Strangeness and Phase Changes in Relativistic Heavy Ion Collisions

QCD Critical Point BNL-9/10 March, 2006

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. **STRANGENESS IMPACTS PHASE BOUNDARY** $n_f = 2 + \gamma_s^{\rm QGP}$
3. **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

18 transparencies in 20 minutes

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

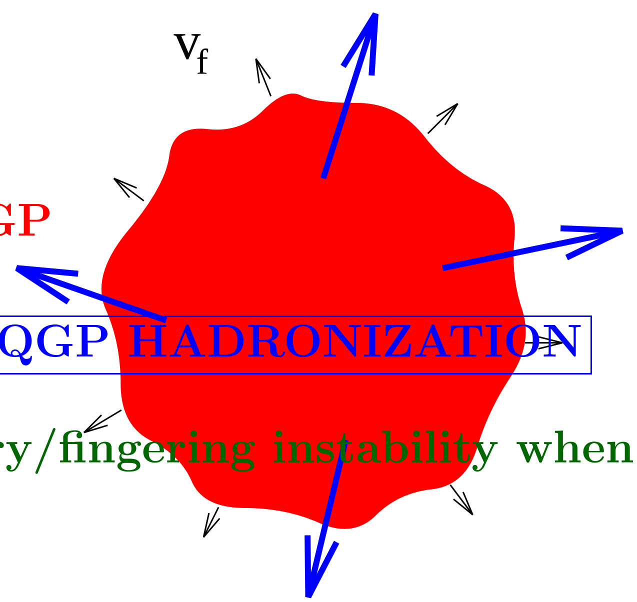
1. MATTER-ANTIMATTER PRODUCTION MECHANISM

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

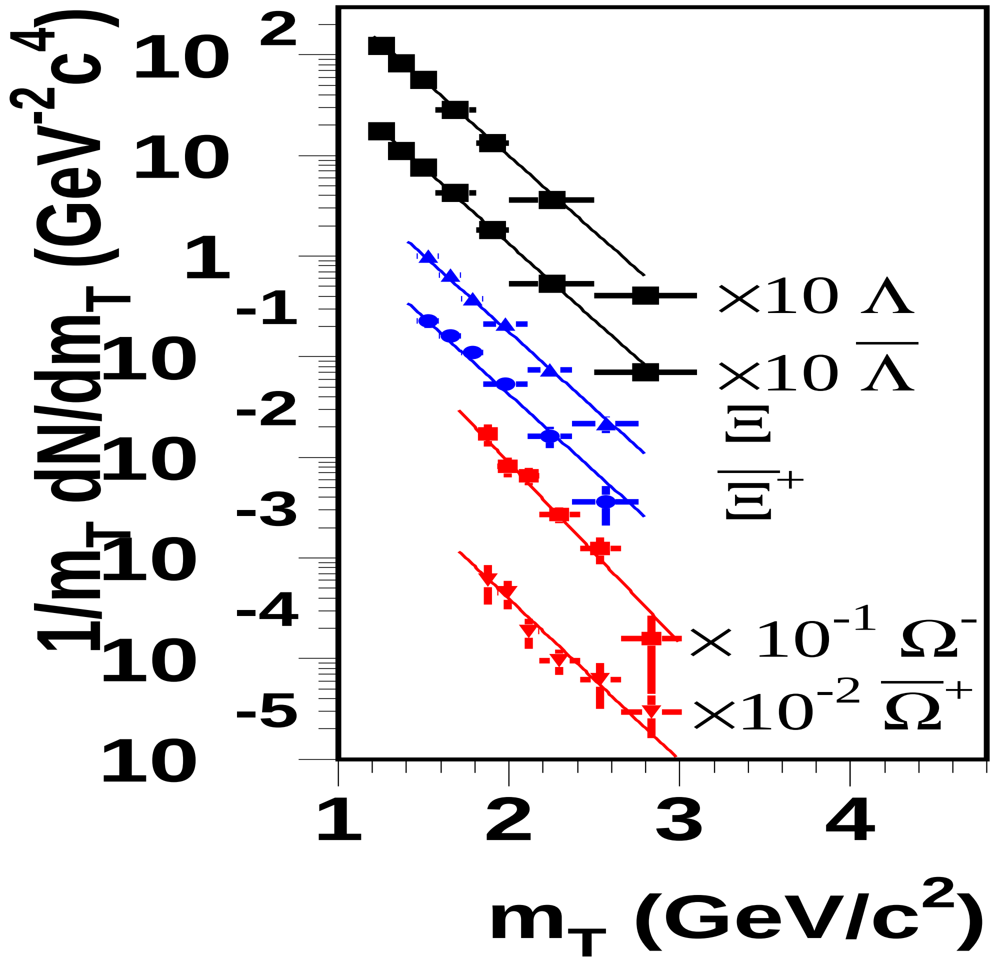
Practically no hadronic 'phase'!
No 'mixed phase' either!
Direct emission of free-streaming
hadrons from exploding filamentary QGP



Develop analysis tools viable in SUDDEN QGP HADRONIZATION

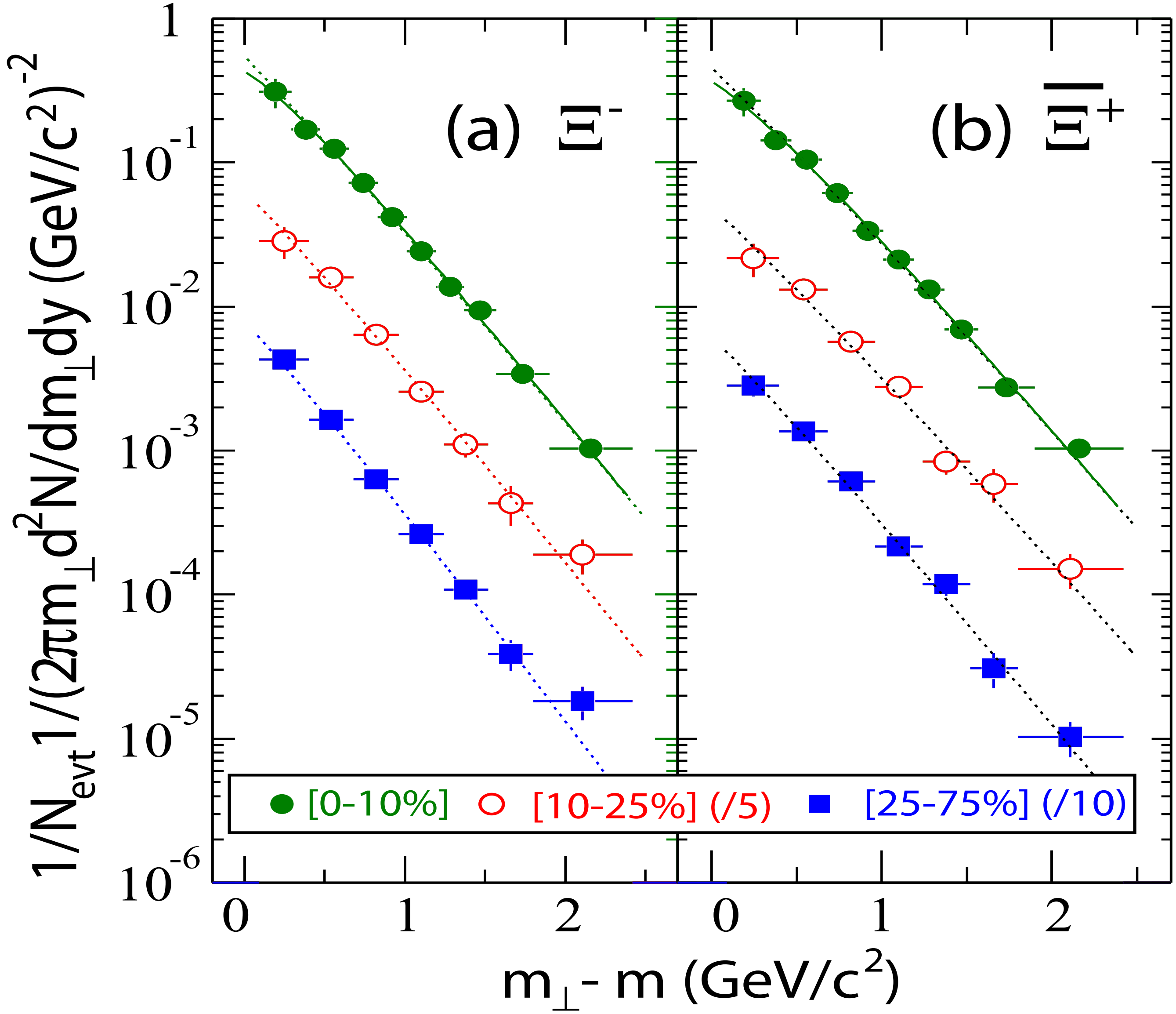
Proposed reaction mechanism: filamentary/fingering instability when in expansion pressure reverses.

WA97	$T_{\perp}^{\rm Pb}$ [MeV]
T^{Λ}	**289 ± 3**
$T^{\overline{\Lambda}}$	**287 ± 4**
T^{Ξ}	**286 ± 9**
$T^{\overline{\Xi}}$	**284 ± 17**
$T^{\Omega+\overline{\Omega}}$	**251 ± 19**



<u>T_{Λ} **within 1% of** $T_{\overline{\Lambda}}$</u>

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



EXPLORE THIS B–$\overline{B}$ BEHAVIOR BELOW THE HORN

We know that in NN reactions spectra of baryons B, and antibaryons $\overline{B}$ completely different. So at least as function of A, and perhaps also $\sqrt{s_{NN}}$ the matter-antimatter symmetry should go away.

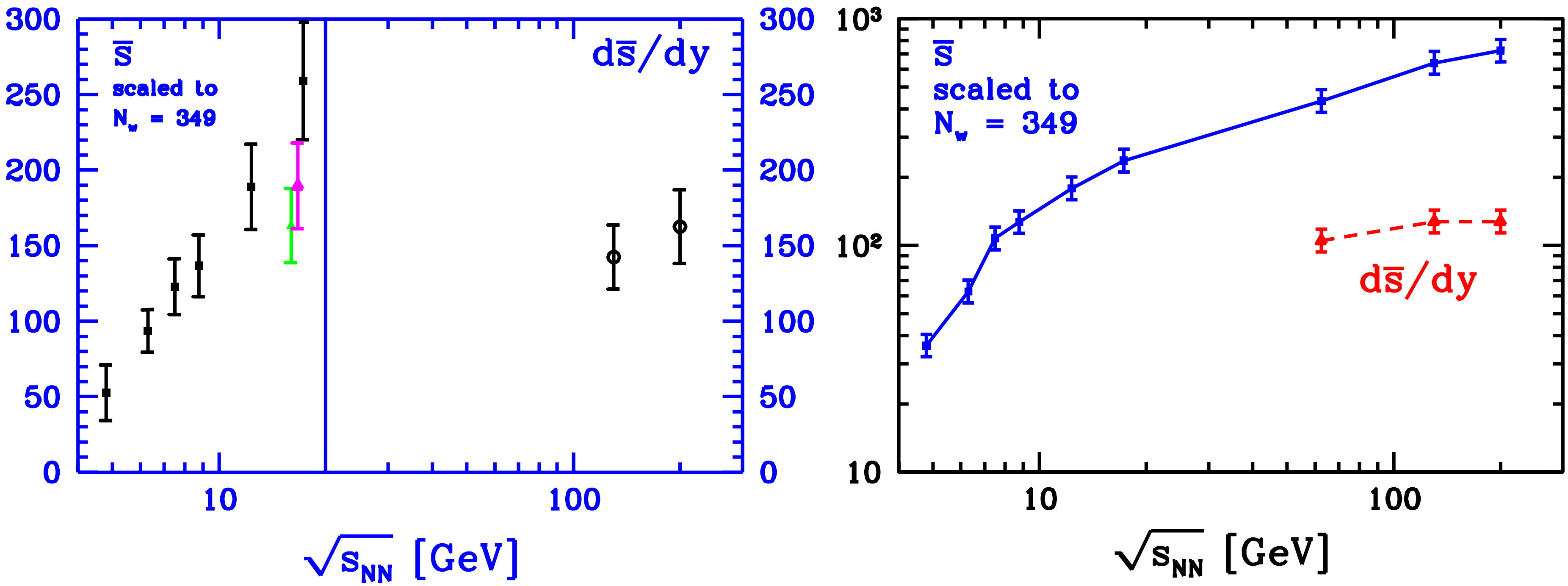
NOTE: should we find that the matter–antimatter symmetry and thus sudden hadronization not valid at lower energies, maybe phase boundary disappears? WAIT, we are looking for appearance of critical point.... There is a caveat, count flavor degrees of freedom!

As energy is lowered, below the horn, the density of entropy drops by factor 3, the yield of strangeness diminishes such that in the QGP $\gamma_s^{\rm QGP} \ll 1$ so $n_{\rm f}$ diminishes from 2+1 to 2 and the phase boundary moves up in temperature and it turns from first order transition into 2nd order.

2. STRANGENESS IMPACTS PHASE BOUNDARY

Experimental STRANGENESS EXCITATION FUNCTION

No change in production reaction mechanism visible in the s yield

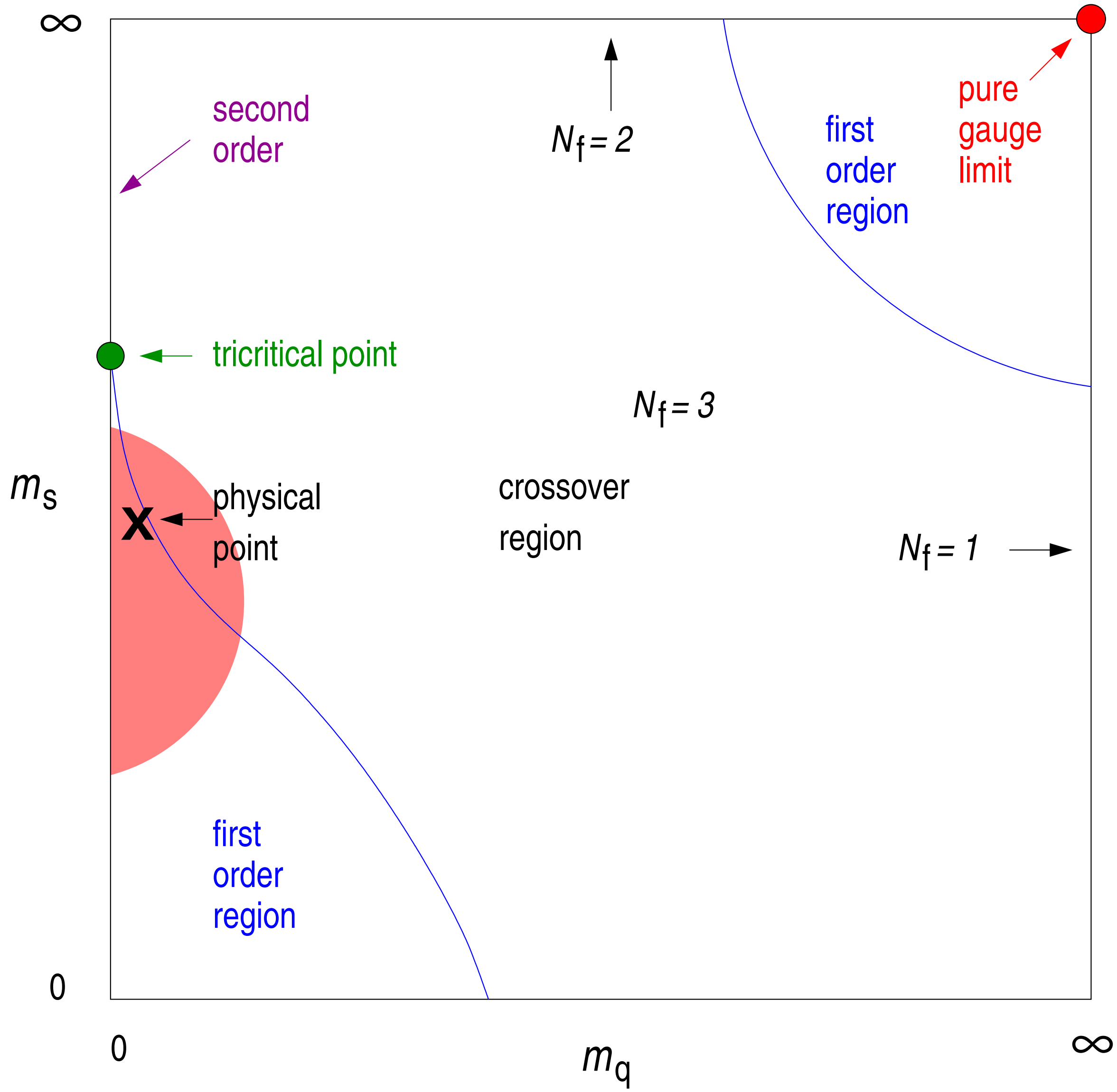


LEFT: sum of $\bar{s}$ quarks in all hadrons. At low energy practically $2K^+$, Experiment Green: C–C and Violet: Si–Si, other Au–Au, Pb–Pb, Right: Fit to data

Temperature of phase transition depends on available degrees of freedom

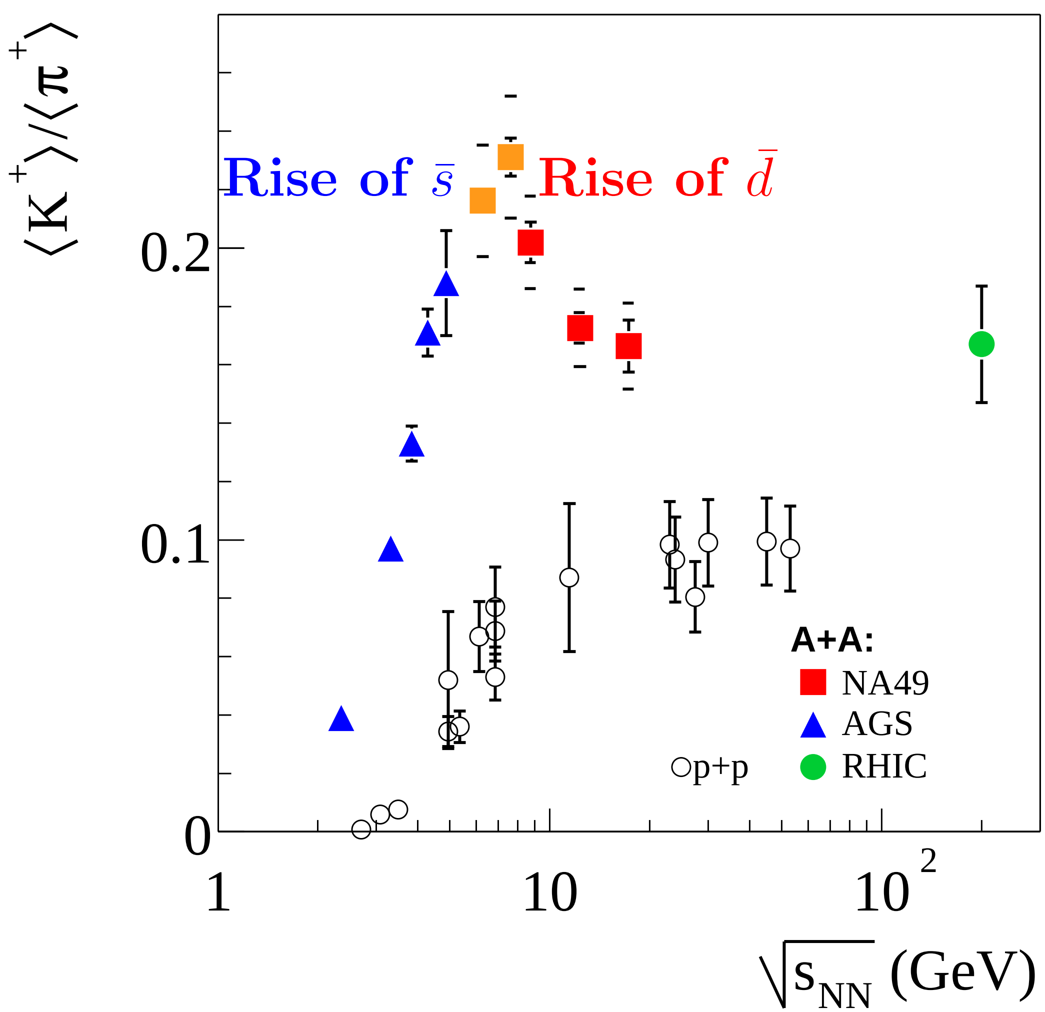
- For 0 flavor theory $T > 200$ MeV
- For 2 flavors: $T \to 170$ MeV more importantly 1st order turns into 2nd order
- For 2+1 flavors: $T = 162 \pm 3$ and appearance of minimum $\mu_{\rm B}$
  we need extra quarks to reach a 1st order transition
- For 3, 4 flavors further drop in T.

Phase boundary considering Fermi degrees of freedom



adapted from: "The three flavor flavor chiral phase transition with an improved quark and gluon action in lattice QCD", **A. Peikert, F. Karsch , E. Laermann, B. Sturm,**(LATTICE 98), in Nucl.Phys.Proc.Suppl.73:468-470,1999.**Chemical equilibrium of strangeness. What if $\gamma_s^{QGP} < 1$?**

3. INTERPRETATION OF THE NA49 'HORN'



left strangeness wins over $\bar{d}$, right, $\bar{d}$ wins over s

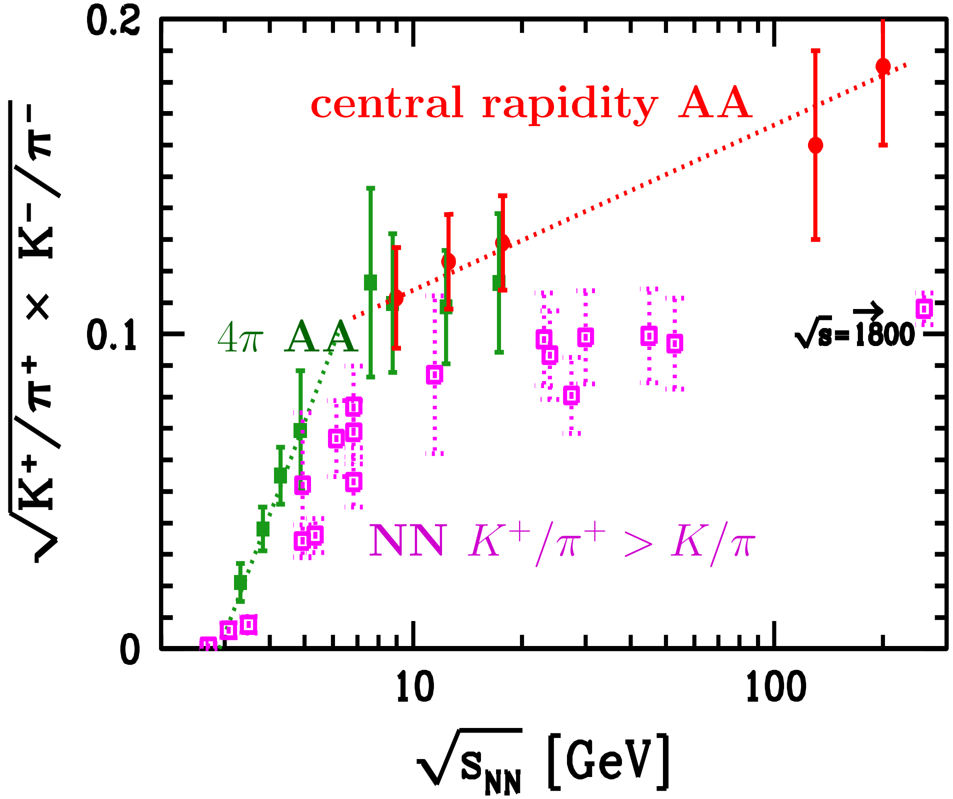
WHAT DOES THIS MEAN AND HOW CAN WE DESCRIBE THE HORN?

final state $\bar{s}/\bar{d} \propto \gamma_s/\gamma_d$

Evidence for the role of $\bar{d}$: The particle yield products

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

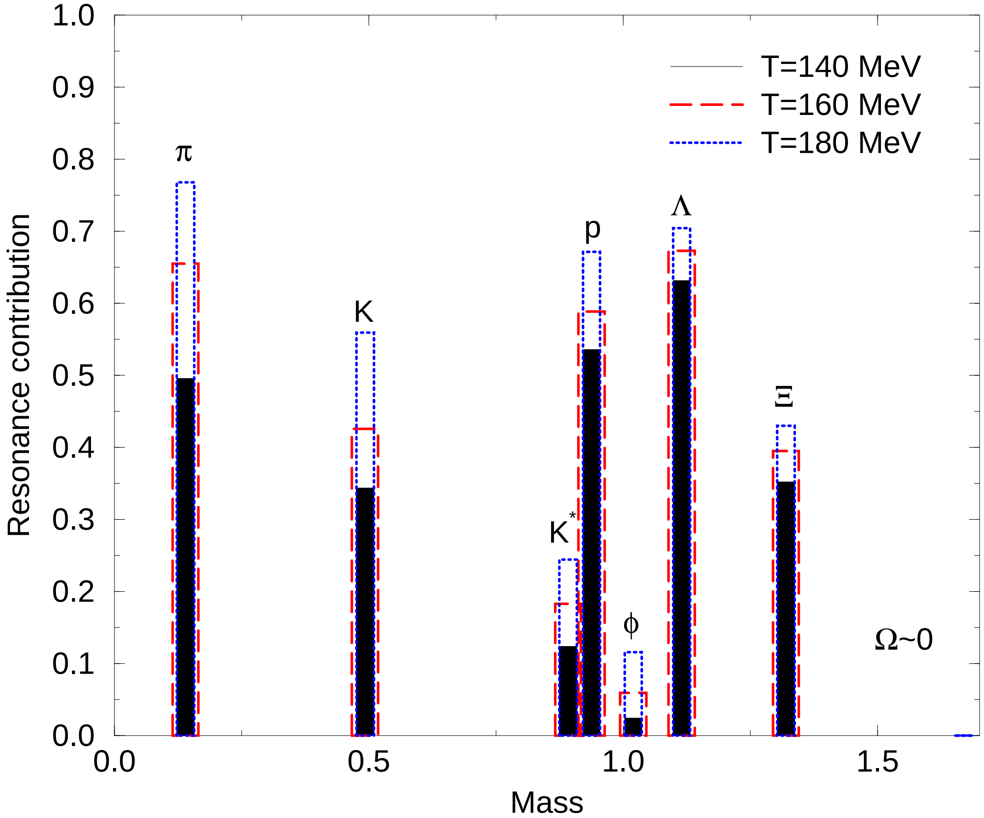
are much less dependent on chemical conditions including baryon density, just relative particle number of strange and light quarks matter γ_s/γ_q.



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.

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.



HOW TO TEST SH:

Study of particle yields with same quark content, e.g. the relative yield of $\Delta(1230)/N$, K^*/K, $\Sigma^*(1385)/\Lambda$, etc, which is controlled by chemical freeze-out temperature T:

$$\frac{N^*}{N} = \frac{g^*(m^*T)^{3/2}e^{-m^*/T}}{g(mT)^{3/2}e^{-m/T}}$$

Resonances decay rapidly into 'stable' hadrons and dominate the yield of most stable hadronic particles.

Resonances test both statistical hadronization principle and perhaps more importantly, due to their short and diverse lifespan characterize the dynamics of QGP hadronization.

QUARK CHEMISTRY

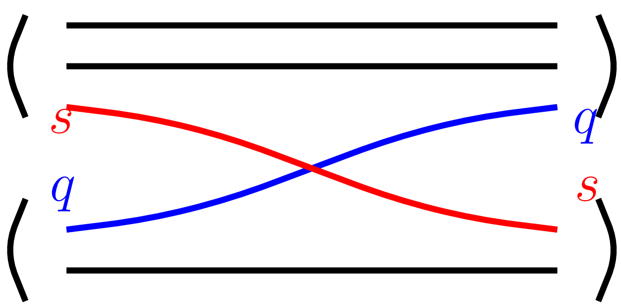
When we compare yields of particles of different quark content we need to consider chemical potentials, in principle one potential for each hadron! Simplification: follow quark content and remember that quarks are produced in pairs.

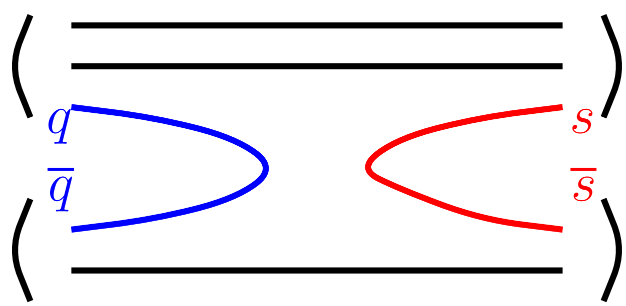
Yields of $s, \overline{s}, q, \overline{q} \rightarrow$ NEED 4 CHEMICAL ABUNDANCE PARAMETERS

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 Absolute chemical equilibrium





EXCHANGE REACTION λ_i

PAIR PRODUCTION REACTION γ_i

Remarks relevant to models of hadron yields

1. **FAST transformation implies chemical nonequilibrium, see e.g. NA49 horn: the phase space density is in general different in the two phases. To preserve entropy (valance quark pair number) across the phases need a jump in the phase space occupancy parameters γ_i. This replaces the jump in volume in a slow reequilibration with mixed phase.**
2. **Incorporate the complete tree of resonance decays please note: not only for yields but also most important for spectra.**
3. **OPTION: Production weighted with the width of the resonances accounts for experimental reaction rates;**

Full analysis of experimental results requires a significant numerical effort. Tucson-(Kraków)-McGill-Paris-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

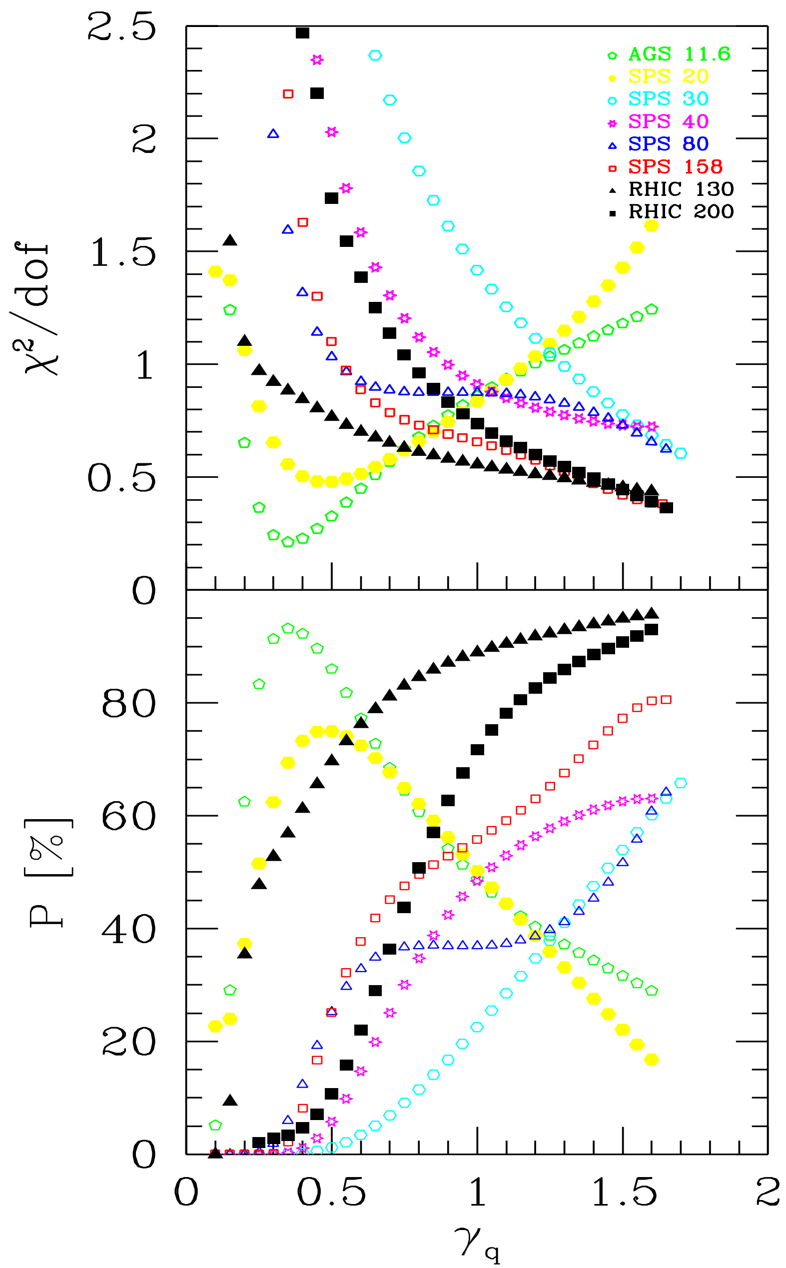
Lead author: Giorgio Torrieri. Online SHARE: Steve Steinke

http://www.physics.arizona.edu/˜steinke/shareonline.html

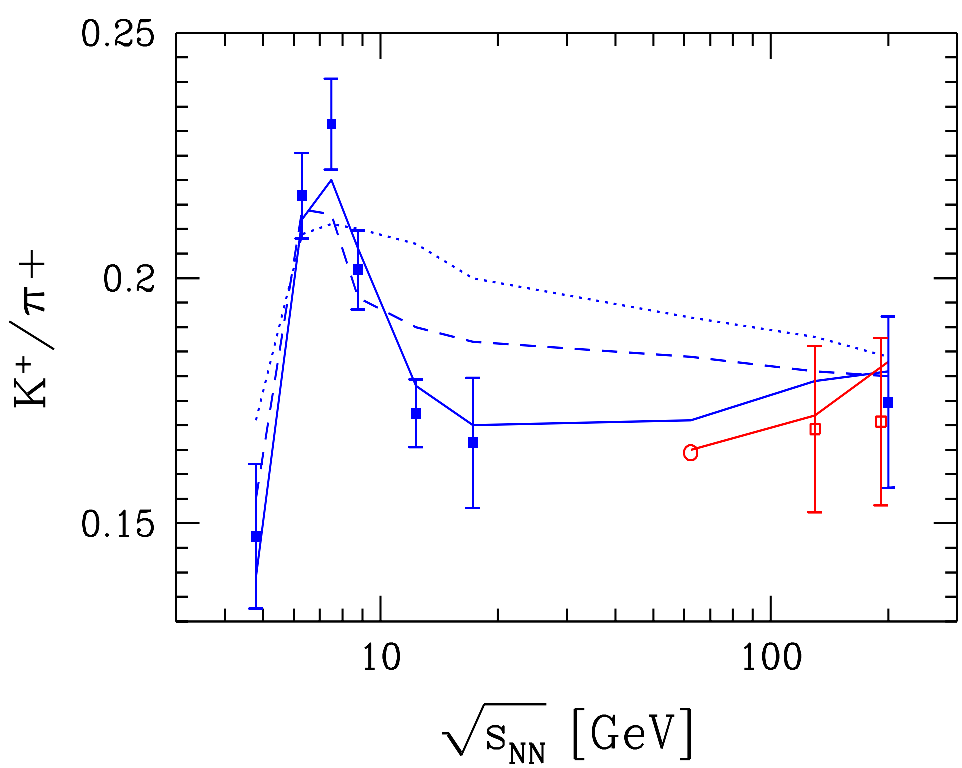
Aside of particle yields, also PHYSICAL PROPERTIES of the source are available, both in SHARE and ONLINE. No fitting online (server too small).

SHARE2 with many improvements and fluctuations on-line since March 8, 2006, see nucl-th/0603026

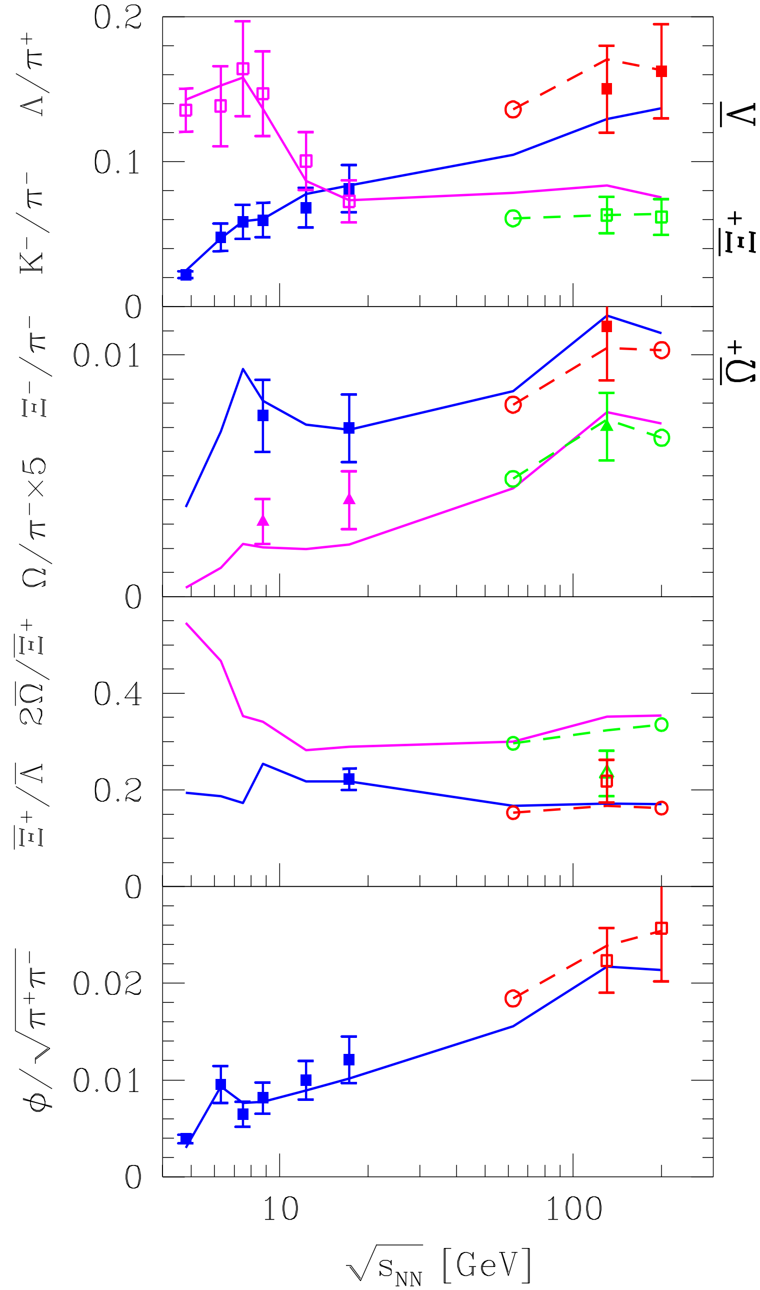
Fit particle yields at every energy: WE DESCRIBE THE HORN

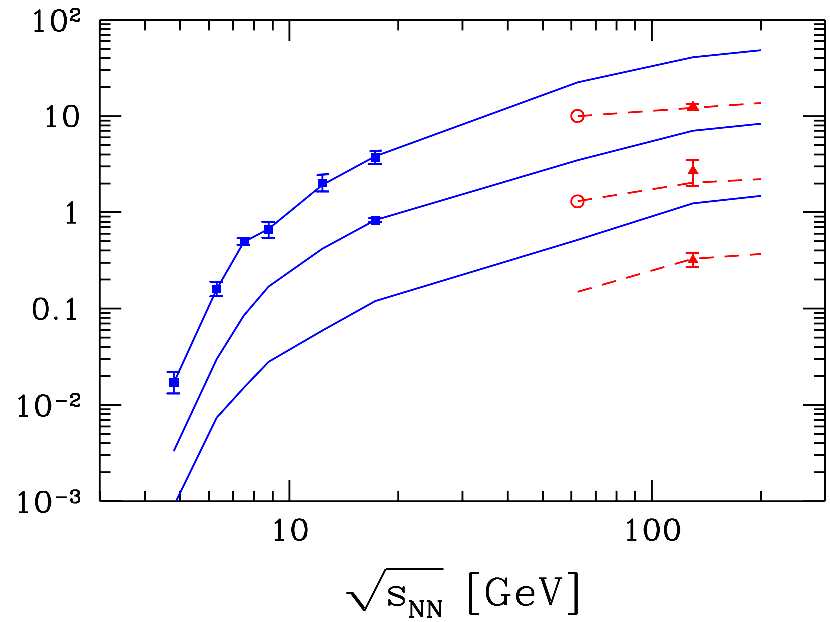


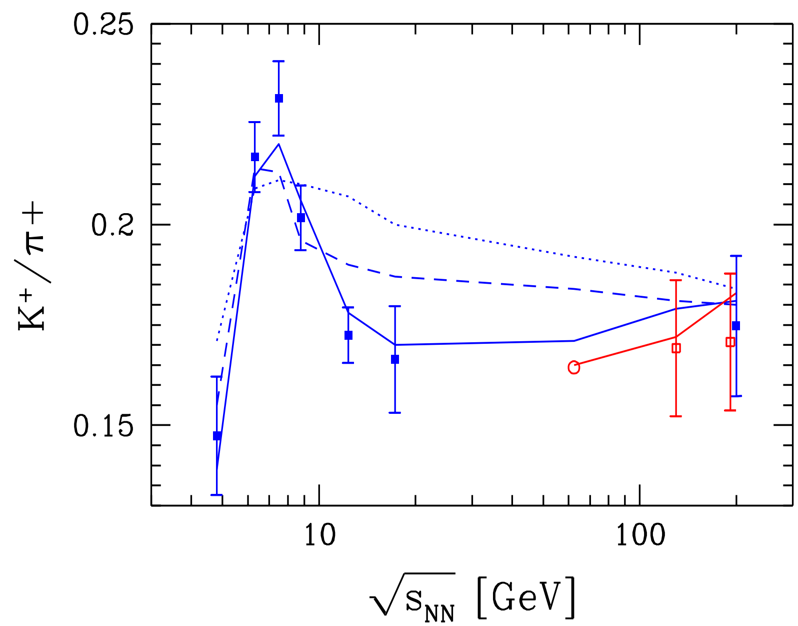
Allowing chemical nonequilibrium we see that between 20 and 30GeV the fit jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The fits have reasonable quality, in particular those relevant to understanding how the horn is created.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



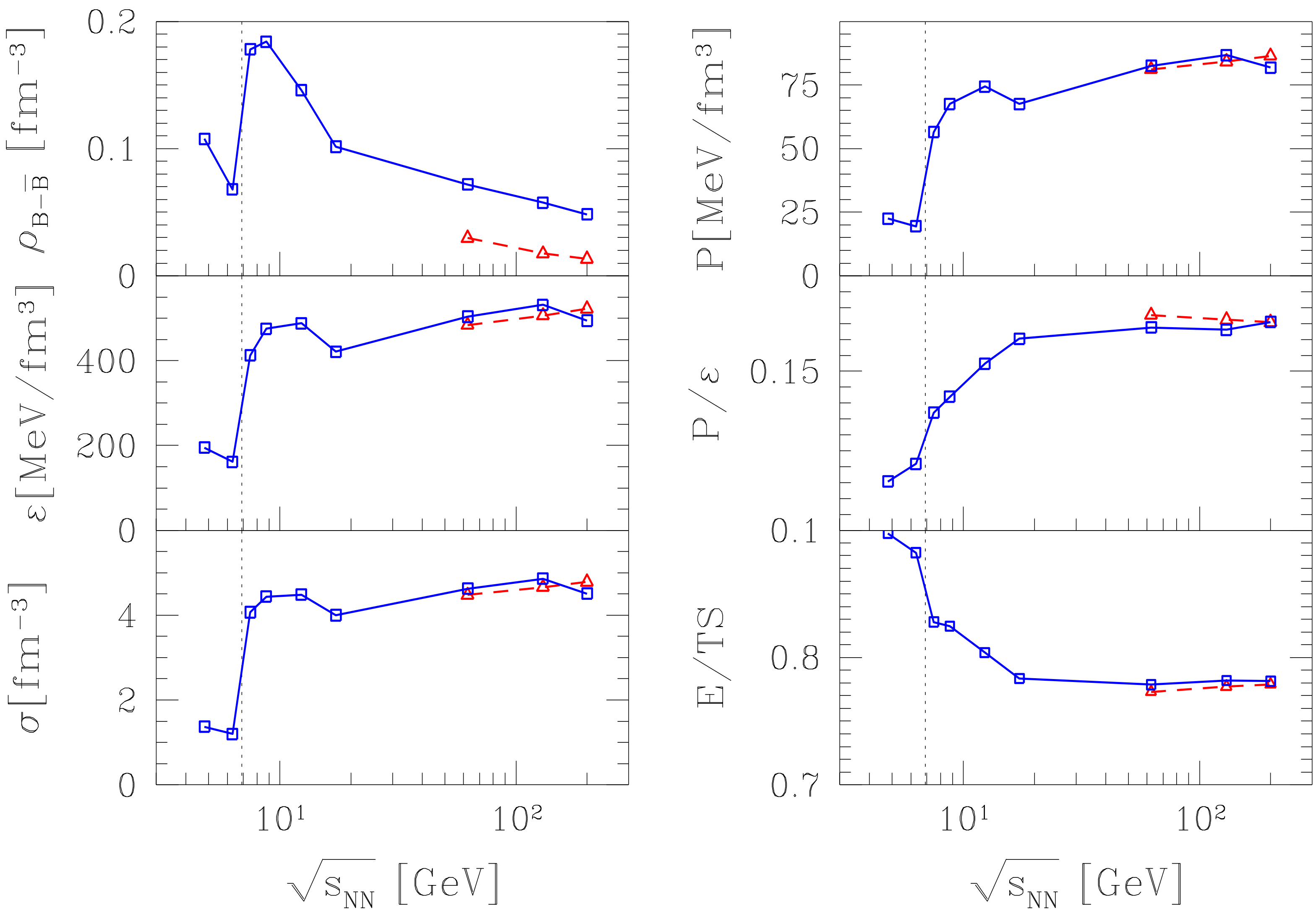
Particle yield systematics





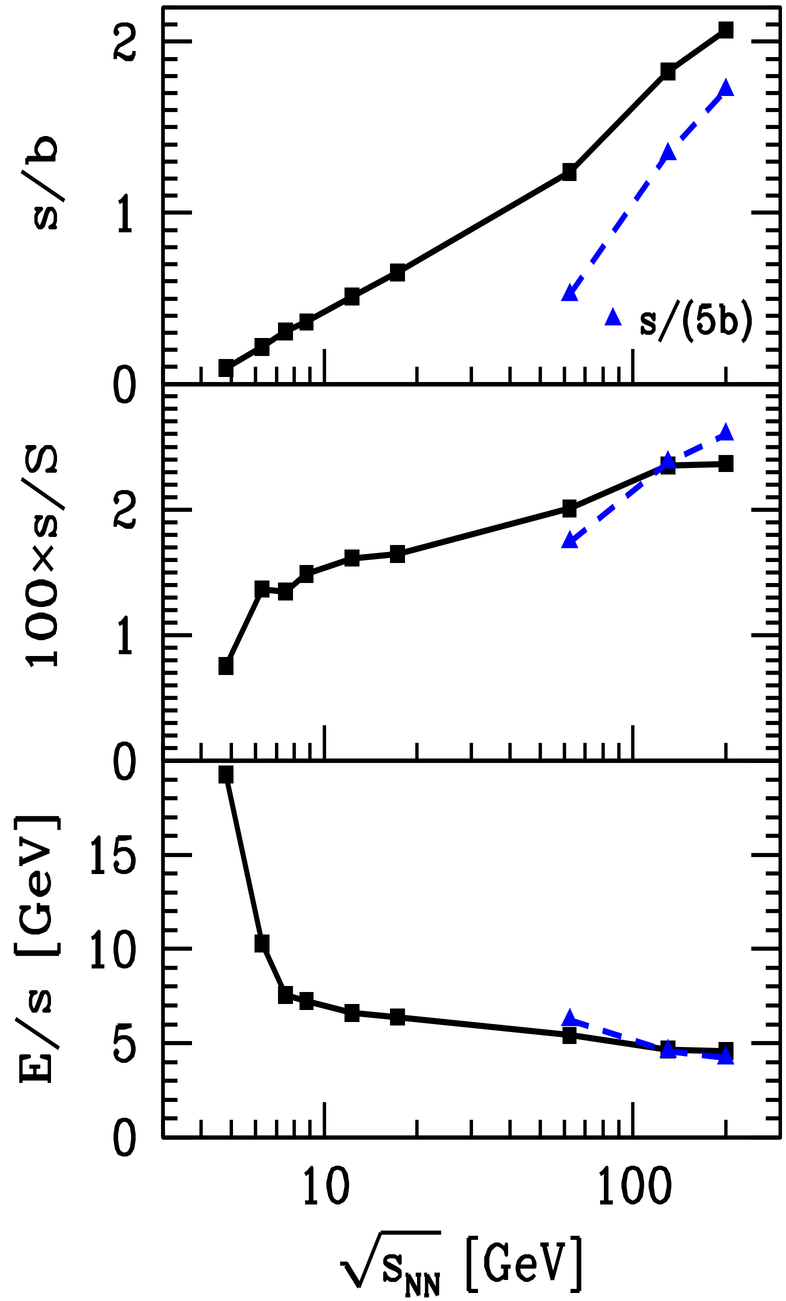


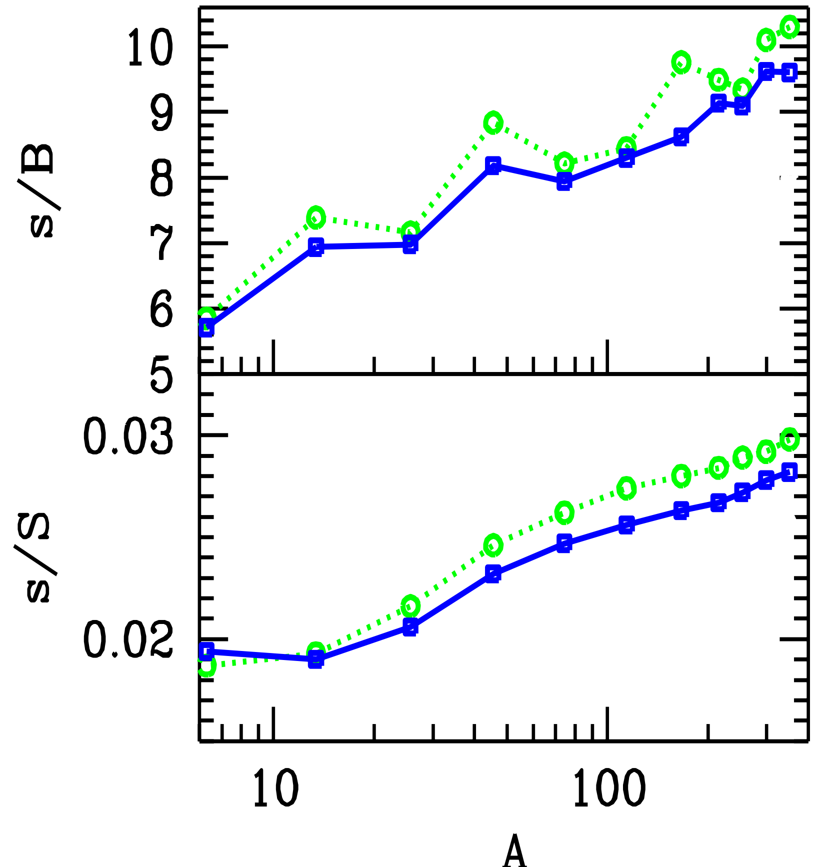
4. PHYSICAL PROPERTIES OF THE FIREBALL



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

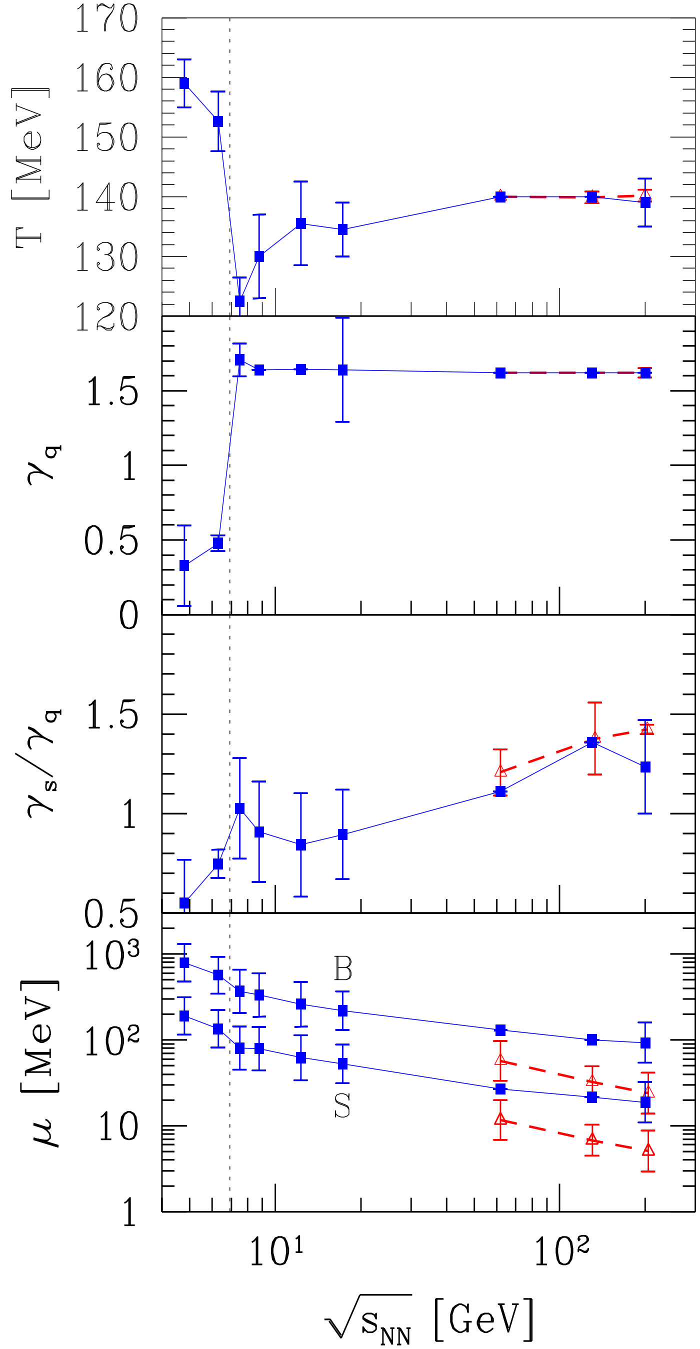


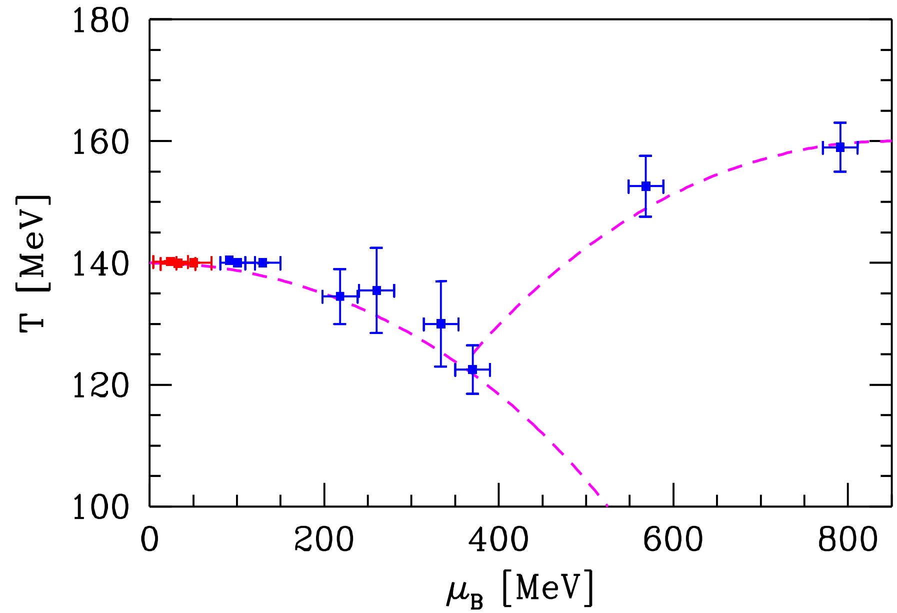


$s/S \to 0.027$ as function of $\sqrt{s_{\rm NN}}$ and V: INITIAL QGP!

Energy/strangeness breaks at $\sqrt{s^{\rm cr}_{\rm NN}}$
Different cost → different mechanism!

Statistical parameters

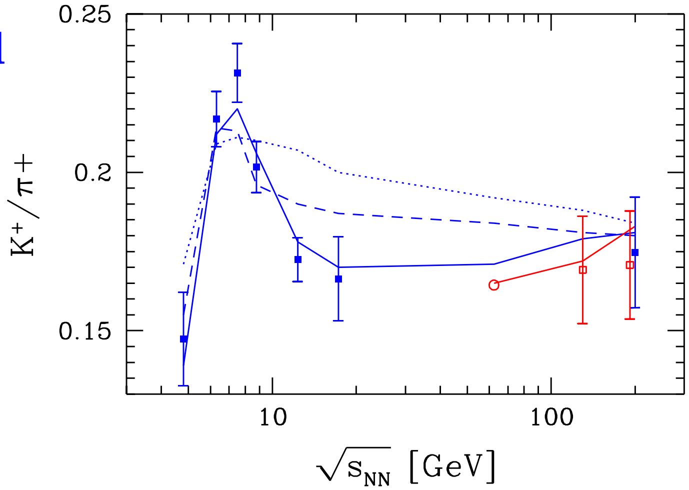




STRANGENESS, ENTROPY, THE HORN, AND QGP DISCOVERY

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 ($s/S \rightarrow 0.027$).
   - 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.