Strangeness and Phase Changes in Relativistic Heavy Ion Collisions

QCD Critical Point BNL-9/10 March, 2006, Presented by J. Rafelski

Strangeness flavor is the natural observable of the baryon-rich deconfined quark-gluon state of matter. We discuss here how deviation from chemical equilibrium of strangeness in QGP impacts phase structure. We show hoe one can interpret the NA49-Horn by allowing chemical nonequilibrium among hadrons.

1. **MATTER-ANTIMATTER PRODUCTION MECHANISM**
2. **RISE OF STRANGENESS YIELD MOVES PHASE BOUNDARY**
   $n_f = 2 + \gamma_s^{\rm QGP}$
3. **THEORETICAL INTERPRETATION OF THE NA49 'HORN'**
4. **PHYSICAL PROPERTIES OF THE FIREBALL**

See also nucl-th/0504028, nucl-th/0511016 by J.Letessier and J.Rafelski

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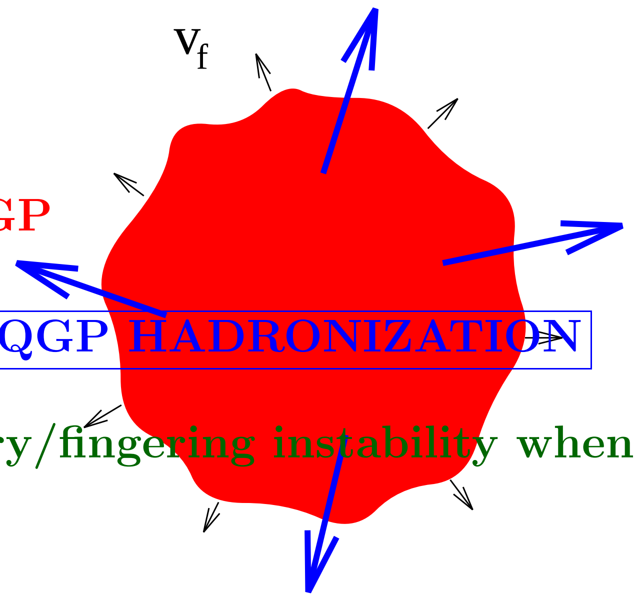
1. MATTER-ANTIMATTER PRODUCTION MECHANISM

For the past 15 years experiments demonstrate symmetry of $m_\perp$ spectra of strange baryons and antibaryons in baryon rich environment.

Interpretation: Common matter-antimatter particle formation mechanism, little antibaryon re-annihilation in sequel evolution.

Appears to be free-streaming particle emission by a quark source into vacuum. Such fast hadronization confirmed by other observables: e.g. reconstructed yield of hadron resonances. Note: within HBT particle correlation analysis: nearly same size pion source at all energies

Practically no hadronic 'phase'!
No 'mixed phase' either!
Direct emission of free-streaming hadrons from exploding filamentary QGP



Develop analysis tools viable in SUDDEN QGP HADRONIZATION

Proposed reaction mechanism: filamentary/fingering instability when in expansion pressure reverses.

SUDDEN HADRONIZATION DOES NOT APPLY TO LOW $\sqrt{s}$

We only have evidence for sudden hadronization at reaction energies ABOVE the horn. It is likely that at $\sqrt{s}$ below the horn hadronization is NOT SUDDEN. To test for this RHIC-critical should measure asymmtry of spectra of strange baryons and antibaryons. Recall that in NN reactions spectra of baryons B, and antibaryons $\overline{B}$ are completely different.

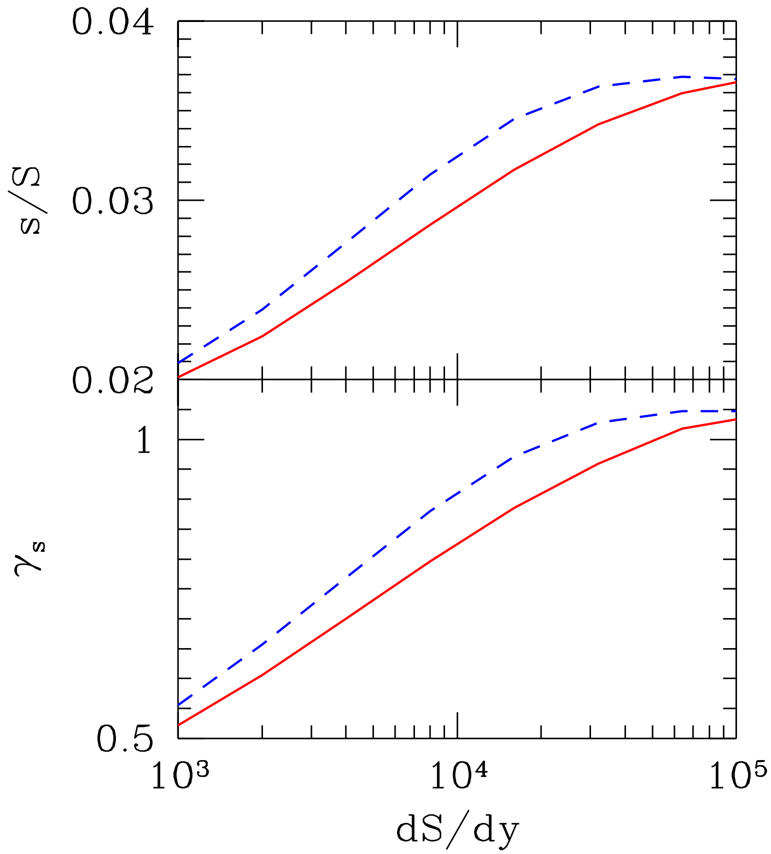
2. RAPID RISE OF STRANGENESS YIELD MOVES PHASE BOUNDARY

Temperature of phase transition depends on available degrees of freedom

- **For 0 flavor theory $T > 200$ MeV**
- **For 2 flavors: $T \to 170$ MeV more importantly 1st order turns into 2nd order**
- **For 2+1 flavors: $T = 162 \pm 3$ and appearance of minimum μ_{B} we need extra quarks to reach a 1st order transition**
- **For 3, 4 flavors further drop in T.**

At low heavy ion reaction energy low value of γ_s and thus effectively 2 flavor phase limit. This means we need a much greater μ_B to reach the tri-critical point. An easy way to test for this using QCD lattice is to consider large values of m_s and see how the value of μ_b^{cr} moves as function of m_s.

A first look at energy dependence



Solid, bulk QGP expansion, dashed donut expansion.

Since the main parameter controlling the reaction energy dependence is the value of entropy (hadron multiplicity) produced, this model calculation shows that in QGP γ_s changes rapidly – diminishing with decreasing entropy and thus energy content.

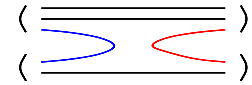
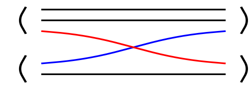
3. INTERPRETATION OF THE NA49 'HORN'

First there is a fast rise of strangeness yield which on the other side of the horn is rivaled by faster rise of entropy. In order to be able to describe the behavior of the horn we thus must have both γ_s, γ_q

ANALYSIS OF DATA: STATISTICAL HADRONIZATION

Fermi (micro canonical)-Hagedorn (grand / canonical) particle 'evaporation' from hot fireball:particles produced into accessible phase space, yields and spectra thus predictable.

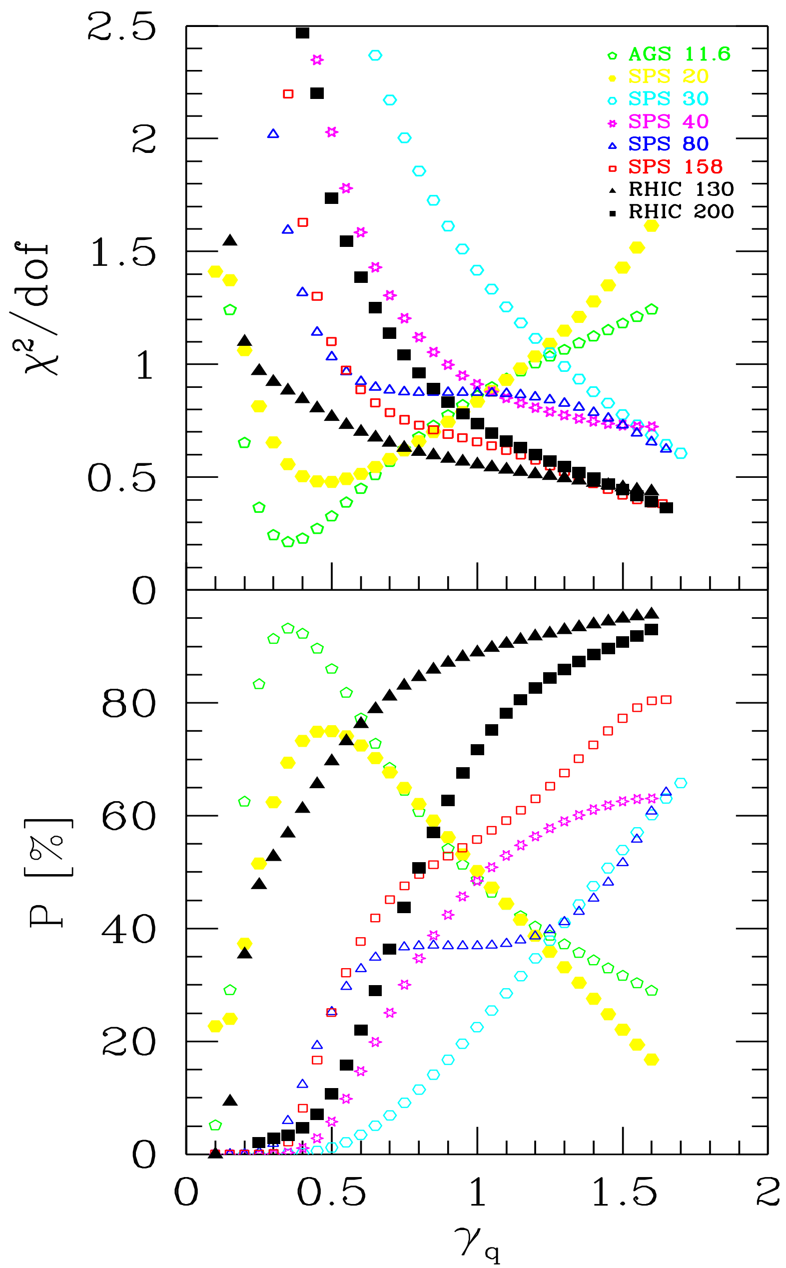
FOUR QUARKS: $s, \overline{s}, q, \overline{q} \rightarrow$ FOUR CHEMICAL PARAMETERS

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** 

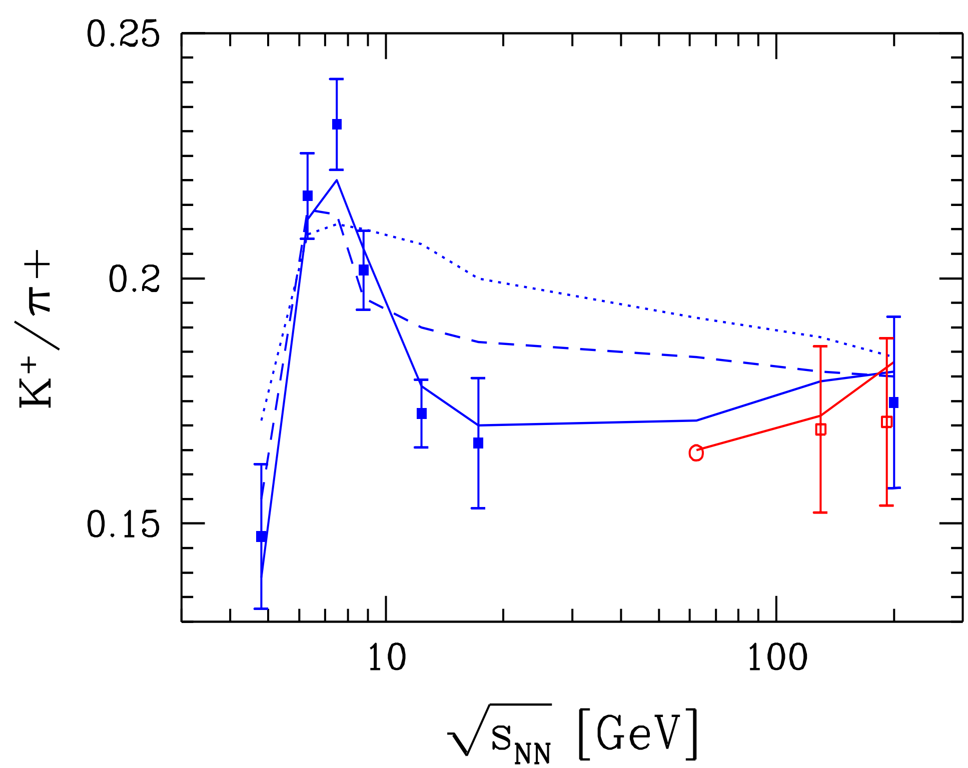
See Physics Reports 1986 Koch, Müller, JR

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

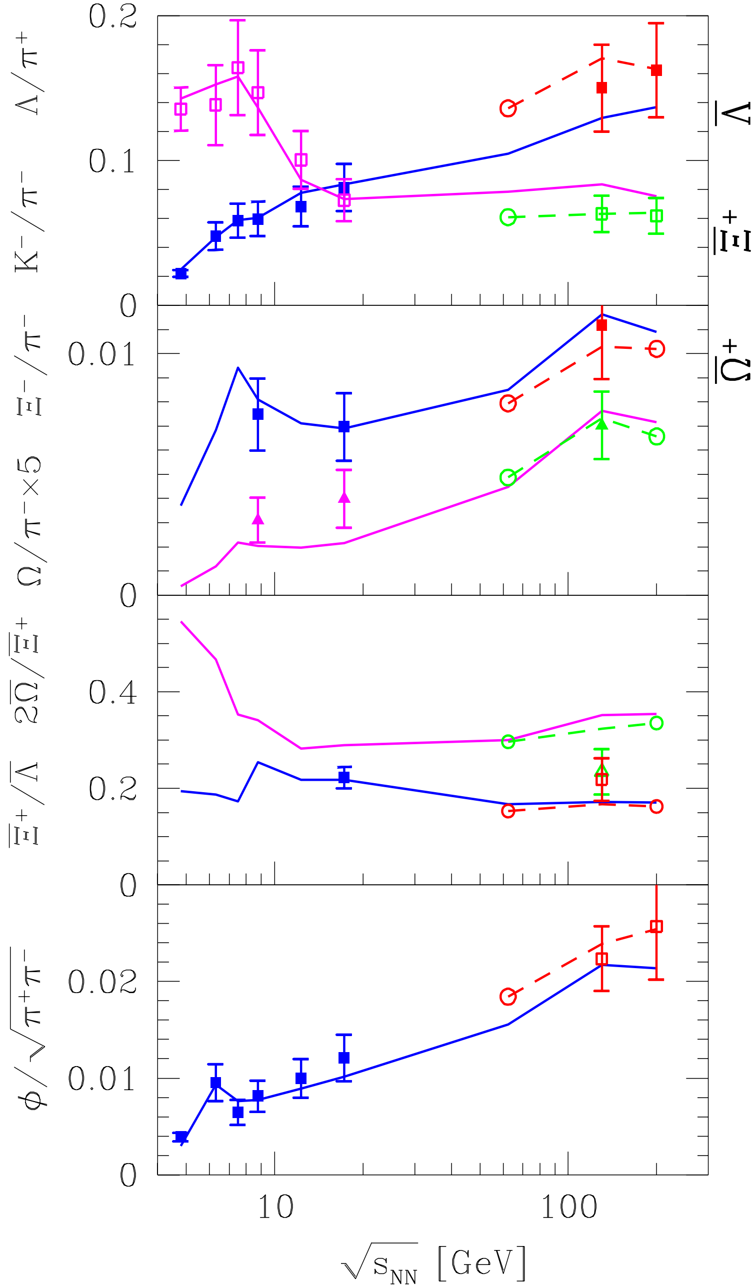
Fit particle yields at every energy: WE DESCRIBE THE HORN

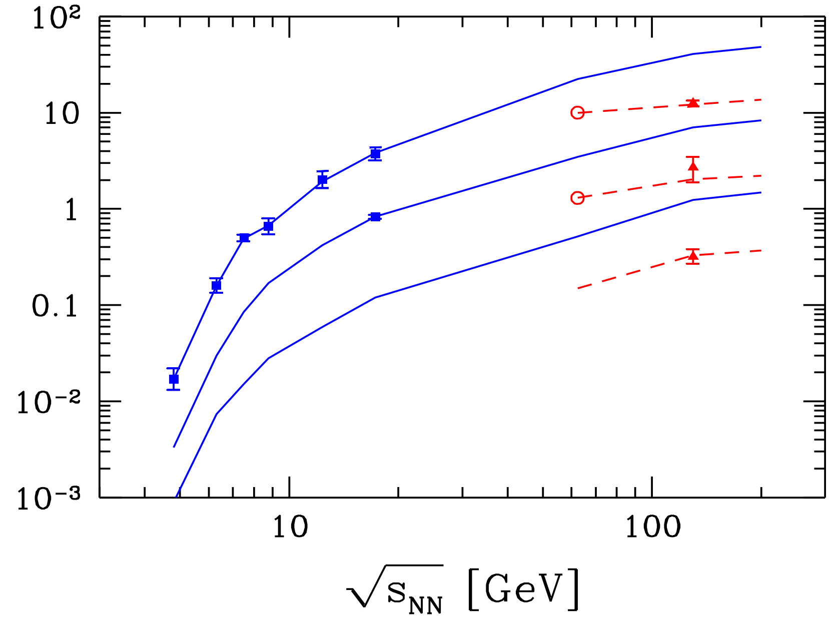


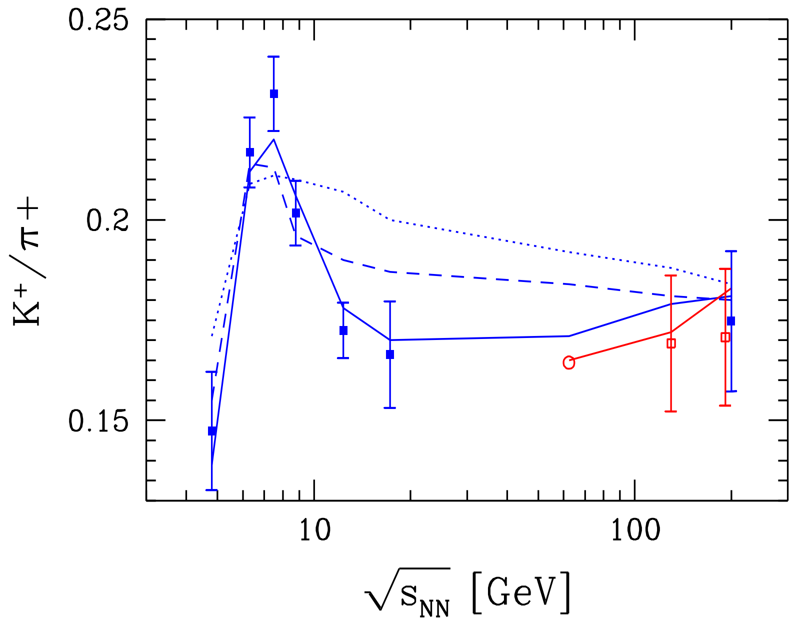
Allowing chemical nonequilibrium we see that between 20 and 30GeV the fit jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The fits have reasonable quality, in particular those relevant to understanding how the horn is created.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



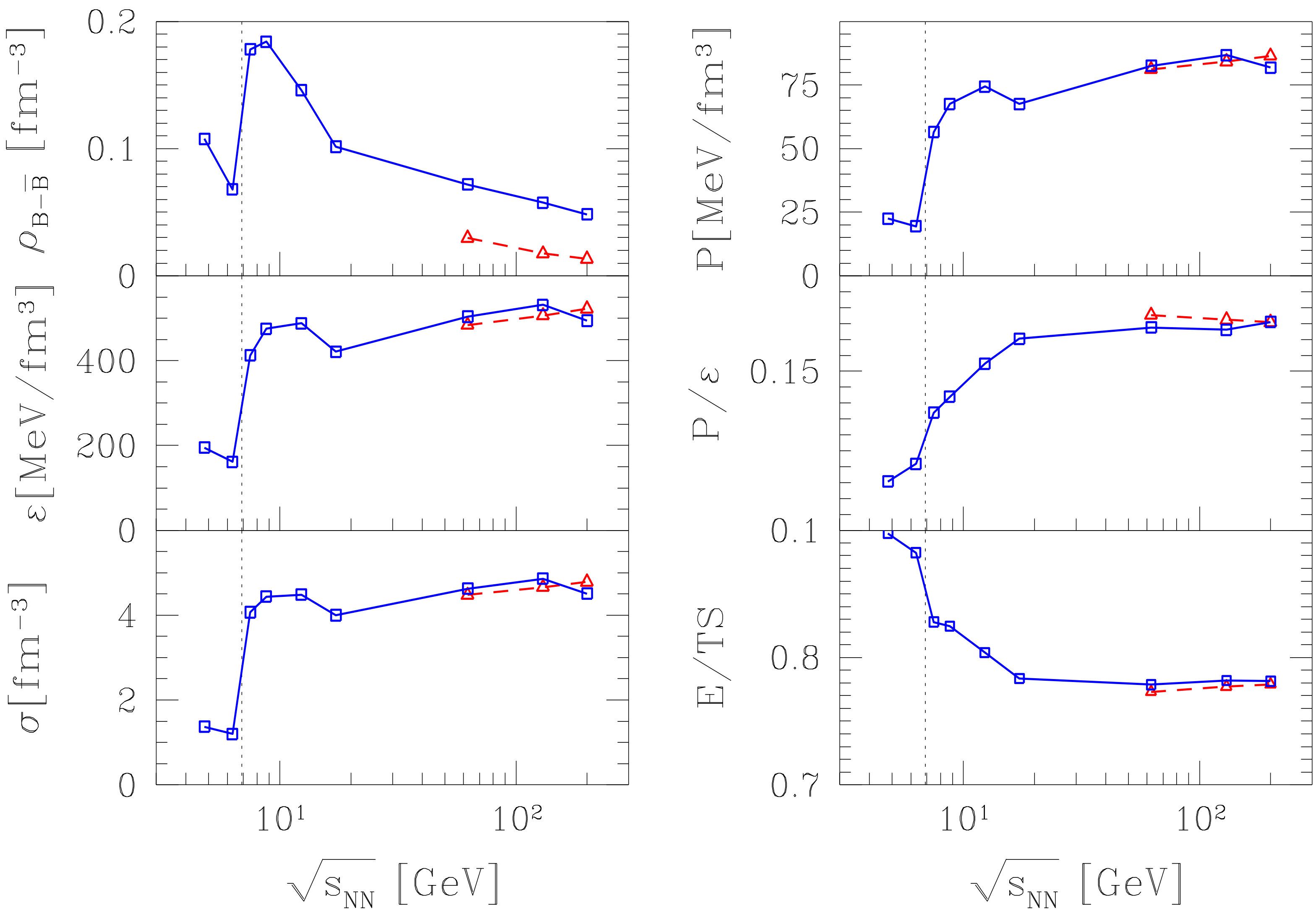
Particle yield systematics





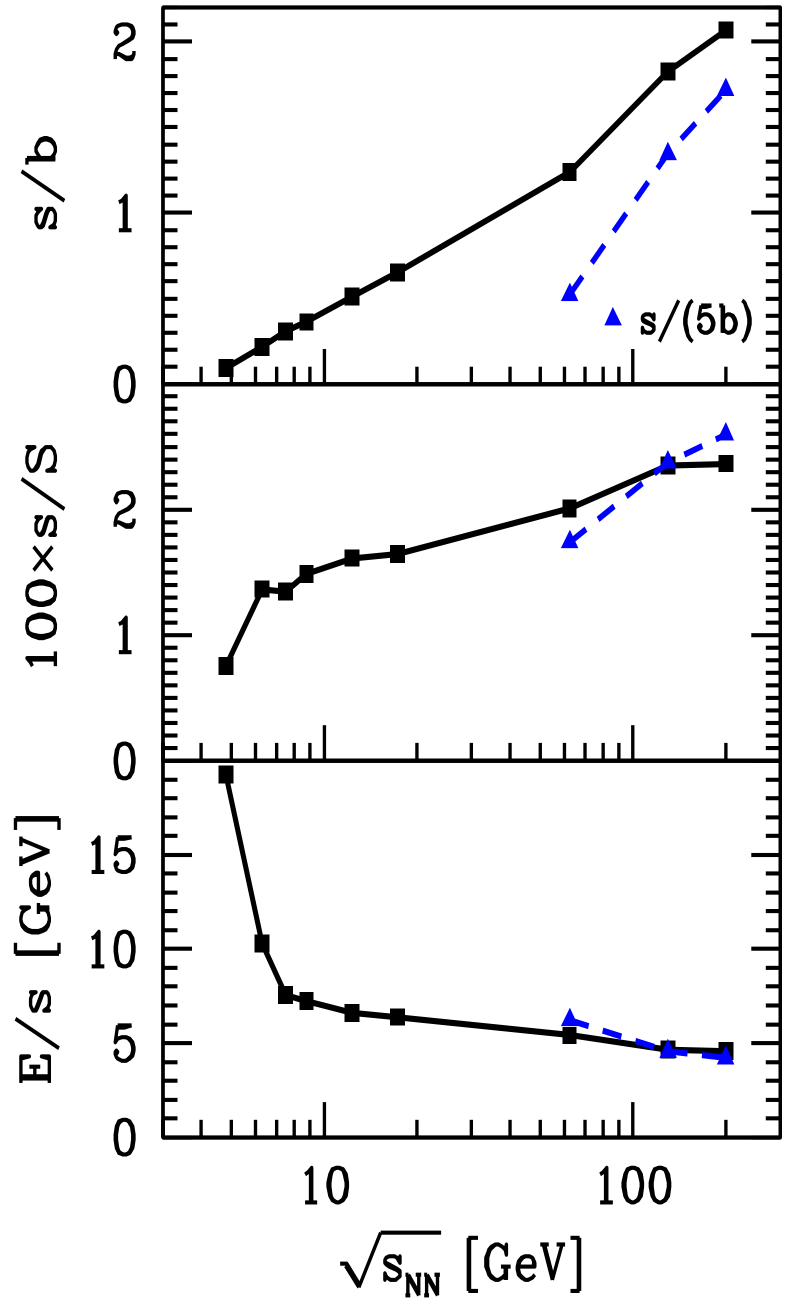


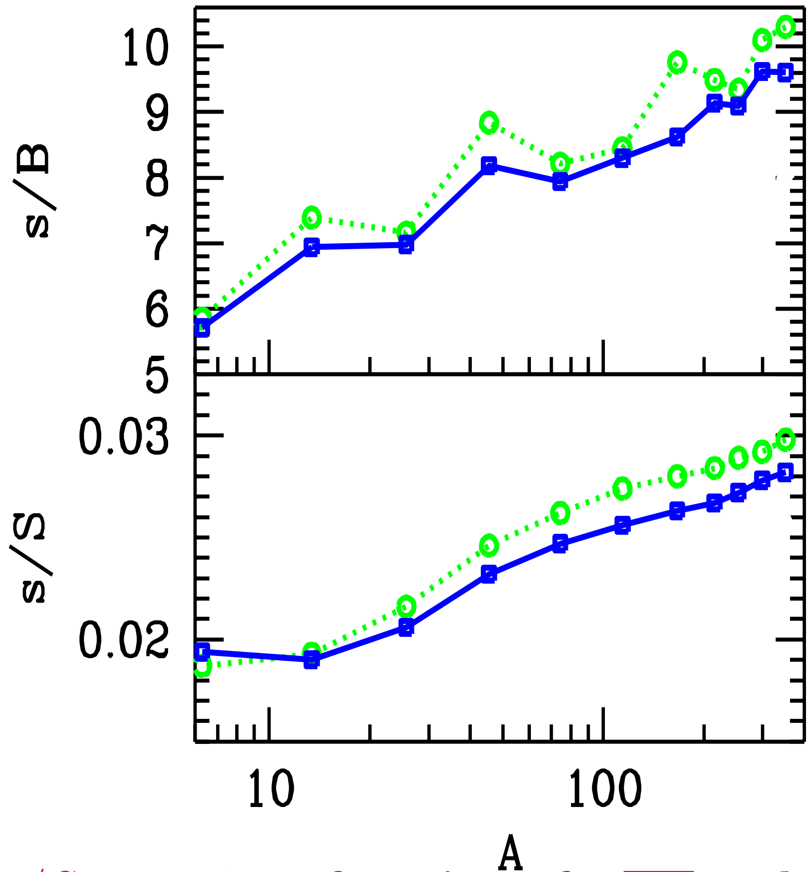
4. PHYSICAL PROPERTIES OF THE FIREBALL



Note 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

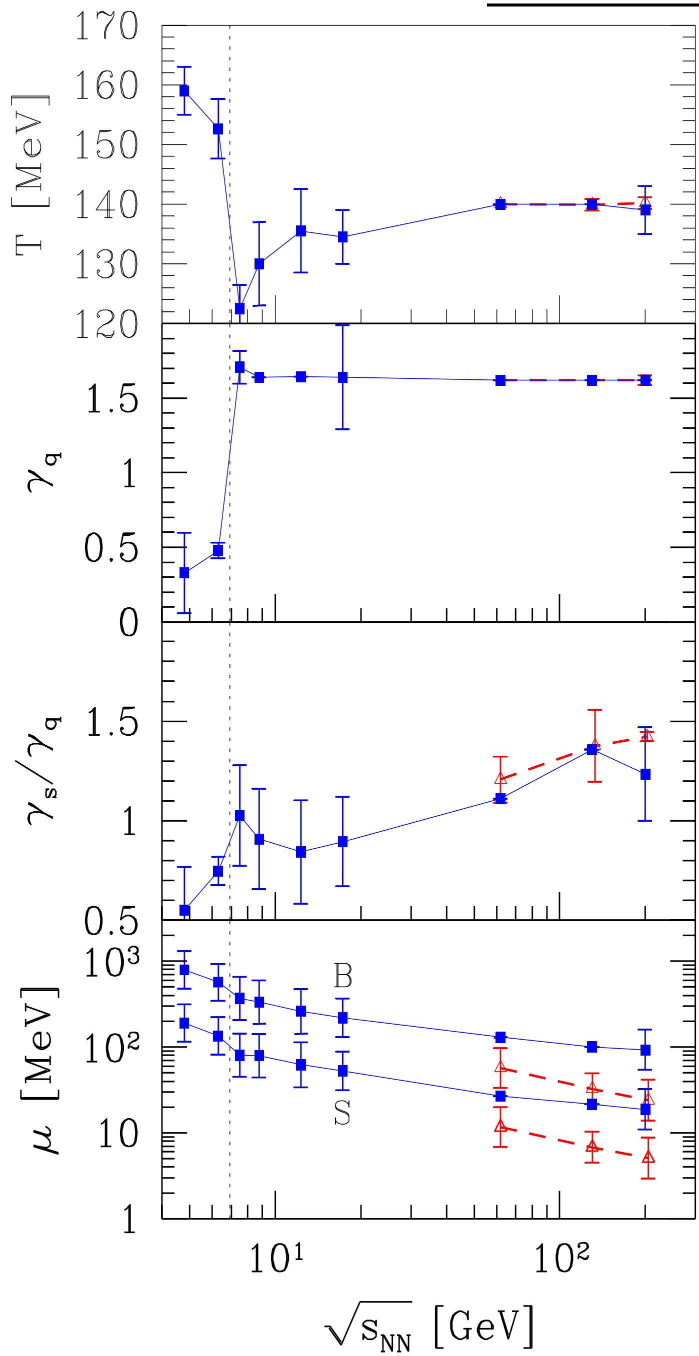


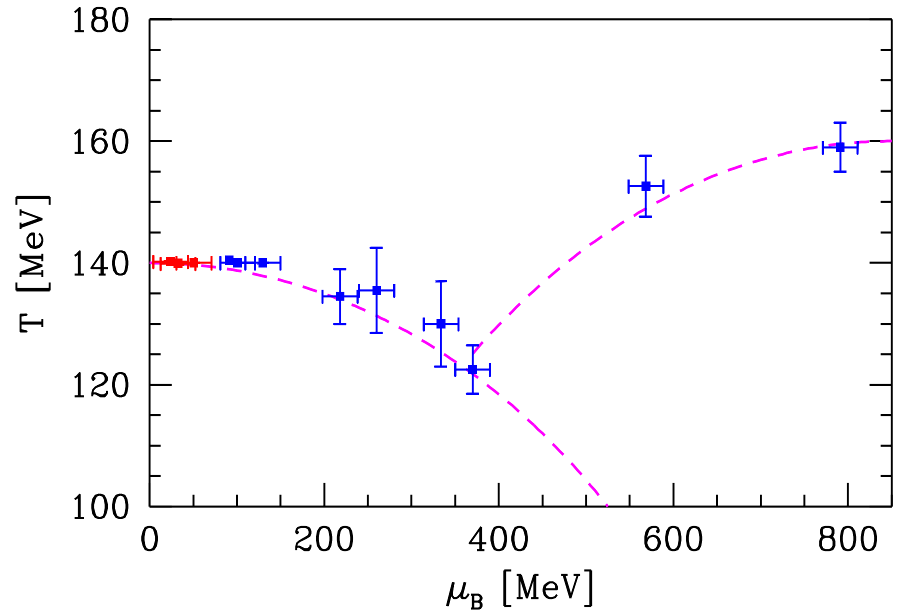


$s/S \rightarrow 0.027$ **as function of** $\sqrt{s_{\mathrm{NN}}}$ **and** V**:**
INITIAL QGP!

Energy/strangeness breaks at $\sqrt{s_{\mathrm{NN}}^{\mathrm{cr}}}$
Different cost → different mechanism!

Statistical parameters

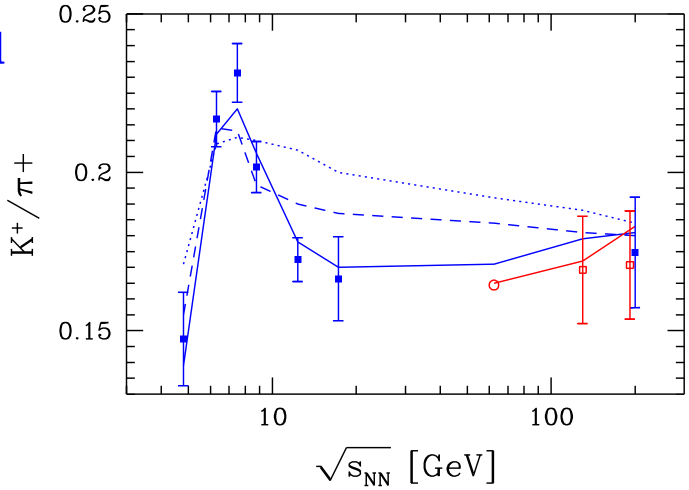




STRANGENESS, ENTROPY, THE HORN, AND QGP DISCOVERY

1. Strange hadrons probe phase properties and phase dynamics; additional task: measure (multi) strange baryons and antibaryons.
2. Deconfinement in baryon rich phase influenced by presence of the third flavor, QCD matter system exceptionally fine tuned.
3. Full analysis of energy excitation functions and centrality dependence is now available
4. 

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

   The gambler and his horn
5. 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 under-saturated
6. At high energy and volume as expected if QGP fireball: strangeness nearly equilibrated at hadronization. Overpopulates HG phase space.