Centrality AND Collision Energy Dependence of Bulk Fireball Properties

APS-Tampa, 17 April 2005

We study both statistical parameters an more importantly, the physical properties of the soft, strange hadron fireball source. We evaluate the entropy and strangeness content of the fireball. We find that as the volume and/or energy increases, there is a sudden change of the chemical composition: a source which at low volume -energy is chemically under-saturated, turns into a chemically over-saturated state. We discuss possible mechanisms associated with the identified rapid change in system properties. We propose that the chemically over-saturated 2+1 flavor hadron matter system undergoes a 1st order phase transition.

BASED ON: nucl-th/0412072 by J. Rafelski, J. Letessier, G. Torrieri and;
nucl-th/0504028 by J. Letessier and J. Rafelski

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

Presented by Johann Rafelski
Department of Physics
University of Arizona
TUCSON, AZ, USA

WHY we study S (entropy):

- **Many QCD degrees of freedom in a chemically equilibrated system, but we must keep track of approach to equilibrium:**

$$8_\mathrm{c} \times 2_\mathrm{s} = 16 \quad \text{for finite lifespan:} \quad 16 \to \gamma_G(t)16,$$
$$3_\mathrm{c} \times 2_q \times 2_\mathrm{s} = 12 \qquad 12 \to \gamma_q^\mathrm{QGP}(t)12,$$
$$3_\mathrm{c} \times 1_s \times 2_\mathrm{s} = 6 \qquad 6 \to \gamma_s^\mathrm{QGP}(t)6\ .$$

- **Phase space occupancy factors normally $\gamma_i < 1$; exceptions:**
  - **Fast expansion-dilution**
  - **Fast phase transition/transformation:**

- **Hierarchy of QGP approach to equilibrium which produces ENTROPY and later STRANGENESS:**

$$\gamma_G(t) \to 1 \ \ \text{followed by}\ \gamma_q^\mathrm{QGP}(t) \to 1,\ \ \text{and finally}\ \gamma_s^\mathrm{QGP}(t) \to 1$$

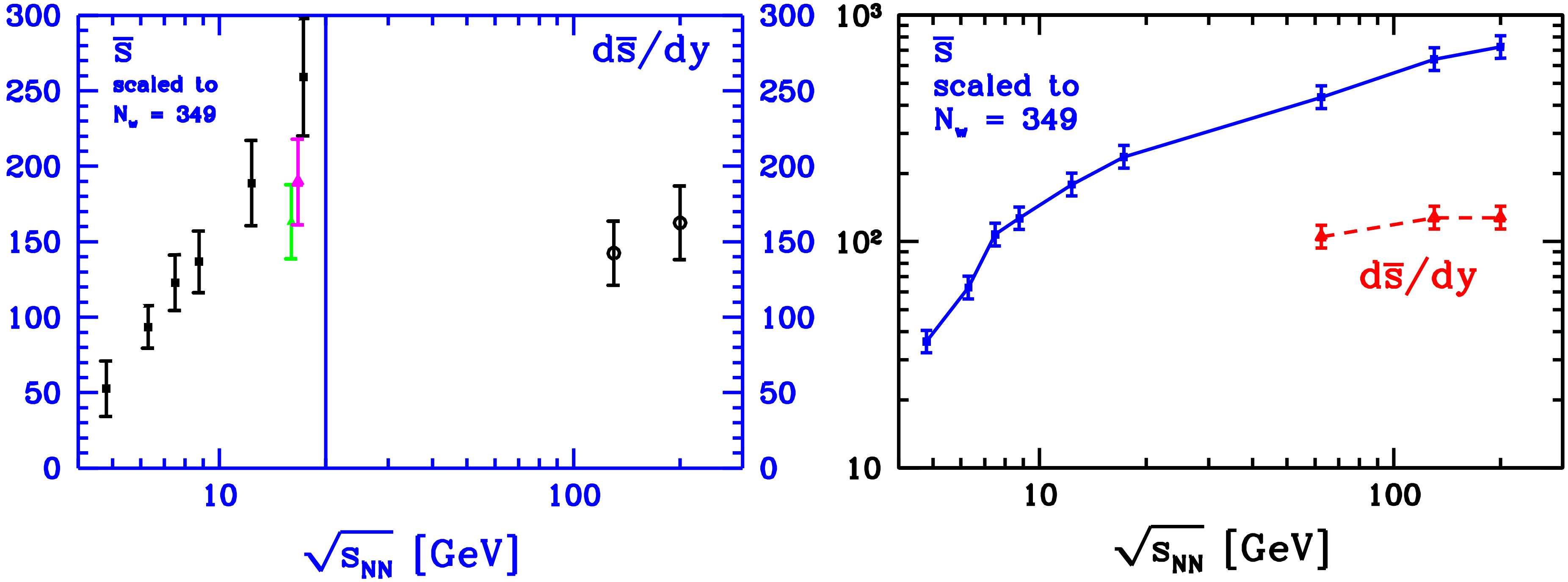
- **V controls the lifespan and T_i the speed of chemical relaxation; QCD reactions many times more effective (faster) for s see P. Koch, B. Müller, JR Phys. Rept. 142,167 (1986) and for S K. Geiger, PRD46,4986 (1992) – entropy and strangeness content at QGP hadronization is higher compared to normal.**

- **Relative s/S yield measures number of active degrees of freedom and degree of relaxation when strangeness production freezes.**

$$\frac{s}{S} = \frac{\gamma_s^\mathrm{QGP}(3/\pi^2)T^3(m_s/T)^2K_2(m_s/T)}{(32\pi^2/45)T^3 + n_\mathrm{f}[(7\pi^2/15)T^3 + \mu_q^2 T]} \to \frac{0.027\gamma_s^\mathrm{QGP}}{0.38\gamma_\mathrm{G} + 0.12\gamma_s^\mathrm{QGP} + 0.5\gamma_q^\mathrm{QGP} + 0.054\gamma_q^\mathrm{QGP}(\ln\lambda_q)^2} \to 0.027.$$

Experimental STRANGENESS EXCITATION FUNCTION

No change in reaction mechanism visible in the s yield



LEFT: sum of $\bar{s}$ quarks in all hadrons. At low energy practically $2K^+$, Experiment Green: C–C and Violet: Si–Si, other Au–Au, Pb–Pb, Right: Fit to data

QUARK CHEMISTRY

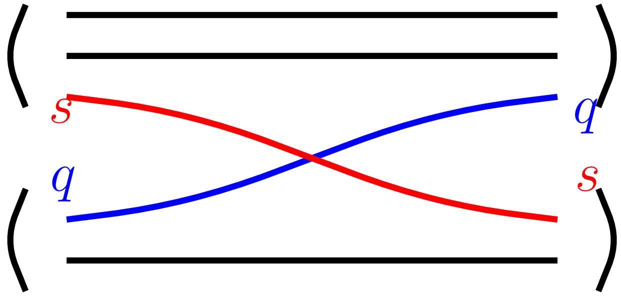
When we compare yields of particles of different quark content we need to consider chemical potentials, in principle one potential for each hadron! Simplification: follow quark content and remember that quarks are produced in pairs.

Yields of $s, \bar{s}, q, \bar{q} \rightarrow$ NEED 4 CHEMICAL ABUNDANCE PARAMETERS

γ_i	controls overall valance abundance of quark $(i = q, s)$ pairs in HADRONS	Absolute chemical equilibrium
λ_i	(μ_B, μ_S) controls difference between strange and non-strange quarks $(i = q, s)$	Relative chemical equilibrium

HG-EXAMPLE: redistribution, production of strangeness

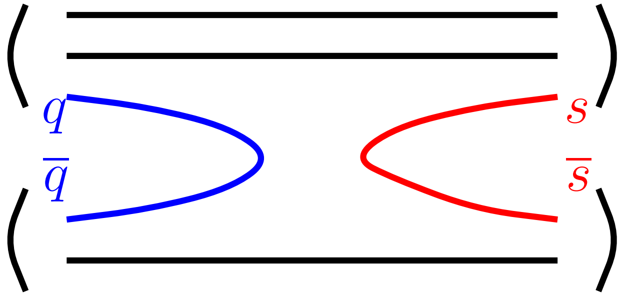
Relative chemical equilibrium



EXCHANGE REACTION

λ_i

Absolute chemical equilibrium



PAIR PRODUCTION REACTION

γ_i

Statistical Hadronization fits of hadron yields

FAST phase transformation implies chemical nonequilibrium:
the phase space density is in general different in the two phases. To preserve entropy (the valance quark pair number) across the phase boundary there must be a jump in the phase space occupancy parameters γ_i.
This replaces the jump in volume in a slow reequilibration with mixed phase.

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 NATO supported 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 (next speaker) nucl–th/0404083
Online SHARE: Steve Steinke No fitting online (server too small)
http://www.physics.arizona.edu/˜steinke/shareonline.html

Aside of particle yields, also PHYSICAL PROPERTIES of the source are available, both in SHARE and ONLINE.

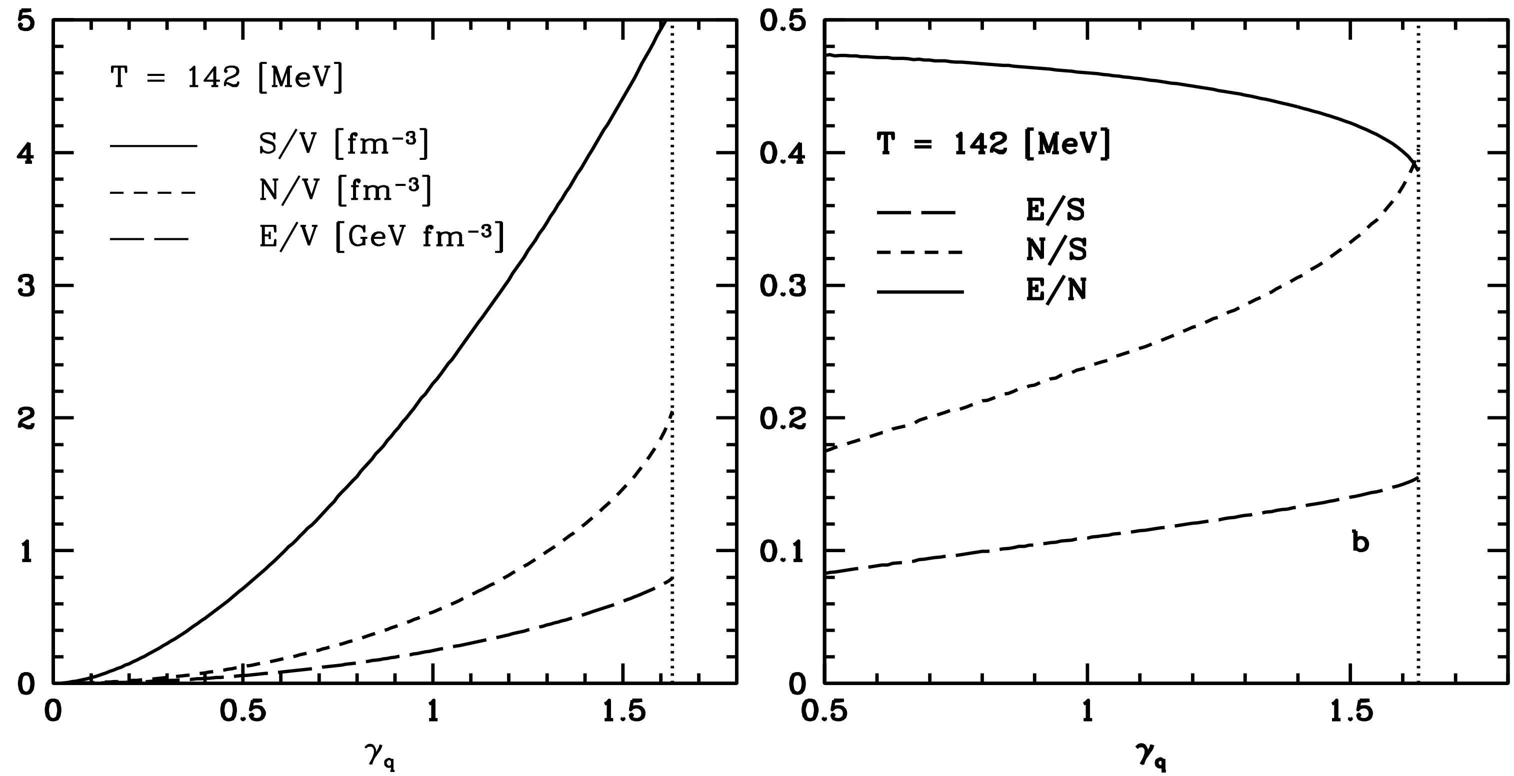
CAN WE ESTIMATE THE EXPECTED γ_q^{HG} from QGP?

Maximize entropy density to meet the high S/V density at hadronization.

$\gamma_q^2 \to e^{m_\pi/T}$: **Example:maximization of entropy density in pion gas** $E_\pi = \sqrt{m_\pi^2 + p^2}$

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

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

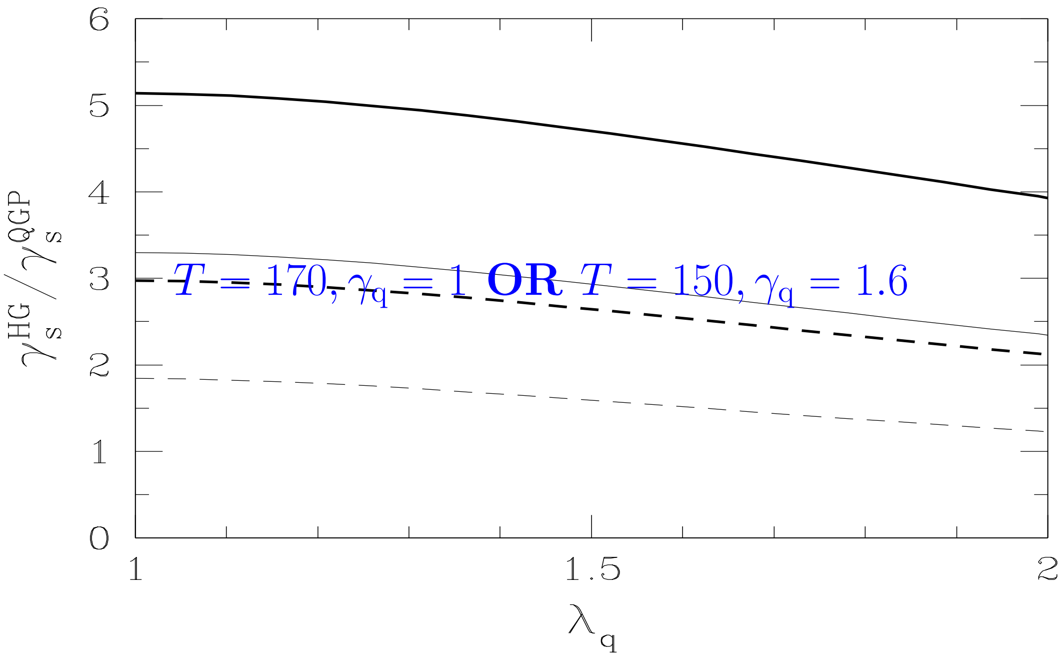


CAN WE ESTIMATE THE EXPECTED $\gamma_s^{\rm HG}$ from QGP?

COMPUTE EXPECTED RATIO OF $\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$

In sudden hadronization, $V^{\rm HG} \simeq V^{\rm QGP}$, $T^{\rm QGP} \simeq T^{\rm HG}$,
the chemical occupancy factors accommodate the different magnitude of particle phase space, JR and J. Letessier, Nucl.Phys.A715:98-107,2003

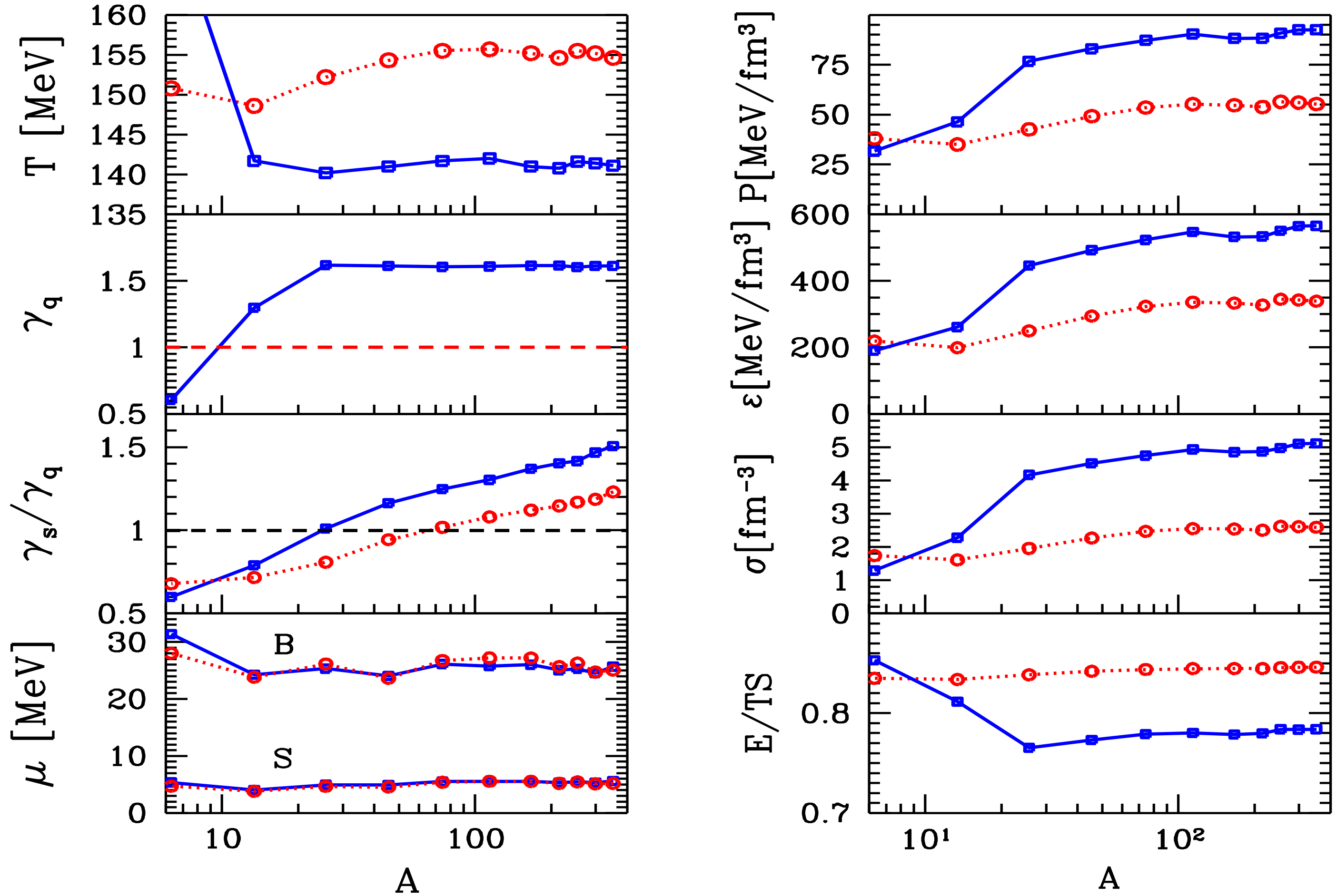
→ $T = 170, \gamma_{\rm q} = 1$ **OR** $T = 150, \gamma_{\rm q} = 1.6$



$\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$ in sudden hadronization as function of $\lambda_{\rm q}$. Solid lines $\gamma_{\rm q} = 1$, and short dashed $\gamma_{\rm q} = 1.6$. Thin lines for $T = 170$ and thick lines $T = 150$ MeV, common to both phases.

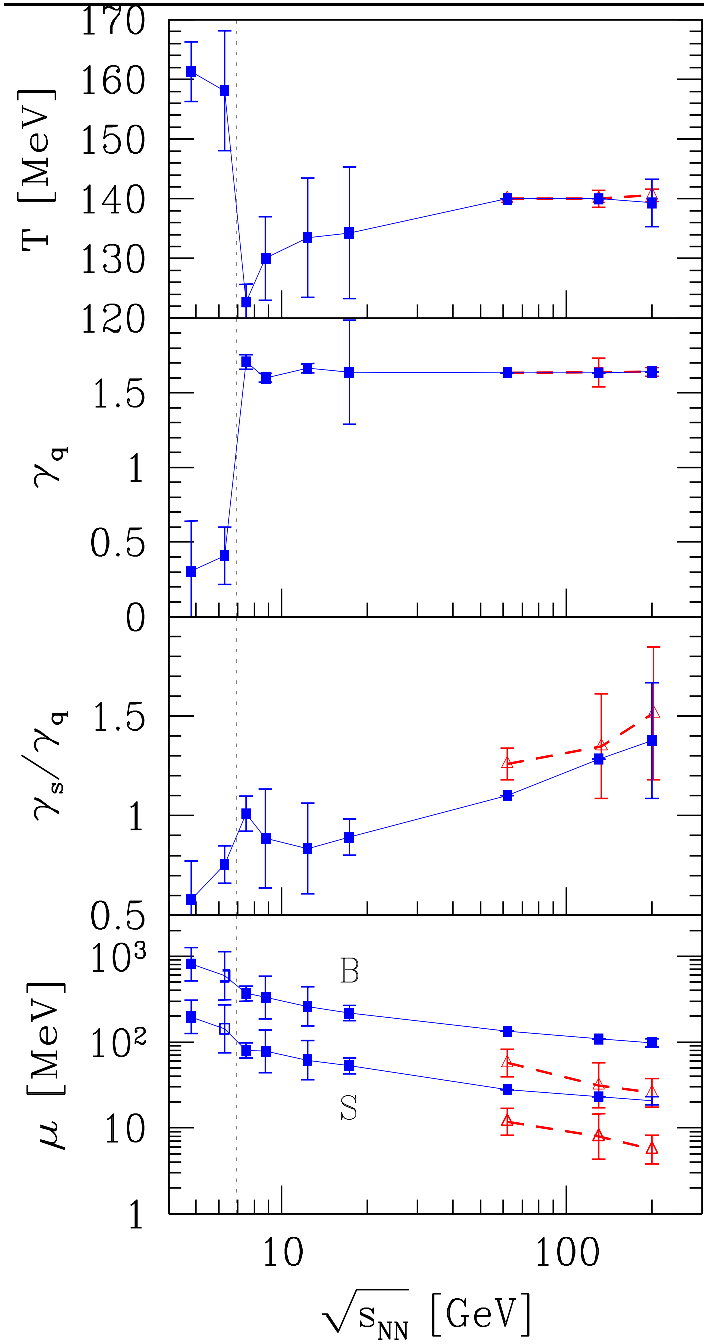
$$\gamma_s^{\rm HG} \simeq 2...5\gamma_s^{\rm QGP}$$

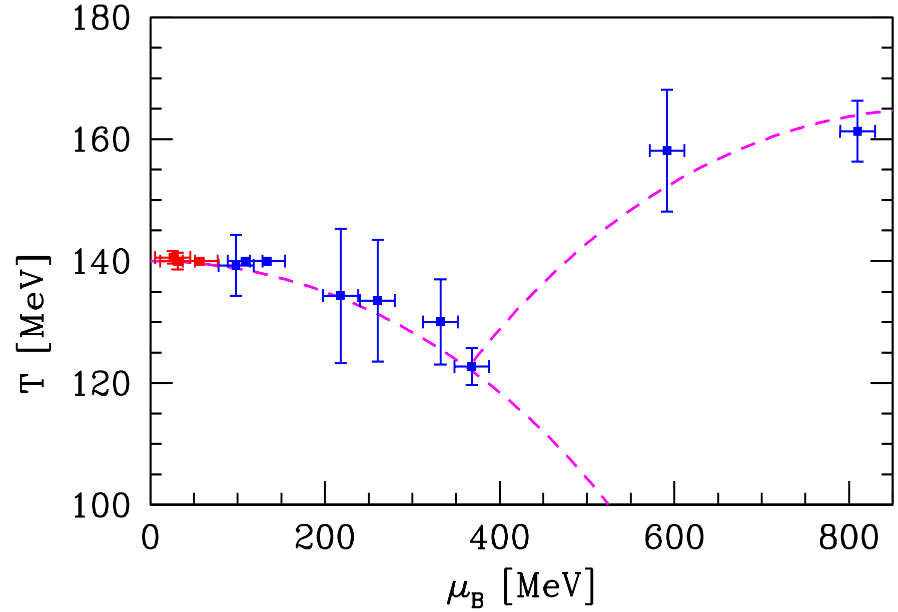
RHIC200 dependence on centrality



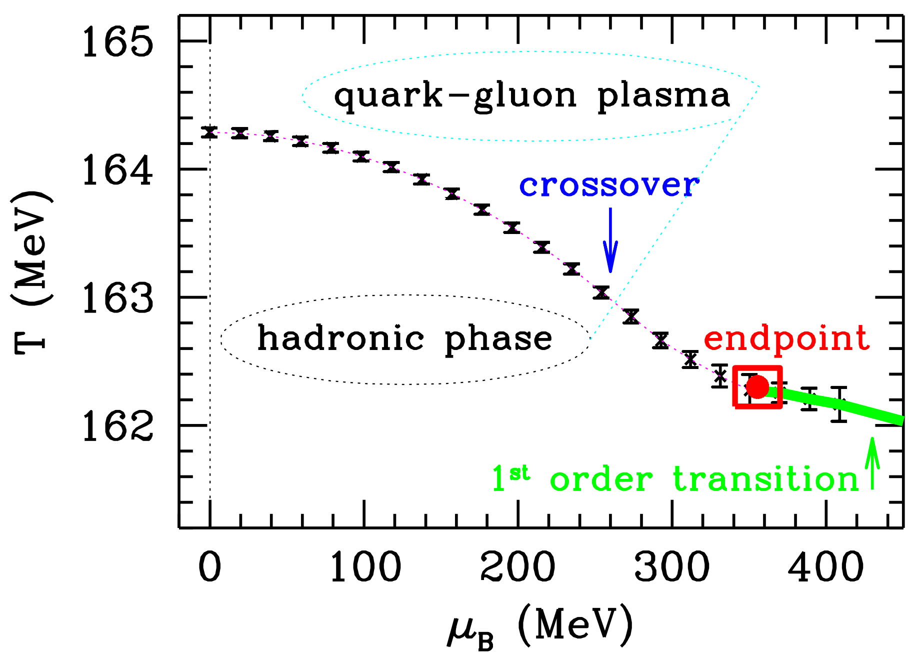
LINES: $\gamma_s \neq 1, \gamma_q = 1$ $\gamma_s, \gamma_q \neq 1$ **Note:** γ_q **moves from under-saturated to over-saturated value,** P, σ, ϵ **increase by factor 2–3, at** $A > 20$, E/TS **decreases with** A. **To obtain this result: use data from PHENIX, PRC69,034909 (2004) for** $\pi^{\pm}, \mathrm{K}^{\pm}, p, \bar{p}$ **and STAR nearly centrality independent** ϕ/K^{-}, K^{*}/K^{-}, **employ constrains on** Q/b, $\langle s\rangle - \langle \bar{s}\rangle = 0$. **Statistical + fit errors are seen in fluctuations, systematic error impacts absolute normalization by** $\pm 10\%$. **JR, J. Letessier and G. Torrieri, nucl-th/0412072**

SUMMARY OF $\sqrt{s_{\rm NN}}$ FIT RESULTS: Statistical parameters





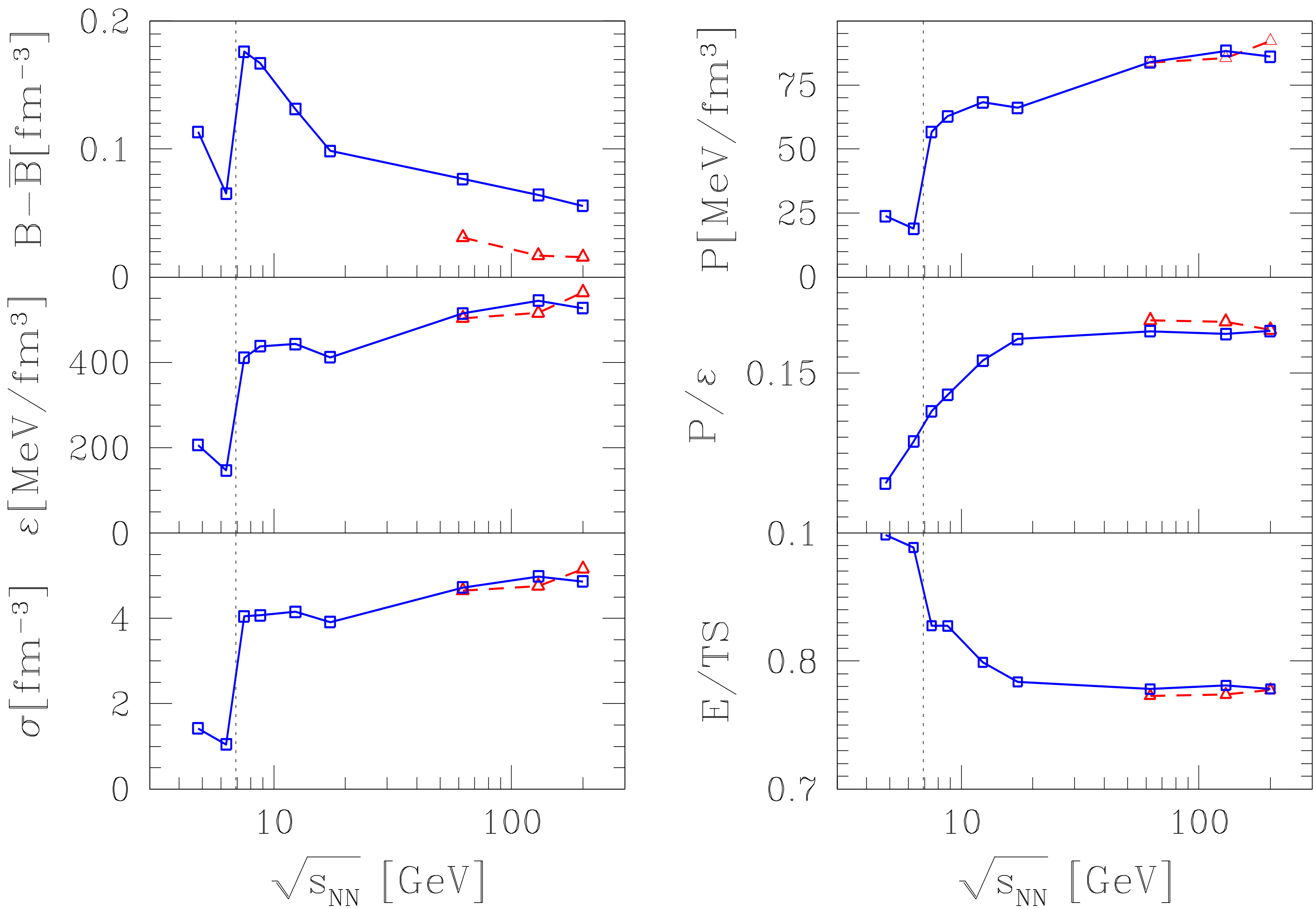
to be compared to, see below:



Why low/high PHASE BOUNDARY Temperature?

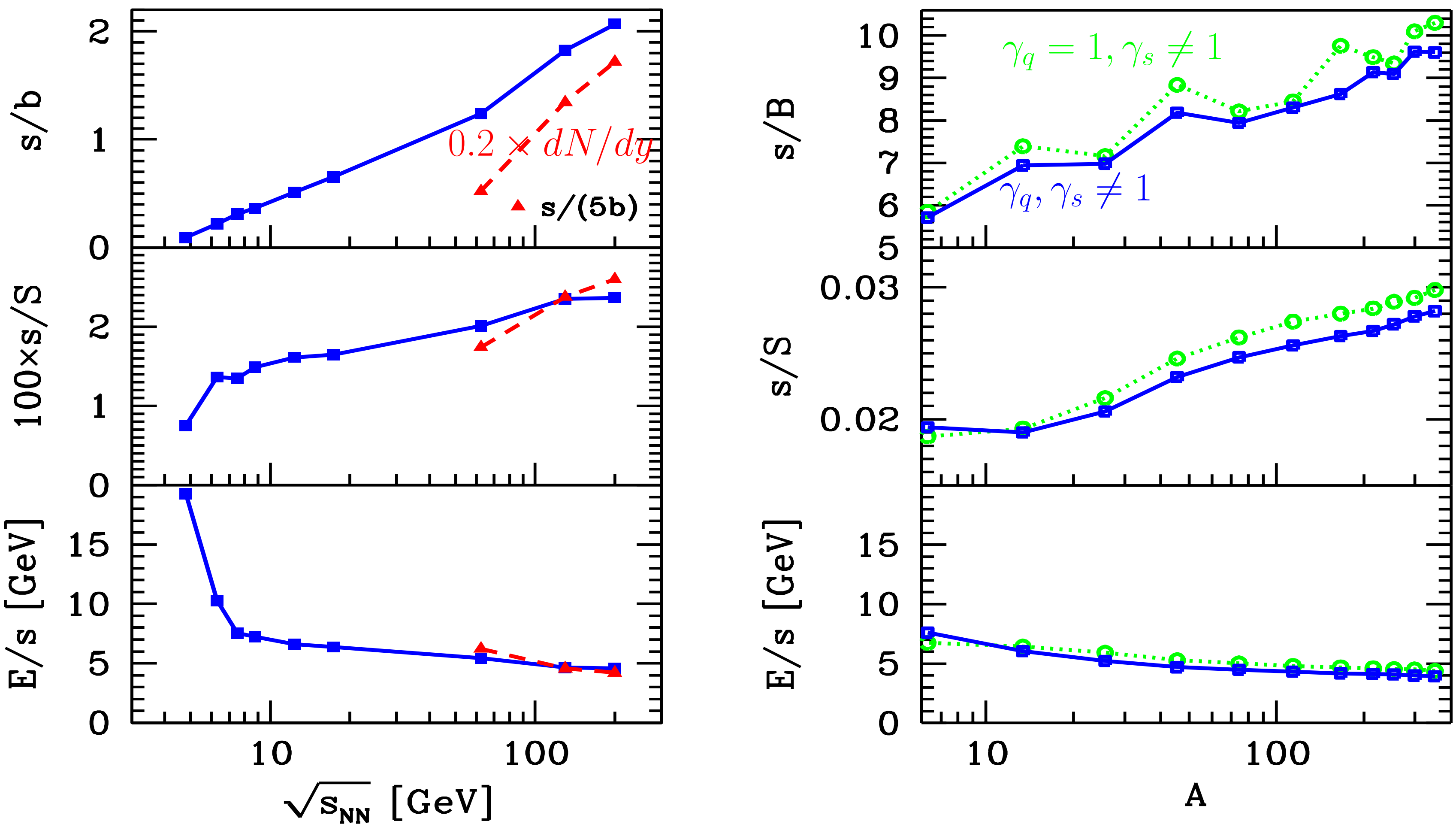
- **Dynamical effects of expansion:**
  colored partons like a wind, blow out the boundary
- **Degrees of freedom**
  - **Temperature of phase transition depends on available degrees of freedom.**
    For 2+1 flavors: $T = 162 \pm 3$, **for** $\gamma_s \to 0$
    $2 + 1 \to 2$ **flavor theory with** $T \to 170$ **MeV,**
    what happens when $\gamma_s \to 1.5$?
  - **The nature of phase transition/transformation changes when number of flavors rises from 2+1 to 3 is effect of** $\gamma_i > 1$ **creating a real phase transition?**
- **at high** μ_B **we encounter**
  - **either conventional hadrons (contradiction with continuity of quark related variables: strangeness, strange antibaryons).**
  - **or more likely, a new heavy (valon) quark phases.**
    Undersaturation of phase space compatible with higher T**.**

PHYSICAL PROPERTIES as function of $\sqrt{s_{\rm NN}}$



Note that behavior is the same as we saw as function of *A*: the large jumps by factor 2–3 in densities (to left) and pressure (on right) as the collision energy changes from 20 GeV to 30 GeV. **There is clear evidence of change in reaction mechanism.** **There no difference between top SPS and RHIC energy range.**

s/b and s/S rise with energy and centrality E/s falls



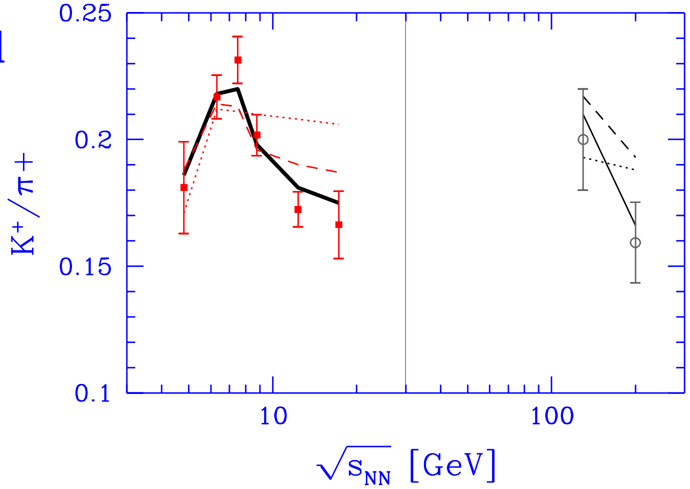
$s/S \to 0.027$ as function of $\sqrt{s_{\rm NN}}$ and V: INITIAL QGP?!
Energy/strangeness cost difference at $\sqrt{s_{\rm NN}^{\rm cr}}$, $\to$ new mechanism!?

STRANGENESS, ENTROPY, THE HORN, AND QGP DISCOVERY

1. **Full analysis of energy excitation functions and centrality dependence is now available**

2. 

   Structure between 20 and 30 GeV understood within chemical nonequilibrium model, same type of sudden behavior change as is seen in centrality dependence.

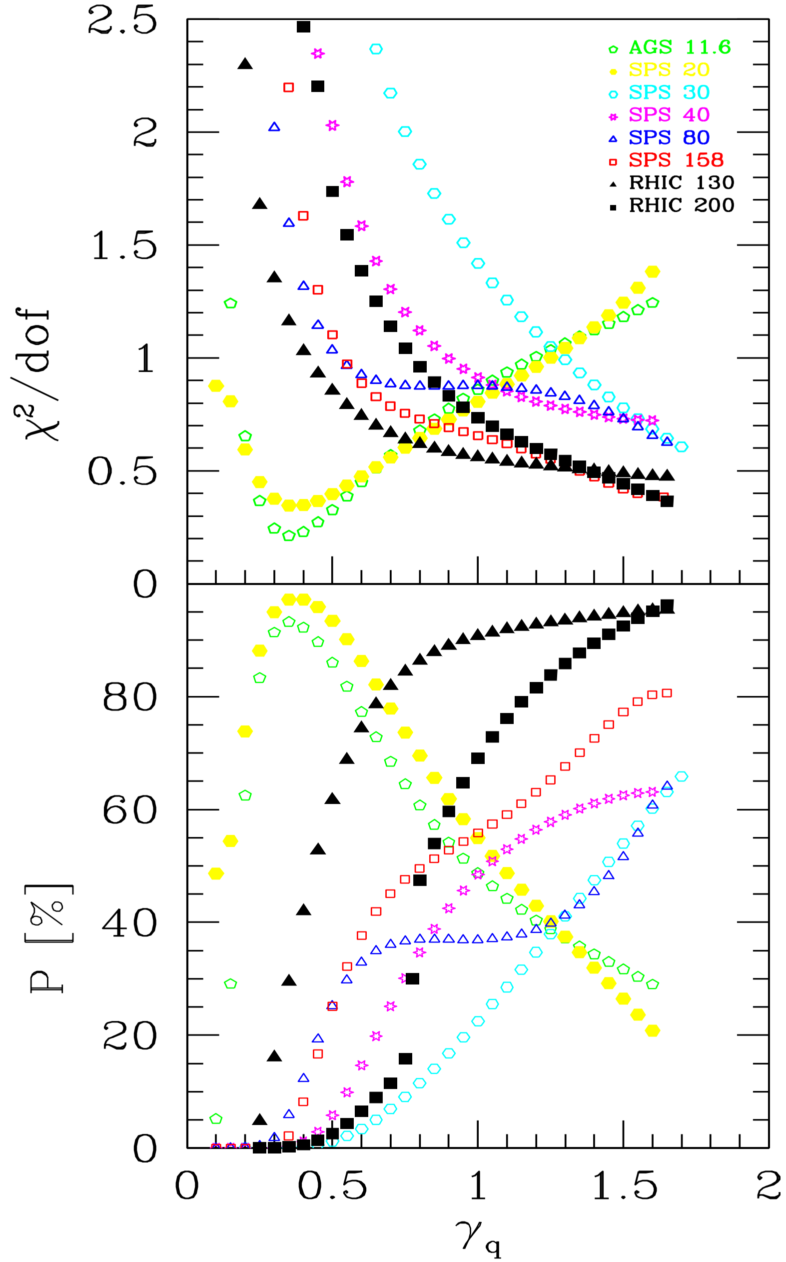
   The winner **and his horn**

3. **Two different phases hadronize - see phase diagram.**
   - **At high energy and volume, an entropy rich phase with the count of degrees of freedom expected from QGP ($s/S \to 0.027$).**
   - **At low collision energy we find a high energy cost to produce strangeness, and phase space undersaturated**

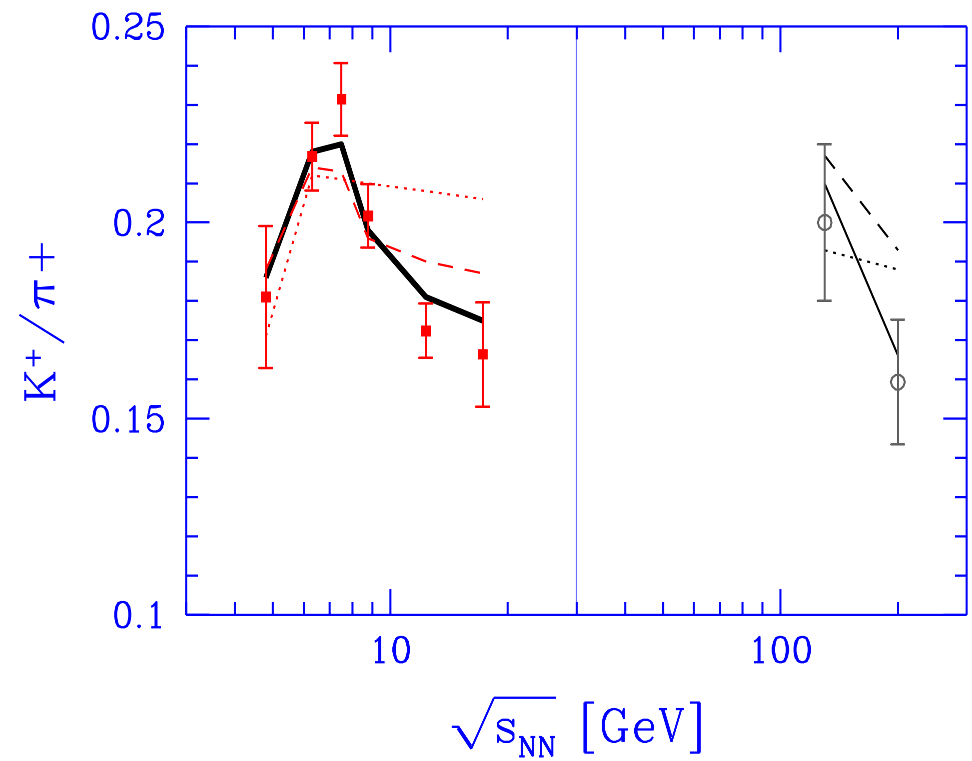
4. **At high energy and volume as expected if QGP fireball: strangeness nearly equilibrated at hadronization. Overpopulates HG phase space.**

Have we found QGP threshold?
My opinion: 'valon' quark deconfinement at AGS transition to pQGP at SPS/RHIC.

Fit particle yields at every energy: WE DESCRIBE THE HORN



Allowing chemical nonequilibrium we see that between 20 and 30GeV the fit jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The fits have reasonable quality, in particular those relevant to understanding how the horn is created.



Particle yield systematics