Chemical Nonequilibrium in QGP and The Phase Boundary to Hadron Matter

Vienna Equilibration Workshop, August 12, 2005

Jean Letessier and JR, nucl-th/0504028, other works

Is there a chemical nonequilibrium in deconfined and/or confined phase?

Can chemical nonequilibrium change the phase transition properties?

What is strangeness content in RHIC-200 CERN-SPS?

Is it consistent with deconfinement?

Where as function of volume and energy is a threshold of deconfinement?

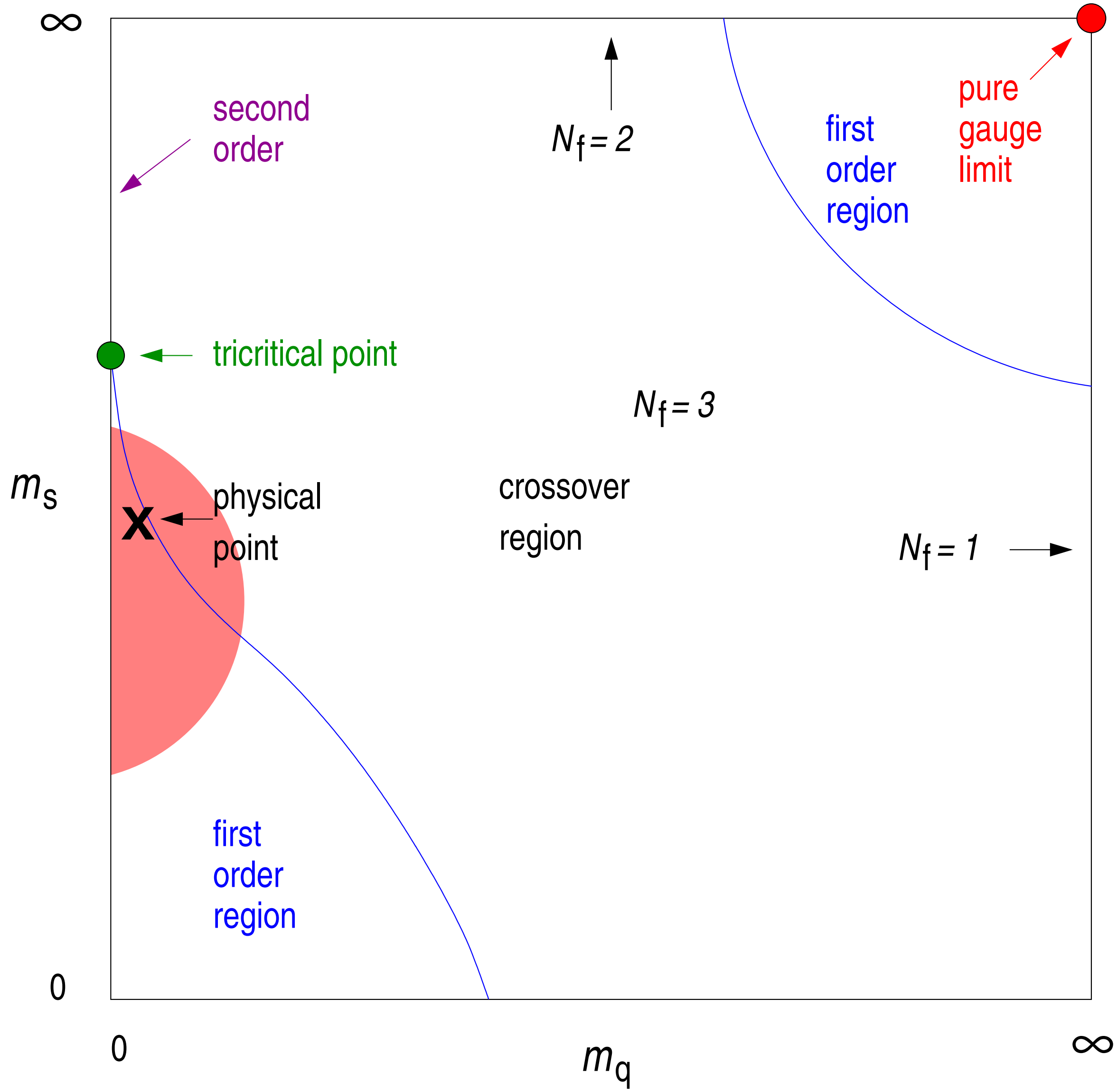
What is the nature of the phase created at low energies?

We propose that the chemically over-saturated 2+1 flavor hadron matter system undergoes a 1st order phase transition.

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

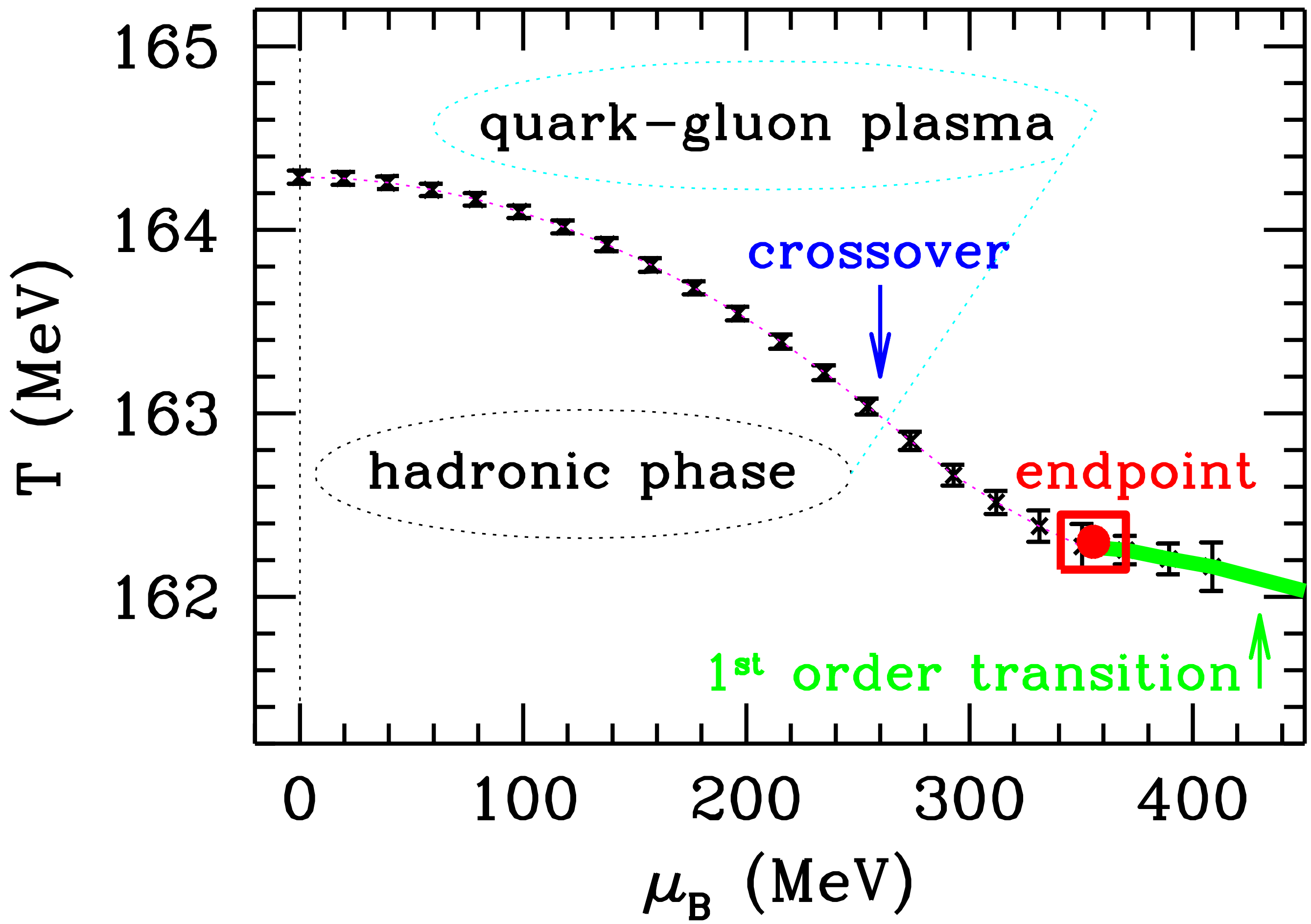
Johann Rafelski
Department of Physics
University of Arizona
TUCSON, AZ, USA

Phase boundary considering Fermi degrees of freedom



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.**

....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 **Maybe the cross-over *T* is *TODAY* at 180 MeV, this is of no relevance to the point made.**

Chemical Equilibrium Phase Boundary

Temperature of phase transition depends on available degrees of freedom (up to systematic errors):

- **For 0 flavor theory $T > 200$ MeV**
- **For 2 flavors: $T \to 170$ MeV**
- **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.**

Heavy Ions Collision Situation

Experiments are carried out in a nonequilibrium environment. What can we expect?

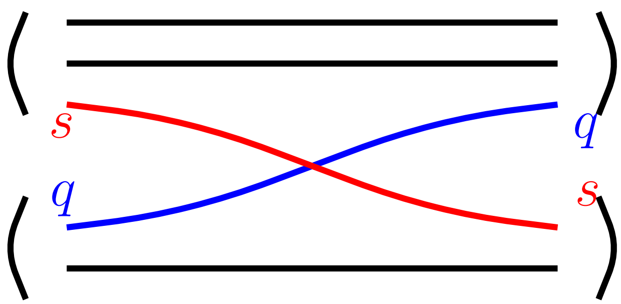
- **Chemical non-equilibrium can increase or decrease quark 'occupancy', favoring/disfavoring presence of a real phase transition, and thus help/hinder phase transition. What $\mu_{\rm B}$ can do, γ_i can do better as both quark and anti-quark number increases.**
- **Dynamical expansion is enhancing the deconfined phase pressure, expect decrease of transition temperature, no change of the nature of the phase transition expected.**

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

γ_i controls overall abundance of quark $(i = q, s)$ pairs	Absolute chemical equilibrium
$\lambda_i = e^{\mu_i/T}$ controls difference between strange and non-strange quarks $(i = q, s)$	Relative chemical equilibrium

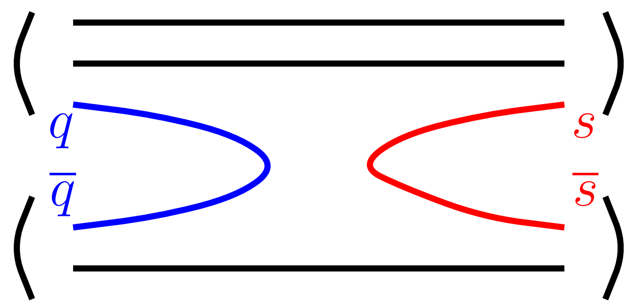
HG-EXAMPLE: redistribution, Relative chemical equilibrium

production of strangeness Absolute chemical equilibrium



EXCHANGE REACTION

λ_i



PAIR PRODUCTION REACTION

γ_i

See Physics Reports 1986 Koch, Müller, JR

Particle yields in chemical (non)equilibrium

The counting of hadrons is conveniently done by counting the valence quark content $(u, d, s, \ldots \lambda_q^2 = \lambda_u\lambda_d,\ \lambda_{I3} = \lambda_u/\lambda_d)$:

$$\Upsilon_i \equiv \Pi_i \gamma_i^{n_i} \lambda_i^{k_i} = e^{\sigma_i/T}$$

There is a natural relation of quark fugacities with hadron fugacities, for particle 'i' but for one complication: for historical reasons hyperon number is opposite to strangeness, thus $\mu_S = \frac{\mu_b}{3} - \mu_s$**, where** $\lambda_q^3 = e^{\mu_b/T}$, **and**

Example of NUCLEONS $\gamma_N = \gamma_q^3$**:**

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

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

Meaning of parameters from e.g. the first law of thermodynamics:

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

μ_b **controls the particle difference = baryon number.**

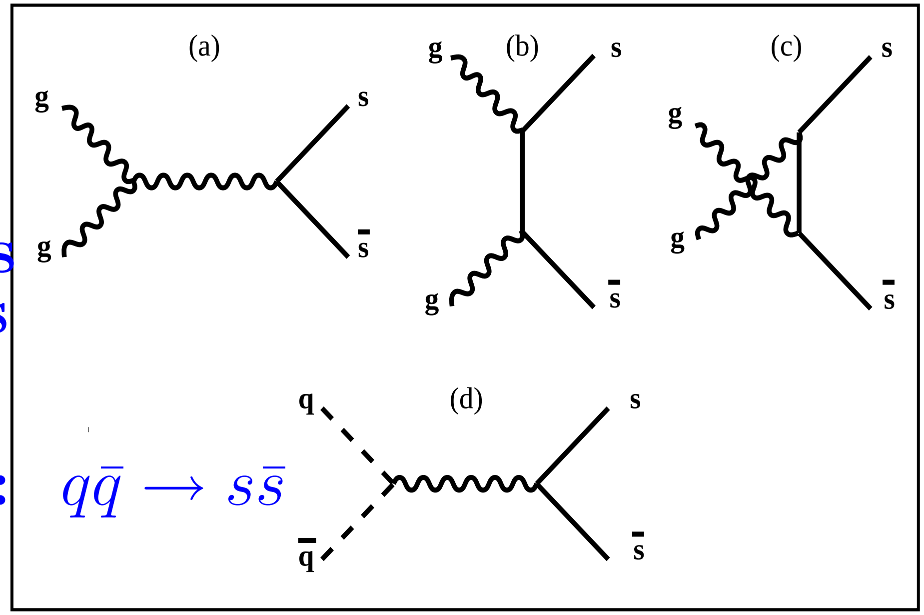
γ **regulates the number of particle-antiparticle pairs present.**

DISTINGUISH HG and QGP parameters: γ_i **are discontinuous so the entropy, etc preserved despite change in nature of the phase,** μ_i **continuous.**

IS OVERPOPULATION OF PHASE SPACE POSSIBLE?

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

  B.Müller&JR 1981
  dominant processes:
  $$GG \to s\bar{s}$$
  abundant strangeness
  =evidence for gluons



  10–15% of total rate: $q\bar{q} \to s\bar{s}$

- coincidence of scales:
  $m_s \simeq T_c$ $\longrightarrow$ $\tau_s \simeq \tau_{\rm QGP}$ $\longrightarrow$
  strangeness a clock for hot-glue-QGP phase

- $\bar{s} \simeq \bar{q}$ $\longrightarrow$ strange antibaryon enhancement
  at RHIC (anti)hyperon dominance of (anti)baryons.

- at LHC $\gamma_s^{\rm QGP}|_{\rm Had} >> 1$ Phase transition for $\mu_{\rm B} = 0$?

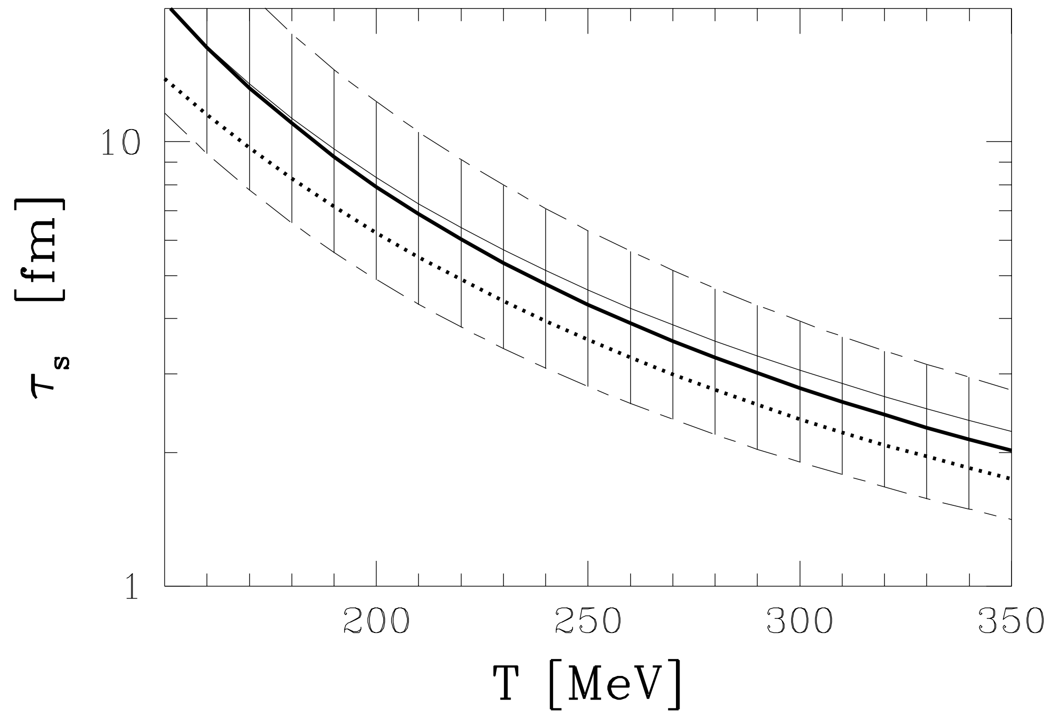
Strangeness relaxation to/BEYOND chemical equilibrium

Strangeness density time evolution in local rest frame:

$$\frac{d\rho_s}{d\tau} = \frac{d\rho_{\bar{s}}}{d\tau} = \frac{1}{2}\rho_g^2(t)\,\langle\sigma v\rangle_T^{gg\to s\bar{s}} + \rho_q(t)\rho_{\bar{q}}(t)\langle\sigma v\rangle_T^{q\bar{q}\to s\bar{s}} - \rho_s(t)\,\rho_{\bar{s}}(t)\,\langle\sigma v\rangle_T^{s\bar{s}\to gg,q\bar{q}}$$

Evolution for s and $\bar{s}$ identical, which allows to set $\rho_s(t) = \rho_{\bar{s}}(t)$.
characteristic time constant τ_s:

$$2\tau_s \equiv \frac{\rho_s(\infty)}{A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} + \ldots} \qquad A^{12\to 34} \equiv \frac{1}{1+\delta_{1,2}}\gamma_1\gamma_2\rho_1^\infty\rho_2^\infty\langle\sigma_s v_{12}\rangle_T^{12\to 34}.$$



Dotted line: 1981 estimate. Dashed area: m_s uncertainty. Thick line: running α_s.

Include ENTROPY CONSERVING EXPANSION: The volume expansion and temperature change such that $\delta(T^3V)=0$. We introduce phase space occupancy:

$$\gamma_s(t)\equiv\frac{n_s(t)}{n_s^\infty(T(t))}\,,\qquad n_s(t)=\gamma_s(t)T(t)^3\frac{3}{\pi^2}z^2K_2(z)\,,\qquad z=\frac{m_s}{T(t)}\,,\qquad K_i:\text{Bessel f.}$$

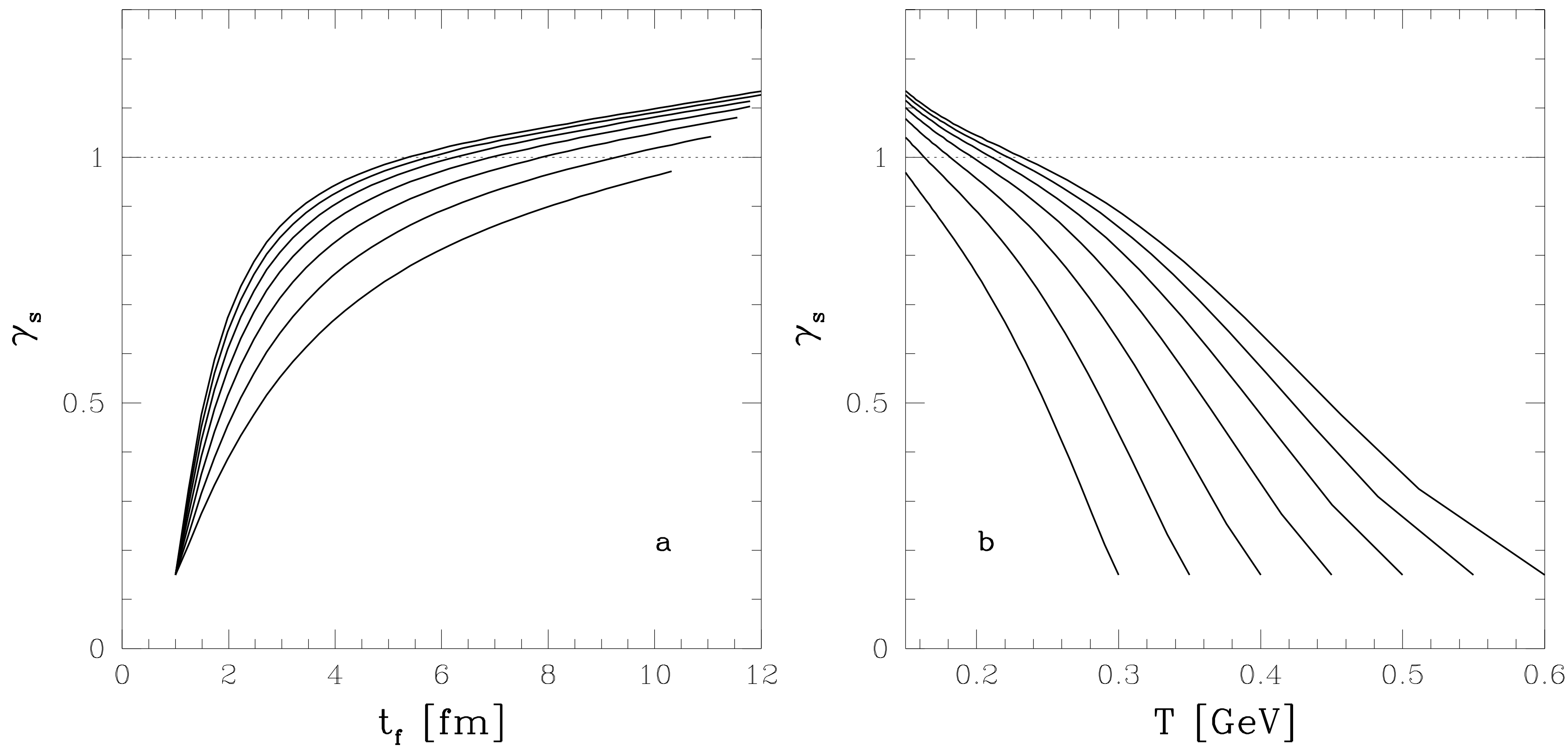
Strangeness has a mass scale, its time evolution follows:

$$2\tau_s\frac{d\gamma_s}{d\tau}=1-{\gamma_s}^2-\gamma_s 2\tau_s\frac{d\ln z^2K_2(z)}{d\tau}=1-{\gamma_s}^2+\gamma_s 2\tau_s\frac{dz}{d\tau}\frac{K_1(z)}{K_2(z)}\,.$$

Last term presents the residual effect of expansion. Without scale ($m\to 0$) it disappears, and $\gamma_s\le 1$, but its importance grows with mass of the quark, $z=m/T$. Since the volume expansion reduces temperature, $dz/d\tau>0$, early on produced strangeness can overpopulate the smaller final phase space. This effect is more significant for more massive particles. Pivotal role for strangeness due to $T_{\rm cr}\simeq m_s$: strangeness can rise well above chemical equilibrium near to $T_{\rm cr}$. This may facilitate presence of a real phase transition at zero baryon density.

Requirement: initial state hot, and expansion time $\tau_{\rm QGP}>\tau_s$.

RHIC EXAMPLE



$$T(\tau) = T_0 \left[\frac{1}{(1+\tau\ 2c/d)(1+\tau\ v_\perp/R_\perp)^2} \right]^{1/3}, \quad d(T_0) = (0.5\,\mathbf{GeV}/T_0)^3 1.5\,\mathbf{fm}\,. \qquad (1)$$

We took $d(T_0 = 0.5)/2 = 0.75\,$**fm,** $R_\perp = 4.5\,$**fm,** $\tau_0 = 1$**fm/**c**.**

JR/JL Phys.Lett.B469:12-18,1999

HOW TO MEASURE γ_s^{QGP}

STRANGENESS / ENTROPY CONTENT s/S

Strangeness s and entropy S produced predominantly in early hot parton phase. Yield ratio eliminates dependence on reaction geometry. Strangeness and entropy could increase slightly in hadronization. s/S relation to K^+/π^+ is not trivial when precision better than 25% needed.

CONFIRM BY: STRANGENESS / NET BARYON NUMBER s/b

Baryon number b is conserved, strangeness could increase slightly in hadronization. s/b ratio probes the mechanism of primordial fireball baryon deposition and strangeness production. Ratio eliminates dependence on reaction geometry.

Strangeness / Entropy

Relative s/S yield measures the number of active degrees of freedom and degree of relaxation when strangeness production freezes-out. Perturbative expression in chemical equilibrium:

$$\frac{s}{S} = \frac{(3/\pi^2)T^3(m_s/T)^2K_2(m_s/T)}{(32\pi^2/45)T^3 + n_{\rm f}[(7\pi^2/15)T^3 + \mu_q^2 T]} \simeq 0.027$$

assumption: $\mathcal{O}(\alpha_s)$ interaction effects cancel out between S, s

Allow for chemical equilibrium of strangeness n $\gamma_s^{\rm QGP}$, and possible quark-gluon pre-equilibrium:

$$\frac{s}{S} = \frac{0.027\gamma_s^{\rm QGP}}{0.38\gamma_{\rm G} + 0.12\gamma_s^{\rm QGP} + 0.5\gamma_q^{\rm QGP} + 0.054\gamma_q^{\rm QGP}(\ln\lambda_q)^2} \to 0.027.$$

We expect the yield of gluons and light quarks to approach chemical equilibrium first: $\gamma_{\rm G} \to 1$ and $\gamma_q^{\rm QGP} \to 1$, thus $s/S \propto \gamma_s^{\rm QGP}$.

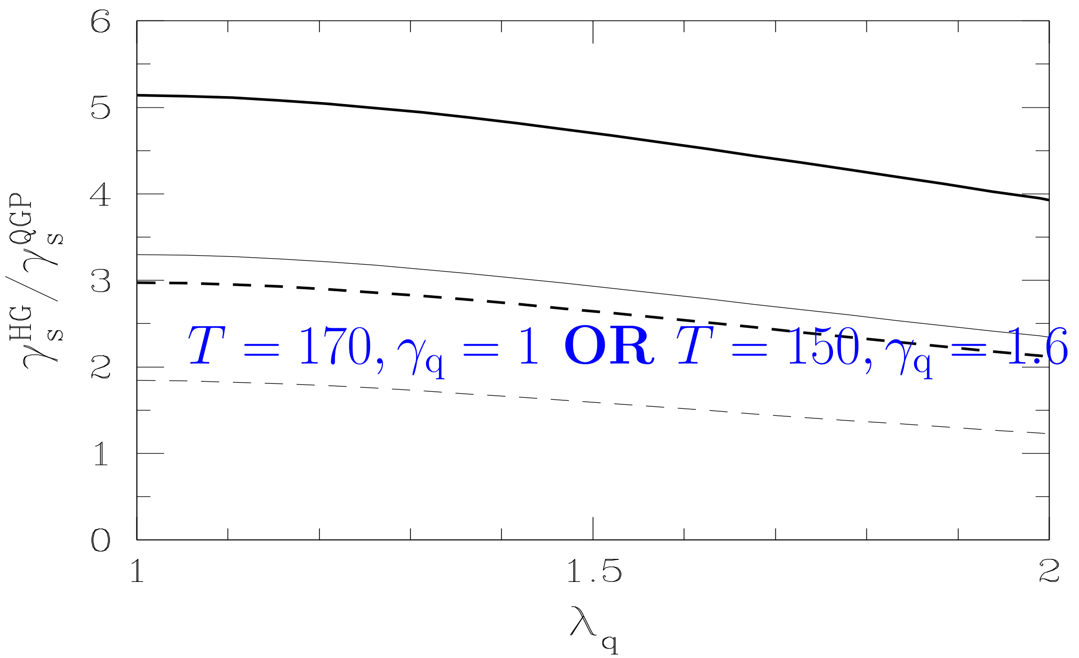
HOW TO USE: FIT YIELDS OF PARTICLES, EVALUATE STRANGENESS AND ENTROPY CONTENT AND COMPARE WITH EXPECTED RATIO

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

In fast breakup of expanding QGP, $V^{\rm HG} \simeq V^{\rm QGP}$, $T^{\rm QGP} \simeq T^{\rm HG}$, the chemical occupancy factors accommodate the different magnitude of particle phase space. Chemical equilibrium in one phase means non-equilibrium in the the other.

Compare phase spaces to obtain $\gamma_s^{\rm HG}/\gamma_s^{\rm QGP}$

$\rightarrow$



Solid lines $\gamma_q^{\rm HG} = 1$, short dashed $\gamma_q^{\rm HG} = 1.6$ Thin lines for $T = 170$ and thick lines $T = 150$ MeV, T common to both phases. m_s relevant.

$$\gamma_s^{\rm HG} \simeq 2 - 3\gamma_s^{\rm QGP}$$

Most people TACITLY assume $\gamma_q = 1$ and fit γ_s/γ_q which they call γ_s, which ranges $0.5 < \gamma_s/\gamma_q < 1$

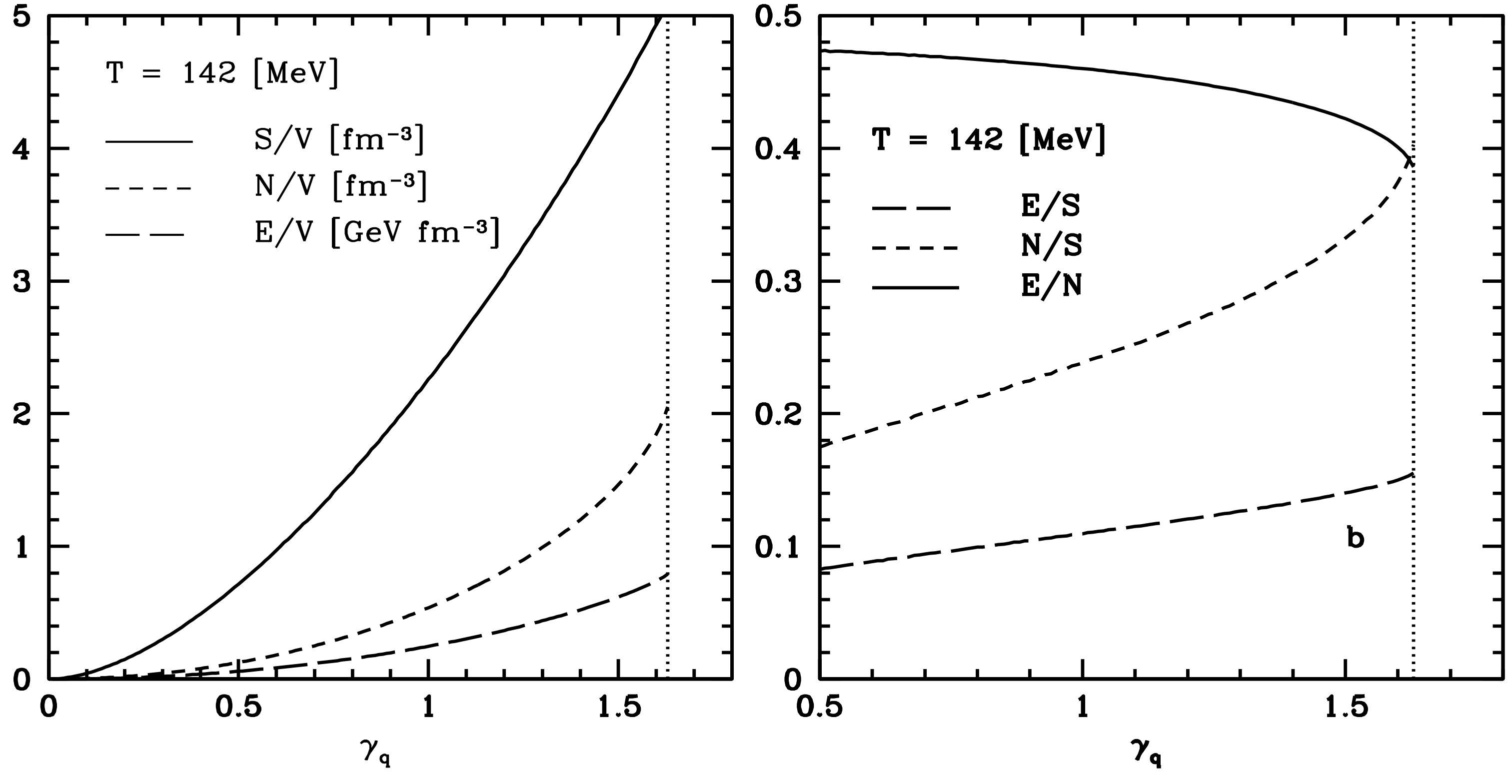
ESTIMATE THE EXPECTED $\gamma_q^{\rm HG}$

QGP has excess of entropy, maximize entropy density at hadronization: $\gamma_q^2 \to e^{m_\pi/T}$**:**

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

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

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



SPECIFIC STRANGENESS YIELD IN QGP MEASURES $\gamma_s^{QGP}/\gamma_q^{QGP}$

$$\frac{\rho_s}{\rho_b}=\frac{s}{q/3}=\frac{\gamma_s^{QGP}\frac{3}{\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{\gamma_q^{QGP}\frac{2}{3}\left(\mu_q T^2+\mu_q^3/\pi^2\right)}\,,\rightarrow\frac{s}{b}\simeq\frac{\gamma_s^{QGP}}{\gamma_q^{QGP}}\frac{0.7}{\ln\lambda_q+(\ln\lambda_q)^3/\pi^2}\,.$$

assumption: $\mathcal{O}(\alpha_s)$ interaction effects cancel out between b, s
We consider $m_s = 200$ MeV and hadronization $T = 150$ MeV,

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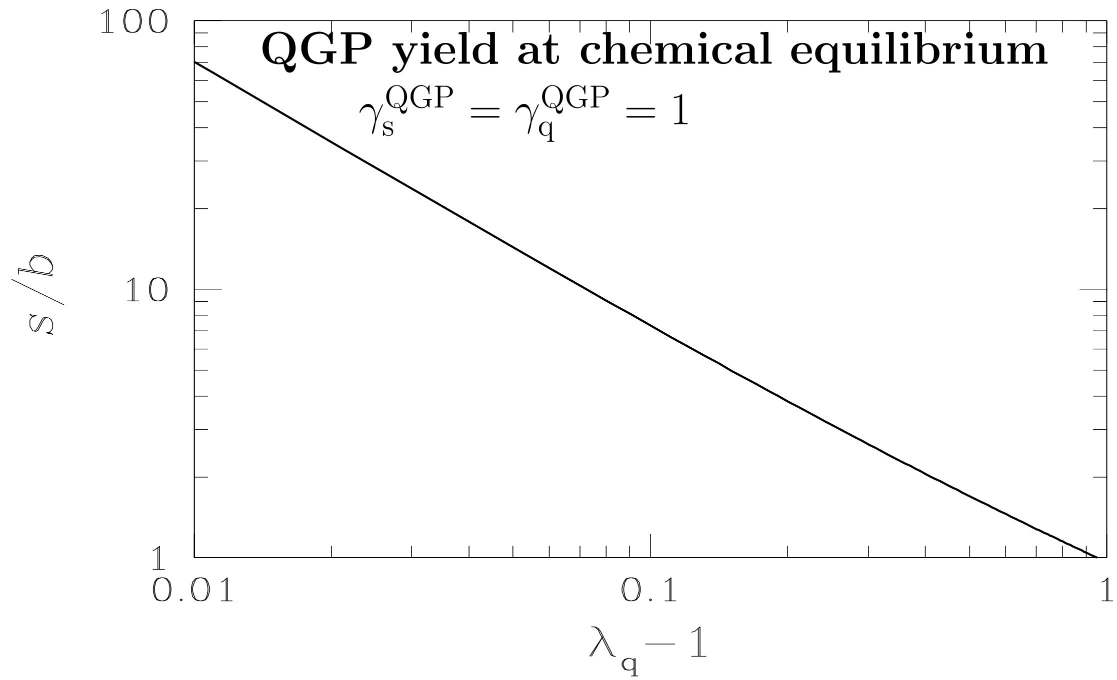


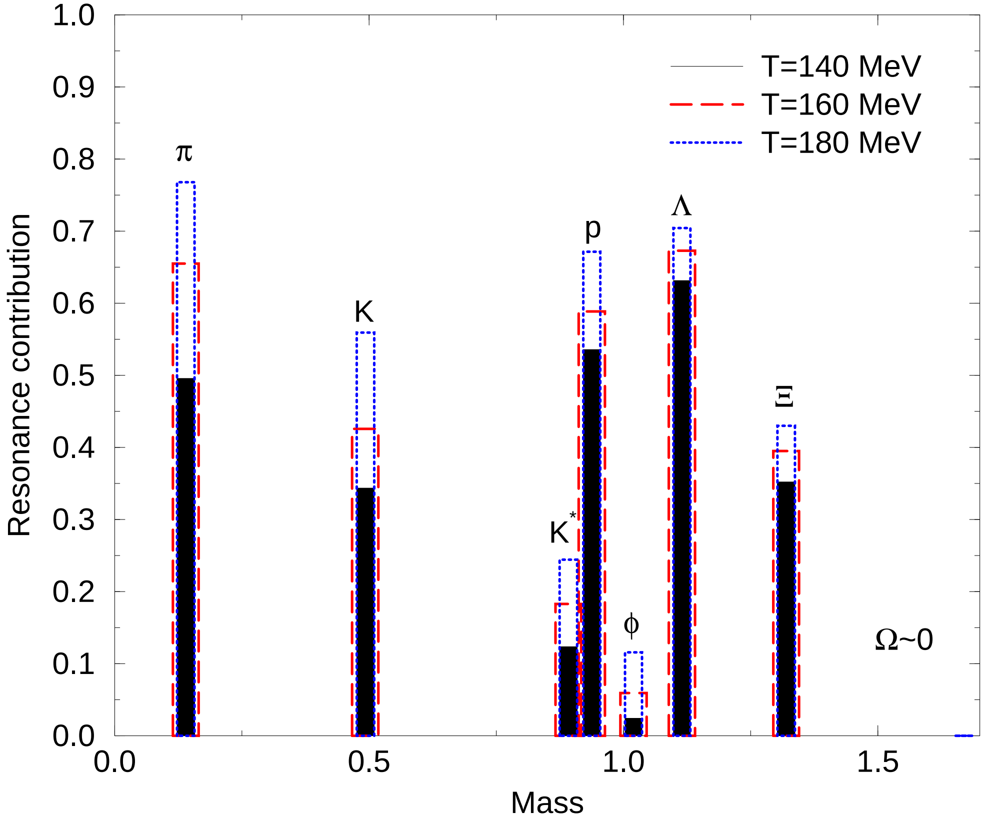
EXAMPLE: SPS Pb–Pb 158 A GeV λ_q=1.5–1.6, implies $s/b \simeq 1.5$.
Observation: $s/b \simeq 0.75 \rightarrow \gamma_s^{QGP}/\gamma_q^{QGP} = 0.5$.

DATA ANALYSIS WITHIN STATISTICAL HADRONIZATION

Hypothesis (Fermi, Hagedorn): particle production can be described by evaluating the accessible phase space.

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 $T_{\rm H}$:



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

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.

HADRONIZATION GLOBAL FIT:→

Statistical Hadronization fits of hadron yields

Chemical nonequilibrium implies phase space with additional γ-parameters:
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 increase in volume in a slow re-equilibration with mixed phase which accommodates transformation of entropy dense phase into dilute 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 nucl–th/0404083 Comp. Phys. Com. 167, 229 (2005)
Online SHARE: Steve Steinke No fitting online (server too small)
http://www.physics.arizona.edu/˜steinke/shareonline.html

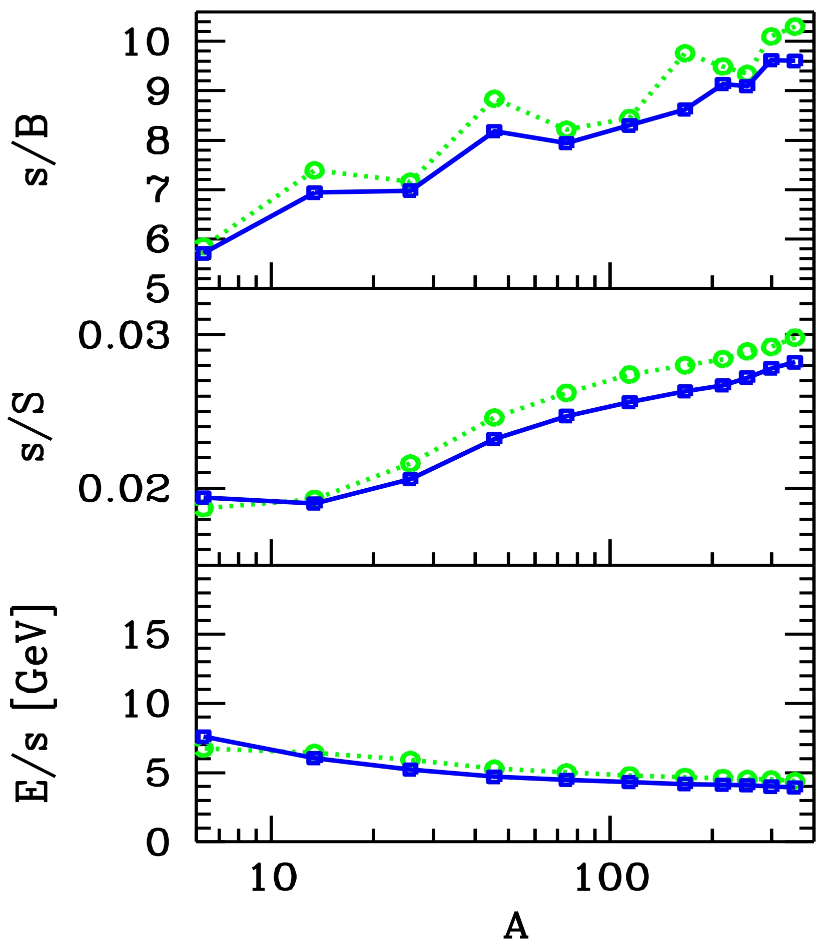
Aside of particle yields, also PHYSICAL PROPERTIES of the source are available, both in SHARE and ONLINE. Several papers use this tool: nucl-th/0412072 (PRC in press) and nucl-th/0506044 [address impact parameter], nucl-th/0504028 [E-dependence], hep-ph/0506140 [LHC]

Centrality dependence of dN/dy for $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$. The errors are systematic only. The statistical errors are negligible. PHENIX data

N_{part}	π^+	π^-	K^+	K^-	p	$\bar{p}$
351.4	**286.4 ± 24.2**	**281.8 ± 22.8**	**48.9 ± 6.3**	**45.7 ± 5.2**	**18.4 ± 2.6**	**13.5 ± 1.8**
299.0	**239.6 ± 20.5**	**238.9 ± 19.8**	**40.1 ± 5.1**	**37.8 ± 4.3**	**15.3 ± 2.1**	**11.4 ± 1.5**
253.9	**204.6 ± 18.0**	**198.2 ± 16.7**	**33.7 ± 4.3**	**31.1 ± 3.5**	**12.8 ± 1.8**	**9.5 ± 1.3**
215.3	**173.8 ± 15.6**	**167.4 ± 14.4**	**27.9 ± 3.6**	**25.8 ± 2.9**	**10.6 ± 1.5**	**7.9 ± 1.1**
166.6	**130.3 ± 12.4**	**127.3 ± 11.6**	**20.6 ± 2.6**	**19.1 ± 2.2**	**8.1 ± 1.1**	**5.9 ± 0.8**
114.2	**87.0 ± 8.6**	**84.4 ± 8.0**	**13.2 ± 1.7**	**12.3 ± 1.4**	**5.3 ± 0.7**	**3.9 ± 0.5**
74.4	**54.9 ± 5.6**	**52.9 ± 5.2**	**8.0 ± 0.8**	**7.4 ± 0.6**	**3.2 ± 0.5**	**2.4 ± 0.3**
45.5	**32.4 ± 3.4**	**31.3 ± 3.1**	**4.5 ± 0.4**	**4.1 ± 0.4**	**1.8 ± 0.3**	**1.4 ± 0.2**
25.7	**17.0 ± 1.8**	**16.3 ± 1.6**	**2.2 ± 0.2**	**2.0 ± 0.1**	**0.93 ± 0.15**	**0.71 ± 0.12**
13.4	**7.9 ± 0.8**	**7.7 ± 0.7**	**0.89 ± 0.09**	**0.88 ± 0.09**	**0.40 ± 0.07**	**0.29 ± 0.05**
6.3	**4.0 ± 0.4**	**3.9 ± 0.3**	**0.44 ± 0.04**	**0.42 ± 0.04**	**0.21 ± 0.04**	**0.15 ± 0.02**

include STAR data on K* and ϕ yields.

s/b and s/S rise with increasing centrality $A \propto V$; E/s falls

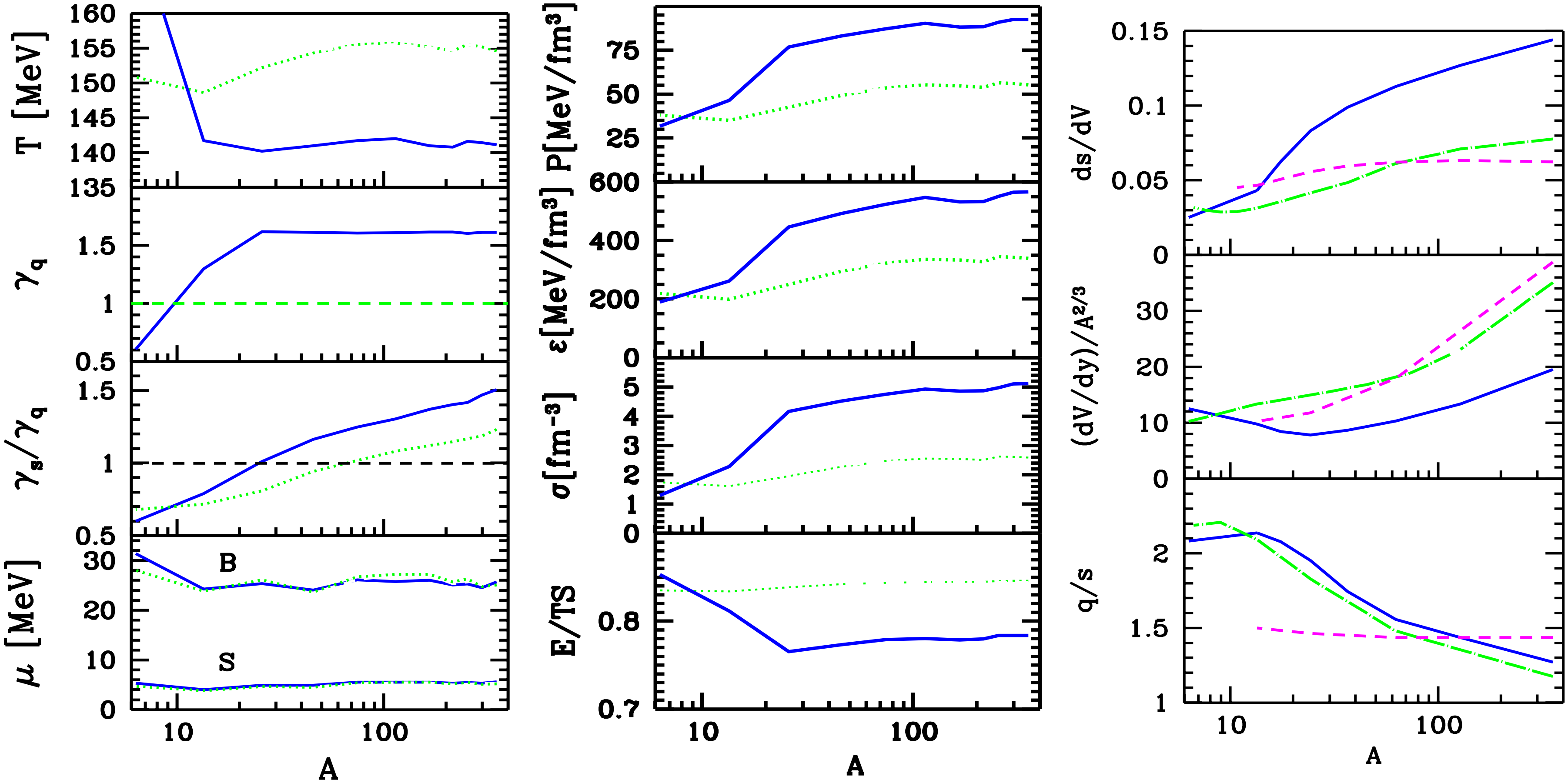


Showing results for both $\gamma_q, \gamma_s \neq 1$ and when $\gamma_q = 1$ is assumed. REASON: there is some hesitance to accept a $T \simeq 140$ when $\gamma_q \to 1.6$. No difference in this result:

$s/S \to 0.027$, **as function of** V **no saturation for largest volumes available. Result consistent with QGP expectation.** $\gamma_s^{\rm QGP} \simeq 1$, **confirmed by** s/B. **Indication that physics is different for most two central reaction bins.**

REMARK ASIDE: The rapidity density of entropy $dS/dy \simeq 5000 \pm 10\%$. **This implies an intial thermally equilibrated parton state with rapidity desntiy** $dN/dy \simeq 1250$.

RHIC200 results: dependence on centrality

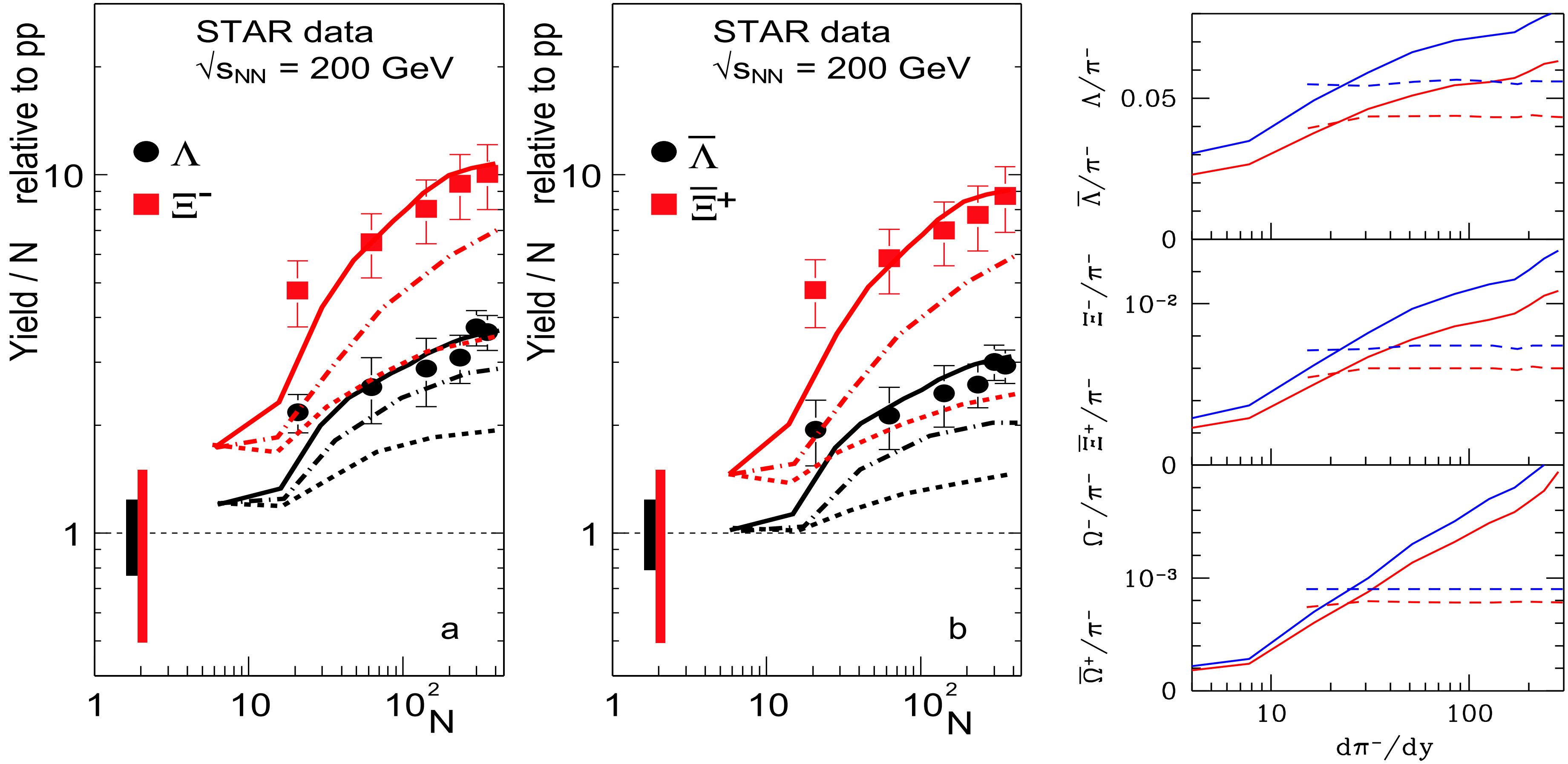


LINES: $\gamma_s, \gamma_q \neq 1$ **and** $\gamma_s \neq 1, \gamma_q = 1$, **also** $\gamma_s = \gamma_q = 1$

γ_q **changes with** $A \propto V$ **from under-saturated to over-saturated value,** $\gamma_s^{\rm HG}$ **increases steadily to 2.4, implying near saturation in QGP.** P, σ, ϵ **increase by factor 2–3, at** $A > 20$ **(onset of new physics?),** E/TS **decreases with** A.

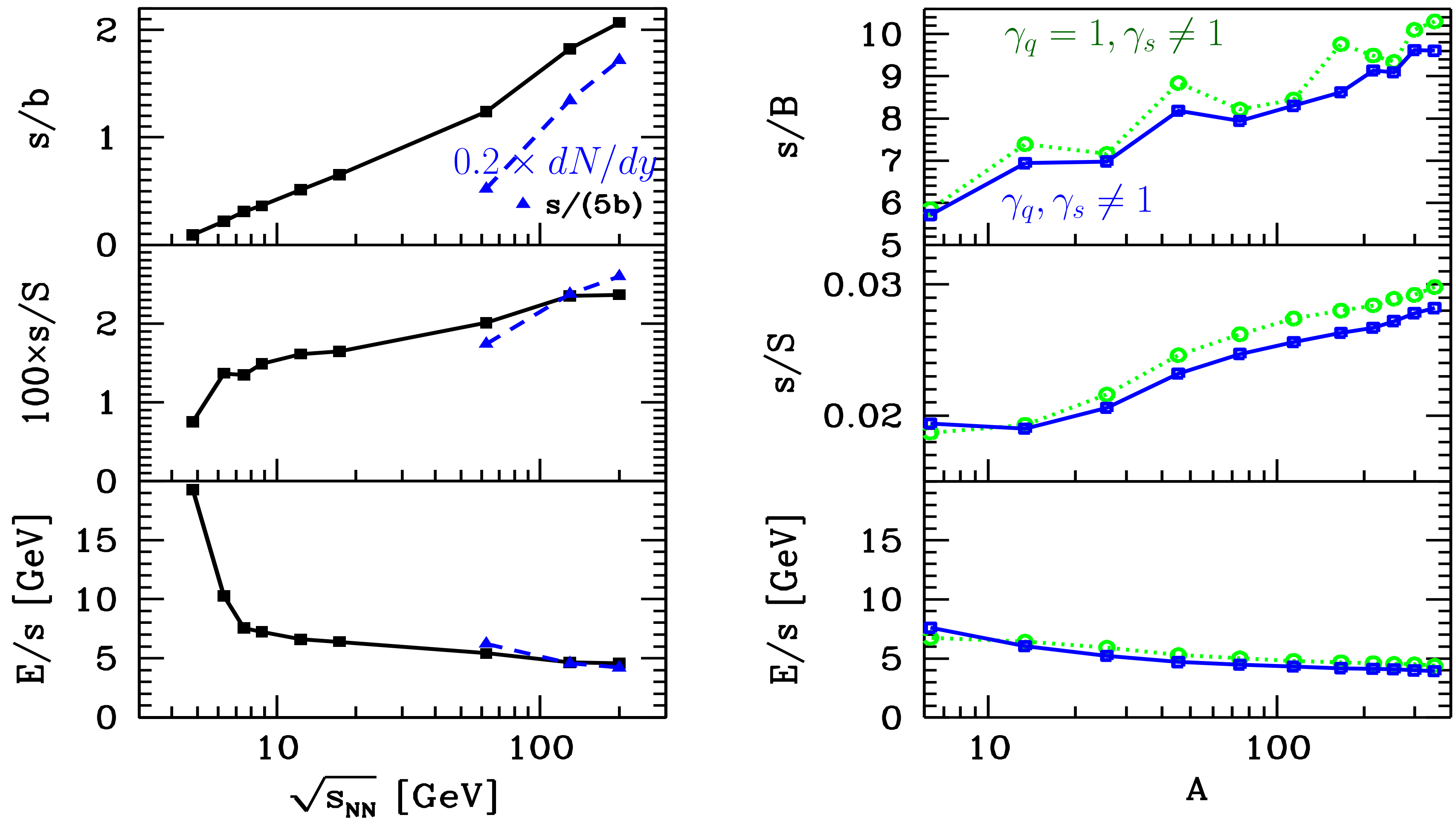
Statistical + fit errors are seen in fluctuations, systematic error impacts absolute normalization by $\pm 10\%$.

RHIC200 PREDICTION OF dependence on centrality



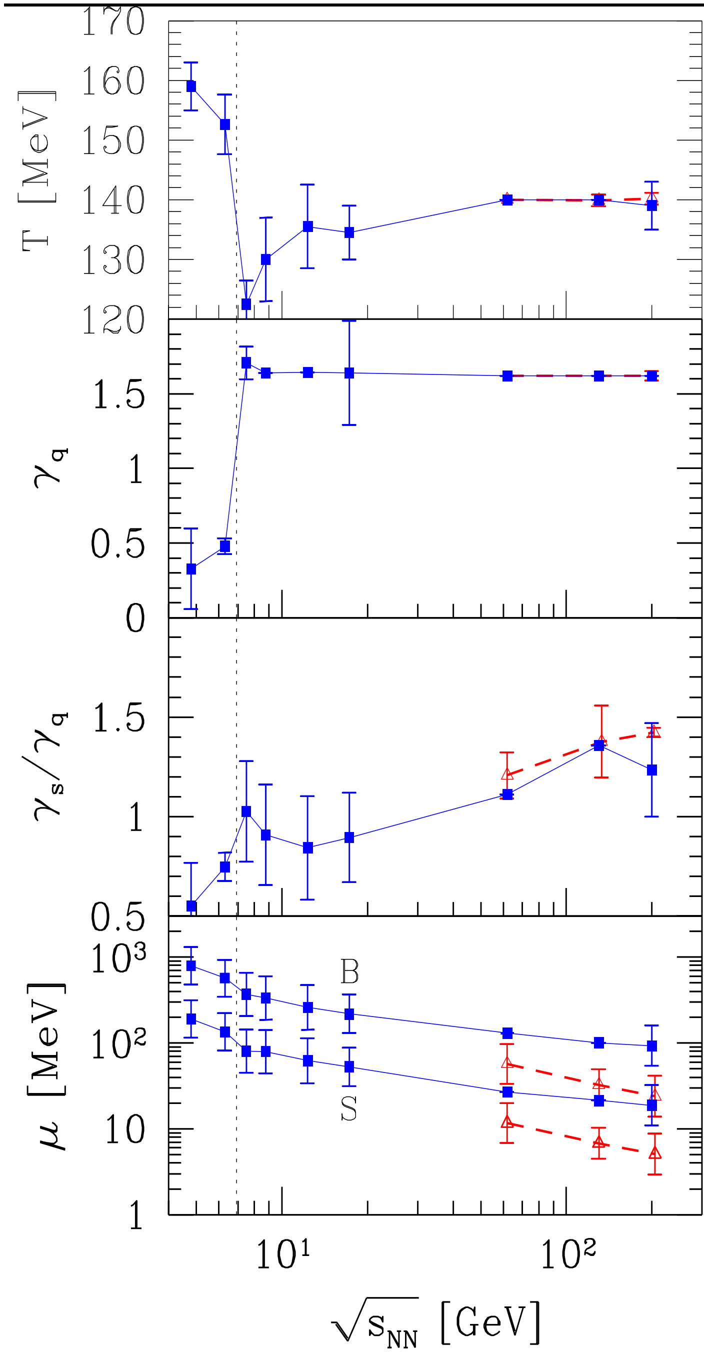
STAR $\sqrt{s_{\rm NN}} = 200$ GeV yields of hyperons $d\Lambda/dy$ and $d\Xi^-/dy$, (a), and antihyperons $d\overline{\Lambda}/dy$ and $d\overline{\Xi}^+/dy$, (b), normalized with, and as function of, A, relative to these yields in pp reactions: $d(\Lambda+\overline{\Lambda})/dy = 0.066\pm0.006$, $d(\Xi^-+\overline{\Xi}^+)/dy = 0.0036\pm0.0012$, $\overline{\Lambda}/\Lambda = 0.88\pm0.09$ and $\overline{\Xi}^+/\Xi^- = 0.90\pm0.09$. Solid lines, chemical non-equilibrium, dashed chemical equilibrium, dotted lines, semi-equilibrium. On right, the predicted hyperons per π^- yields (blue for hyperons and for antihyperons).

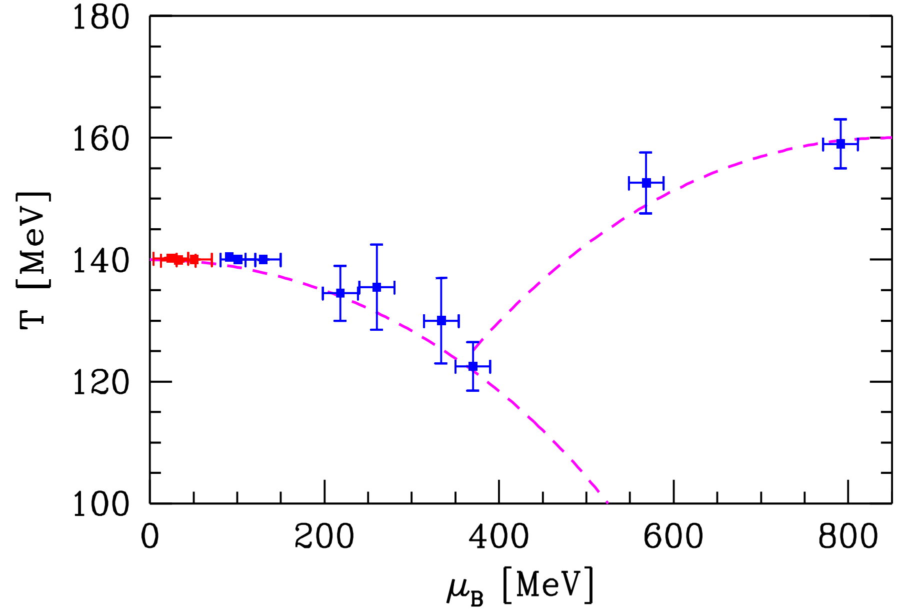
COMPARE $\sqrt{s_{\rm NN}}$ and V dependence of s/b and s/S, E/s



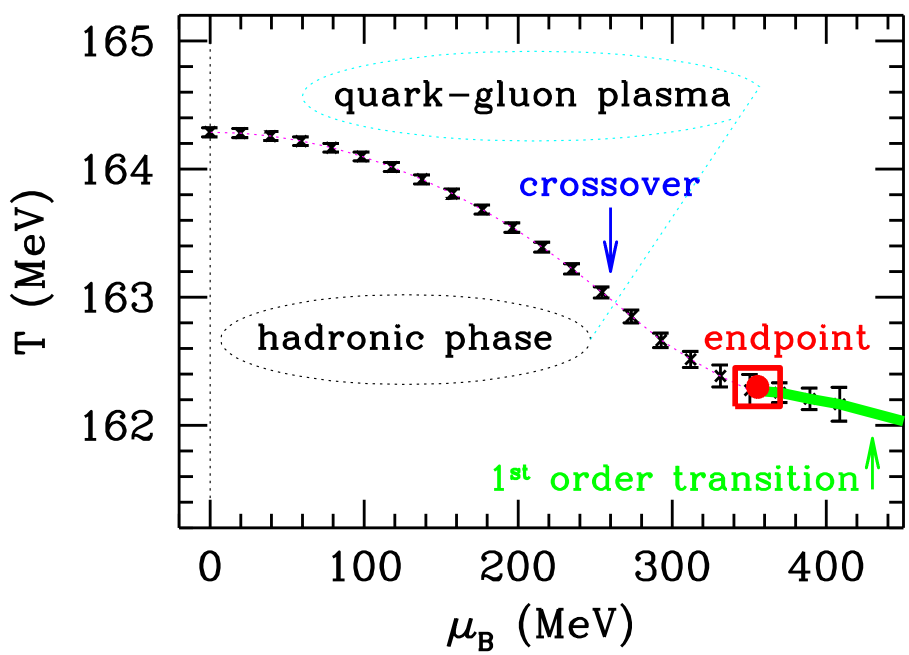
Full 4π and central rapidity results.
We again find $s/S \to 0.027$, as function of $\sqrt{s_{\rm NN}}$ and V: no saturation, consistent with QGP expectation and $\gamma_s^{\rm QGP} \simeq 1$, confirmed by s/B.
Energy/strangeness E/s cost drop at $\sqrt{s_{\rm NN}^{\rm cr}}$, suggests appearance of a new (e.g. $GG \to s\bar{s}$) production mechanism.

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

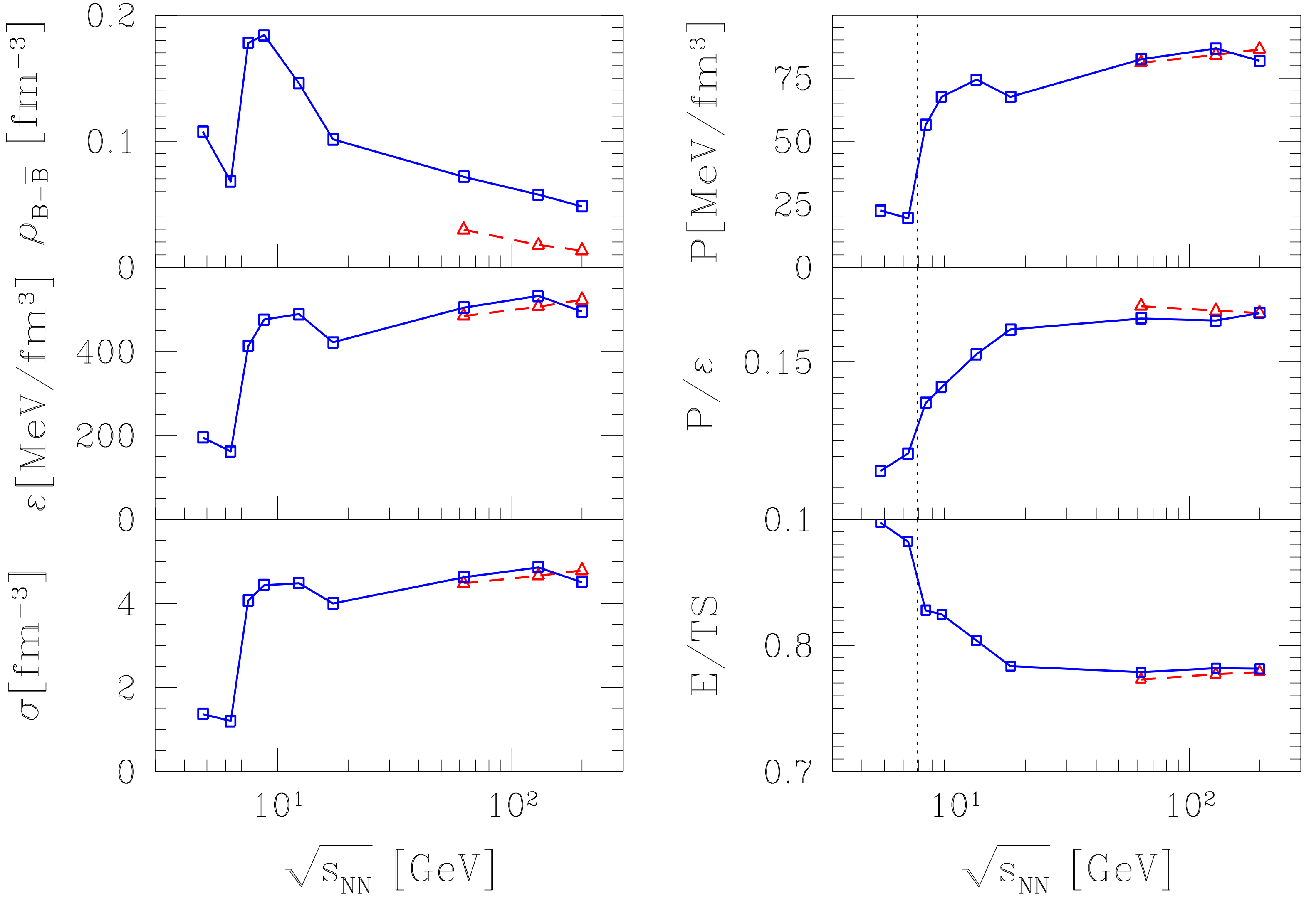




to be compared to, see below:



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.**

Why low/high PHASE BOUNDARY Temperature?

- **Dynamical effects of expansion:**
  colored partons like a wind, displace 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** $\mu_{\rm B}$ **we encounter**
  - **either conventional hadrons (contradiction with continuity of quark related variables: strangeness, strange antibaryons).**
  - **or more likely, a new heavy (valon) quark phases.**
    Under saturation of phase space compatible with higher T**.**

Questions with answers

Is there chemical nonequilibrium?

In QGP: strangeness sector. HG: light and strange sector fast nonequilibrium transformation

Can chemical nonequilibrium impact phase transition properties?

Behavior as function of N_f *suggests that* $\gamma_s^{QGP} > 1$ *helps establish a true 1st order phase transition for* $\mu_{\rm B} \to 0$.

What is strangeness content from CERN-SPS to RHIC-200?

Gradual rise as function of collision energy of the yield s/S *(per entropy), saturating the QGP phase space at RHIC, expected further increase at LHC .*

Is it consistent with deconfinement? Other strangeness evidence for deconfinement?

Threshold seen in s/S, s/b *and* E/s.

Where as function of volume and energy is a PHASE threshold ?

$6.26\text{GeV} < \sqrt{s_{\rm NN}^{\rm cr}} < 7.61\text{GeV}$. *Bulk properties also respond at that threshold. Softer threshold at* $A \simeq 20$.

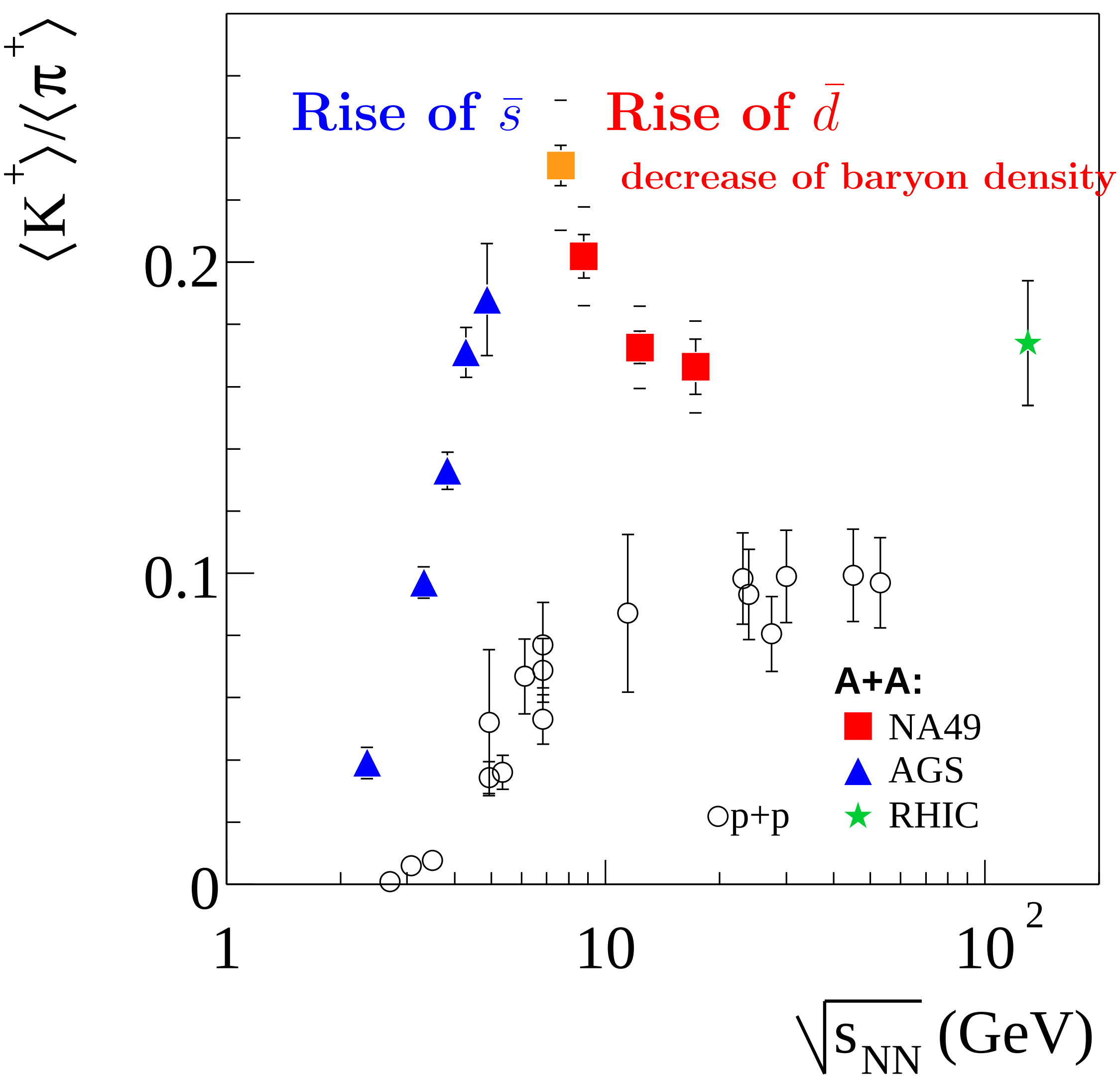
What is the nature of the phase created at low energies?

Phase under-saturates phase space, probably involves effectively massive quarks. To understand E/TS *one can invoke thermal quarks with* $m \simeq 2\text{-}4T$.

Do we describe the particle production as function of energy?

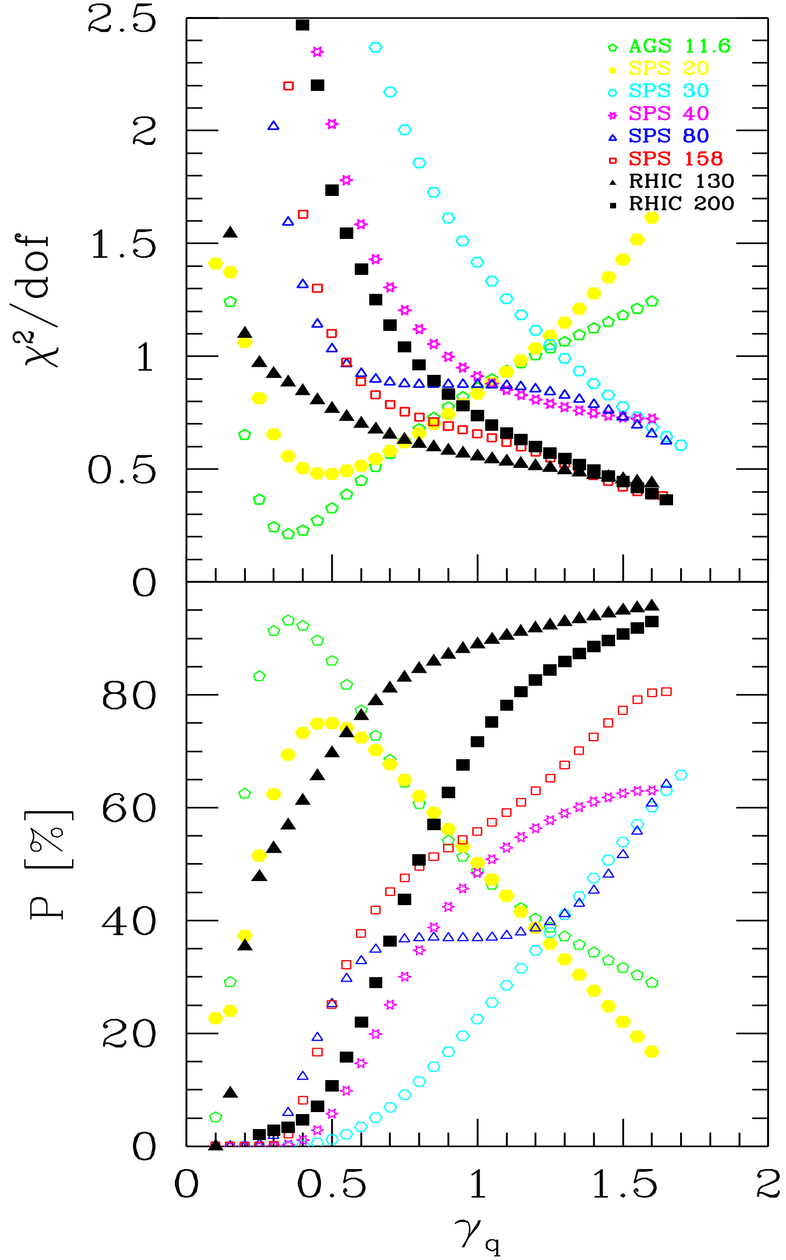
Turn page

THE HORN

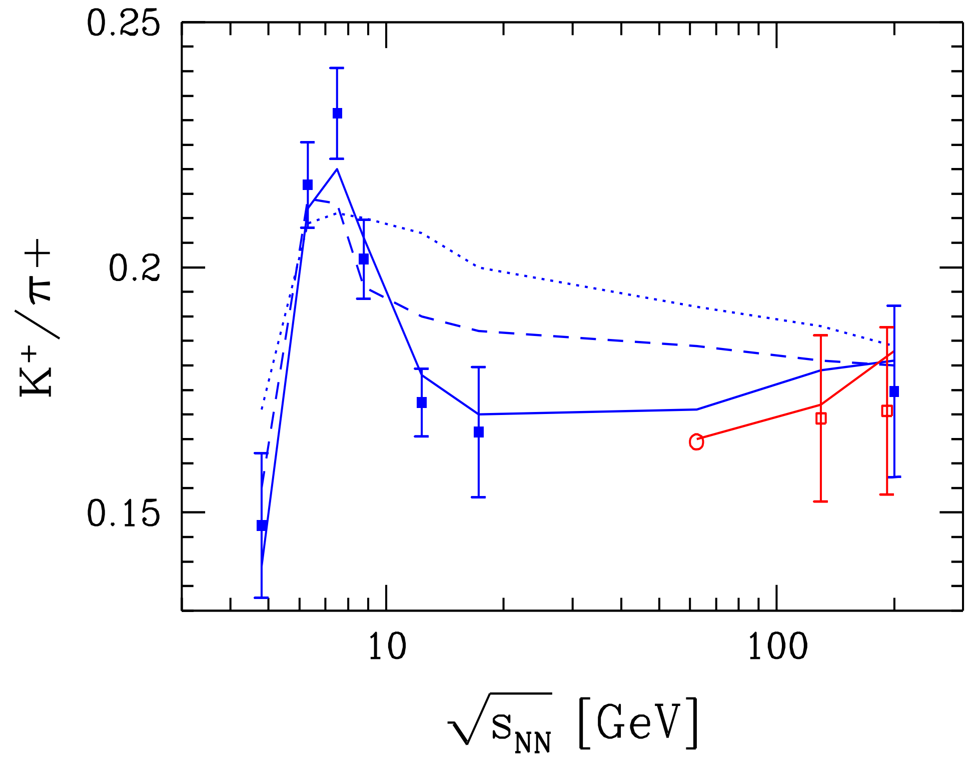


The NA49 (Marek Gaździcki) HORN

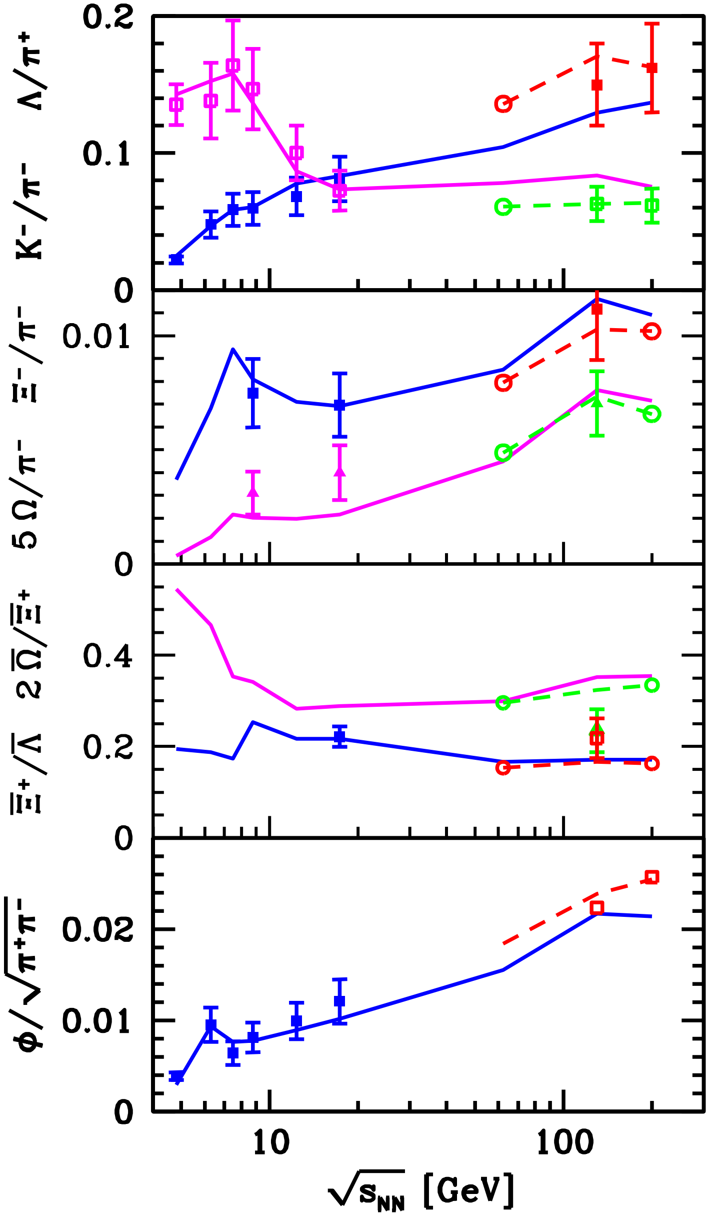
The horn requires a shift in γ_q



Looking a the fit χ^2 we see that between 20 and 30GeV results favor that γ_q jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The individual fits relevant to understanding how the horn is created have good quality - see $P\%$.



Particle yields of interest



$\sqrt{s_{\rm NN}}$ [GeV]	$N_{4\pi}$ 5% 62.4	130	200	$dN/dy\|_{y=0}$ 5% 62.4	130	200
b	350.2	350.2	350.1	32.64	19.79	14.8
π^+	1001	1282	1470	225.8	236.6	237.4
π^-	1072	1368	1558	236.7	246.8	247.2
K^+	194.5	289.9	297.9	43.3	49.5	50.7
K^-	139.4	222.5	236.3	37,5	45.5	47.6
K_S	162.3	248.2	259.2	39.2	45.9	47.5
ϕ	18.6	34.6	32.9	4.96	6.58	7.06
p	156.5	163.9	177.5	21.56	18.91	18.02
$\bar{p}$.	25.9	40.7	50.6	9.77	12.05	12.95
Λ	68.6	89.3	89.0	12.3	11.4	11.4
$\overline{\Lambda}$	16.0	29.1	32.2	5.91	7.94	8.7
Ξ^-	11.3	18.1	16.5	2.18	2.60	2.70
$\overline{\Xi}^+$	3.7	7.85	7.67	1.34	1.97	2.21
Ω	1.13	2.37	1.97	0.27	0.38	0.42
$\overline{\Omega}$	0.56	1.40	1.21	0.20	0.32	0.37
$K^0(892)$	47.9	70.1	80.0	19.5	11.8	12.1
Δ^0	28.8	28.5	31.3	3.76	3.22	3.05
Δ^{++}	27.2	27.8	30.6	3.71	3.19	3.03
$\Lambda(1520)$	4.43	5.73	5.76	0.72	0.73	0.73
$\Sigma^+(1385)$	8.50	10.94	10.93	1.37	1.38	1.37
$\Xi0(1530)$	2.98	4.90	4.45	0.59	0.71	0.74
η	110.2	158.7	172.7	26.3	29.6	30.3
η'	8.45	13.03	13.75	2.08	2.44	2.54
ρ^0	84.4	106	125	18.9	19.5	19.6
$\omega(782)$	75.5	94.9	112.2	17.1	17.6	17.6
$f_0(980)$	7.08	10.79	11.47	1.74	2.02	2.09