Soft hadron production and thresholds of phase changes in relativistic heavy ion collisions

LC2005, Cairns, 11 July 2005

Jean Letessier and JR, nucl-th/0504028

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.

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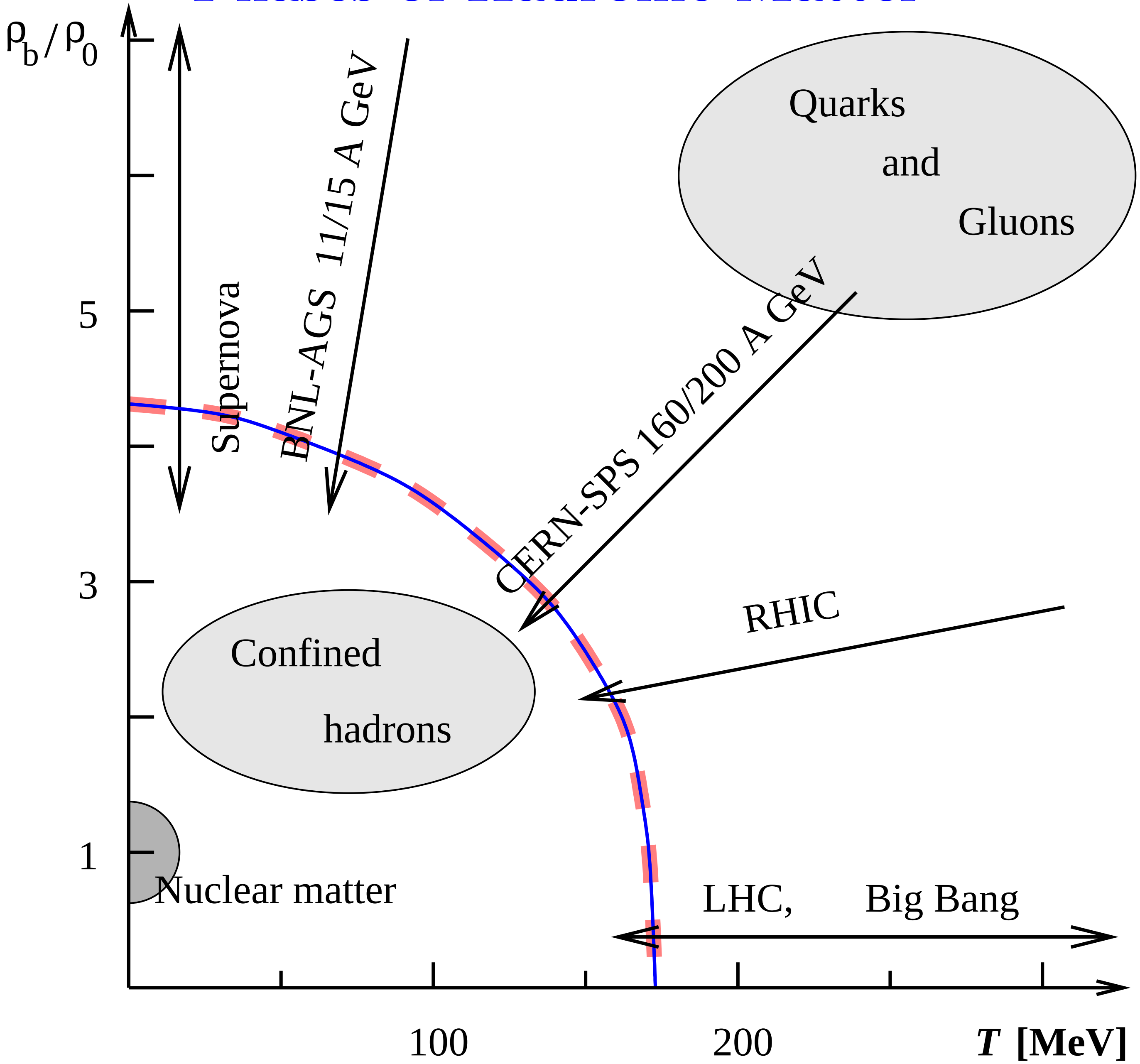
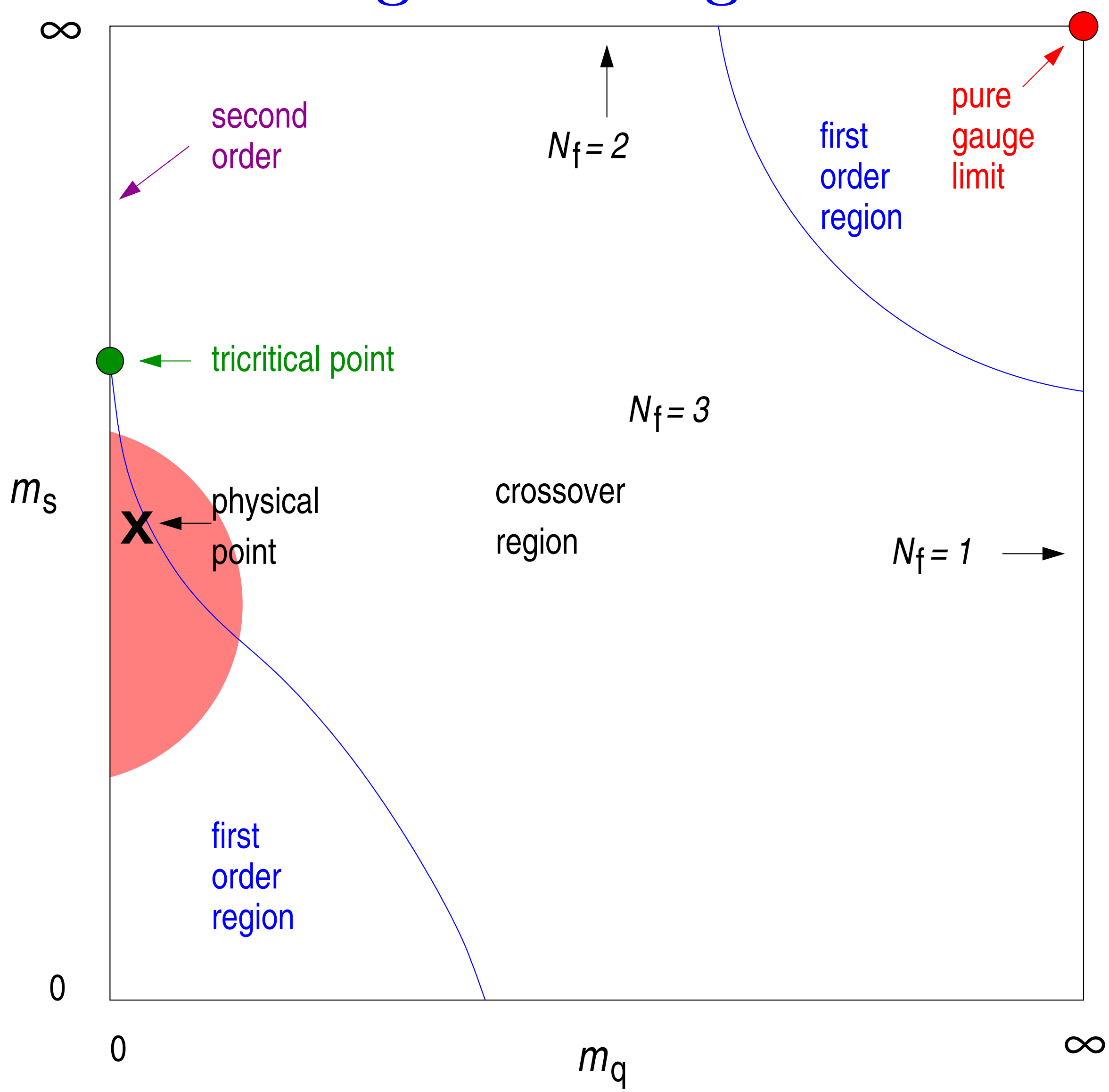
Phases of Hadronic Matter

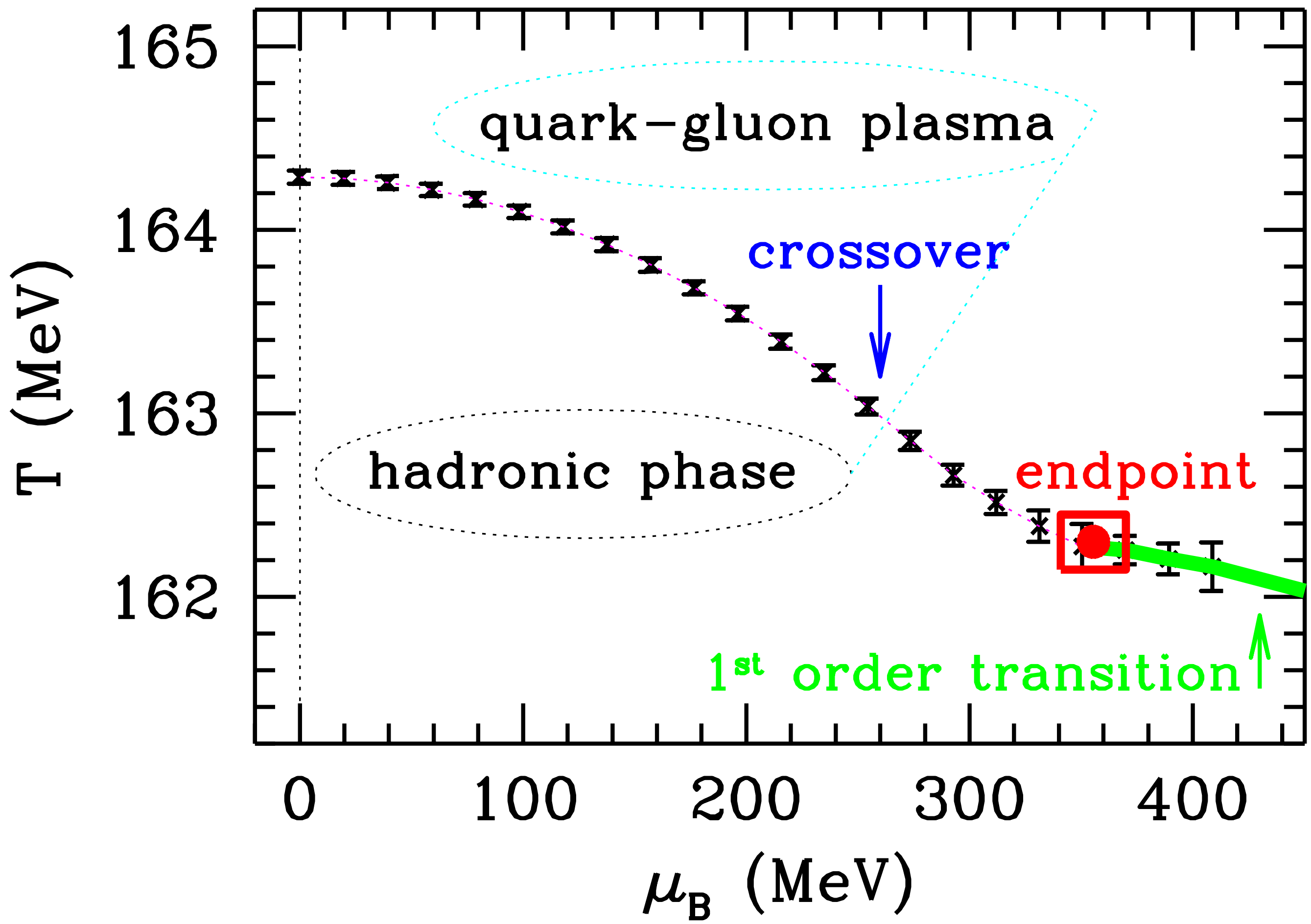


...and considering Fermi degrees of freedom



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

Limiting Hagedorn Temperature

A gas of hadrons with exponentially rising mass spectrum:

$$\ln \mathcal{Z}_{\rm HG}^{\rm cl} = cV\left(\frac{T}{2\pi}\right)^{3/2}\int_M^\infty m^a e^{m/T_{\rm H}} m^{3/2} e^{-m/T}\, dm + D(T,M),$$

Cutoff $M > m_a > T_{\rm H}$ is arbitrary, its role is to separate off $D(T,M) < \infty$. Because of the exponential factor, the first integral can be divergent for $T > T_{\rm H}$, and the partition function is singular for $T \to T_{\rm H}$ for a range of a:

$$P(T) \to \begin{cases} \left(\frac{1}{T}-\frac{1}{T_{\rm H}}\right)^{-(a+5/2)}, & \textbf{for} \quad a > -\frac{5}{2}, \\ \ln\left(\frac{1}{T}-\frac{1}{T_{\rm H}}\right), & \textbf{for} \quad a = -\frac{5}{2}, \\ \textbf{constant}, & \textbf{for} \quad a < -\frac{5}{2}; \end{cases} \qquad \epsilon \to \begin{cases} \left(\frac{1}{T}-\frac{1}{T_{\rm H}}\right)^{-(a+7/2)}, & \textbf{for} \quad a > -\frac{7}{2}, \\ \ln\left(\frac{1}{T}-\frac{1}{T_{\rm H}}\right), & \textbf{for} \quad a = -\frac{7}{2}, \\ \textbf{constant}, & \textbf{for} \quad a < -\frac{7}{2}. \end{cases}$$

The energy density ϵ goes to infinity for $a \geq -\frac{7}{2}$, when $T \to T_{\rm H}$.
Mass spectrum slope $T_{\rm H}$ appears as the limiting Hagedorn temperature beyond which we cannot heat a system which can have an infinite energy density. The partition function can be singular even when $V < \infty$.

Hagedorn Temperature is:

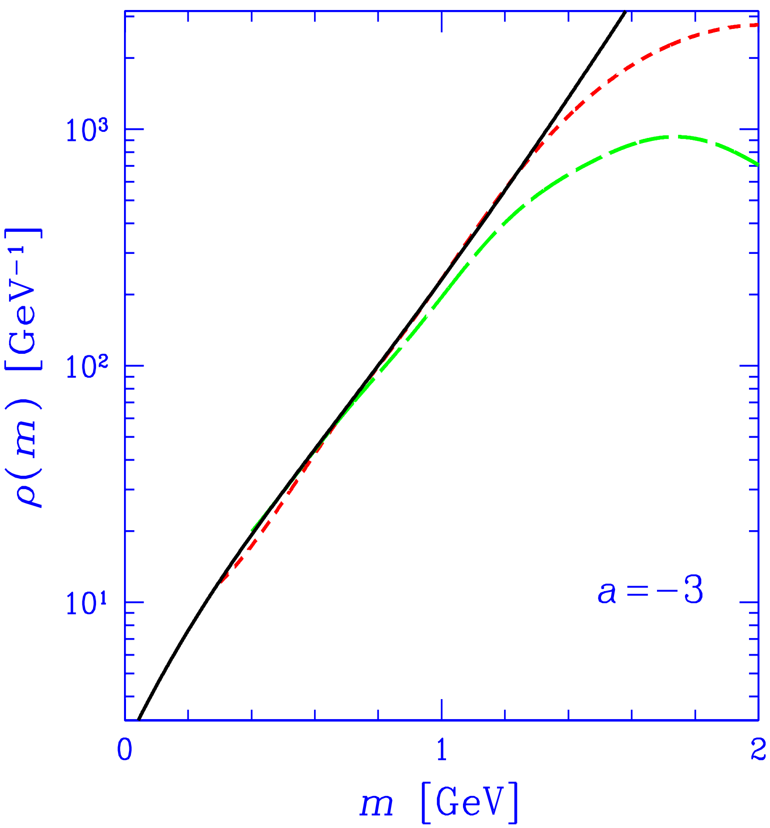
1. **The intrinsic temperature at which hadronic particles are formed, in pp interactions seen as the inverse slope of hadron spectra.**
2. **This boiling point of hadrons which is the (inverse) slope of exponentially rising hadron mass spectrum.**
3. **The boundary value of temperature at which finite size hadrons coalesces into one cluster consisting of a new phase comprising hadron constituents.**

Statistical Bootstrap Model is:

1. **A connection between hadronic particle momentum distribution and properties of hadronic interactions dominated by resonant scattering, and exponentially rising mass spectrum.**
2. **A theoretical framework for study of the properties of the equations of state of dense and hot baryonic matter (nuclear matter at finite temperature).**
3. **It is not a fundamental dynamical theory, in fact SBM is to be motivated today in terms of properties of the fundamental dynamical approach (QCD).**

Exponential Hadron Mass Spectrum

RH discovered that the exponential growth of the hadronic mass spectrum could lead to an understanding of the limiting hadron temperature $T_{\rm H} \simeq 160$ MeV,



The solid line is the fit:

$$\rho(m) \approx c(m_a^2 + m^2)^{a/2} \exp(m/T_{\rm H})$$

with $a=-3$, $m_a = 0.66$ GeV, $T_{\rm H} = 0.158$ GeV.
Long-dashed line: 1411 states of 1967.
Short-dashed line: 4627 states of 1996.

Experimental lines include Gaussian smoothing:

$$\rho(m) = \sum_{m^*=m_\pi, m_\rho, \ldots} \frac{g_{m^*}}{\sqrt{2\pi}\sigma_{m^*}} \exp\left(-\frac{(m-m^*)^2}{2\sigma^2_{m^*}}\right).$$

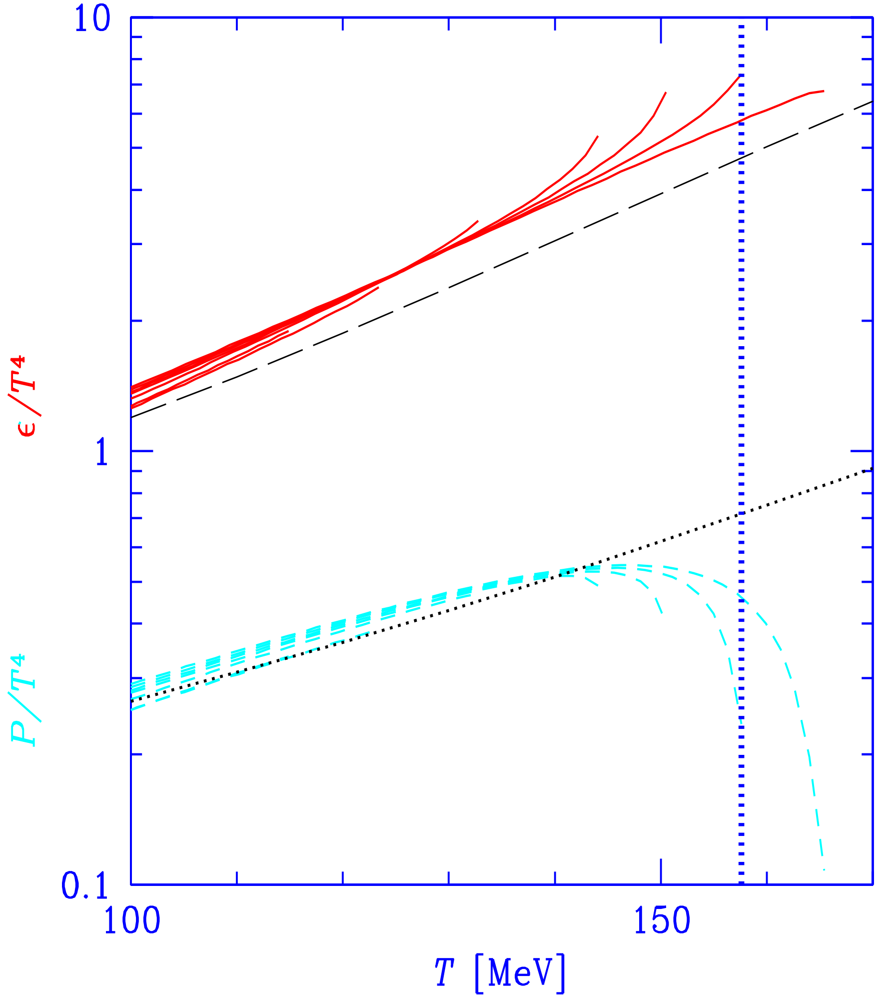
$\sigma = \Gamma/2$, $\Gamma = \mathcal{O}(200)$ MeV is the assumed width of the resonance, excluding the 'stable' pion, a special case.

Note the missing resonances at $m > 1.4 GeV$.
The 'pentaquark' resonances nicely fill this gap.

Finite Volume Hadron Gas Model

The gas of finite size hadrons with exponential mass spectrum has nearly the same properties as a gas of point hadrons with today experimentally observed mass spectrum. That is why 'statistical hadronization works'.

Point hadron gas in free available volume Δ to have the properties of finite size hadron gas in total mean volume $\langle V\rangle$ (RH/JR 1978+)



$$\boxed{\ln \mathcal{Z}_{\rm pt}(T,\Delta,\lambda) \equiv \ln \mathcal{Z}(T,\langle V\rangle,\lambda)}$$

Proper particle volume in the rest frame is assumed to be proportional to mass. For a gas of moving hadrons, in gas rest-frame: $\langle V\rangle = \Delta + \langle E\rangle/4\mathcal{B}$.

$$\langle E\rangle = \langle V\rangle \epsilon(\beta,\lambda) = -\frac{\partial}{\partial\beta}\ln \mathcal{Z}(\beta,\langle V\rangle,\lambda) =$$

$$= -\frac{\partial}{\partial\beta}\ln \mathcal{Z}_{\rm pt}(\beta,\Delta,\lambda) = \Delta\epsilon_{\rm pt}(\beta,\lambda)$$

$$\langle V\rangle = \Delta\big(1+\epsilon_{\rm pt}(\beta,\lambda)/4\mathcal{B}\big),$$

$$\frac{\langle E\rangle}{\langle V\rangle} \equiv \epsilon(\beta,\lambda) = \frac{\epsilon_{\rm pt}(\beta,\lambda)}{1+\epsilon_{\rm pt}(\beta,\lambda)/(4\mathcal{B})},$$

$$P = \frac{P_{\rm pt}(\beta,\lambda)}{1+\epsilon_{\rm pt}(\beta,\lambda)/4\mathcal{B}}.$$

Chemical Equilibrium Phase Boundary

Temperature of phase transition depends on available degrees of freedom:

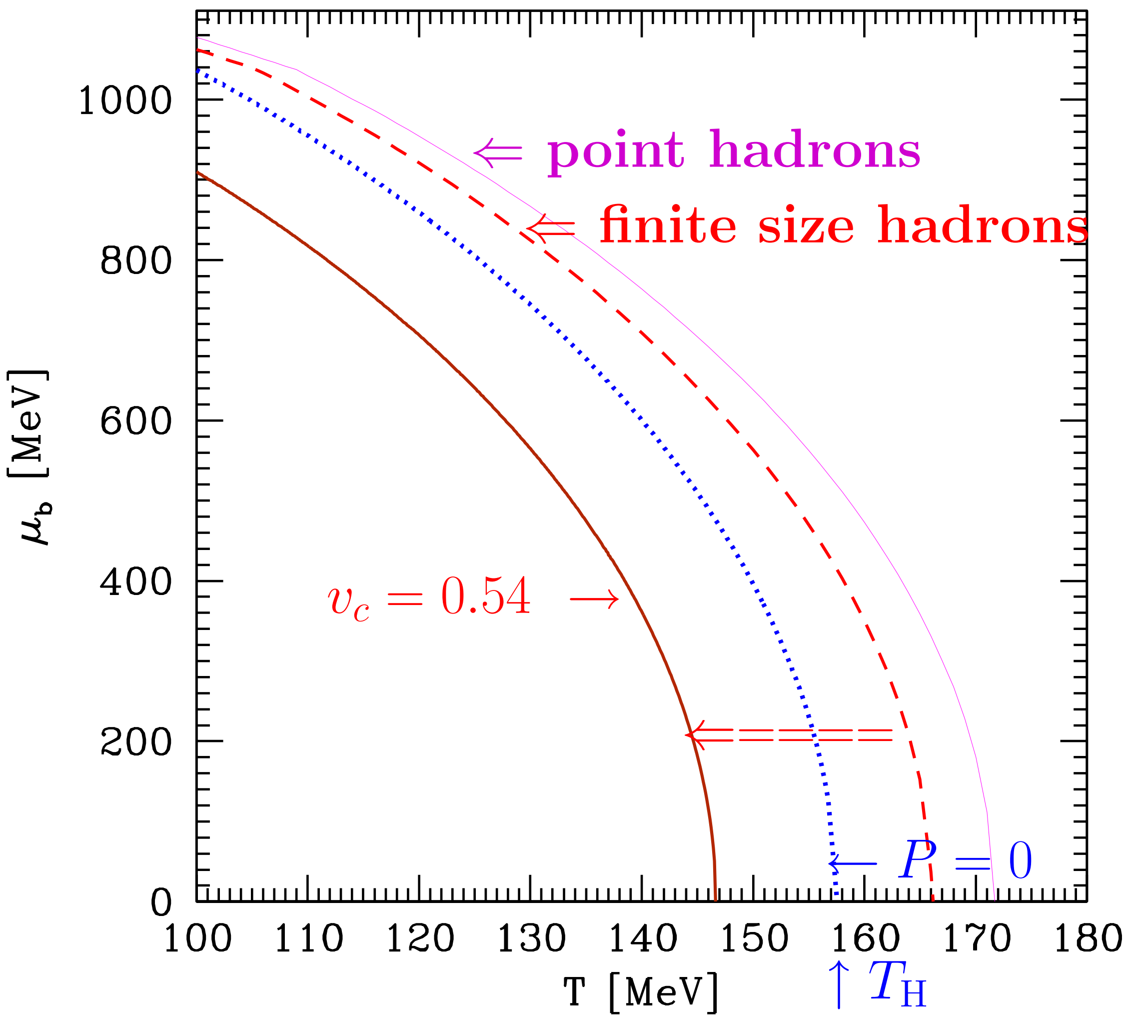
- **For 0 flavor theory $T > 200$ MeV**
- **For 2 flavors: $T \to 170$ MeV**
- **For 2+1 flavors: $T = 162 \pm 3$ and appearance of minimum $\mu_{\rm B}$ we need extra quarks to reach a 1st order transition**
- **For 3, 4 flavors further drop in T.**

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.**
- **Dynamical expansion is enhancing the deconfined phase pressure, expect decrease of transition temperature**

Phase boundary and 'wind' of flow of matter



PRL 85 (2000) 4695

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 $T \simeq 166$.

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,

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

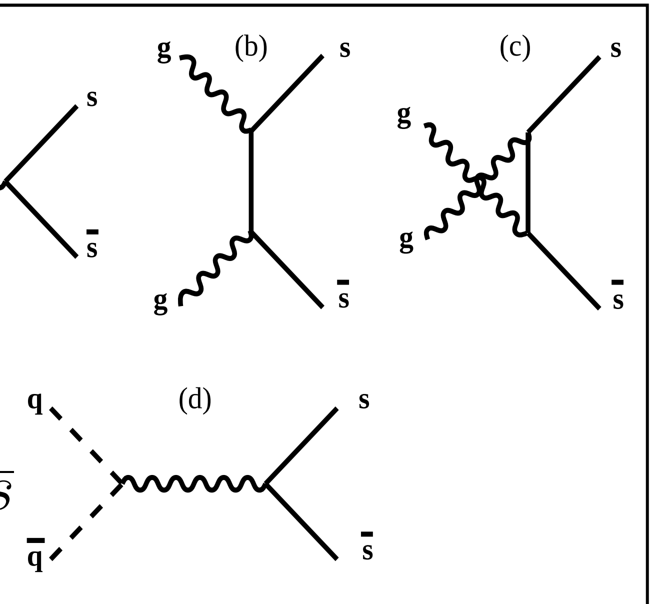
This requires $P_{\rm p} < \mathcal{B}$: QGP phase pressure P must be NEGATIVE. A fireball surface region which reaches $\mathcal{P} \to 0$ and continues to flow outward is torn apart in a rapid instability. This can ONLY arise since matter presses again the vacuum which is not subject to collective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

IS OVERPOPULATION OF PHASE SPACE POSSIBLE?

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

  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:**
  $$\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\rm QGP}} \to$$
  strangeness a clock for QGP phase

- $\boxed{\bar{s} \simeq \bar{q}} \to$ **strange antibaryon enhancement**
  at RHIC (anti)hyperon dominance of (anti)baryons.
- **at LHC** $\gamma_s >> 1$ **Phase transition for** $\mu_{\rm B} = 0$**?**

Thermal average rate of strangeness production

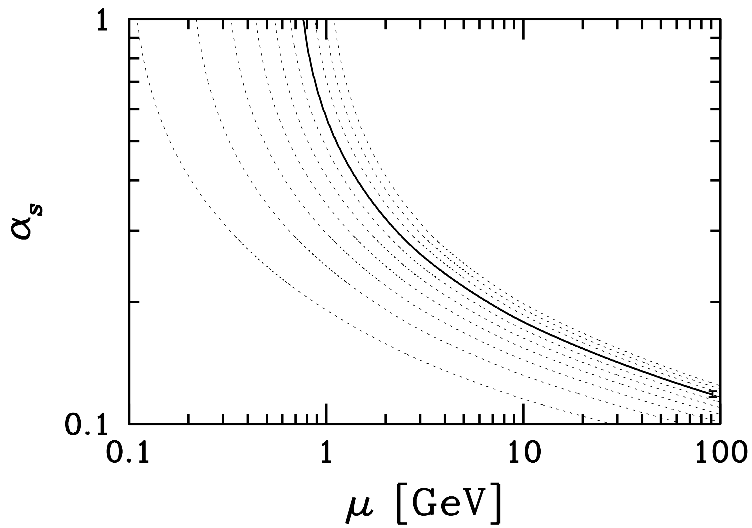
Kinetic (momentum) equilibration is faster than chemical, use thermal particle distributions $f(\vec{p}_1, T)$ to obtain average rate:

$$\langle \sigma v_{\rm rel} \rangle_T \equiv \frac{\int d^3p_1 \int d^3p_2 \sigma_{12} v_{12} f(\vec{p}_1, T) f(\vec{p}_2, T)}{\int d^3p_1 \int d^3p_2 f(\vec{p}_1, T) f(\vec{p}_2, T)} \, .$$

The generic angle averaged cross sections for (heavy) flavor s, $\bar{s}$ production processes $g + g \to s + \bar{s}$ and $q + \bar{q} \to s + \bar{s}$, are:

$$\bar{\sigma}_{gg\to s\bar{s}}(s) = \frac{2\pi\alpha_{\rm s}^2}{3s}\left[\left(1 + \frac{4m_{\rm s}^2}{s} + \frac{m_{\rm s}^4}{s^2}\right)\tanh^{-1}W(s) - \left(\frac{7}{8} + \frac{31m_{\rm s}^2}{8s}\right)W(s)\right] ,$$

$$\bar{\sigma}_{q\bar{q}\to s\bar{s}}(s) = \frac{8\pi\alpha_{\rm s}^2}{27s}\left(1 + \frac{2m_{\rm s}^2}{s}\right)W(s) \, . \qquad W(s) = \sqrt{1 - 4m_{\rm s}^2/s}$$



RESUMMATION

The relatively small experimental value $\alpha_{\rm s}(M_Z) \simeq 0.118$, established in recent years helps to achieve QCD resummation with running $\alpha_{\rm s}$ and $m_{\rm s}$ taken at the energy scale $\mu \equiv \sqrt{s}$. also $m_{\rm s}(M_Z) = 90 \pm 20\%$ MeV i.e. $m_s(1\mathbf{GeV}) \simeq 2.1 m_s(M_Z) \simeq 200$MeV.

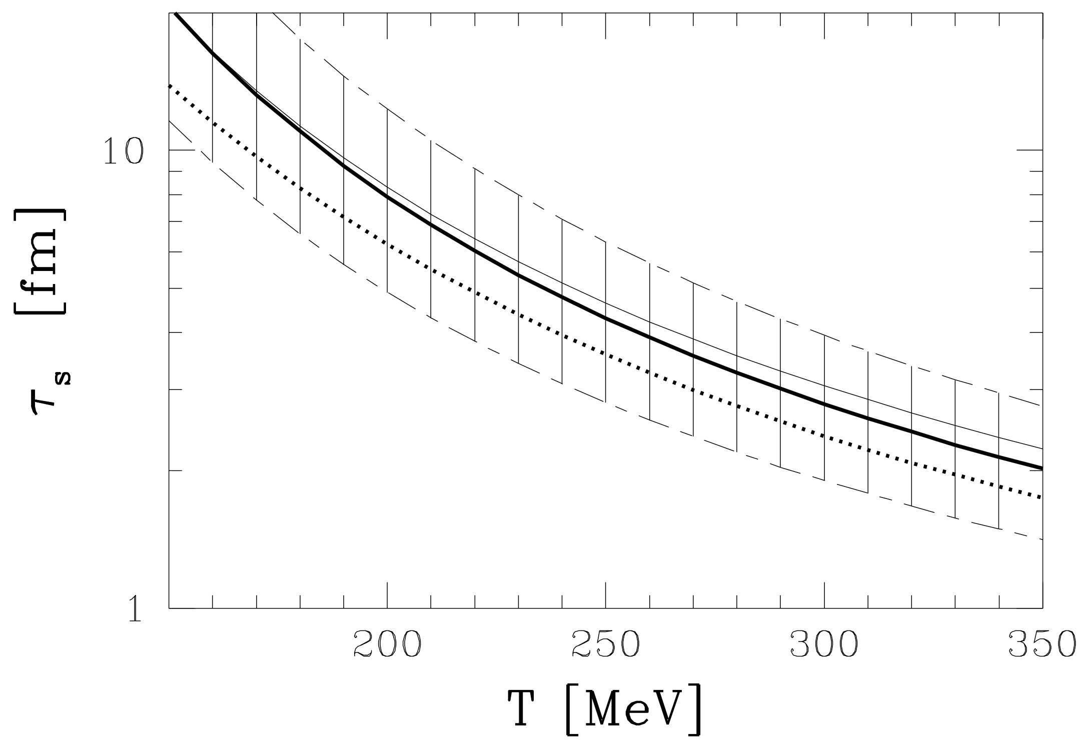
Strangeness relaxation to chemical equilibrium

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:

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



ENTROPY CONSERVING EXPANSION

With $m_q \simeq 0, m_G = 0$, a sytem of nearly massless quarks and gluons, each thermal particle contains about 4 units of entropy, adiabatic expansion preserves number of particles, i.e.

$$N \propto VT^3 = \textbf{Const.}\ .$$

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

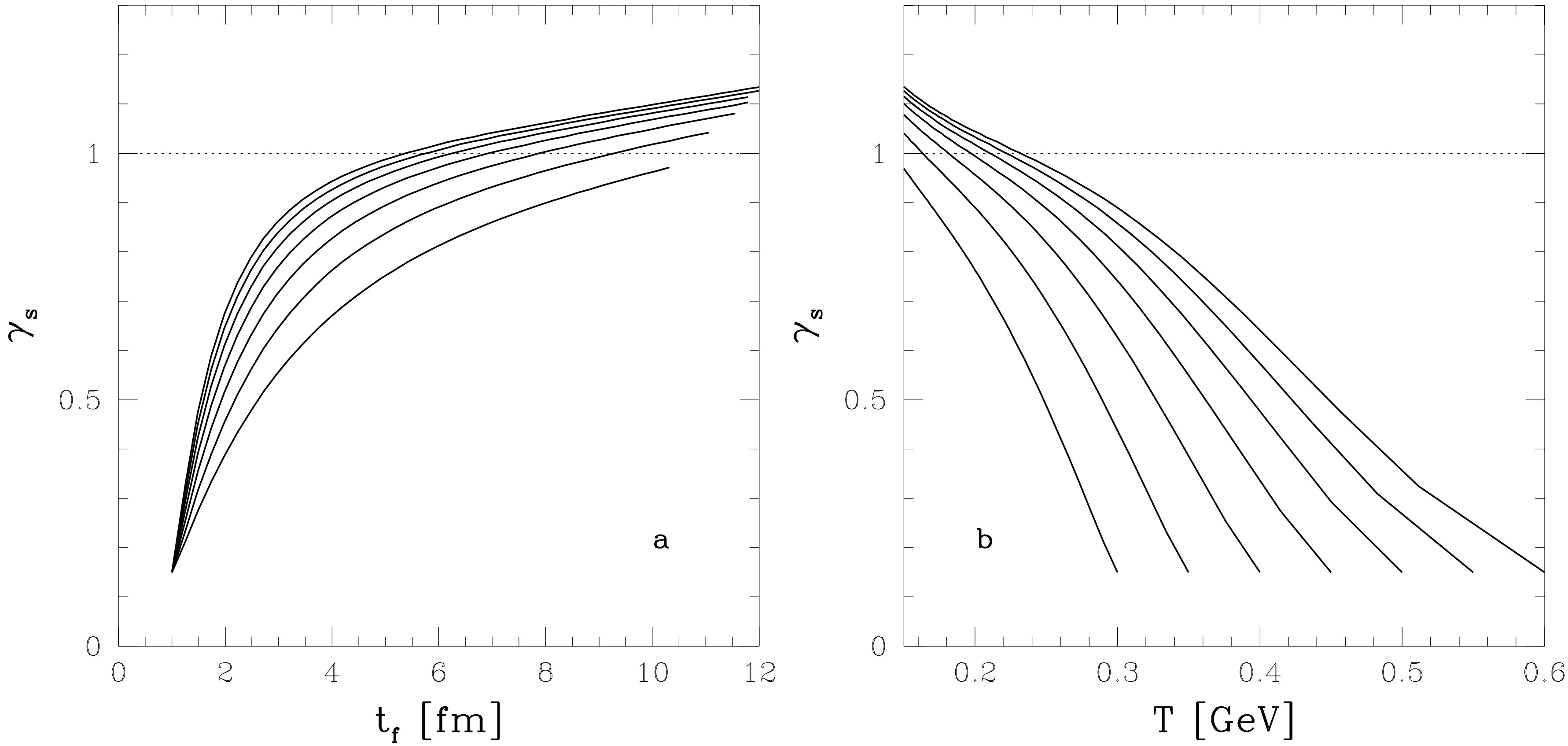
$$\gamma_s(t) \equiv \frac{n_s(t)}{n_s^\infty(T(t))}, \quad n_s(t) = \gamma_s(t)T(t)^3\frac{3}{\pi^2}z^2K_2(z), \quad z = \frac{m_s}{T(t)}, \quad K_i : \text{Bessel f.}$$

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 (Logarithmic) term presents the residual effect of expansion. Note that its importance grows with mass of the quark, $z = m/T$.
Without it, there is appraoch to chemical equilibrium $\gamma_s \to 1 - e^{t/\tau_s}$ by strangeness formation.
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 $T_{\rm cr}$ and help create a real phase transtion at zero baryon density.
Requirement: intial state hot, and expansion time $\tau_{\rm QGP} > \tau_s$

RHIC EXAMPLE



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

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

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.

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:

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

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

Allow for chemical equilibrium of strangeness n γ_s^{QGP}, and possible quark-gluon pre-equilibrium:

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

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

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

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

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

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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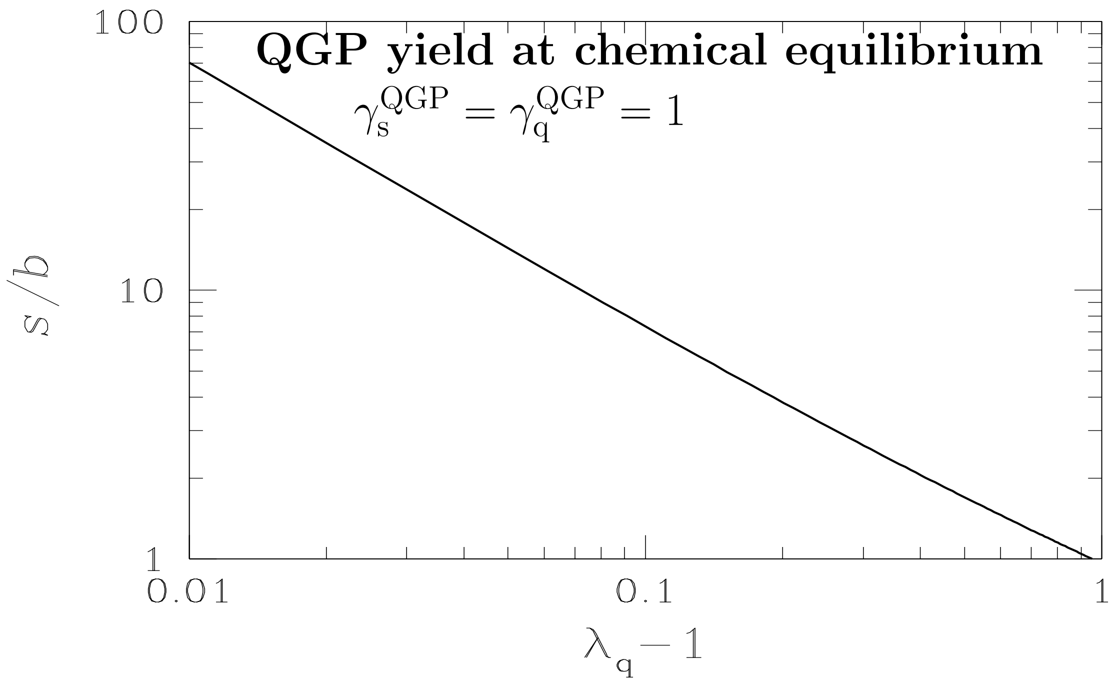

EXAMPLE: SPS Pb–Pb 158 A GeV λ_q=1.5–1.6, implies $s/b\simeq 1.5$.
Observation: $s/b\simeq 0.75\rightarrow\gamma_s^{QGP}/\gamma_q^{QGP}=0.5$.

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

COMPUTE EXPECTED RATIO OF $\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$
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 nonm-equilibrium in the the other.

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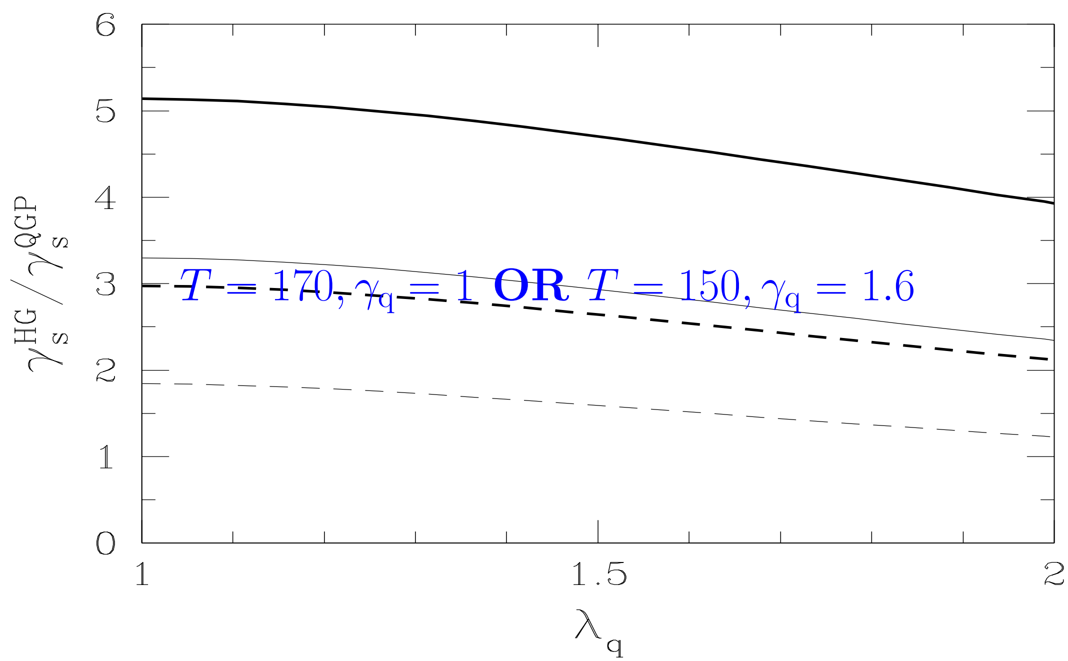


$\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$ Solid lines $\gamma_{\rm q}^{\rm HG} = 1$,
Probably appropriate: short dashed $\gamma_{\rm q}^{\rm HG} = 1.6$.
Thin lines for $T = 170$ and thick lines $T = 150$ MeV, common to both phases.

$$\boxed{\gamma_s^{\rm HG} \simeq 3\gamma_s^{\rm QGP}}$$

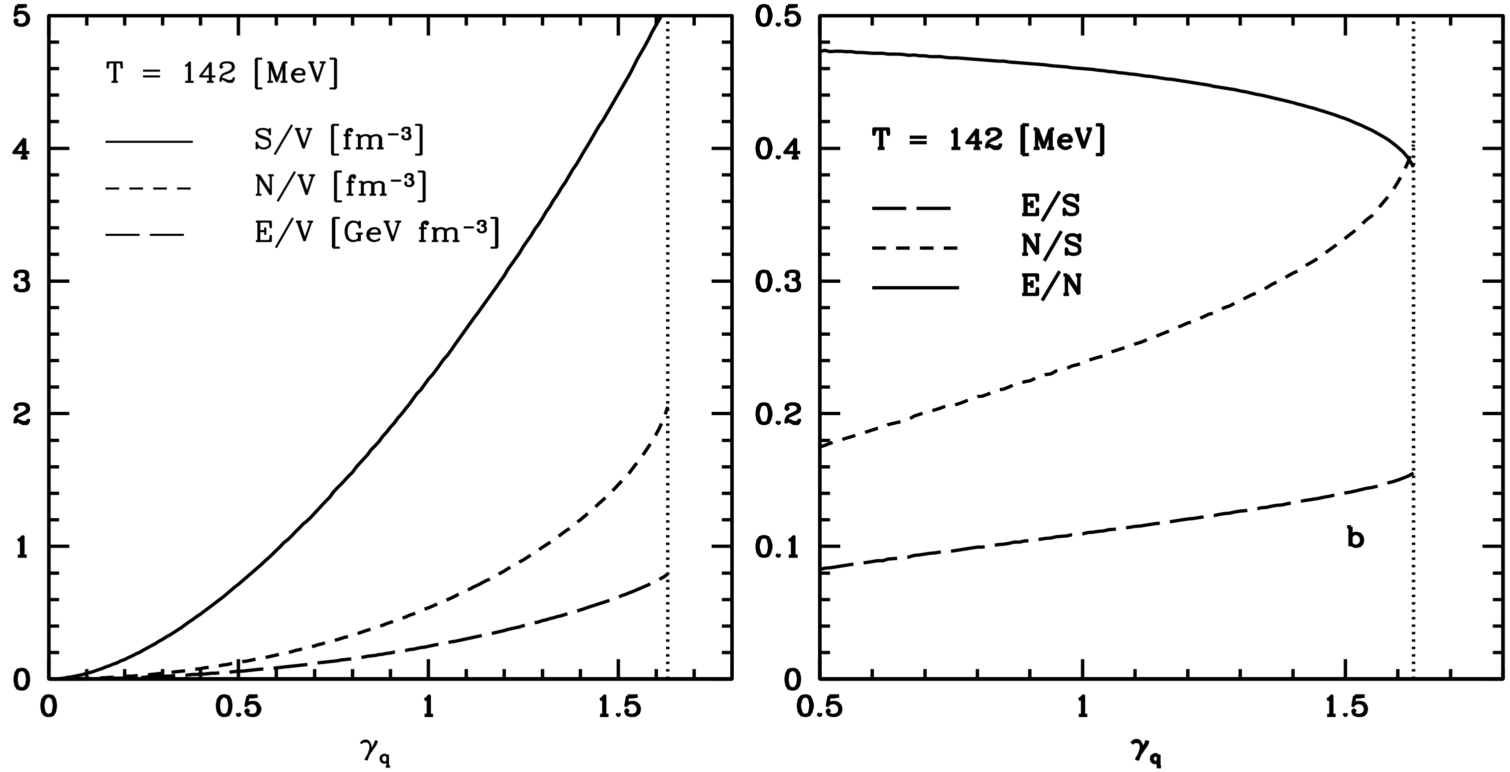
ESTIMATE THE EXPECTED $\gamma_q^{\rm HG}$

QGP has excess of entropy, maximize entropy density 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**.**



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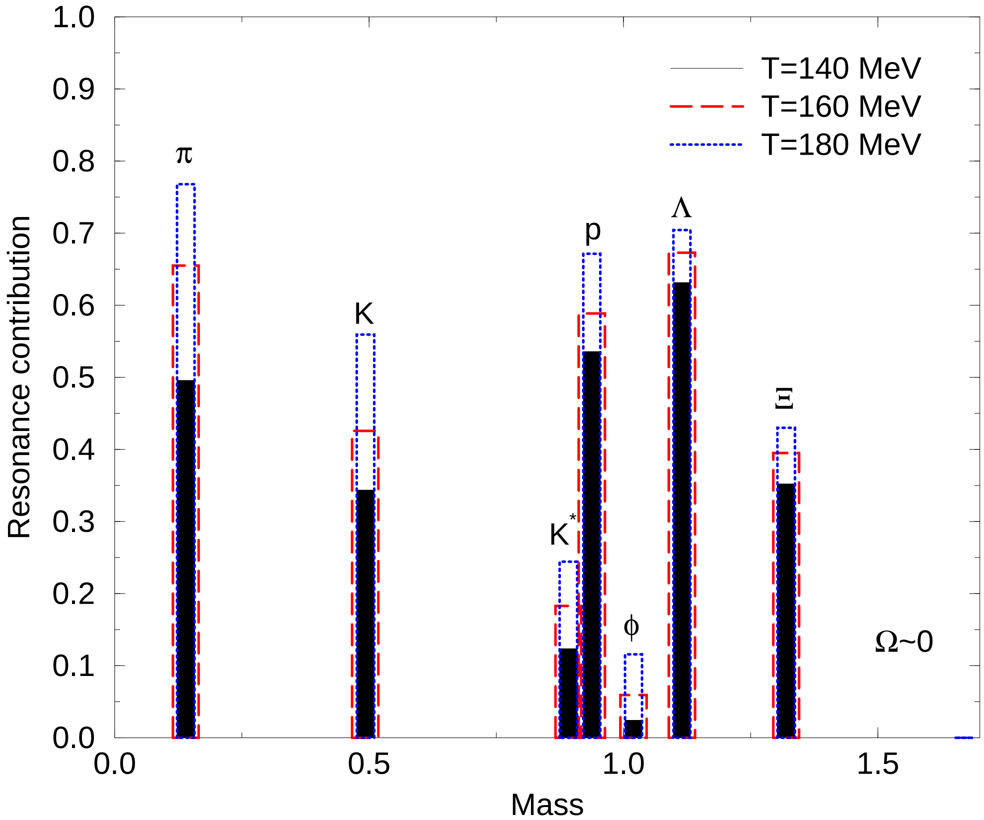
NEXT: HOW WE MEASURE $\gamma_{q,s}$**, observe thresholds of phases?**

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 accomodates 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

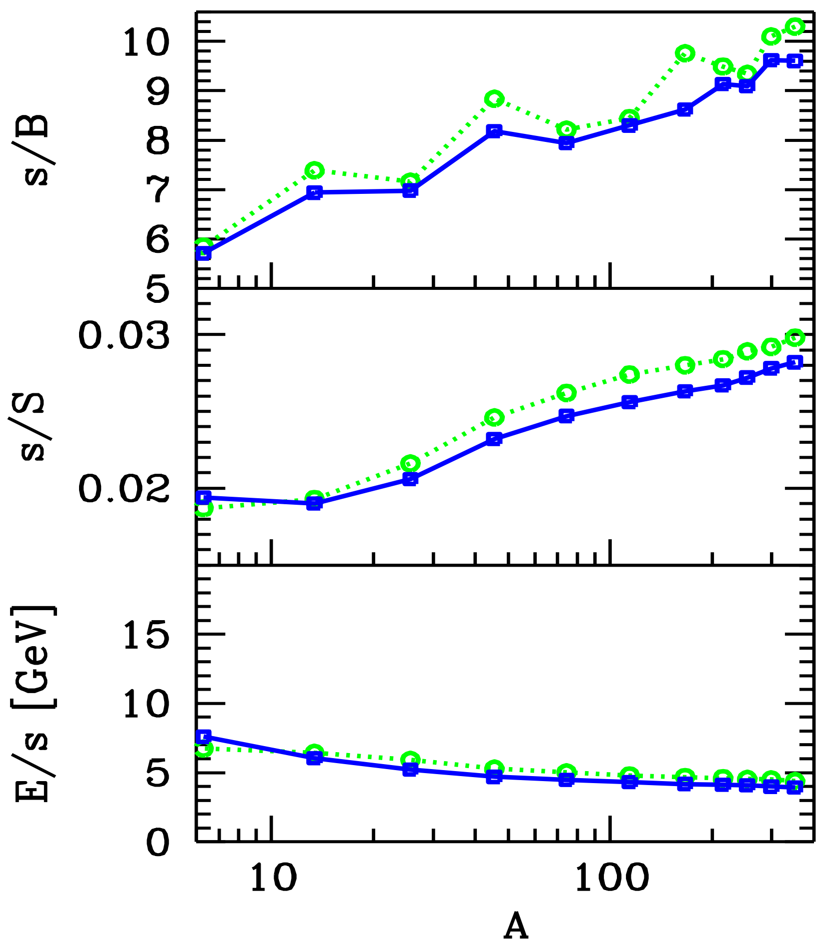
Aside of particle yields, also PHYSICAL PROPERTIES of the source are available, both in SHARE and ONLINE. Several papers use this tool: nucl-th/0412072 (PRC in press) and nucl-th/0506044 [address impact parameter], nucl-th/0504028 [E-dependence], hep-ph/0506140 [LHC]

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.

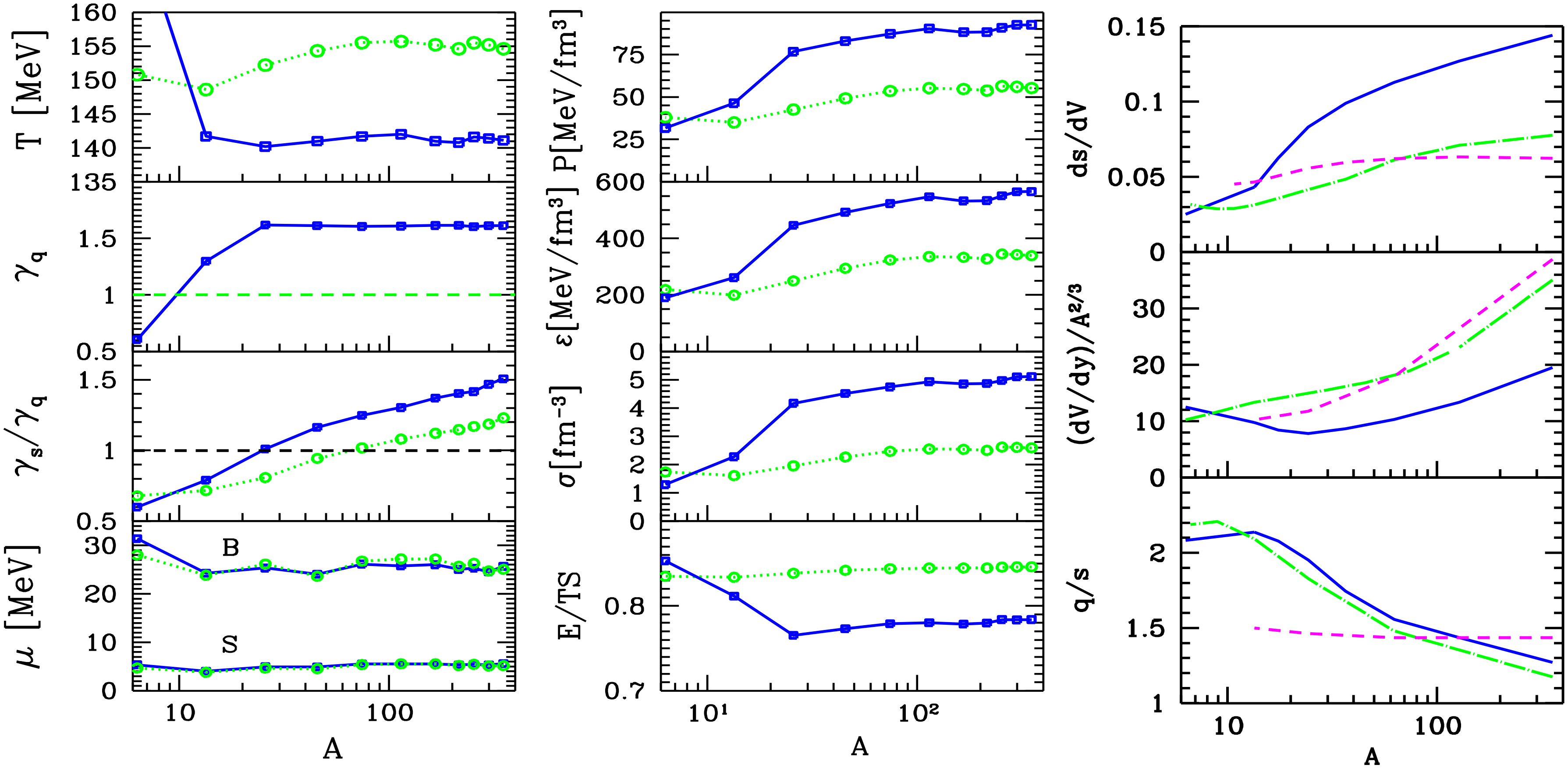
s/b and s/S rise with increasing centrality $A \propto V$; E/s falls



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.

RHIC200 results: dependence on centrality

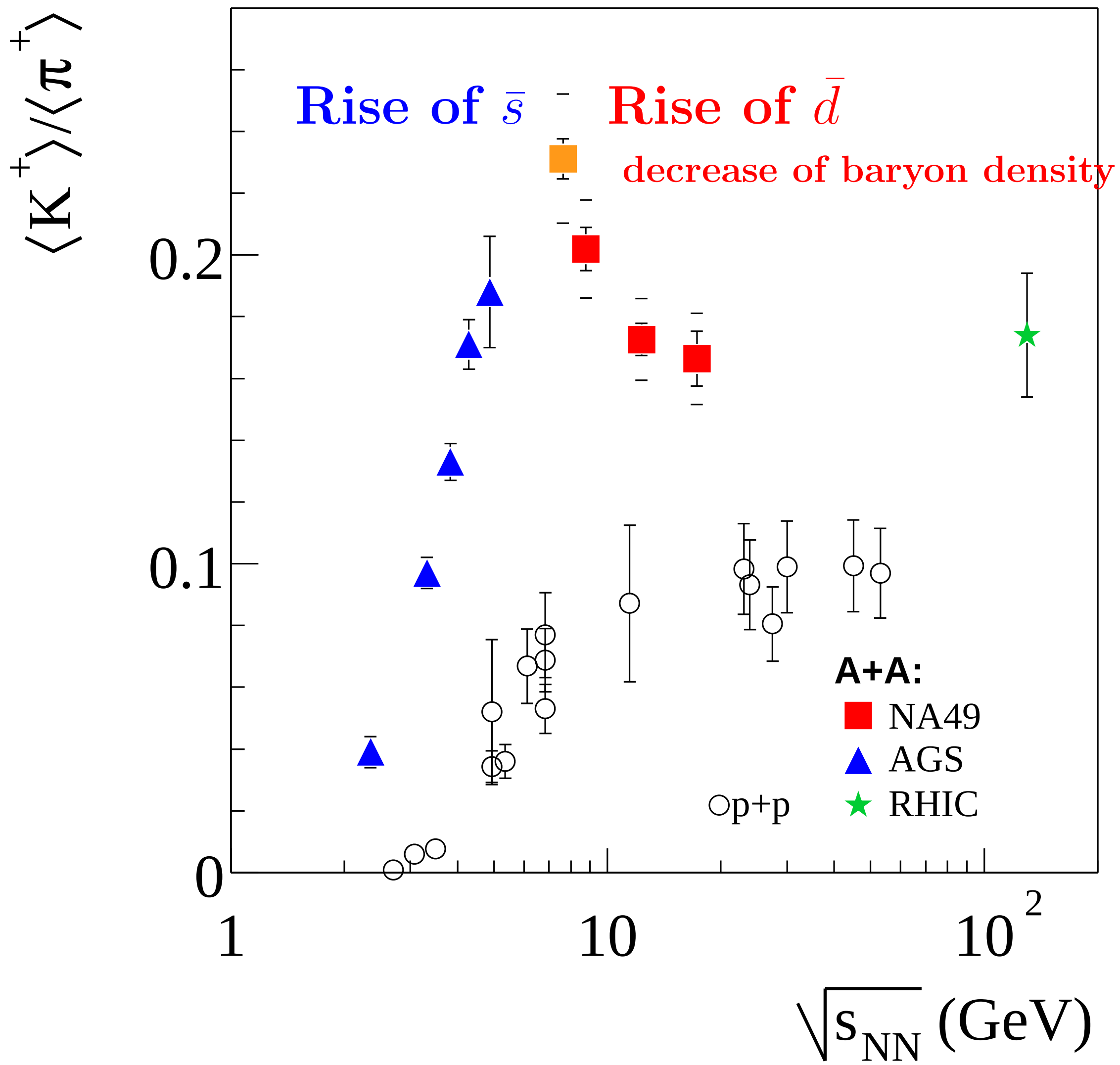


LINES: $\gamma_s, \gamma_q \neq 1$ **and** $\gamma_s \neq 1, \gamma_q = 1$, **also** $\gamma_s = \gamma_q = 1$

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.

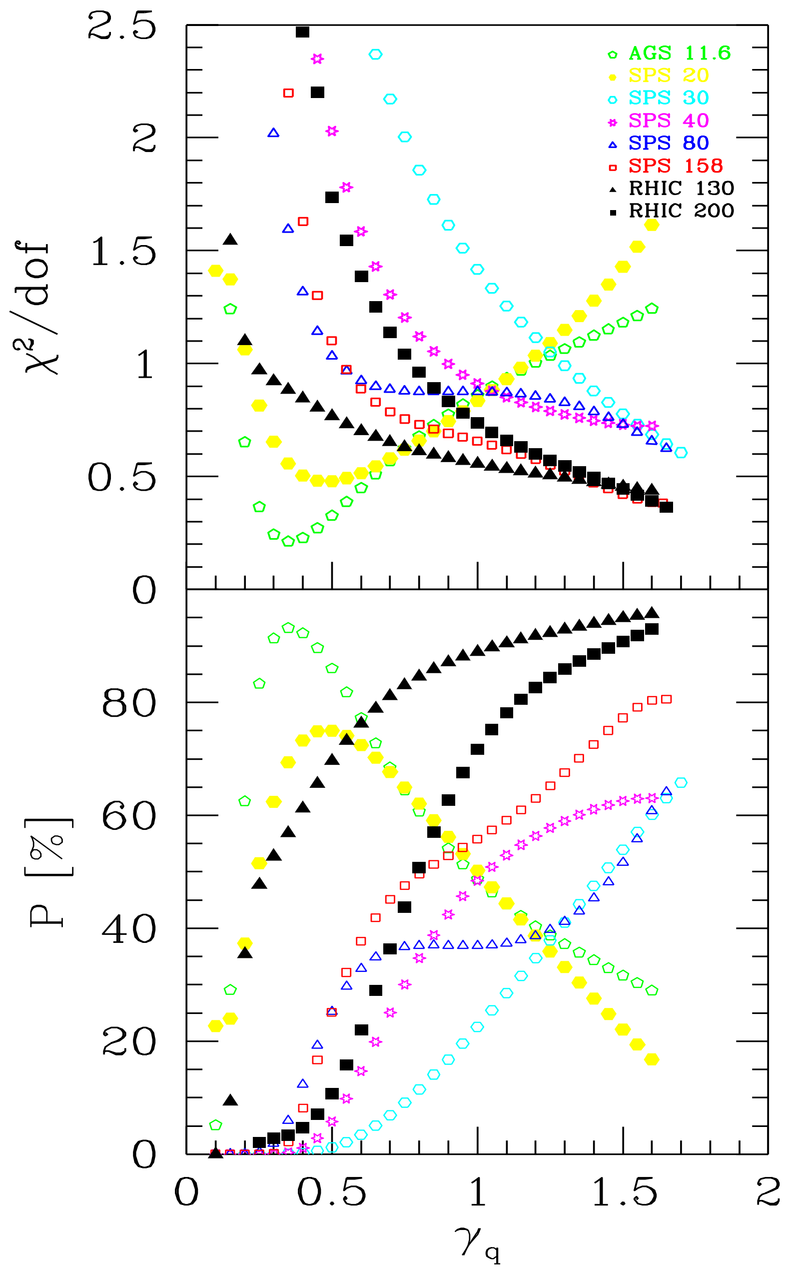
Statistical + fit errors are seen in fluctuations, systematic error impacts absolute normalization by $\pm 10\%$.

SPECTACULAR: direct evidence for phase threshold

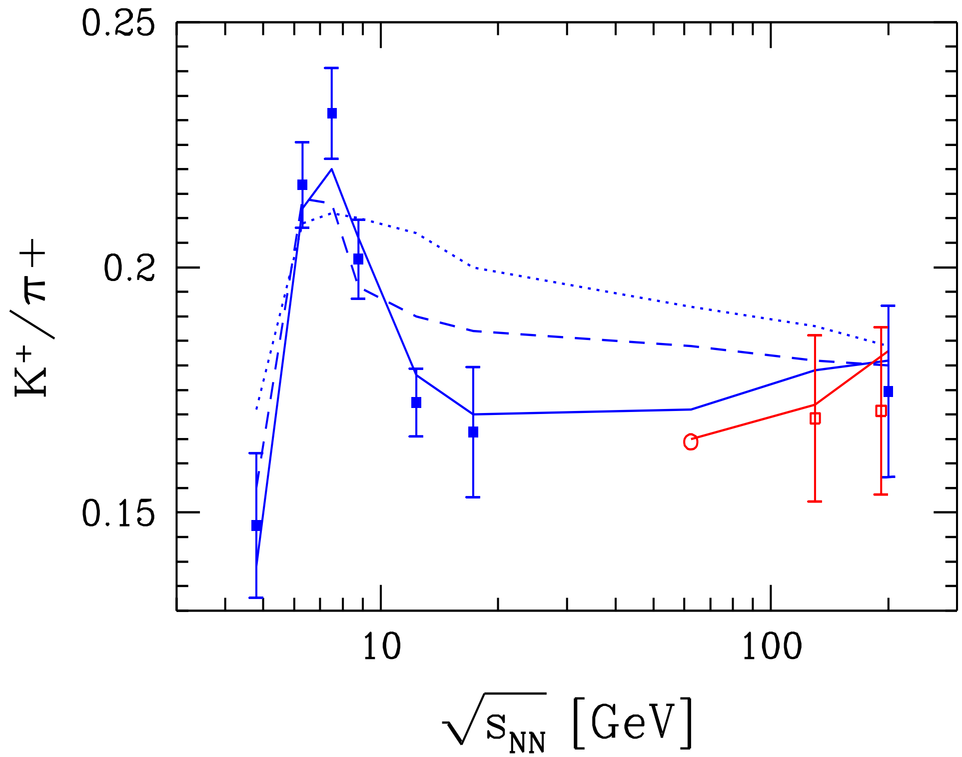


The NA49 (Marek Gaździcki) HORN

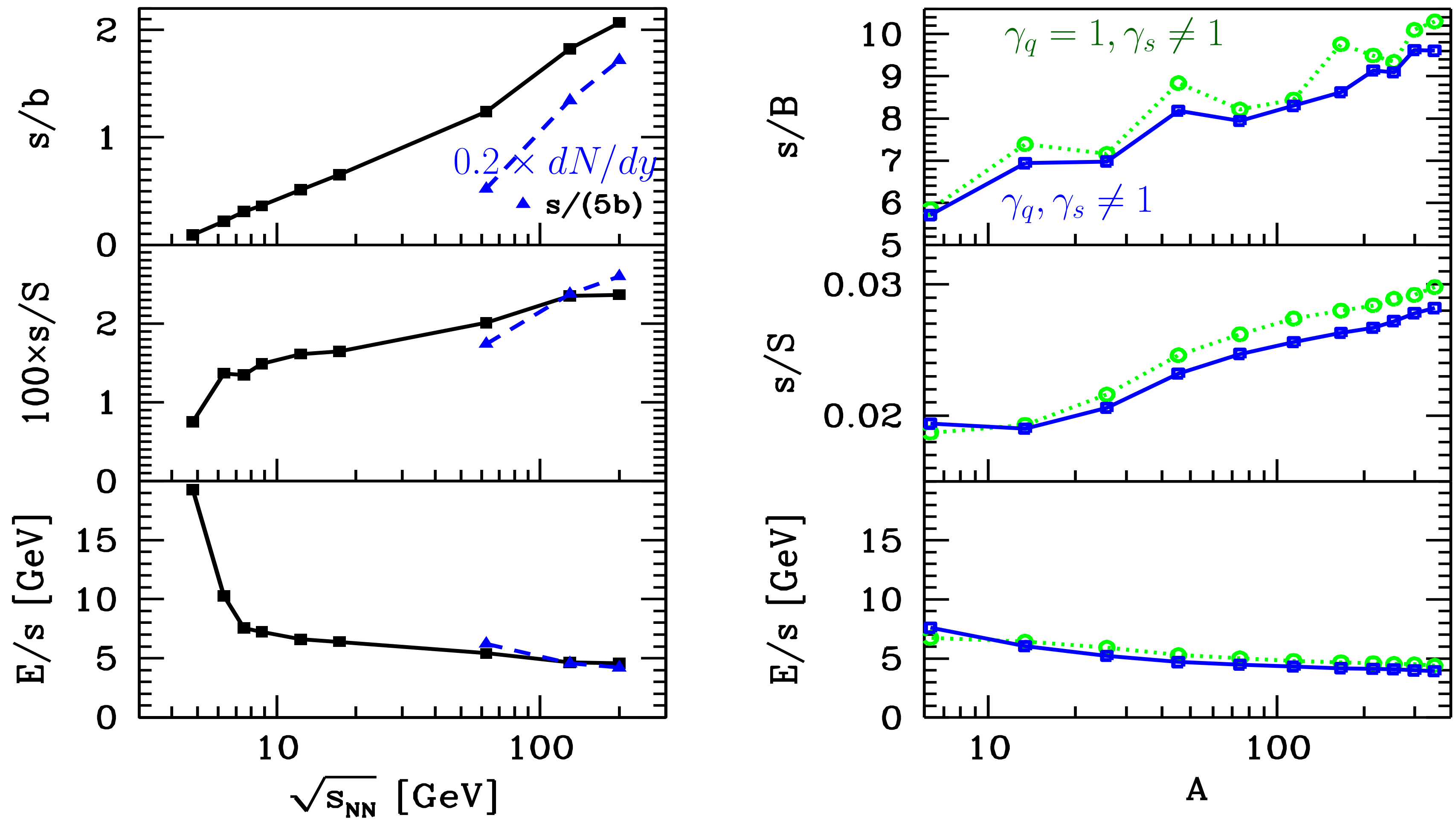
The horn requires a shift in γ_q



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 $P\%$.

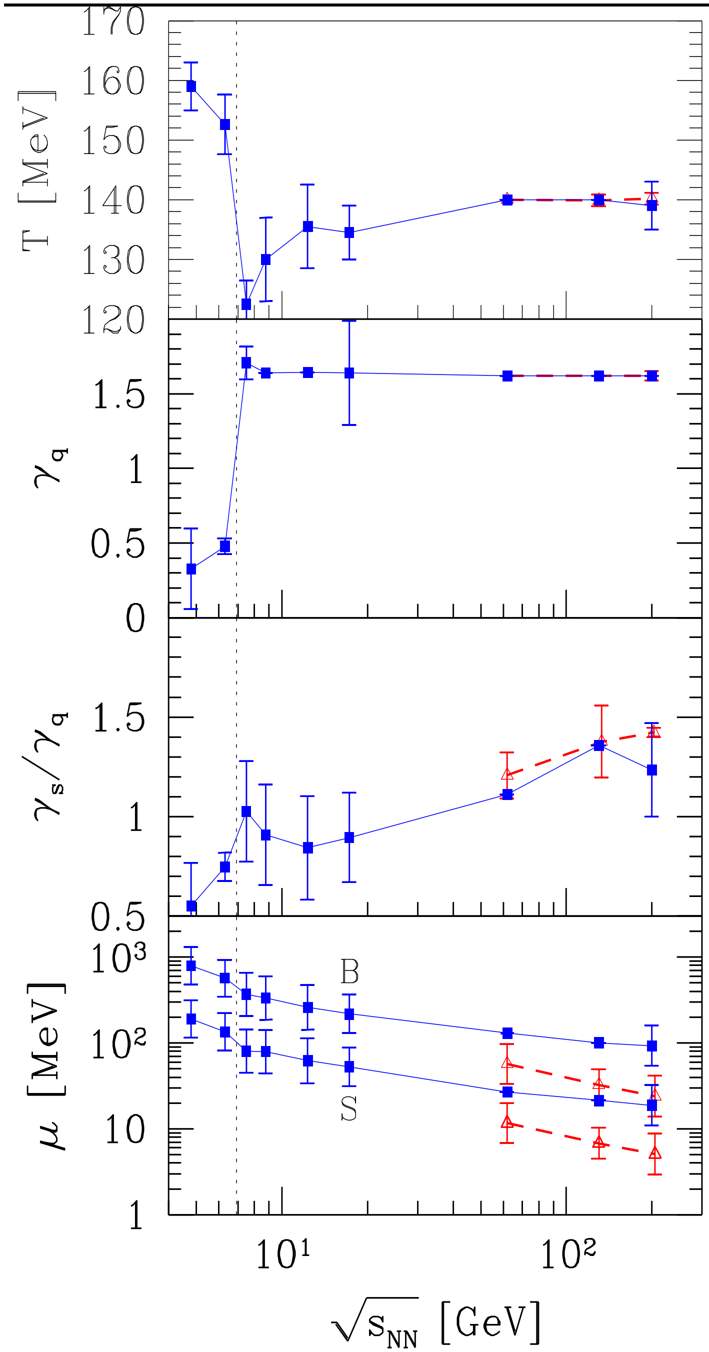


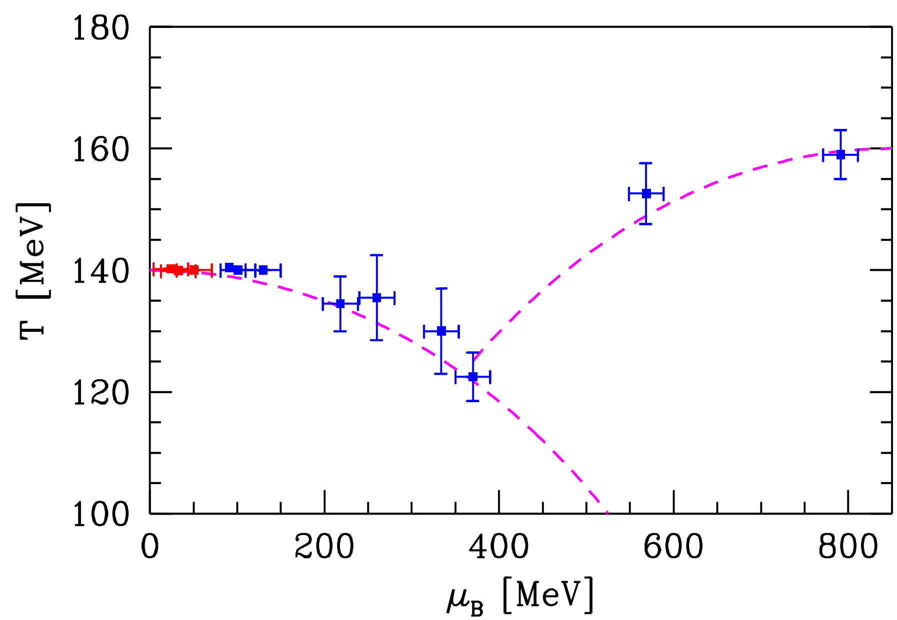
COMPARE $\sqrt{s_{\rm NN}}$ and V dependence of s/b and s/S, E/s



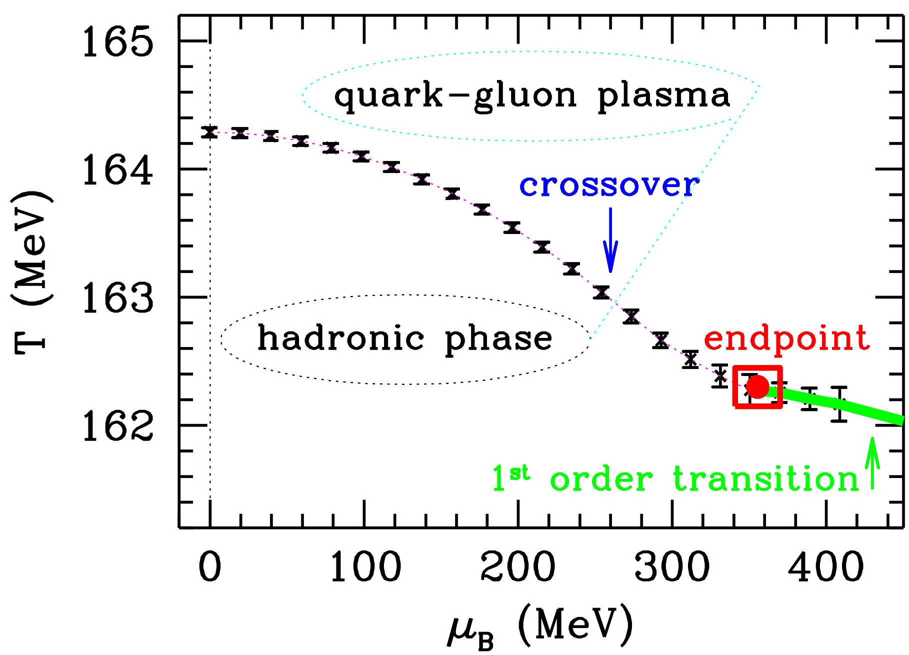
Full 4π and central rapidity results.
We again find $s/S \to 0.027$, as function of $\sqrt{s_{\rm NN}}$ and V: no saturation, consistent with QGP expectation and $\gamma_s^{\rm QGP} \simeq 1$, confirmed by s/B.
Energy/strangeness E/s cost drop at $\sqrt{s_{\rm NN}^{\rm cr}}$, suggests appearance of a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

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

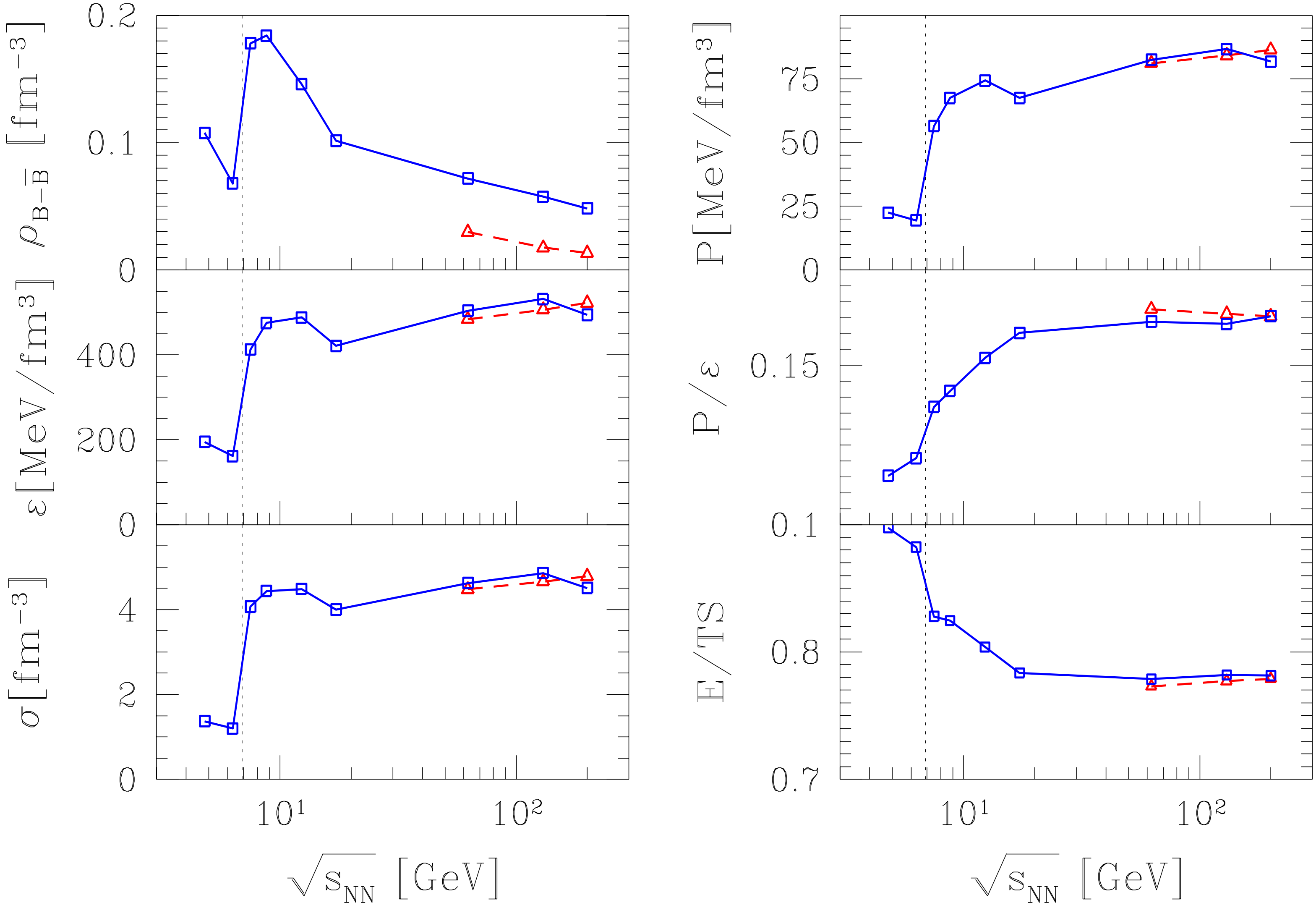




to be compared to, see below:



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

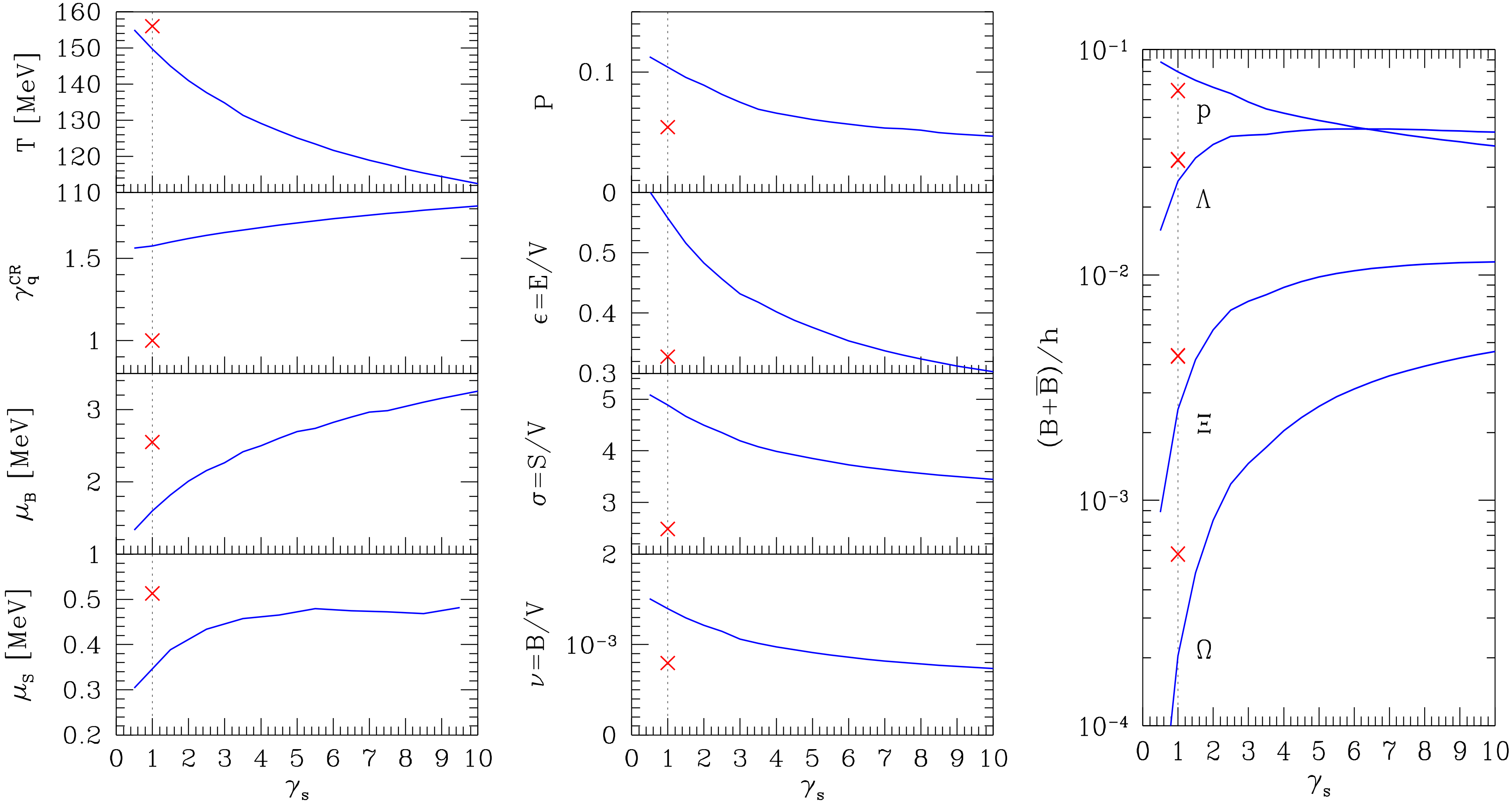


Note that behavior is the same as we saw as function of *A*: the large jumps by factor 2–3 in densities (to left) and pressure (on right) as the collision energy changes from 20 GeV to 30 GeV. There is clear evidence of change in reaction mechanism. There no difference between top SPS and RHIC energy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

Sample of LHC predictions: physical properties and particle yields



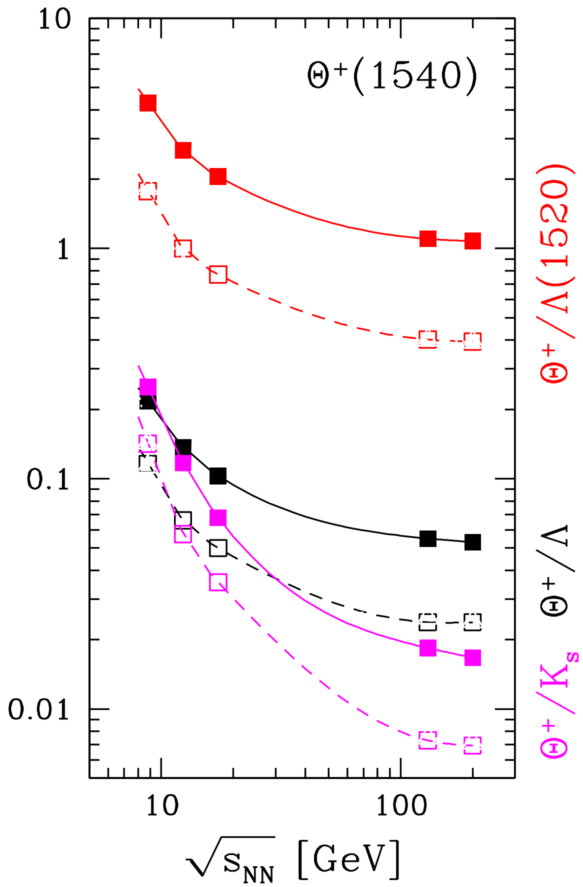
Best estimate $\gamma_s^{\mathrm{HG}} \simeq 5$. Baryochemical potential $\mu_B \simeq 2$ MeV, hard to measure.

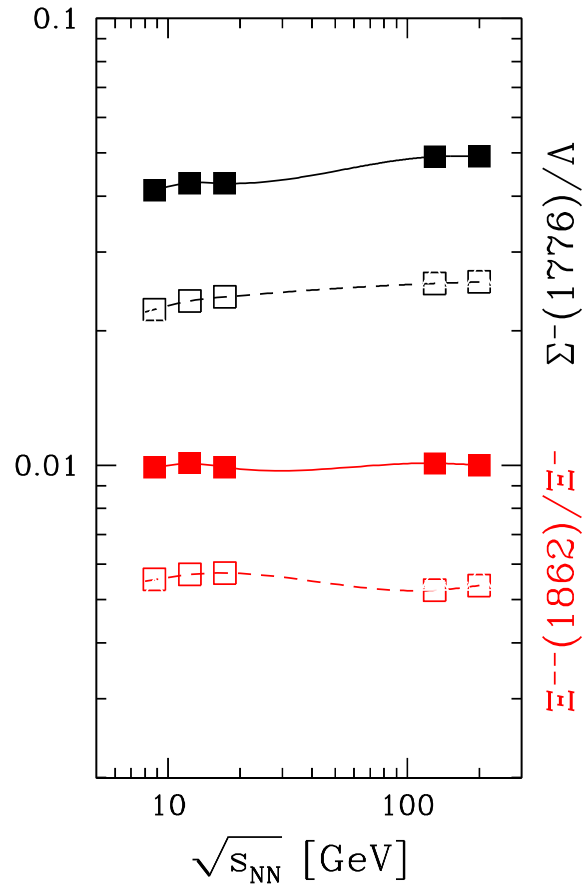
X: chemical equilibrium reference. **Prediction: use $E/TS = 0.78$.**

For $\mu_{\mathrm{B,S}}, \nu_{\mathrm{B}}$ in addition extrapolate E/B or/and S/b.

Excursion to Pentaquarks

Statistical hadronization allows to explore the rate of production of pentaquarks which depend on chemical potentials [PRC68, 061901 (2003), hep-ph/0310188]; $\Theta^+(1540)$ is best looked for at low reaction energy.





Expected relative yield of $\Theta^+(1540)$(left); $\Xi^{--}(1862)$ and $\Sigma^-(1776?)$ (right), based on statistical hadronization conditions at SPS and RHIC: solid lines γ_s and γ_q fitted; dashed lines γ_s fitted, $\gamma_q = 1$.

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 threshold of deconfinement?

$6.26\mathrm{GeV} < \sqrt{s_{\rm NN}^{\rm cr}} < 7.61\mathrm{GeV}$. *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* $m \simeq 2$-$4T$.