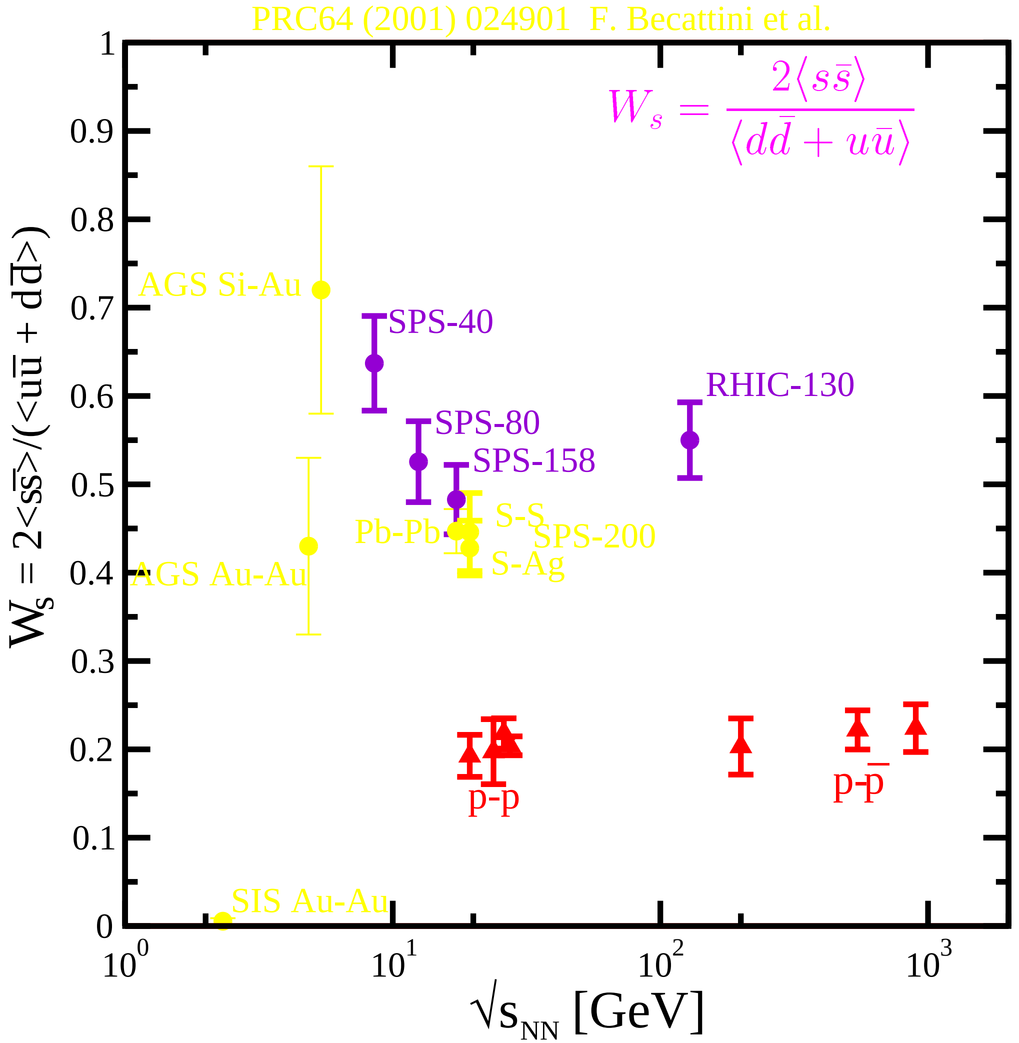
STRANGENESS / NET BARYON NUMBER

Strangeness production per thermal baryon participating in the reaction addresses the reaction energy alone, excluding variation in reaction geometry. Baryon number is conserved in hadronization. Theoretical analysis shows that true 'thermal' participants about 5-10% fewer than inferred from geometric cross section consideration.

PHASE SPACE OVERPOPULATION

At RHIC clear incompatibiloity with adiabatic relaxation via mixed phase. See large excess of (strange)particles. Explain by supercooling and sudden breakup in filamentation instability.

FROM SPS to RHIC: STRANGENESS vs FINAL STATE LIGHT QUARK PAIRS

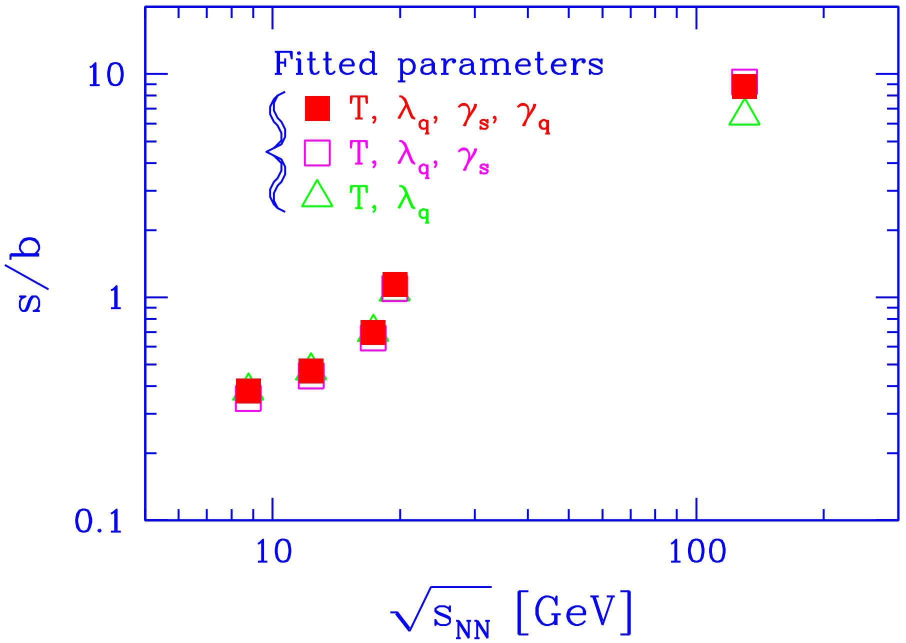


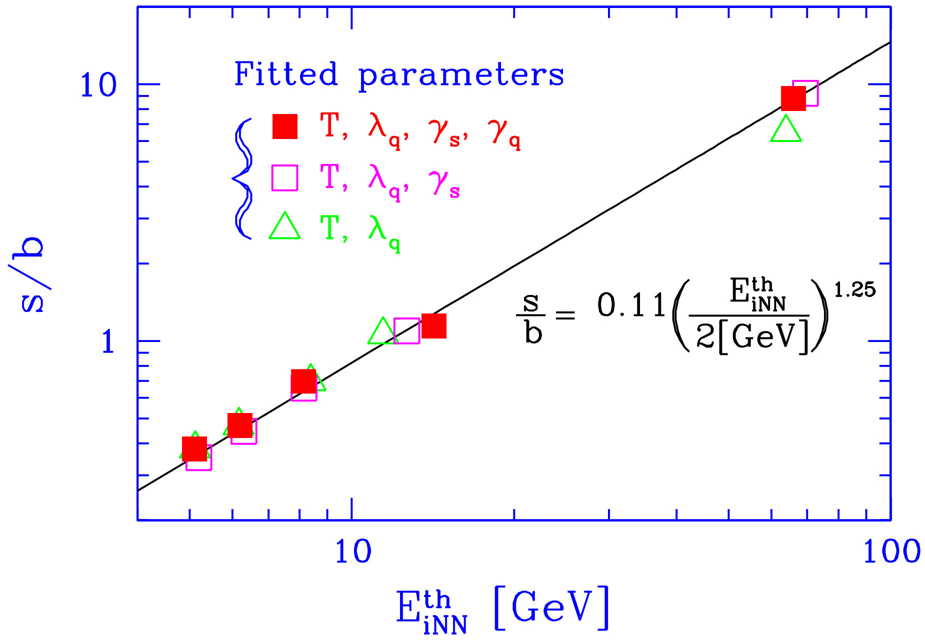
Strangeness compared to light quark production: (**"Wróblewski ratio"**)

only newly made s- and q-pairs are counted

Yield and $\sqrt{s}$ dependence very different for AA and elementary reactions

STRANGENESS vs NET BARYON CONTENT





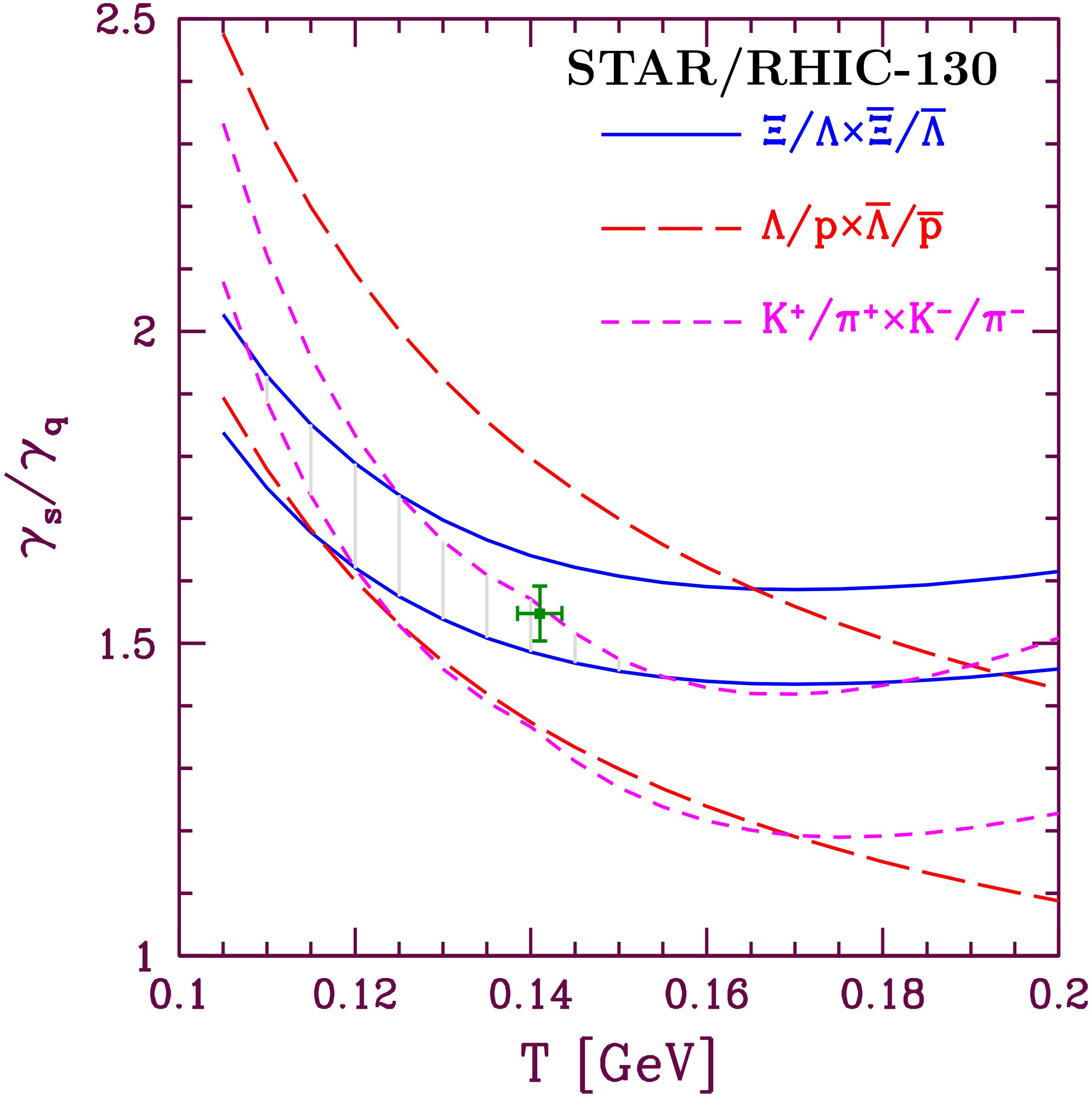
Strangeness per thermal baryon participating in the reaction grows rapidly and continuously. Gluon based thermal production mechanism UNDERSTOOD.

Strangeness production rises faster than entropy.

YIELD MUCH GREATER THAN IN NN-REACTIONS

The greatest difference between SPS and RHIC:
9-fold increase in strangeness per baryon
this is more than just increase in multiplicity

STRANGENESS PHASE SPACE OVERPOPULATED at RHIC



In some particle ratios all chemical factors but the ratio of final state phase space occupancies γ_s/γ_q cancel.

Equilibrium population CONVINCINGLY excluded.

CROSS: best fit to all data, Note:

OUTLOOK: Use particle distributions to determine matter dynamics (flow), and hadronization hyper surface.

Super-cooling 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} :

$$\vec{\mathcal{P}} \equiv \widehat{\mathcal{T}}\cdot\vec{n} = P\vec{n} + (P+\varepsilon)\frac{\vec{v}_{\rm c}\,\vec{v}_{\rm c}\cdot\vec{n}}{1-\vec{v}_{\rm c}^{\,2}}\,.$$

The pressure and energy comprise particle and the vacuum properties: $P = P_{\rm p} - \mathcal{B}\,, \quad \varepsilon = \varepsilon_{\rm p} + \mathcal{B}\,.$ Condition $\vec{\mathcal{P}} = 0$ reads:

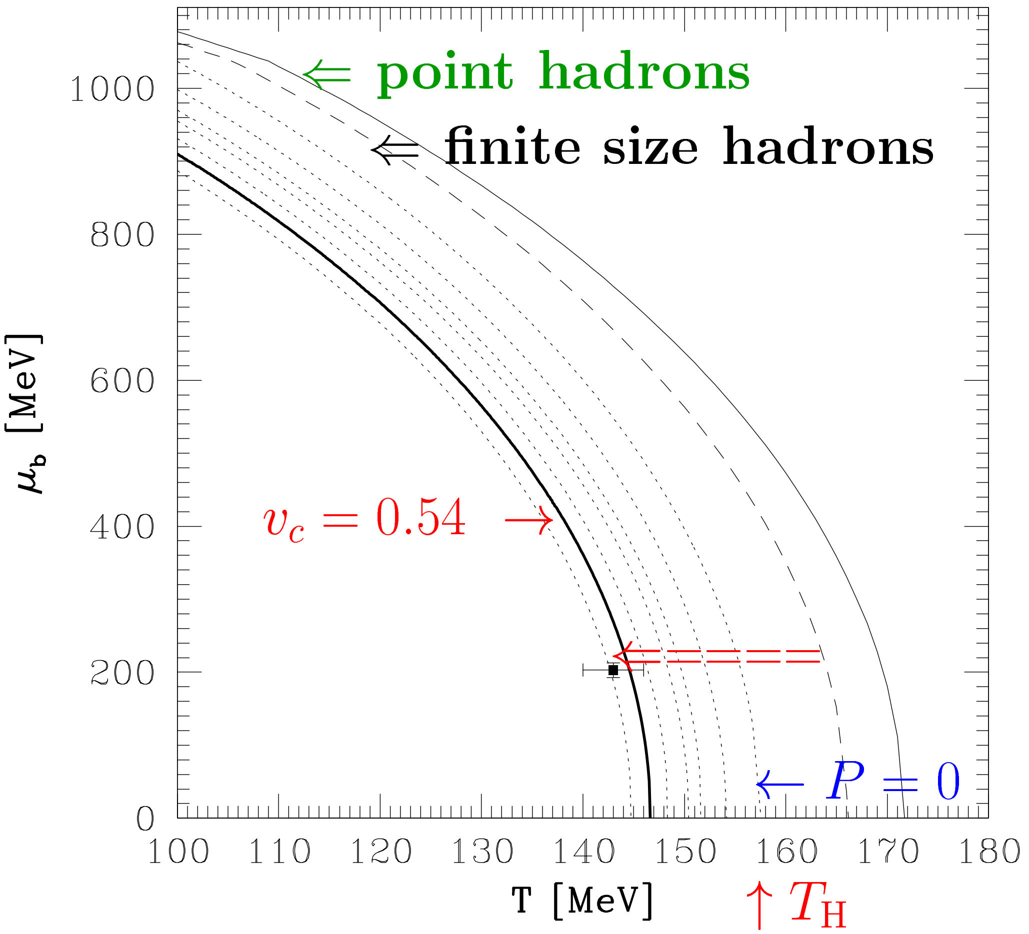
$$\mathcal{B}\vec{n} = P_{\rm p}\vec{n} + (P_{\rm p}+\varepsilon_{\rm p})\frac{\vec{v}_{\rm c}\,\vec{v}_{\rm c}\cdot\vec{n}}{1-v_{\rm c}^2}\,,$$

Multiplying with $\vec{n}$, we find,

$$\mathcal{B} = P_{\rm p} + (P_{\rm p}+\varepsilon_{\rm p})\frac{\kappa v_{\rm c}^2}{1-v_{\rm c}^2}\,, \qquad \kappa = \frac{(\vec{v}_{\rm c}\cdot\vec{n})^2}{v_{\rm c}^2}\,.$$

This requires $P_{\rm p} < \mathcal{B}$: QGP phase pressure P must be NEGATIVE. A fireball surface region which reaches $\mathcal{P}\to 0$ and continues to flow outward is torn apart in a rapid instability. This can ONLY arise since matter presses again 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: $T_c(\mu_{\rm b})|_{P_{eff}-\mathcal{B}=0}$ 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

$T_{\rm H} = 158$ **MeV Hagedorn temperature where** $P = 0$**, no hadron** P

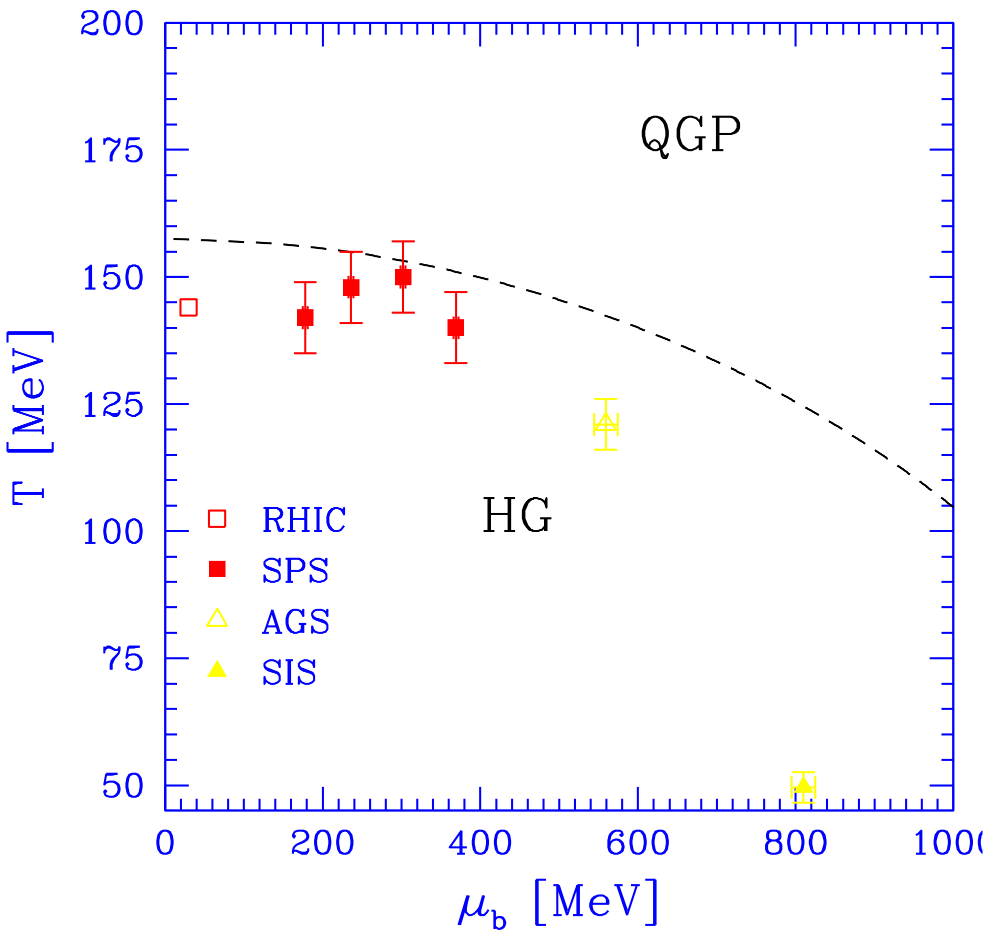
$T_f \simeq 0.9 T_H \simeq 143$ **MeV is where supercooled QGP fireball breaks up**

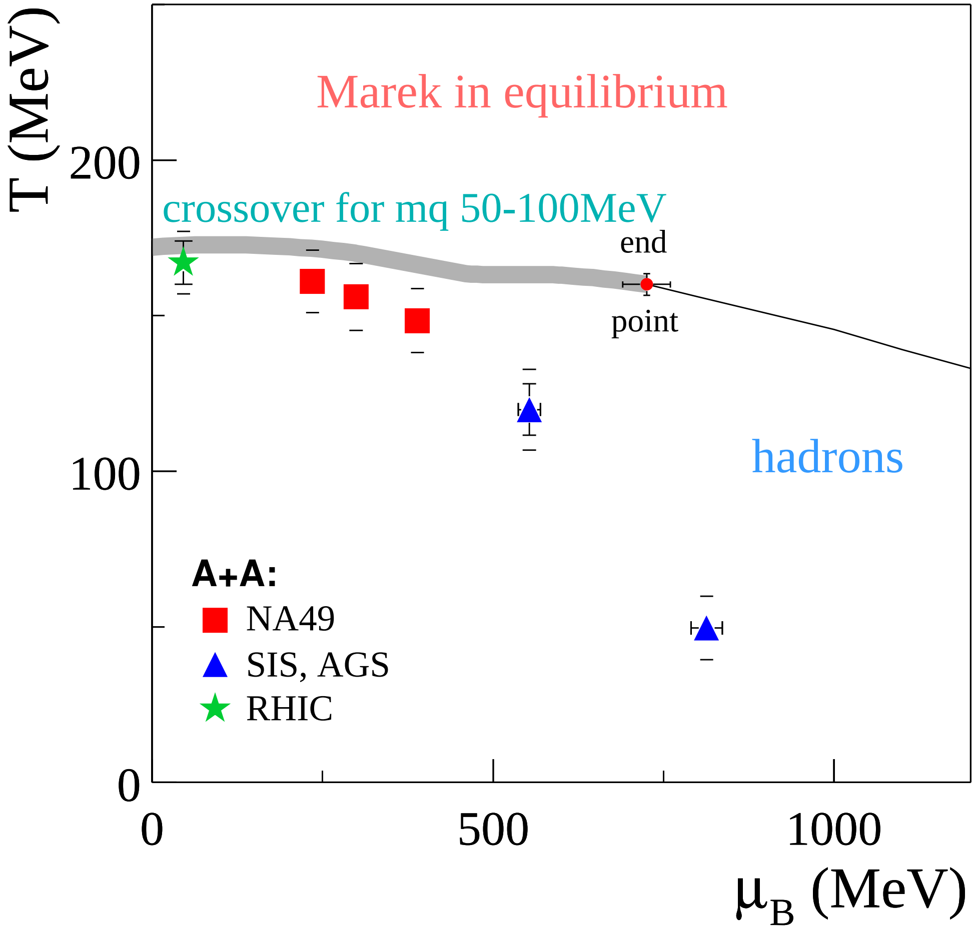
equilibrium phase transformation is at $\simeq 166$.

IV WHERE IS Onset of QGP Formation

Where is the onset of deconfinement as we change collision energy?

Consider hadron freeze-out conditions.





SUPERCOOLING CONFIRMED HERE

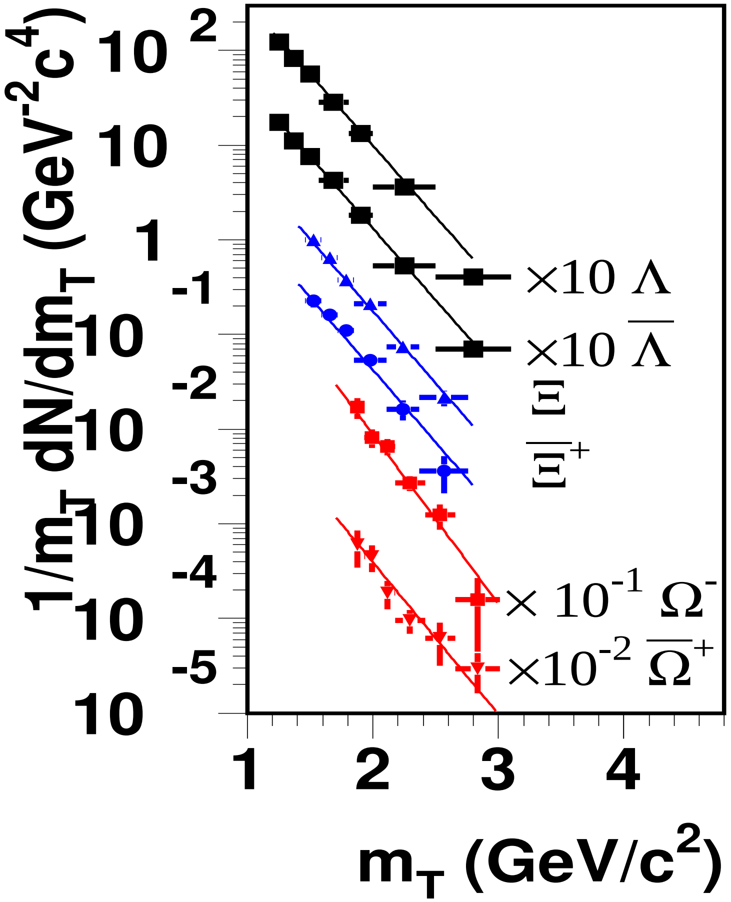
NOTE possibility of phase boundary hadronization

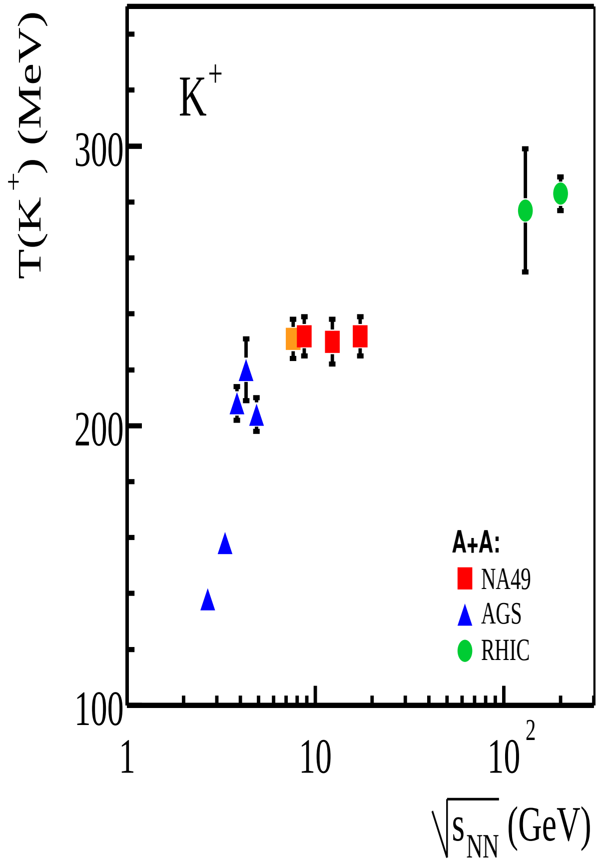
SPS: flatness of $m_\perp$ slopes as function of particle type, collision energy, centrality

This is expression of SUDDEN hadronization of a new phase of matter at SPS&RHIC.

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 $\overline{\Lambda}$





LOOKING ONLY AT Kaons and Pions WE ERR

Consider the K/π ratio – we would like to eliminate variation in this ratio due to change in baryon density, i.e. chemical conditions: look at

$$K^+(u\bar{s}) \propto \frac{\lambda_q}{\lambda_s}, \quad K^-(\bar{u}s) \propto \frac{\lambda_s}{\lambda_q} \quad \textbf{consider} \quad \frac{K}{\pi} = \sqrt{\frac{K^+}{\pi^+}\frac{K^-}{\pi^-}}$$

In Boltzmann limit the chemical potentials cancel.
K/π **dependent on Temperature** T **and phase space occupancy** $\gamma_s\gamma_q$**.**

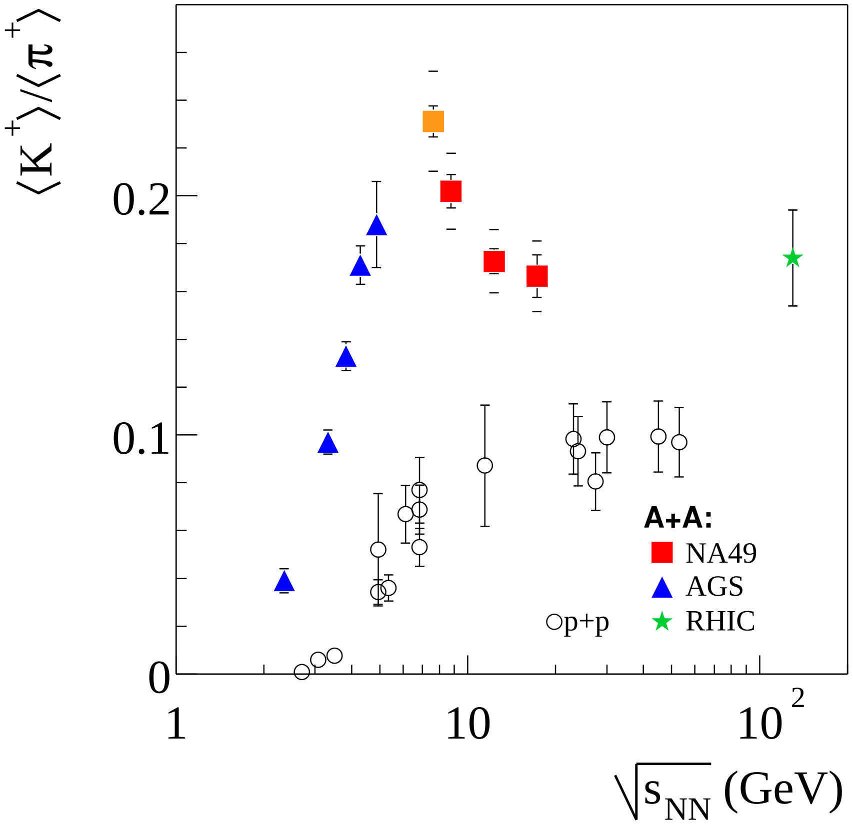
	Au–Au	Pb–Pb	Pb–Pb	Pb–Pb	Pb–Pb	Au–Au
$\sqrt{E_{\rm lab}}$ [GeV]	65+65	158	80	40	30	11.6
$\sqrt{s_{NN}}$ [GeV]	130	17.2	12.3	8.75	7.60	4.85
K/π	0.16	0.12	0.11	0.11	0.12	0.077

NO CHANGE AT SPS – Marek tooth due to baryon density
Step-up from SPS to RHIC is part of general s-enhancement.
A more sudden step between SPS and AGS maybe related to phase boundary, suggests a change in reaction mechanism producing strangeness.

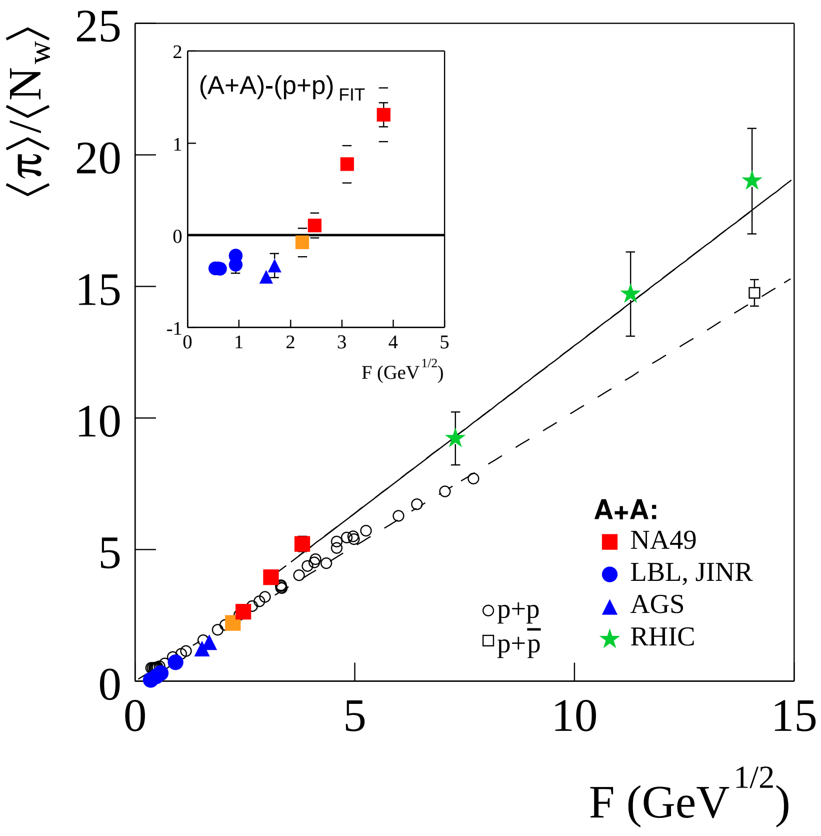
No tooth

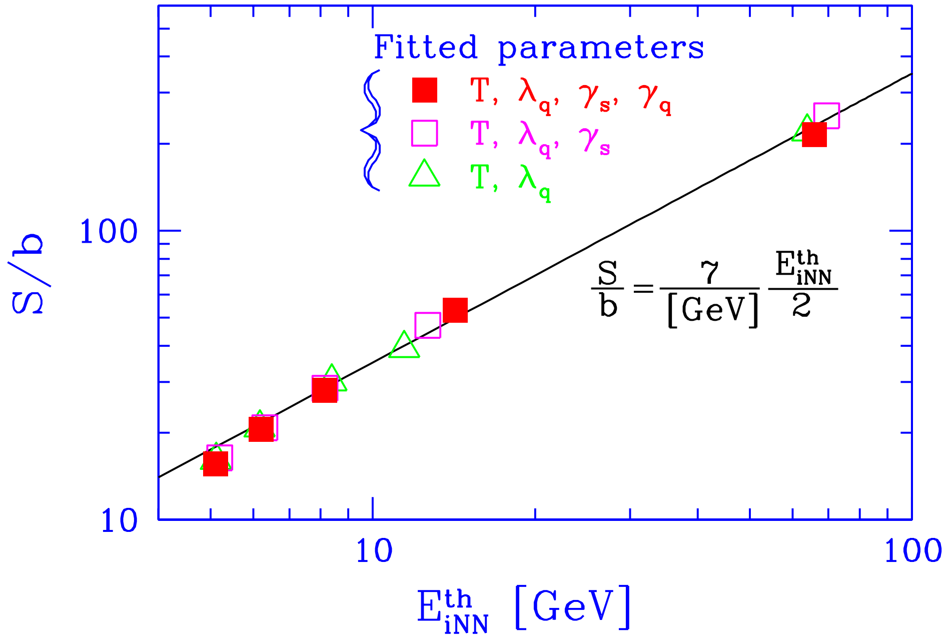
	Au–Au	Pb–Pb	Pb–Pb	Pb–Pb	Pb–Pb	Au–Au
$\sqrt{E_{\rm lab}}$ [GeV]	65+65	158	80	40	30	11.6
$\sqrt{s_{NN}}$ [GeV]	130	17.2	12.3	8.75	7.60	4.85
K/π	0.16	0.12	0.11	0.11	0.12	0.077

Compare to the renoun tooth:



Entropy Production



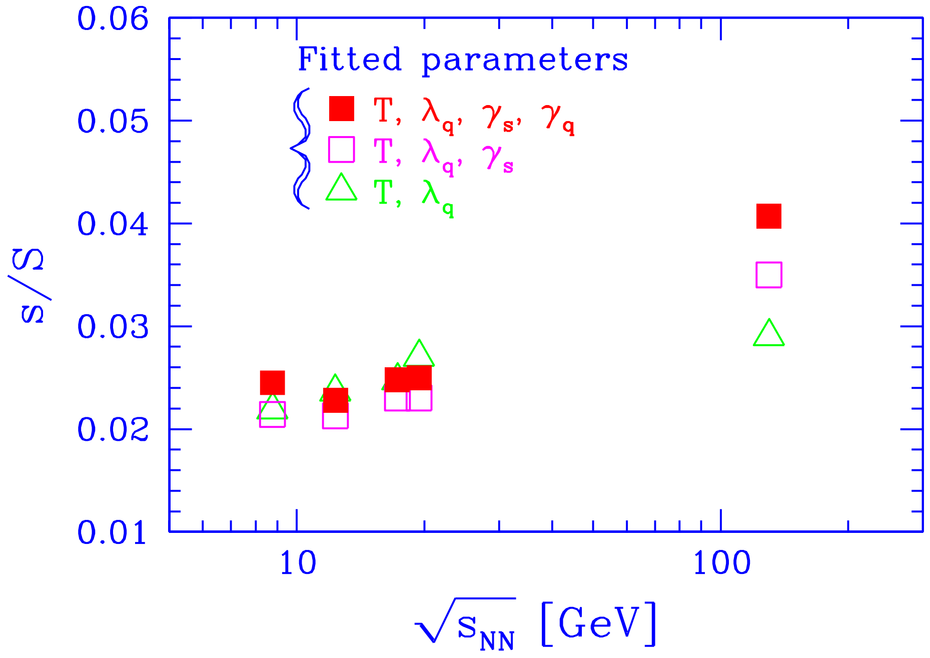


According to Marek

ENTROPY PRODUCTION per unit of available energy is UNIVERSAL Mechanism for parton based entropy production common for SPS and RHIC, possible drop off at 40AGeV. DATA: SPS for 40,80,158 AGeV Pb, 200AGeV S-W/Pb, RHIC for 65+65AGeV Au

STRANGENESS vs ENTROPY CONTENT

We see the rise of the K/π ratio in the strangeness per entropy rise between SPS and RHIC. Beware of equilibrium fits. AGS level expected to be significantly lower.



CONCLUSION: situation about QGP onset much less clear than suggested.
Supercooling stops around 80AGeV. Strangeness step up between 10 and 30AGeV.
RECOMMEND: obtain $\sqrt{K^+/\pi^+ \cdot K^-/\pi^-}$ as function of stopped energy content - finda step = onset of QGP

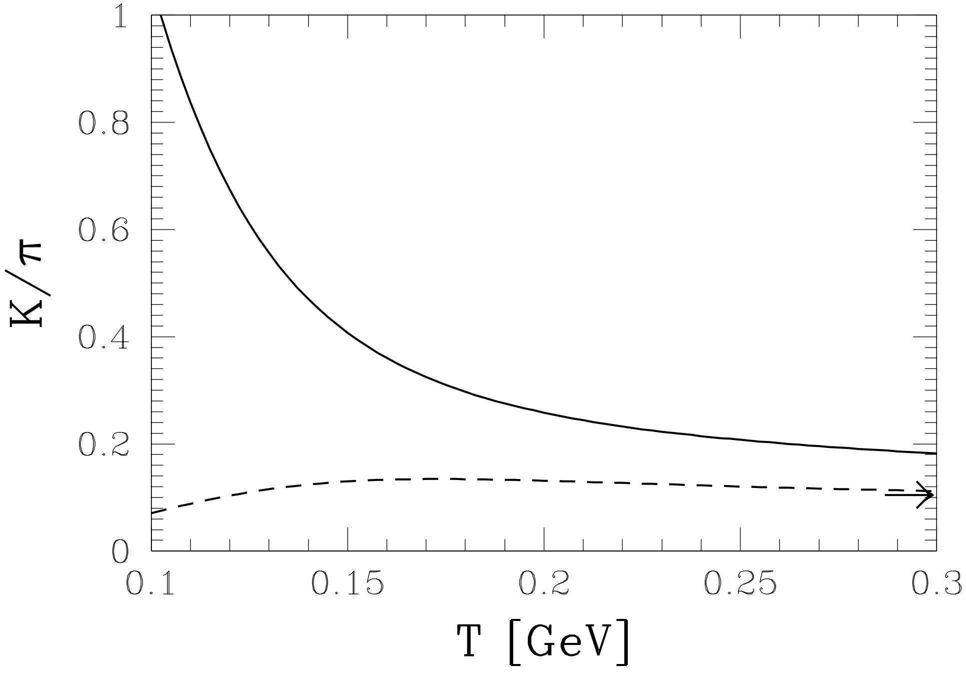
Future: Strangeness at LHC

LHC-Ions will be a 6000GeV collider, 30 times the maximum energy at RHIC.

Strangeness is slower to equilibrate chemically. This leads to overpopulation of phase space. At RHIC-130 $\gamma_s/\gamma_q \simeq 1.5$. What could be the maximum? **Condensation limits**

$$\gamma_q^2 \le e^{\frac{m_\pi}{T}} \qquad \gamma_s\gamma_q \le e^{\frac{m_K}{T}}$$

$$\to \gamma_s/\gamma_q \le e^{\frac{m_K-m_\pi}{T}}$$



Expect a relatively large enhancement. This will also enhance other strange particles, and favor strangeness over light quarks in the Wróblewski ratio.

FINAL REMARKS

Strangeness at CERN-SPS and BNL-RHIC is a well developed tool

allowing to study

Deconfinement and The Dynamics of QGP-Hadronization

Systematic study of strange hadrons fingerprint a new state of matter

---

Outlook:

Low energy: search for the onset of deconfinement

at RHIC study of hadronization dynamics, with the help of strange resonances

---

FUTURE:

strangeness highly overpopulated at LHC?

ALSO: charm at RHIC and LHC

another flavor tool in the study of deconfined matter

. . . Only deconfinement specific observable studied is strangeness and there is no doubt that QGP has been formed at RHIC and most probably at SPS