Strangeness and threshold of phase changes

Contributors: Inga Kuznetsova, Jean Letessier, Giorgio Torrieri

SQM2007-Levoca, June 25, 2007

1) Bulk strangeness enhancement, from $\bar{s}/\bar{q}$ to s/S in QGP

2) Association with chemical final hadron non-equilibrium

3) Influence of explosive dynamics on observable phase boundary

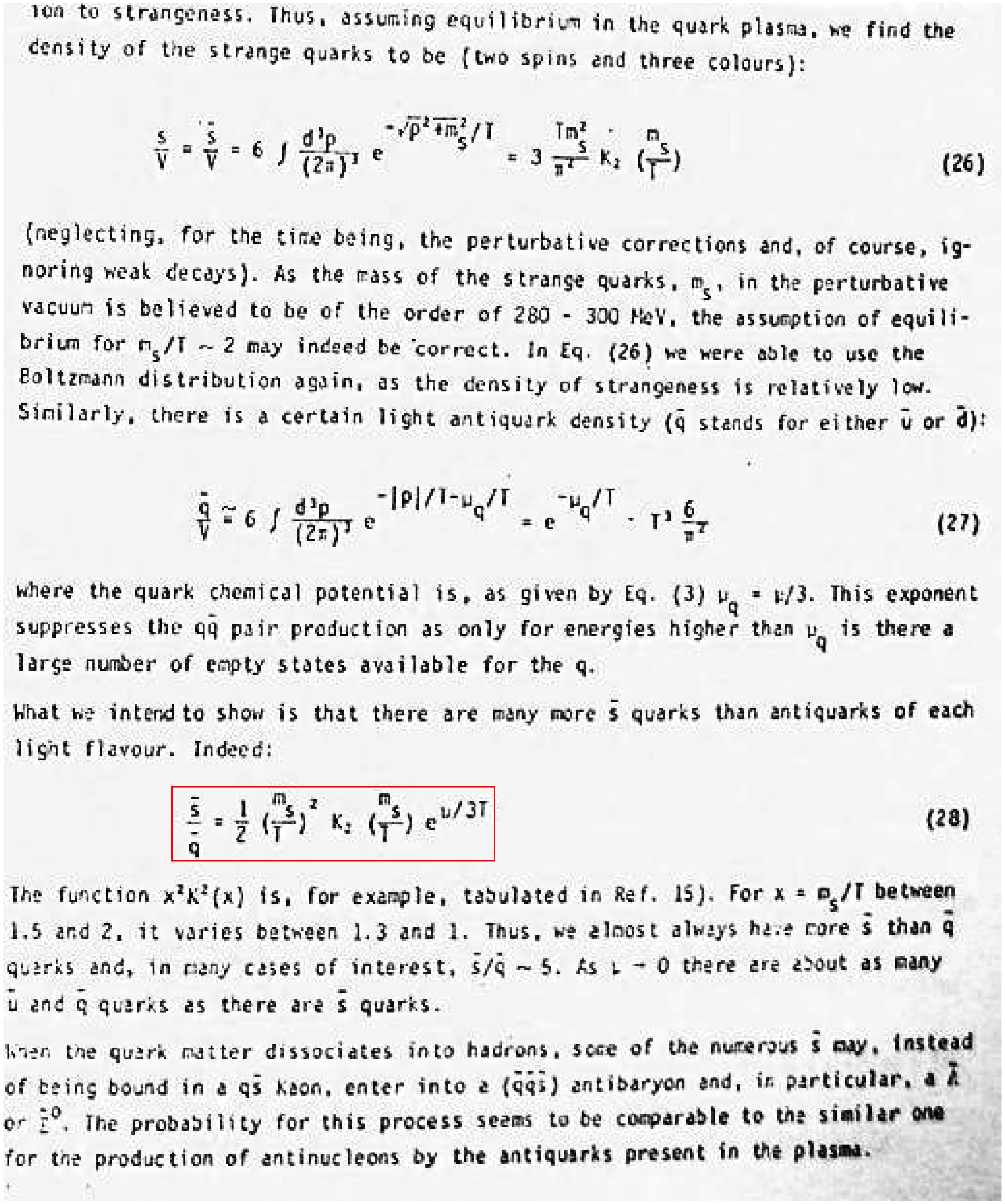
4) Principles of statistical hadronization analysis of particle yields

5) Results of full 2007 reanalysis of AGS/SPS (and RHIC in figures):

- **Chemical non-equilibrium**
- **Yields of interest**
- **Conditions of hadronization**

Johann Rafelski
University of Arizona
TUCSON, Arizona

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



ion to strangeness. Thus, assuming equilibrium in the quark plasma, we find the density of the strange quarks to be (two spins and three colours):

$$\frac{s}{V} = \frac{\bar{s}}{V} = 6\int \frac{d^3p}{(2\pi)^3}\, e^{-\sqrt{p^2+m_s^2}/T} = 3\,\frac{Tm_s^2}{\pi^2}\, K_2\left(\frac{m_s}{T}\right) \qquad (26)$$

(neglecting, for the time being, the perturbative corrections and, of course, ignoring weak decays). As the mass of the strange quarks, m_s, in the perturbative vacuum is believed to be of the order of 280 - 300 MeV, the assumption of equilibrium for $m_s/T \sim 2$ may indeed be correct. In Eq. (26) we were able to use the Boltzmann distribution again, as the density of strangeness is relatively low. Similarly, there is a certain light antiquark density ($\bar{q}$ stands for either $\bar{u}$ or $\bar{d}$):

$$\frac{\bar{q}}{V} \cong 6\int \frac{d^3p}{(2\pi)^3}\, e^{-|p|/T-\mu_q/T} = e^{-\mu_q/T}\cdot T^3\,\frac{6}{\pi^2} \qquad (27)$$

where the quark chemical potential is, as given by Eq. (3) $\mu_q = \mu/3$. This exponent suppresses the $q\bar{q}$ pair production as only for energies higher than μ_q is there a large number of empty states available for the q.

What we intend to show is that there are many more $\bar{s}$ quarks than antiquarks of each light flavour. Indeed:

$$\boxed{\frac{\bar{s}}{\bar{q}} = \frac{1}{2}\left(\frac{m_s}{T}\right)^2 K_2\left(\frac{m_s}{T}\right) e^{\mu/3T}} \qquad (28)$$

The function $x^2K^2(x)$ is, for example, tabulated in Ref. 15). For $x = m_s/T$ between 1.5 and 2, it varies between 1.3 and 1. Thus, we almost always have more $\bar{s}$ than $\bar{q}$ quarks and, in many cases of interest, $\bar{s}/\bar{q} \sim 5$. As $\mu \to 0$ there are about as many $\bar{u}$ and $\bar{q}$ quarks as there are $\bar{s}$ quarks.

When the quark matter dissociates into hadrons, some of the numerous $\bar{s}$ may, instead of being bound in a $q\bar{s}$ kaon, enter into a $(\bar{q}\bar{q}\bar{s})$ antibaryon and, in particular, a $\bar{\Lambda}$ or $\bar{\Xi}^0$. The probability for this process seems to be comparable to the similar one for the production of antinucleons by the antiquarks present in the plasma.

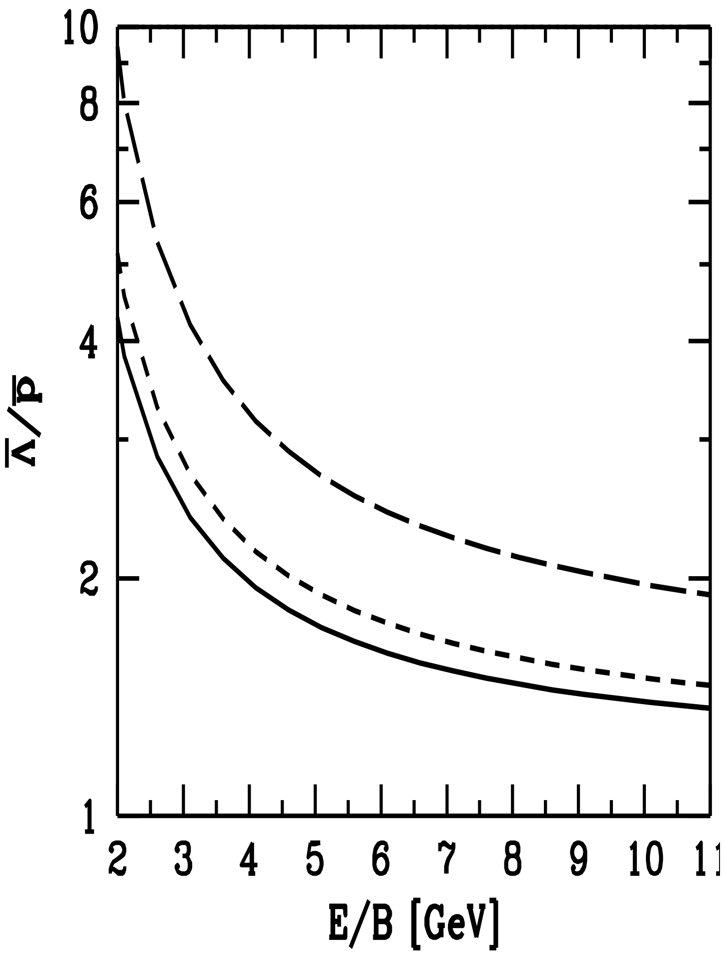
Strangeness

First literature mention of strange particle production as probe of quark-gluon plasma and as signature of phase transition between nuclear and quark matter appears in the CERN Theory preprint CERN-TH-2969 of October 1980 (Rafelski & Hagedorn). Published in "Statistical Mechanics of Quarks and Hadrons" Elsevier 1981. Strangeness enhancement $\bar{s}/\bar{q} \rightarrow K^+/\pi^+$, and strange antibaryons $\bar{s}/\bar{q} \rightarrow \overline{\Lambda}/p$ are proposed and discussed in qualitative terms as signatures of deconfined QGP phase.

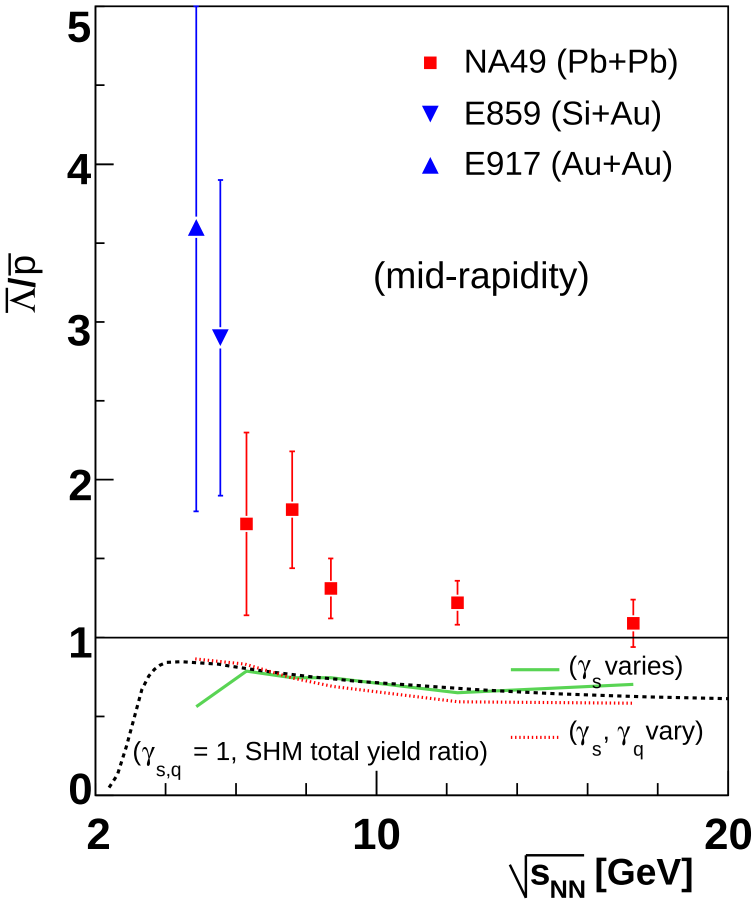
Chemical equilibrium in QGP presumed. A point of considerable later research effort.

$\overline{\Lambda}/\bar{p} > 1$ ratio anomaly predicted 1980: today status

$$\left.\frac{\overline{\Lambda}}{\bar{p}}\right|_{\rm QGP} = \frac{N_{\bar{s}}N_{\bar{u}}N_{\bar{d}}}{N_{\bar{u}}N_{\bar{u}}N_{\bar{d}}} \simeq \frac{\gamma_s^{\rm QGP}}{\gamma_q^{\rm QGP}}\left[\frac{1}{2}\frac{m_s^2}{T_h^2}K_2(m_s/T)\right] e^{(\mu_u^{\rm QGP}-\mu_s^{\rm QGP})/T} \to 0.7\, e^{\mu_u^{\rm QGP}/T}$$

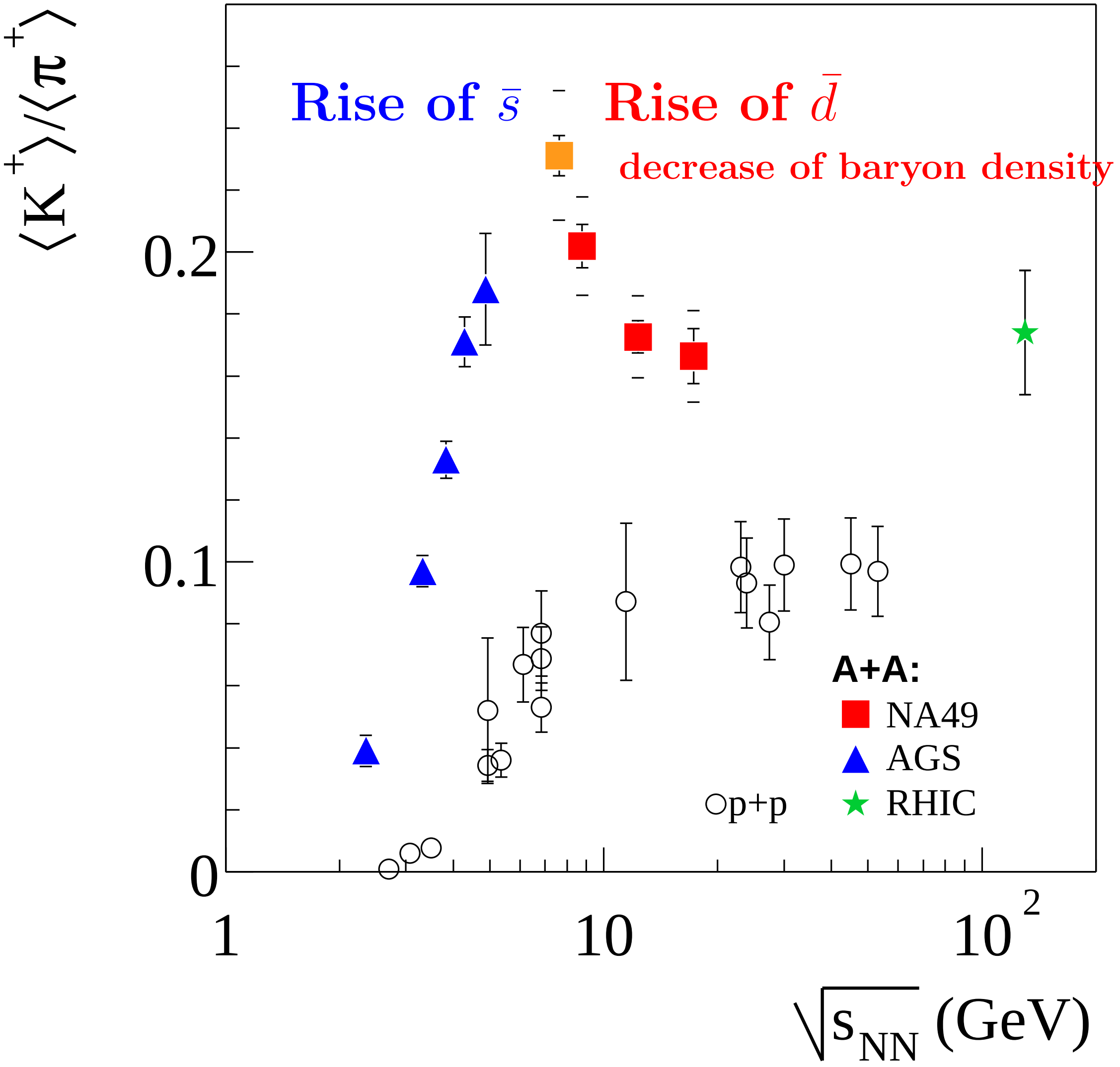


Theory: from Acta.Phys.Pol. 1996 review



Exp: CERN NA49 April 2006

K^+/π^+ ratio anomaly predicted 1980: today status


Rise of $\bar{s}$ **Rise of $\bar{d}$**

decrease of baryon density

The NA49 (Marek Gaździcki) HORN

TODAY: Strangeness / Entropy (=Particle Multiplicity)

s/S: ratio of the number of active degrees of freedom in QG plasma,

For chemical equilibrium:

$$\frac{s}{S} \simeq \frac{1}{4}\frac{n_s}{n_s+n_{\bar{s}}+n_q+n_{\bar{q}}+n_G} = \frac{\frac{g_s}{2\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{(g2\pi^2/45)T^3+(g_s n_{\mathrm{f}}/6)\mu_q^2 T} \simeq \frac{1}{35} = 0.0286$$

with $\mathcal{O}(\alpha_s)$ **interaction** $s/S \to 1/31 = 0.0323$

CENTRALITY A, and ENERGY DEPENDENCE: $\gamma_s^{\mathrm{Q}} \to 1$

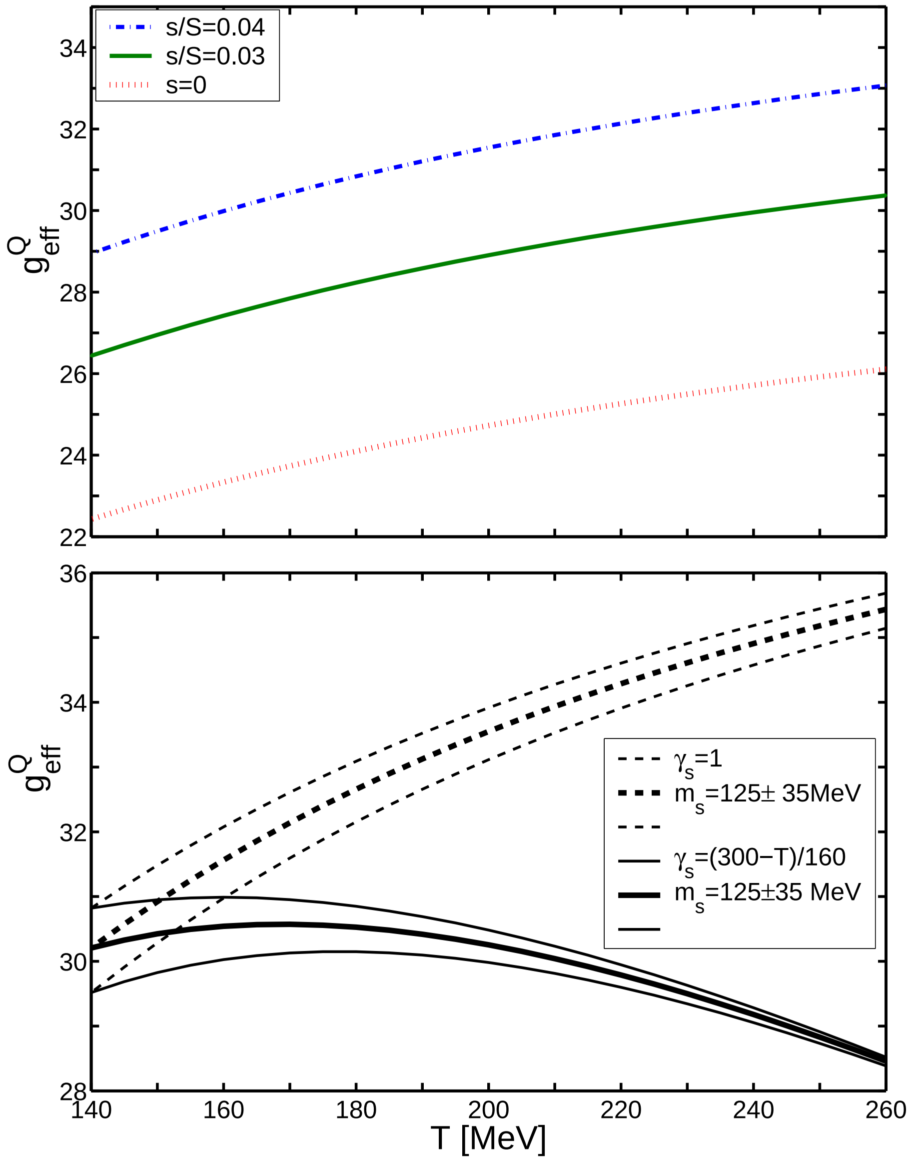
Chemical non-equilibrium occupancy of strangeness γ_s^{Q}

$$\frac{s}{S} = \frac{0.03\gamma_s^{\mathrm{Q}}}{0.4\gamma_{\mathrm{G}} + 0.1\gamma_s^{\mathrm{Q}} + 0.5\gamma_q^{\mathrm{Q}} + 0.05\gamma_q^{\mathrm{Q}}(\ln\lambda_q)^2} \to 0.03\gamma_s^{\mathrm{Q}}.$$

Analysis of experiment: we count all strange/nonstrange hadrons in final state, we use Fermi model (statistical hadronization) to extrapolate to unmeasured particle yields and/or kinematic domains, and evaluate resonance cascading:

$$\frac{s}{S} \simeq \frac{\text{count of primary strange hadrons}}{(\text{nonstrange}+\text{strange})\ \text{entropy} = 4\,\text{number of primary mesons} + \ldots}$$

QGP-EOS: Stephan-Boltzmann dof: $g^Q_{\rm eff}(T) = g_g(T) + \frac{7}{4} g_q(T) + 2g_s \frac{90}{\pi^4} + \frac{\mathcal{A}^{\rm pert}}{T^4}\frac{90}{4\pi^2}$.



defined to reproduce the entropy content of QGP

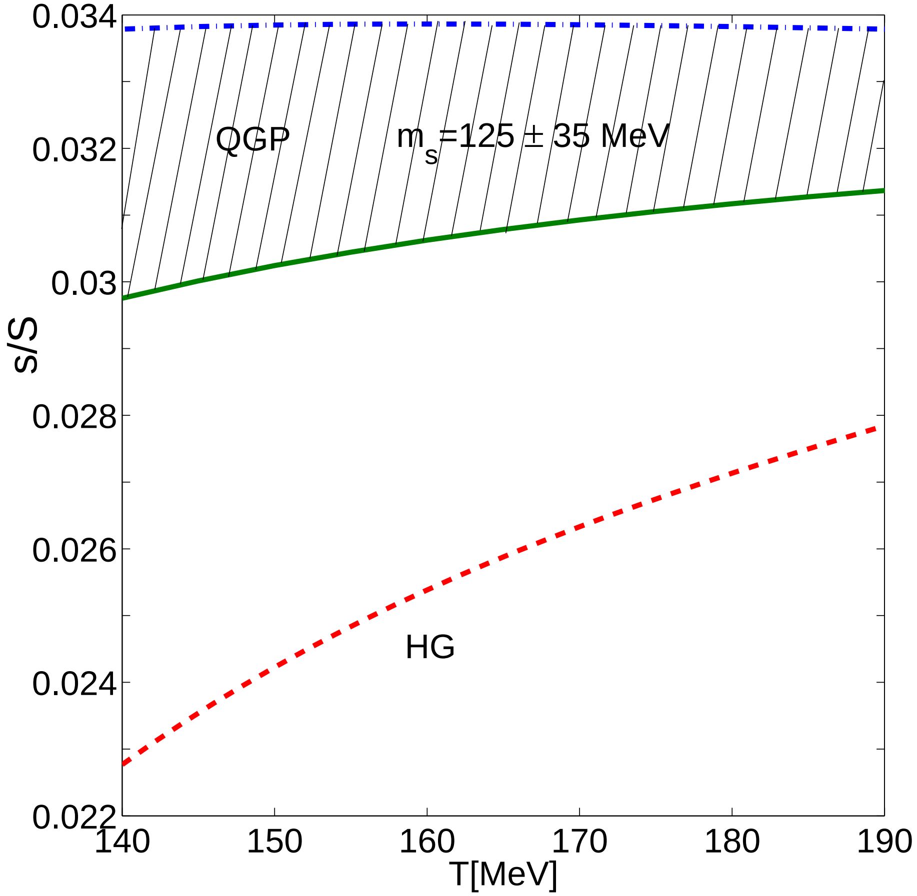
$$\sigma = \frac{4\pi^2}{90} g^Q_{\rm eff} T^3,$$

Upper frame: fixed s/S
green solid line $s/S = 0.03$
blue dot-dashed $s/S = 0.04$.
red dotted 2-flavor QCD $-u, d, G$;

Bottom:
2+1-flavor QCD with $m_s = 125 \pm 35$ MeV
dashed: equilibrated u, d, s, G system
solid lines: strangeness contents increasing with decreasing temperature
$\gamma_s = (300 - T)/160$

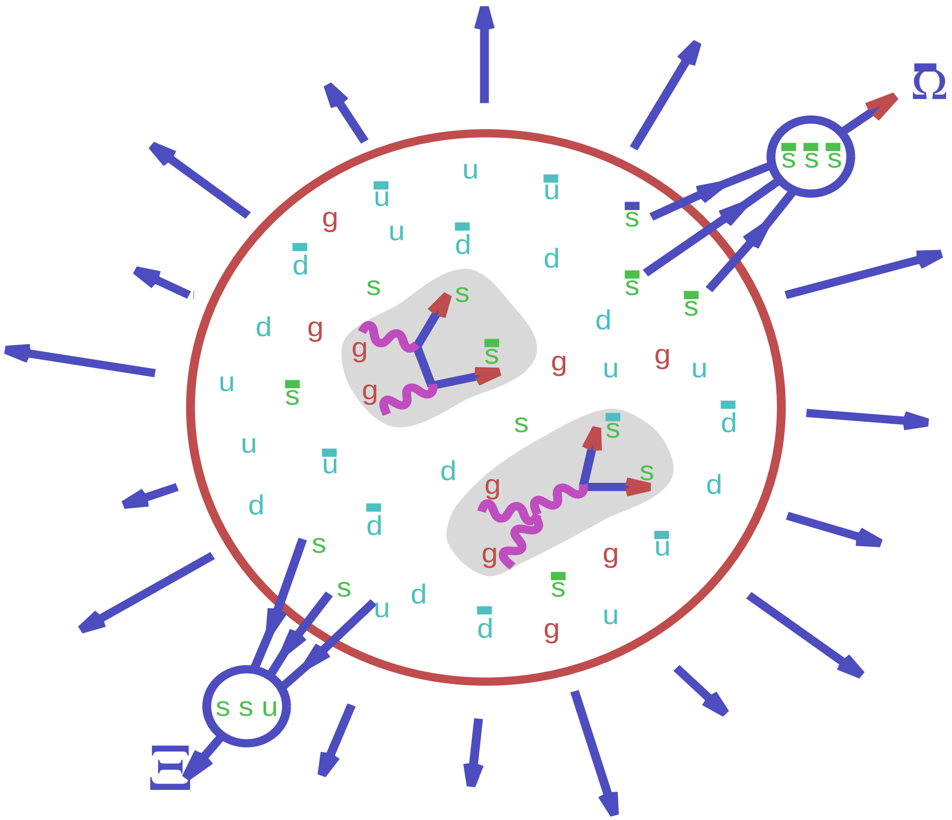
STRANGENESS ENHANCEMENT DUE TO DECONFINEMENT

We compare deconfined quark-gluon plasma with hadron gas at common measured T.



Strangeness to entropy ratio $s/S(T;\mu_B=0,\mu_S=0)$ for the chemically equilibrated QGP (green, solid line for $m_s=160$ MeV, blue dash-dot line for $m_s=90$ MeV); and for chemically equilibrated HG (red, dashed). The excess of SPECIFIC strangeness not assured if QGP not chemically equilibrated. However, since QGP is a high entropy and strangeness density phase, in absolute terms, there is both entropy and strangeness excess ALWAYS when QGP is formed.

Bulk Hadronization by Recombination of Quarks

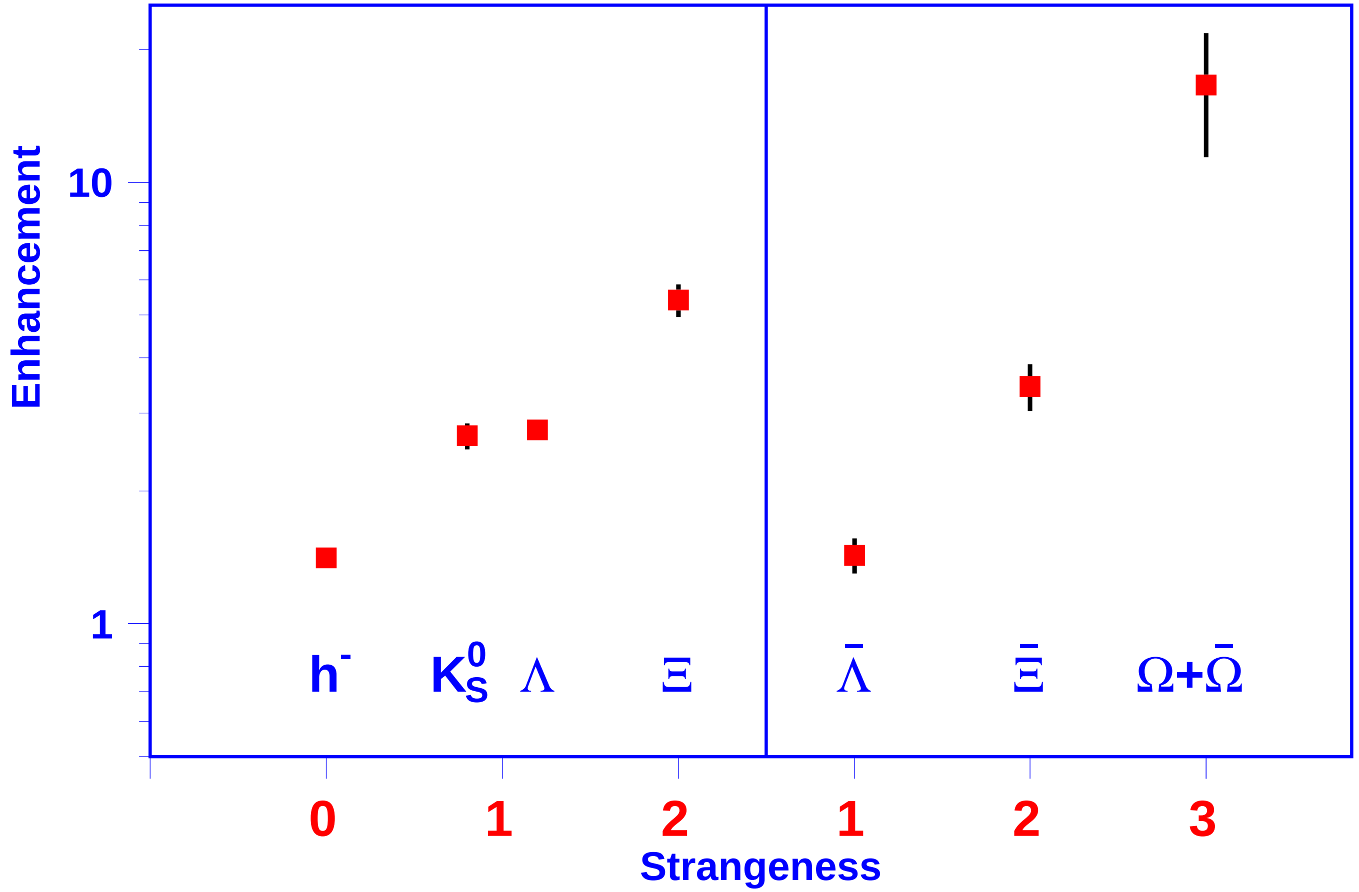


1. **$GG \to s\bar{s}$ (thermal gluons collide)**
   $GG \to c\bar{c}$ (initial parton collision)
   $GG \to b\bar{b}$ (initial parton collision)
   gluon dominated reactions
2. **RECOMBINATION of pre-formed $s,\ \bar{s},\ c,\ \bar{c},\ b,\ \bar{b}$ quarks**

Formation of complex rarely produced multi flavor (exotic) (anti)particles enabled by coalescence between $s,\ \bar{s},\ c,\ \bar{c},\ b,\ \bar{b}$ quarks made in different microscopic reactions; this is signature of quark mobility and independent action, thus of deconfinement. Moreover, strangeness enhancement = gluon mobility.

Enhancement of flavored antibaryons progressing with ‘exotic’ flavor content. Anomalous meson to baryon relative yields.

MULTI STRANGE HYPERON ENHANCEMENT

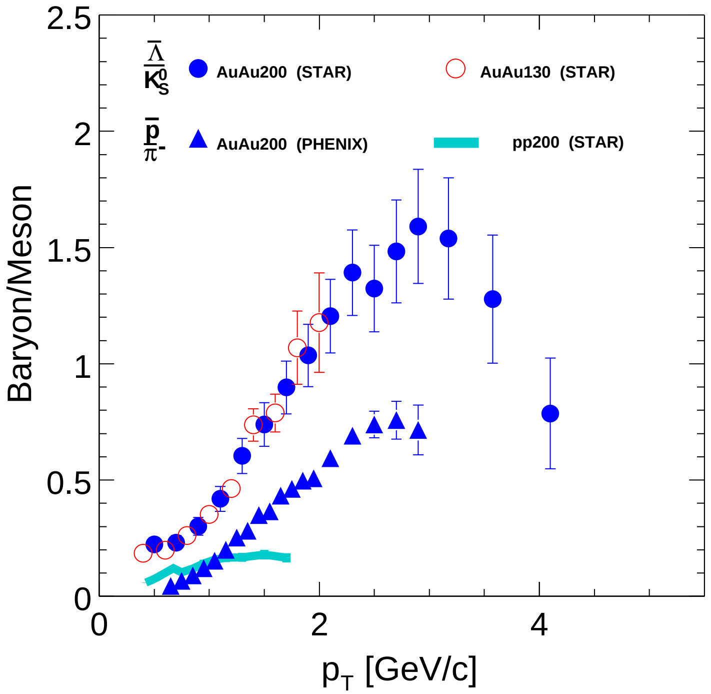


First results: CERN WA97 collaboration from 158 A GeV Pb–Pb reactions,

By the chair of SQM07, Prof. Ladislav Sandor

about 10 years ago: Enhancement GROWS with a) strangeness b) antiquark content as predicted. Enhancement is defined with respect to yield in p–Be collisions, scaled up with the number of 'wounded' nucleons.

The new and dominant hadronization mechanism is visible in:



Baryon to Meson Ratio

Ratios $\overline{\Lambda}/K_S$ and $\overline{p}/\pi$ in Au-Au compared to pp collisions as a function of $p_\perp$. The large ratio at the intermediate $p_\perp$ region: evidence that particle formation (at RHIC) is distinctly different from fragmentation processes for the elementary e^+e^- and pp collisions.

To describe recombinant yields: nonequilibrium parameters needed

- γ_q $(\gamma_s, \gamma_c, \ldots)$: u, d $(s, c, \ldots)$ **quark phase space yield, absolute chemical equilibrium:** $\gamma_i \to 1$

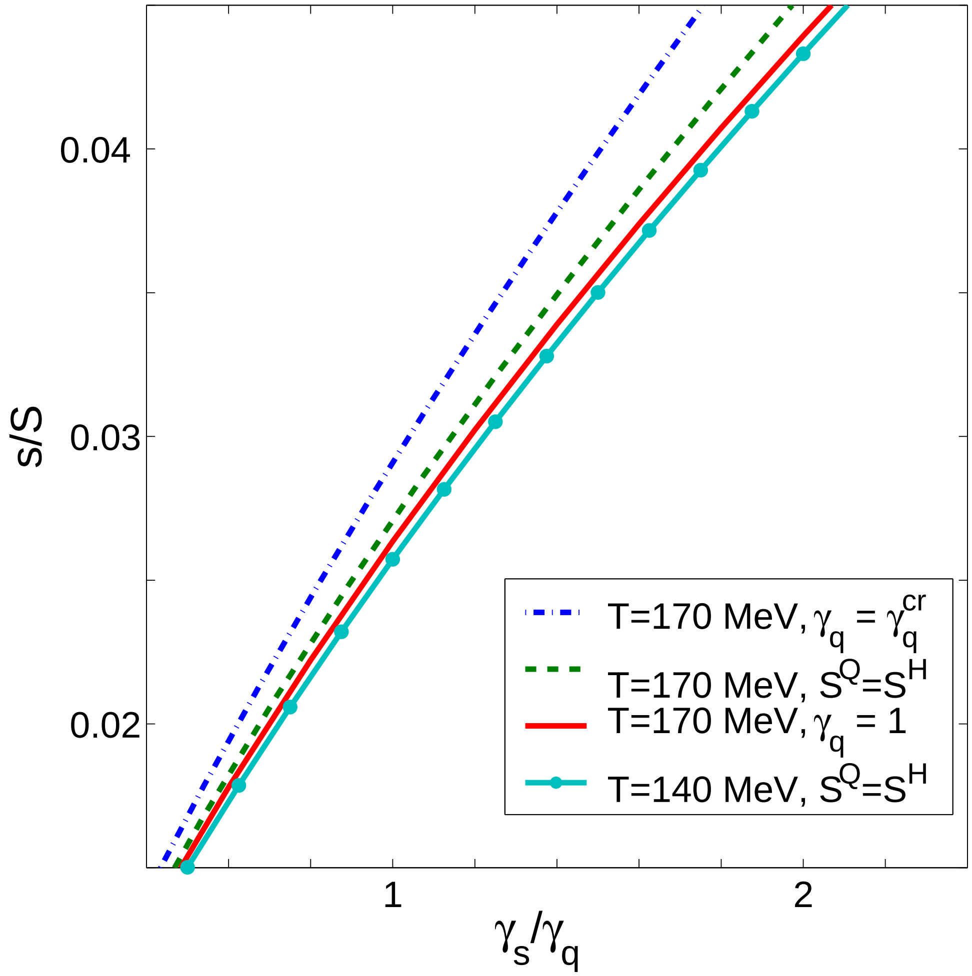
$$\frac{\text{baryons}}{\text{mesons}} \propto \frac{\gamma_q^3}{\gamma_q^2} \cdot \left(\frac{\gamma_s}{\gamma_q}\right)^n$$

- γ_s/γ_q **shifts the yield of strange vs non-strange hadrons:**

$$\frac{\overline{\Lambda}(\bar{u}\bar{d}\bar{s})}{\bar{p}(\bar{u}\bar{u}\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \qquad \frac{\mathrm{K}^+(u\bar{s})}{\pi^+(u\bar{d})} \propto \frac{\gamma_s}{\gamma_q}\,, \qquad \frac{\phi}{h} \propto \frac{\gamma_s^2}{\gamma_q^2}\,, \qquad \frac{\Omega(sss)}{\Lambda(sud)} \propto \frac{\gamma_s^2}{\gamma_q^2}\,,$$

STRANGENESS ENHANCEMENT CONSEQUENCE

Hadronizing QGP leads to chemical nonequilibrium HG phase space.



Strangeness to entropy ratio s/S at $\lambda_q = \lambda_s = 1$, as function of γ_s^H/γ_q^H, the final state hadron occupancy in chemically NON-equilibrated HG. **Strangeness excess in QGP leads to over-occupancy observable in particle yield analysis.**

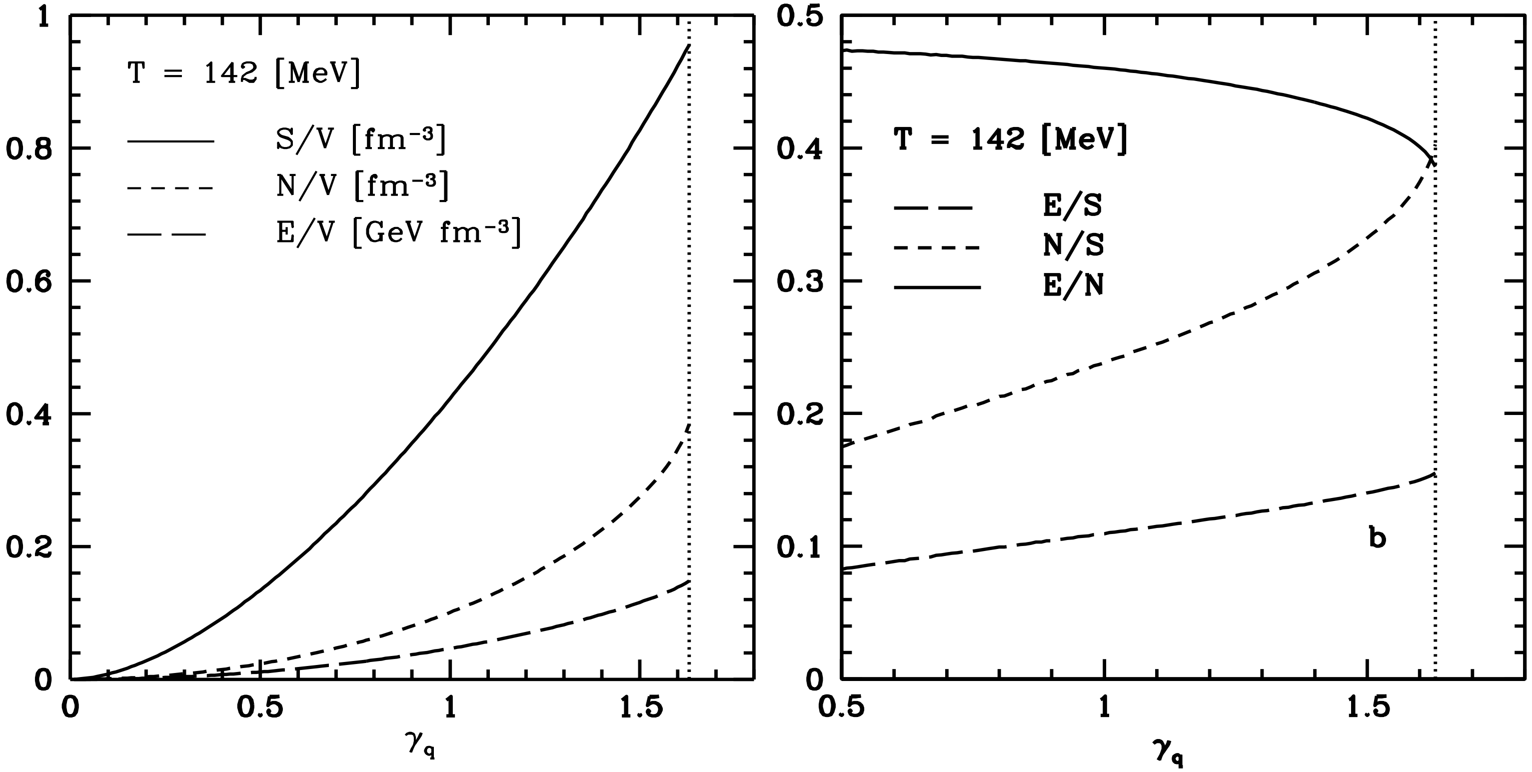
ENTROPY ENHANCEMENT CONSEQUENCE: $\gamma_q^{\rm H} > 1$ at breakup

To maximize entropy density in hadron phase space at hadronization $\boxed{\gamma_q^2 \to e^{m_\pi/T}}$**:**

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

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

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



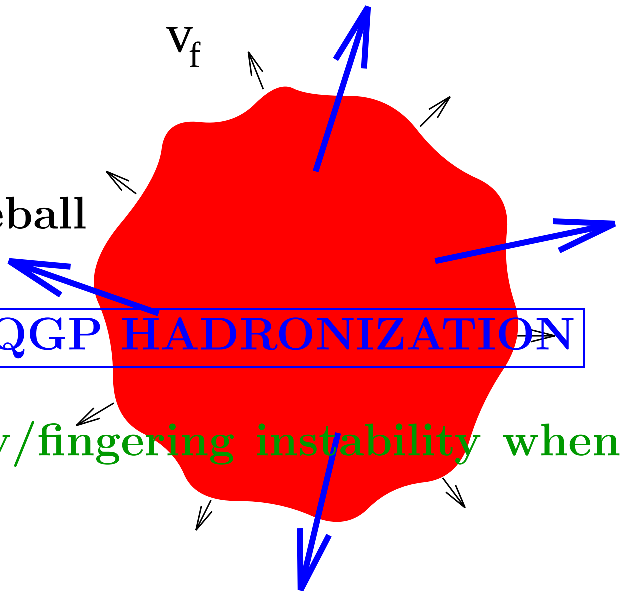
Fast hadronization and:
MATTER-ANTIMATTER SPECTRAL SYMMETRY

Recombination hadronization implies symmetry of $m_\perp$ spectra of (strange) baryons and antibaryons also in baryon rich environment.

CONVERSELY: spectral matter-antimatter symmetry implies; A common matter-antimatter particle formation mechanism, AND negligible antibaryon re-annihilation/re-equilibration/rescattering.

Such a nearly free-streaming particle emission by a quark source into vacuum also required by other observables: e.g. high reconstructed yield of hadron resonances and HBT particle correlation analysis pointing to a short emission time and limited volume of pion source

Practically no hadronic ‘phase’
No ‘mixed phase’
Direct emission of free-streaming
hadrons from exploding filamentary fireball



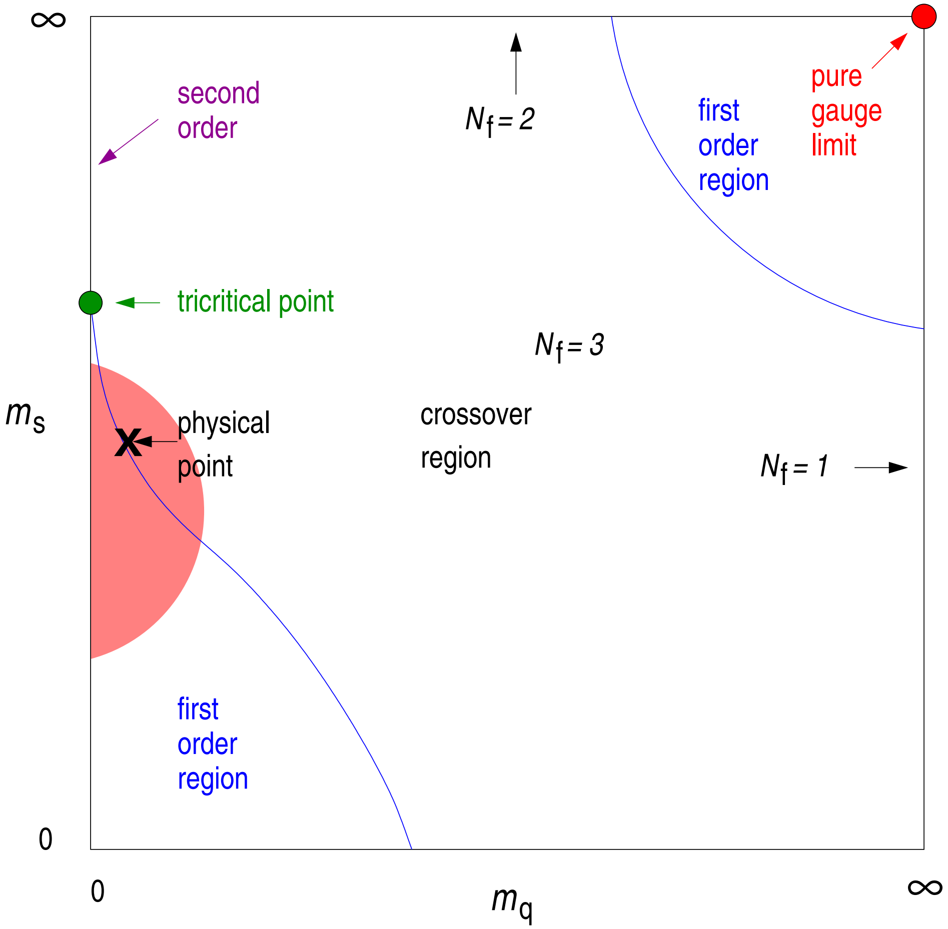
Develop analysis tools viable in SUDDEN QGP HADRONIZATION

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

Fast hadronization and observed PHASE BOUNDARY

- **at low $\mu_B \to 0$ count carefully degrees of freedom**
  - **Temperature of phase transition depends on available degrees of freedom.**
    Physics: For 2+1 flavors. When $2 \to 2+1 \Delta T \simeq 10$–15 MeV,
    When $\gamma_s \to 1.5$ expect $2+1 \to 3$
  - **The nature and position of phase transition/transformation changes when number of flavors rises from $2+1 \to 3$**
    $\gamma_i > 1$ helps create a phase transition at $\mu_B = 0$
- **at high $\mu_{\rm B}$ we can encounter a heavy (valon) quark phases.**
  Under saturation of high mass phase space requires higher T.
- **Dynamical effects of expansion:**
  colored partons like a wind, displace the boundary

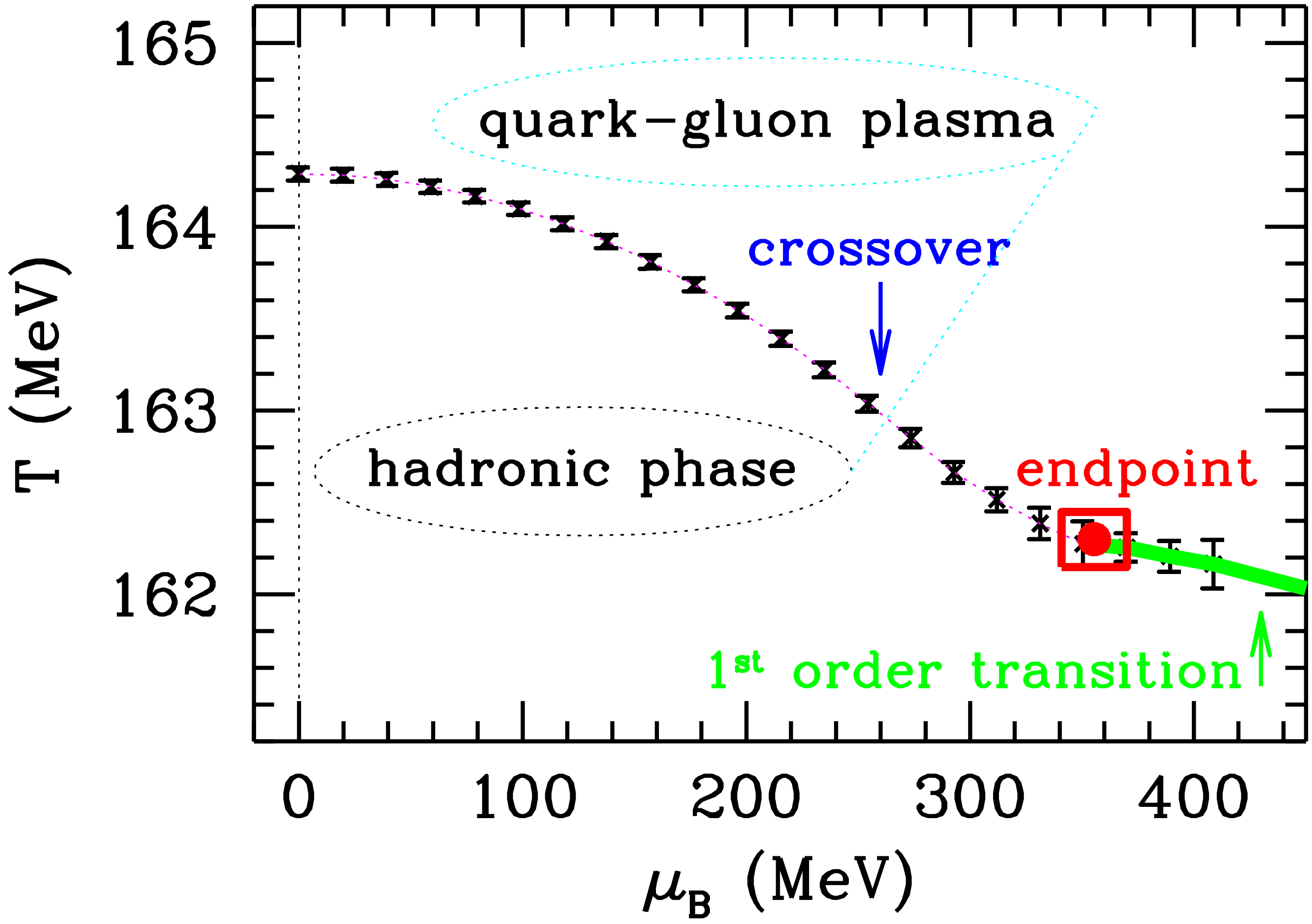
Fermi degrees of freedom and phase transitions in QCD



adapted from: THE THREE FLAVOR CHIRAL PHASE TRANSITION WITH AN IMPROVED QUARK AND GLUON ACTION IN LATTICE QCD. By A. Peikert, F. Karsch, E. Laermann, B. Sturm, (LATTICE 98), Boulder, CO, 13-18 Jul 1998. in Nucl.Phys.Proc.Suppl.73:468-470,1999.

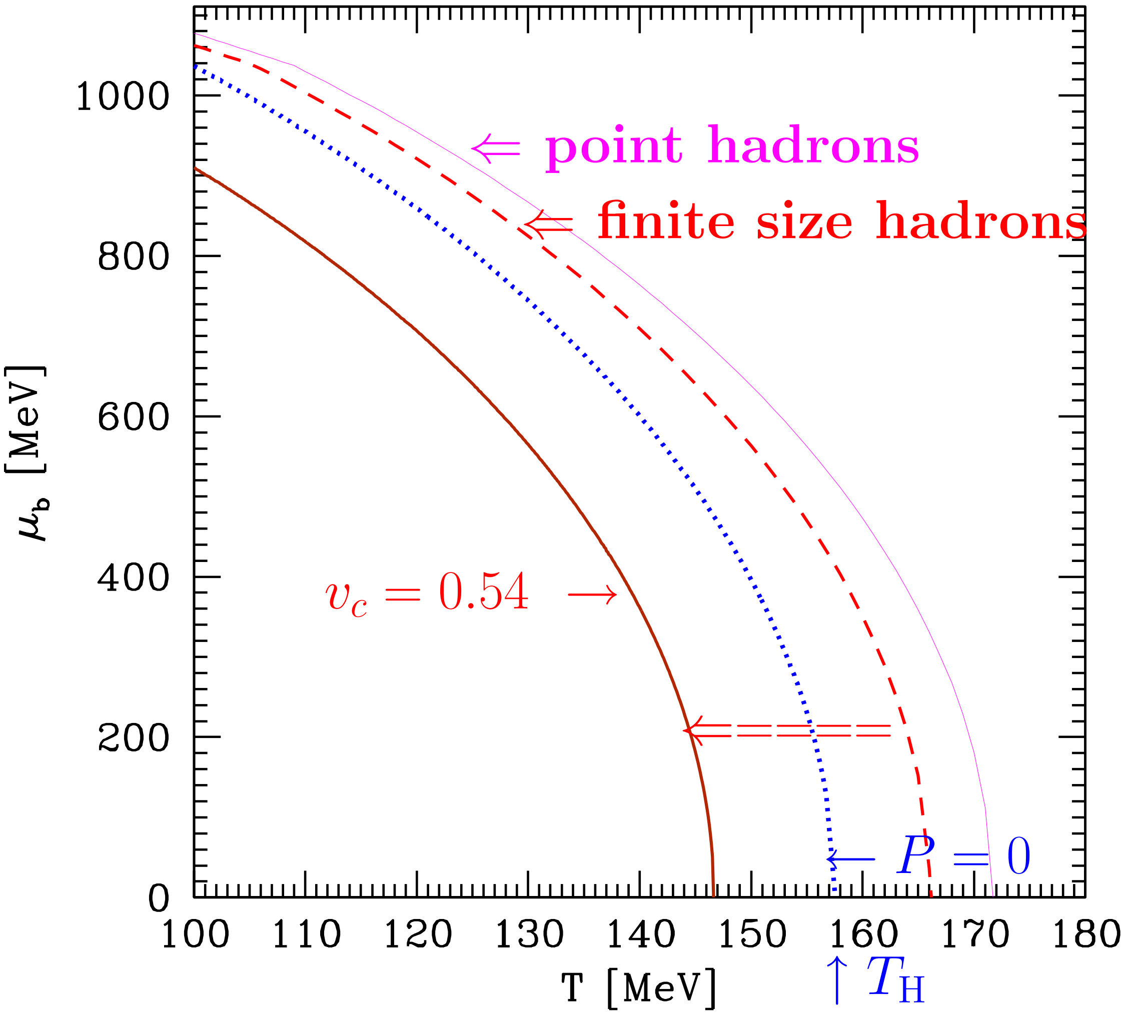
Note that we need some additional quark degrees of freedom to push the system over to phase transition. Conventional wisdom: baryon density:

....and considering the baryochemical potential



adapted from: CRITICAL POINT OF QCD AT FINITE T AND MU, LATTICE RESULTS FOR PHYSICAL QUARK MASSES. By Z. Fodor, S.D. Katz (Wuppertal U.), JHEP 0404:050,2004; hep-lat/0402006. **However, at LHC the baryochemical potential at level of 1-3 MeV. Better hope for γ_s, and** **MOTION:**

(dynamical)Phase boundary and ‘wind’ of flow of matter



Solid: point hadrons T_p

Dashed: finite size hadrons

Thick solid: breakup with
$v = 0.54$ $(\kappa = 0.6)$
Expansion
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 used here was at $T \simeq 166$**.**

SUDDEN MECHANISM: Super-cooling COLOR WIND of an exploding 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,

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

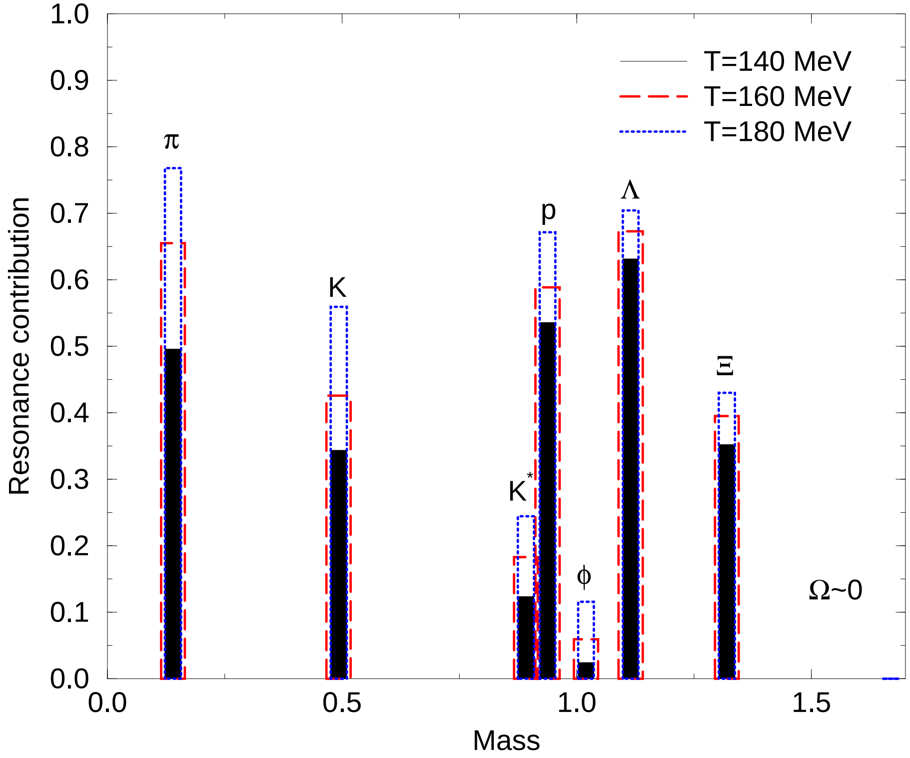
This requires $P_{\rm p} < \mathcal{B}$: QGP phase pressure P must be NEGATIVE. A fireball surface region which reaches $\mathcal{P} \to 0$ and continues to flow outward is torn apart in a rapid instability. This can ONLY arise since matter presses again the vacuum which is not subject to collective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

TESTING EXPECTATIONS

Hypothesis (Fermi, Hagedorn): particle production can be described by evaluating the accessible phase space. Fit result defines hadronization condition $T, \mu_B, \ldots$. Fast hadronization: one set of parameters for each geometric centrality and reaction energy.

Verification of statistical hadronization:

Particle yields with same valance quark content are in relative chemical equilibrium, e.g. the relative yield of $\Delta(1230)/N$ as of K^*/K, $\Sigma^*(1385)/\Lambda$, etc, is controlled by chemical freeze-out i.e. Hagedorn Temperature $T_{\rm H}$:



$$\frac{N^*}{N} = \frac{g^*(m^* T_{\rm H})^{3/2} e^{-m^*/T_{\rm H}}}{g(m T_{\rm H})^{3/2} e^{-m/T_{\rm H}}}$$

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

Resonance yields test statistical hadronization principles.

Resonances reconstructed by invariant mass; important to consider potential for loss of observability.

YIELDS vs SPECTRA FITS

The observation by NA49 and STAR of a strong visible resonance yields requires that spectra of particles are composed and computed from several contributions

1) the directly produced (recombinant) component

2) the dominant direct resonance contribution, decayed into particle of interest;

3) the many other resonance contributions (small contributions of many resonances)

The presence of decays deforms further the spectrum which already depends on:

a) mechanism of formation (statistical hadronization with recombination, etc),

b) parameters of hadronization, (in blast wave model T, v)

c) freeze-out surface dt_f/dx_f (in blast wave $\to 0$ and its dynamics.

Results of 'blast-wave' model without resonance decayed into observed particle as presented by several experimental groups are of limited scientific usefulness for anything but ϕ and Ω.

Theoretical efforts to gain control of the spectra see Krakow single freeze-out model, as example, are very laudable.

Integrated yields have much the same information, assume SHM resonance yields. Model dependence very reduced.

Statistical Hadronization fits of hadron yields

Full analysis of experimental hadron yield results requires a significant book-keeping and fitting effort in order to allow for resonances, particle widths, full decay trees, isospin multiplet sub-states.

Kraków-Tucson (and SHARE 2 Montreal) 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,

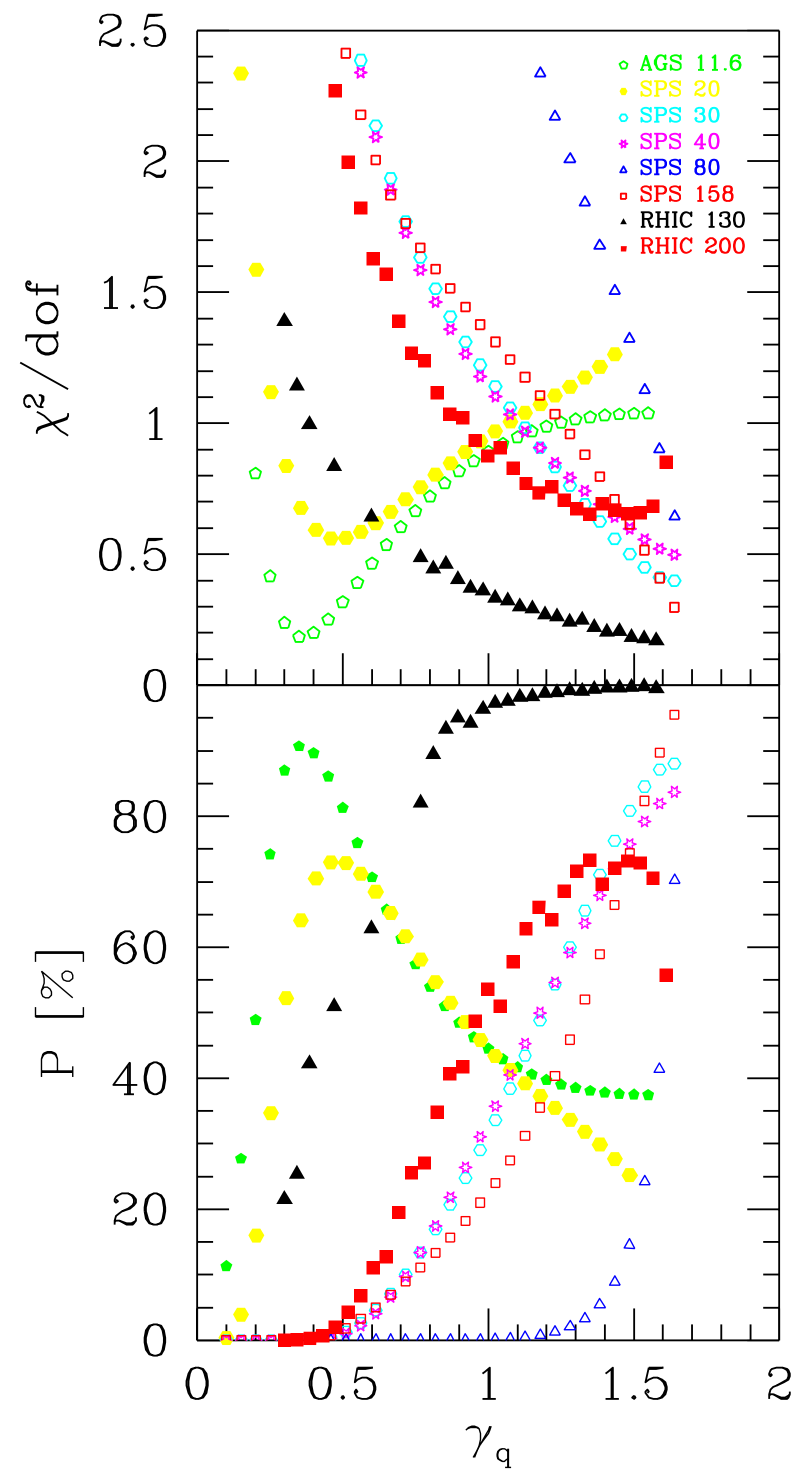
W. Broniowski, W. Florkowski, J. Letessier, et al
nucl–th/0404083 Comp. Phys. Com. 167, 229 (2005)

SHARE 2.2 with flexible weak decays, fluctuations and chemical flexibility now on line. Involves S.Y. Jeon, Montreal, allows fluctuations and better handling of WI corrections.
Comp. Phys. Com. 175, 635 (2006) nucl-th/0603026

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

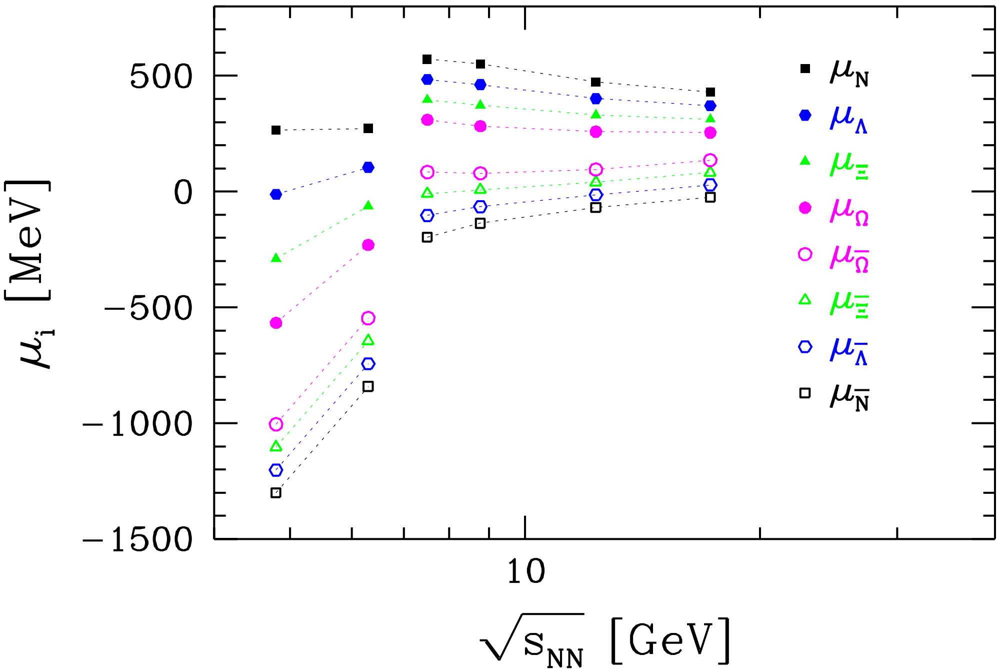
DATA: Energy dependence of geometrically most central interactions (5–7% trigger), use particle yields N_i or/and at RHIC dN/dy

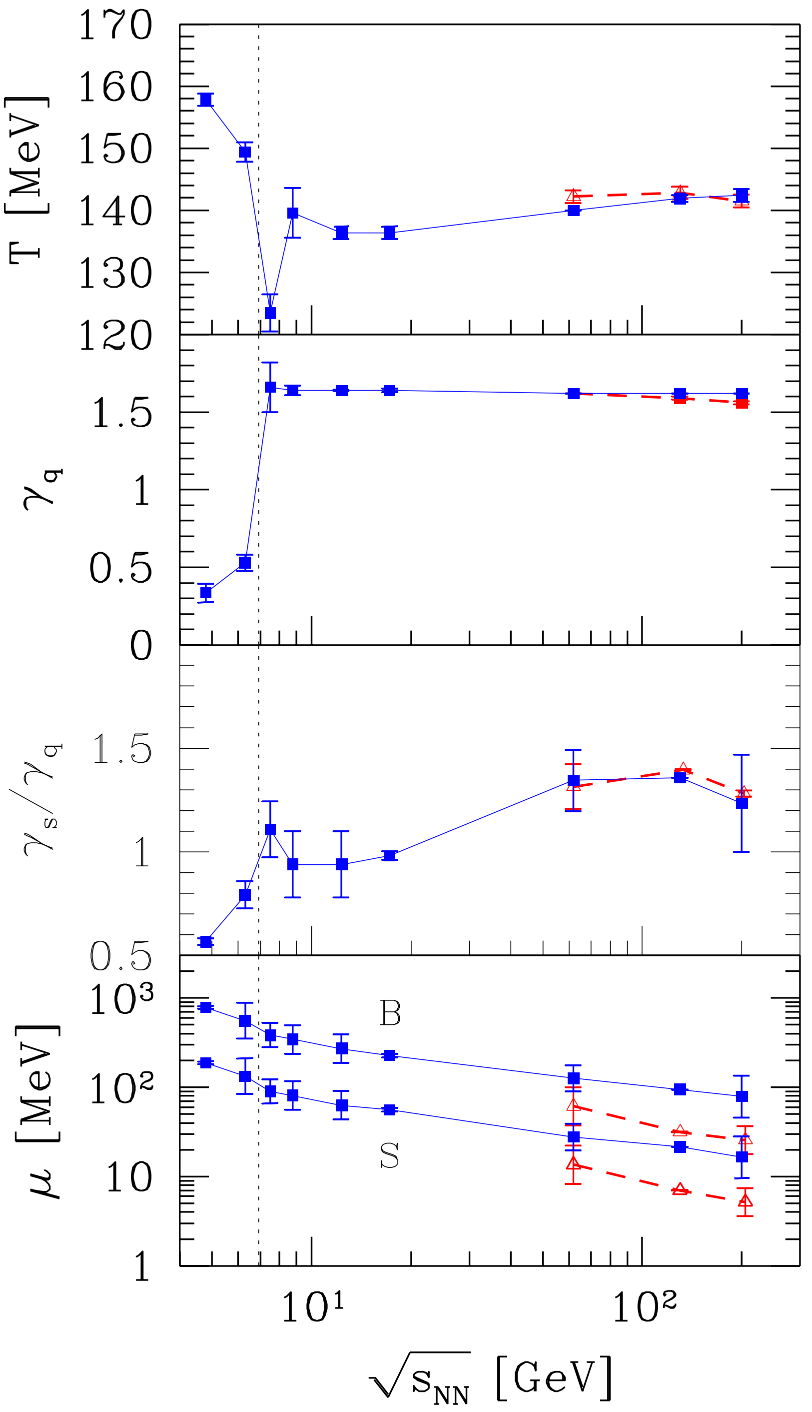
E[AGeV]	**11.6**	**20**	**30**	**40**	**80**	**158**
$\sqrt{s_{\rm NN}}$ **[GeV]**	**4.84**	**6.26**	**7.61**	**8.76**	**12.32**	**17.27**
$y_{\rm CM}$	**1.6**	**1.88**	**2.08**	**2.22**	**2.57**	**2.91**
$N_{4\pi}$ **centrality**	**most central**	**7%**	**7%**	**7%**	**7%**	**5%**
$R = p/\pi^+$, N_W	$R = 1.23 \pm 0.13$	**349±6**	**349±6**	**349±6**	**349±6**	**362±6**
Q/b	**0.39±0.02**	**0.394±0.02**	**0.394±0.02**	**0.394±0.02**	**0.394±0.02**	**0.39±0.02**
π^+	**133.7±9.9**	**184.5±13.6**	**239±17.7**	**293±18**	**446±27**	**619±48**
$R = \pi^-/\pi^+$, π^-	$R = 1.23 \pm 0.07$	**217.5±15.6**	**275±19.7**	**322±19**	**474±28**	**639±48**
$R = {\rm K}^+/{\rm K}^-$,${\rm K}^+$	$R = 5.23 \pm 0.5$	**40±2.8**	**55.3±4.4**	**59.1±4.9**	**76.9±6**	**103±10**
${\rm K}^-$	**3.76±0.47**	**10.4±0.62**	**16.1±1**	**19.2±1.5**	**32.4±2.2**	**51.9±4.9**
$R = \phi/{\rm K}^+$, ϕ	$R = 0.025 \pm 0.006$	**1.91±0.45**	**1.65±0.5**	**2.5±0.25**	**4.58±0.2**	**7.6±1.1**
Λ	**18.1±1.9**	**28±1.5**	**41.9±6.1**	**43.0±5.3**	**44.7±6.0**	**44.9±8.9**
$\overline{\Lambda}$	**0.017±0.005**	**0.16±0.03**	**0.50±0.04**	**0.66±0.1**	**2.02±0.45**	**3.68±0.55**
Ξ^-		**1.5±0.13**	**2.48±0.19**	**2.41±0.39**	**3.8±0.260**	**4.5±0.20**
$\overline{\Xi}^+$			**0.12±0.06**	**0.13±0.04**	**0.58 ±0.13**	**0.83±0.04**
$\Omega + \overline{\Omega}$				**0.14±0.07**		
${\rm K_S}$						**81±4**
$V[{\rm fm}^3]$	**3596±331**	**4519±261**	**1894±409**	**1879±183**	**2102±53**	**3004±1**
T **[MeV]**	**157.8±0.7**	**153.4±1.6**	**123.5±3**	**129.5±3.4**	**136.4±0.1**	**136.4±0.1**
λ_q	**5.23±0.07**	**3.49±0.08**	**2.82±0.08**	**2.42±0.10**	**1.94±0.01**	**1.74±0.02**
λ_s	**1.657***	**1.41***	**1.36***	**1.30***	**1.22***	**1.16***
γ_q	**0.335±0.006**	**0.48±0.05**	**1.66±0.10**	**1.64±0.04**	**1.64±0.01**	**1.64±0.001**
γ_s	**0.190±0.009**	**0.38±0.05**	**1.84±0.32**	**1.54±0.15**	**1.54±0.05**	**1.61±0.02**
λ_{I3}	**0.877±0.116**	**0.863±0.08**	**0.939±0.023**	**0.951±0.008**	**0.973±0.002**	**0.975±0.004**
$\mu_{\rm B}$ **[MeV]**	**783**	**576**	**384**	**344**	**271**	**227**
$\mu_{\rm S}$ **[MeV]**	**188**	**139**	**90.4**	**80.8**	**63.1**	**55.9**



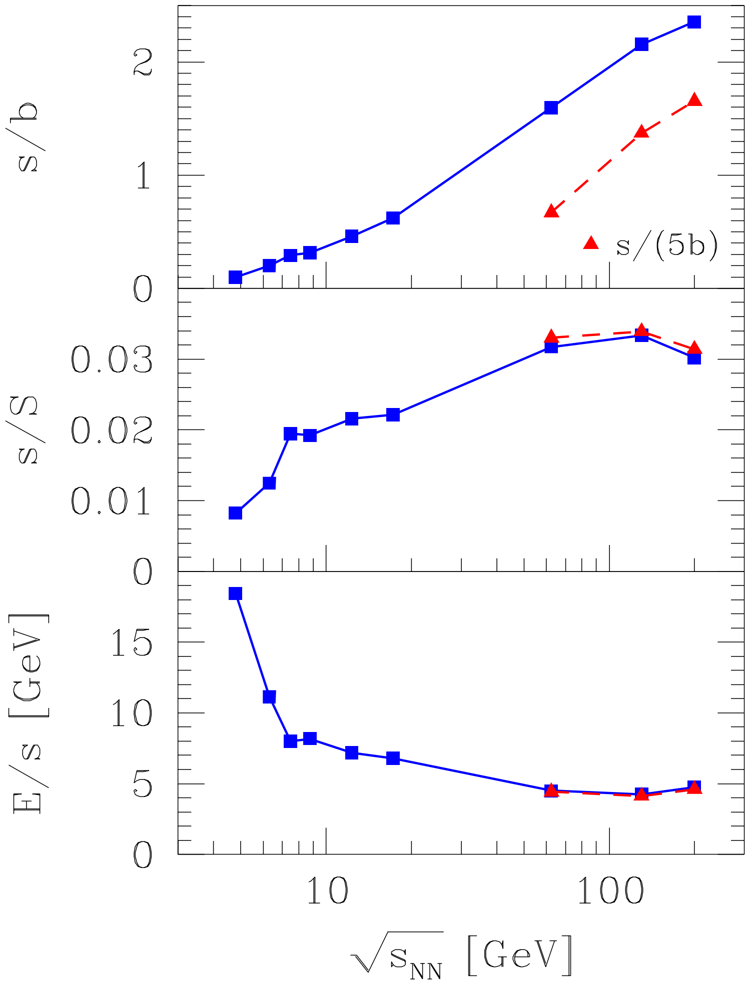
How good is the fit? χ^2/dof and confidence level P[%] as function of γ_q. For lowest two energies (AGS/SPS): small $\gamma_q < 1$ preferred, for other energies $\gamma_q \to e^{m_\pi/2T}$, maximum of entropy. If only one reaction energy is considered one may think $\gamma_q = 1$ is useful.

NOTE: All results recomputed with SHARE 2.2 with updated AGS/NA49 DATA. consequence of some importance: disappearance of baryons and antibaryons (up to nucleon number brought into reaction) , ideal test of the result: if only we had these measurements......

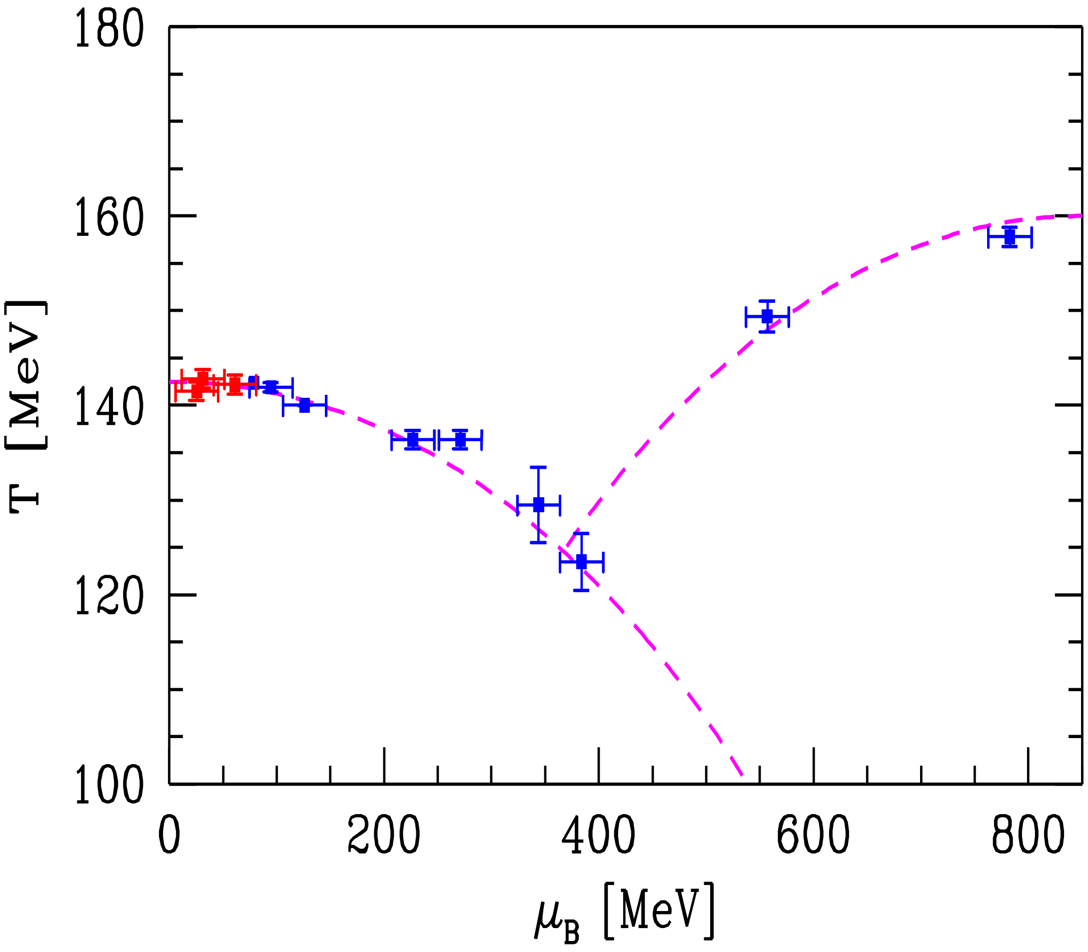


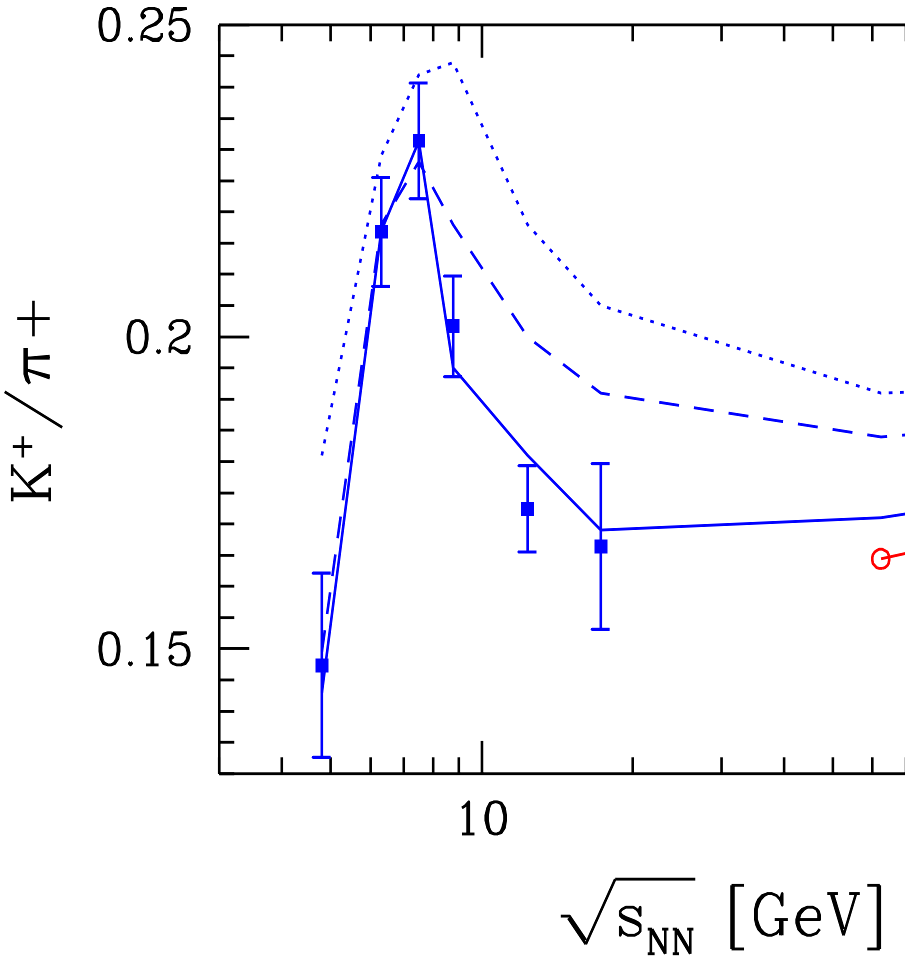


Statistical parameter results for $N_{4\pi}$ (blue online, square). Same for dN/dy at RHIC (red triangles). The lines guide the eye.



strangeness yield as function of reaction energy: s/b, s/S, $s/E_{\rm th}$

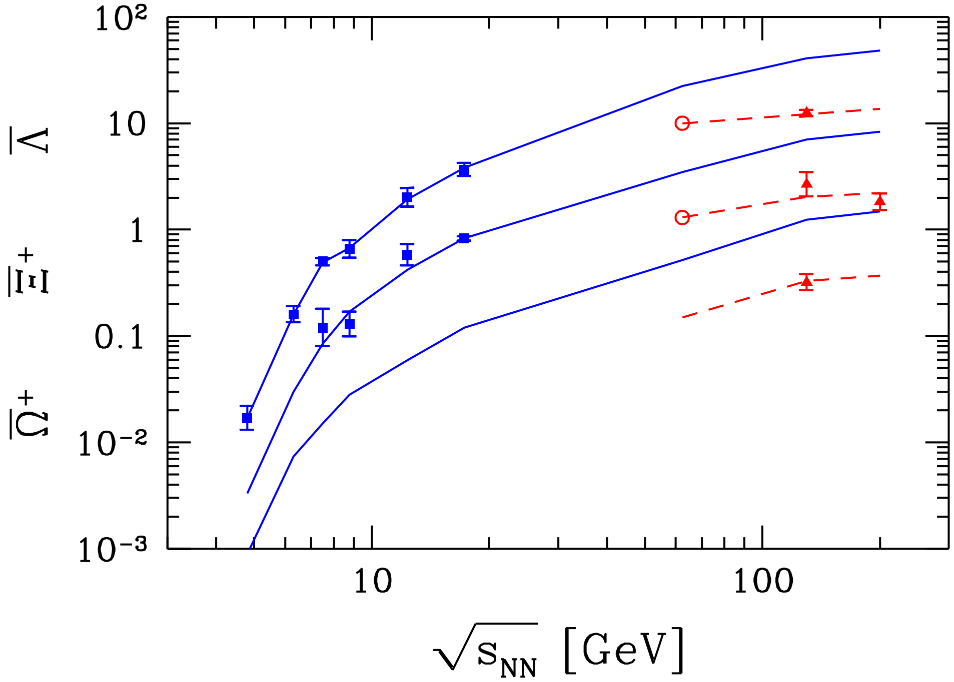




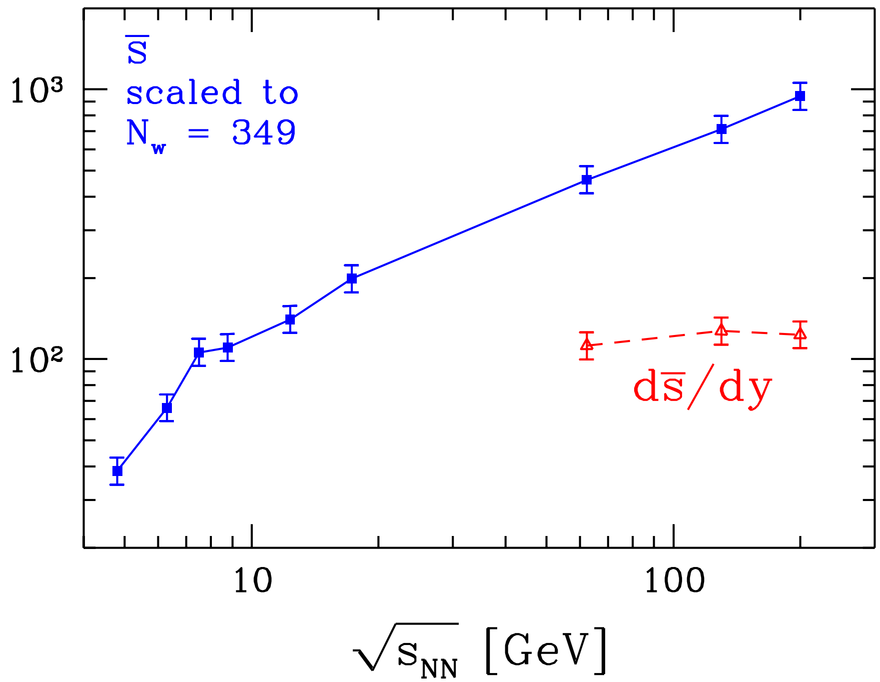
Features: **Reduced T (by 15 MeV), we think due to fast expansion. K^+/π^+ peak at the minimum of μ_B.**

There seems to be at high μ_B (corresponding to 11.8 and 20 GeV on fixed target) a hadronization phase involving 'valons'. Why we reproduce the 'horn': fit with γ_q has build-in capability to dilute K^+/π^+ yield by $\bar{d}$ formation, in valon picture the heavy constituent quarks melt, yield of $\bar{d}$ rapidly rises.

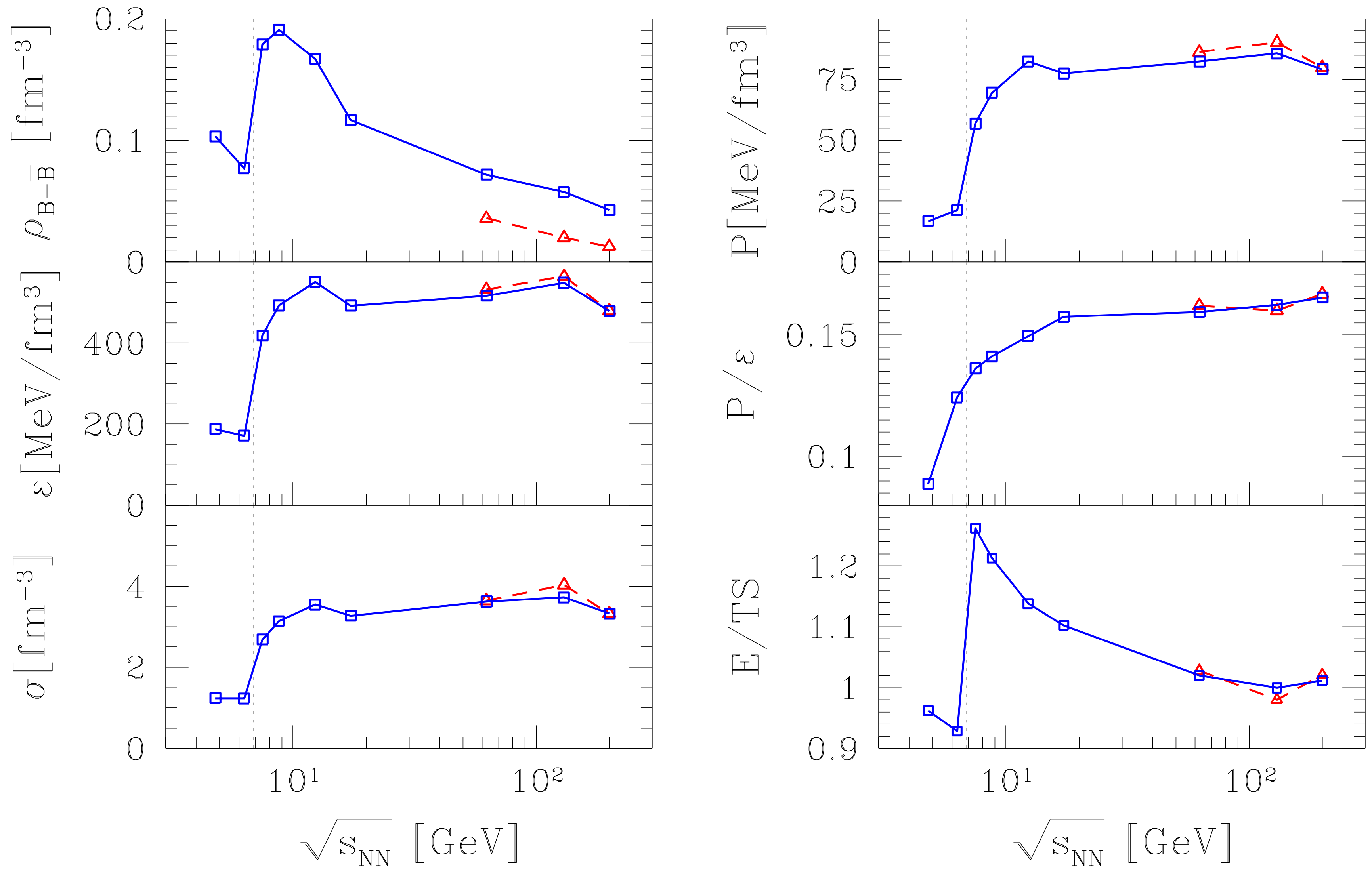
Antibaryon i.e. $\bar{u}, \bar{d}, \bar{s}$ yields



Strangeness Yield



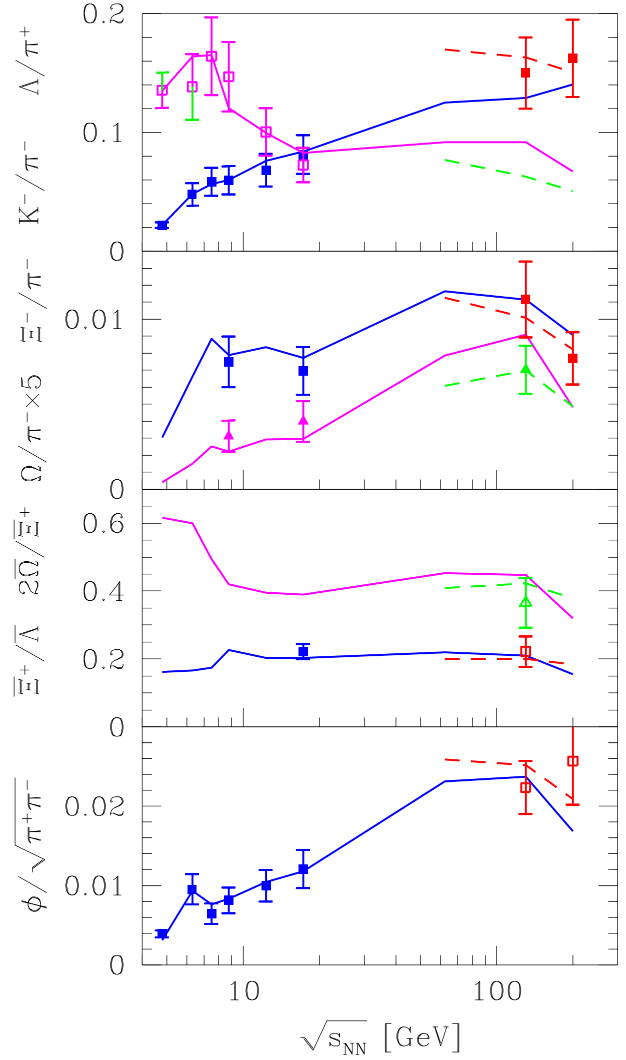
Antibaryons suppressed at low energies. Strangeness yield rises rapidly, slowdown at 30 GeV ($\sqrt{s_{\mathrm{NN}}} = 7.61$ GeV)



Physical Properties of bulk at hadronization show a change, from low density and pressure system at low $\sqrt{s}$ to to a highly compressed phase just above this, see baryon and energy density. Shift in E/TS consistent with change from adiabatic to fast hadronization.

PREDICTIONS: AGS/SPS range:

E [A GeV]	11.6	20	30	40	80	158
$\sqrt{s_{\rm NN}}$ [GeV]	4.84	6.26	7.61	8.76	12.32	17.27
$y_{\rm CM}$	1.6	1.88	2.08	2.22	2.57	2.91
$N_{4\pi}$/ centr.	m.c.	7%	7%	7%	7%	5%
$b \equiv B - \overline{B}$	375.6	347.9	349.2	349.9	350.3	362.0
π^+	135.2	181.5	238.7	290.0	424.5	585.2
π^-	162.1	218.9	278.1	326.0	461.3	643.9
$\rm K^+$	17.2	39.4	55.2	56.7	77.1	109.7
$\rm K^-$	3.58	10.4	15.7	19.6	35.1	54.1
$\rm K_S$	10.7	25.5	35.5	37.9	55.1	80.2
ϕ	0.46	1.86	2.28	2.57	4.63	7.25
p	174.6	161.6	166.2	138.8	138.8	144.3
$\bar{p}$	0.021	0.213	0.68	0.76	2.78	5.46
Λ	18.2	29.7	39.4	34.9	42.2	48.3
$\overline{\Lambda}$	0.016	0.16	0.51	0.63	2.06	4.03
Ξ^-	0.47	1.37	2.44	2.43	3.56	4.49
$\overline{\Xi}^+$	0.0026	0.027	0.089	0.143	0.42	0.82
Ω	0.013	0.068	0.14	0.144	0.27	0.38
$\overline{\Omega}$	0.0008	0.0086	0.022	0.030	0.083	0.16
$\rm K^0(892)$	5.42	13.7	11.03	12.4	18.7	26.6
Δ^0	38.7	33.43	25.02	26.6	27.2	28.2
Δ^{++}	30.6	25.62	22.22	24.2	25.9	26.9
$\Lambda(1520)$	1.36	2.06	1.73	1.96	2.62	2.99
$\Sigma^-(1385)$	2.51	3.99	4.08	4.26	5.24	5.98
$\Xi^0(1530)$	0.16	0.44	0.69	0.73	1.14	1.44
η	8.70	16.7	19.9	24.1	38.0	55.2
η'	0.44	1.14	1.10	1.41	2.52	3.76
ρ^0	12.0	19.4	14.0	18.4	32.1	42.3
$\omega(782)$	6.10	13.0	10.8	15.7	27.0	38.5
$f_0(980)$	0.56	1.18	0.83	1.27	2.27	3.26
$s - \bar{s}/s + \bar{s}$	0	-0.092	-0.085	-0.056	-0.029	-0.062



Conclusions

- **Strangeness enhancement confirmed. Steady rise of s/S with energy towards chemical QGP equilibrium at RHIC**
- **Signatures such as multi strange hadrons and K^+/π^+ indicate early onset of deconfinement.**
- **Successful interpretation of energy dependence of hadron production by QGP source.**
- **Count of the fractional number of degree of freedom of strange quark fraction in all agrees with QGP**
- **Properties of particles from bulk of matter in a resounding confirmation for a fast hadronization of rapidly exploding QGP .**
- **Strangeness contents and QGP expansion dynamics impacts phase boundary and transition properties: QCD matter with 2+1 flavors on lattice is exceptionally fine tuned.**