STRANGENESS AND THE DISCOVERY OF QUARK GLUON PLASMA

ICPAQGP, Kolkata, February 2005

Strangeness flavor is the only known observable of the deconfined quark-gluon state of matter which can be studied in the entire available experimental AGS, SPS, RHIC and LHC energy range. Multi strange hadrons are of particular importance for the understanding of the formation and the properties of the deconfined state. A comparative study of strange hadron production at as function of energy and reaction volume will be presented. Strangeness observables shows regularities and a potential discontinuity indicating a threshold in energy and volume size for deconfinement. . . .

Includes many recent results (publication on-line/in preparation) obtained in collaboration with **Jean Letessier,** Paris *and* **Giorgio Torrieri,** McGill

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Why Strangeness is a diagnostic tool

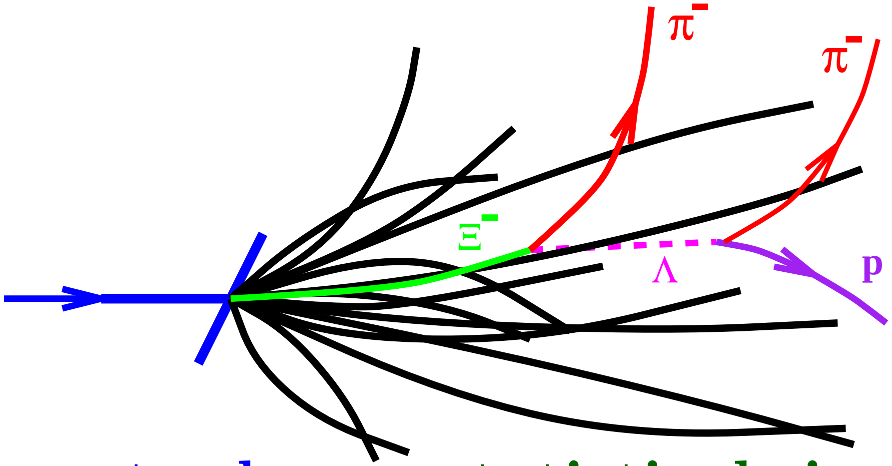
EXPERIMENTAL REASONS

- **There are many strange particles allowing to study different physics questions** $(q = u, d)$**:**

$$\phi(s\bar{s}),\ K(q\bar{s}),\ \overline{K}(\bar{q}s),\ K^*(893),\ \Lambda(qqs),\ \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),\ \Sigma^*(1385),$$

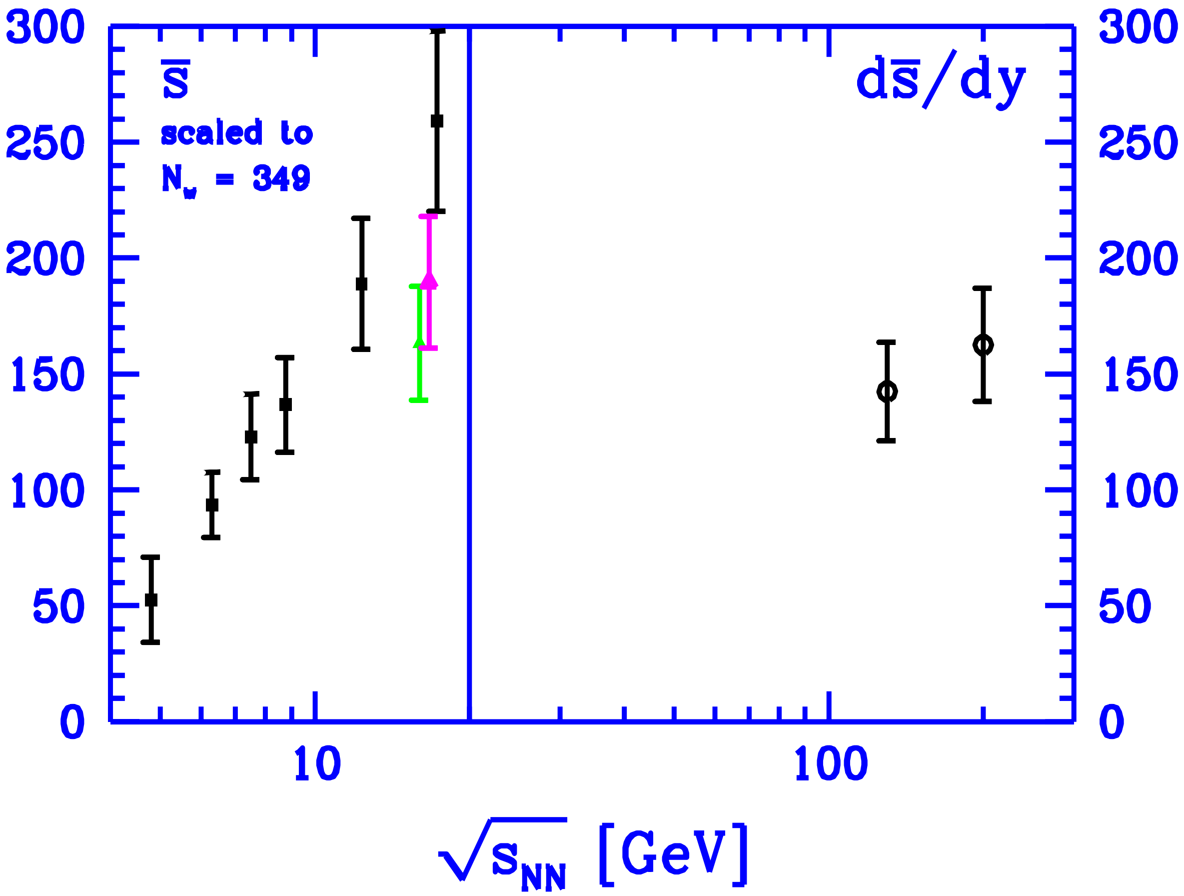
$$\Xi(qss),\ \overline{\Xi}(\bar{q}\bar{s}\bar{s}),\ \Omega(sss),\ \overline{\Omega}(\bar{s}\bar{s}\bar{s})\ \ldots\textbf{more resonances}\ldots$$

- **Strange hadrons are subject to a self analyzing decay within a few cm from the point of production;**



- **Production rates hence statistical significance is high; (strong interaction reaction cross sections)**

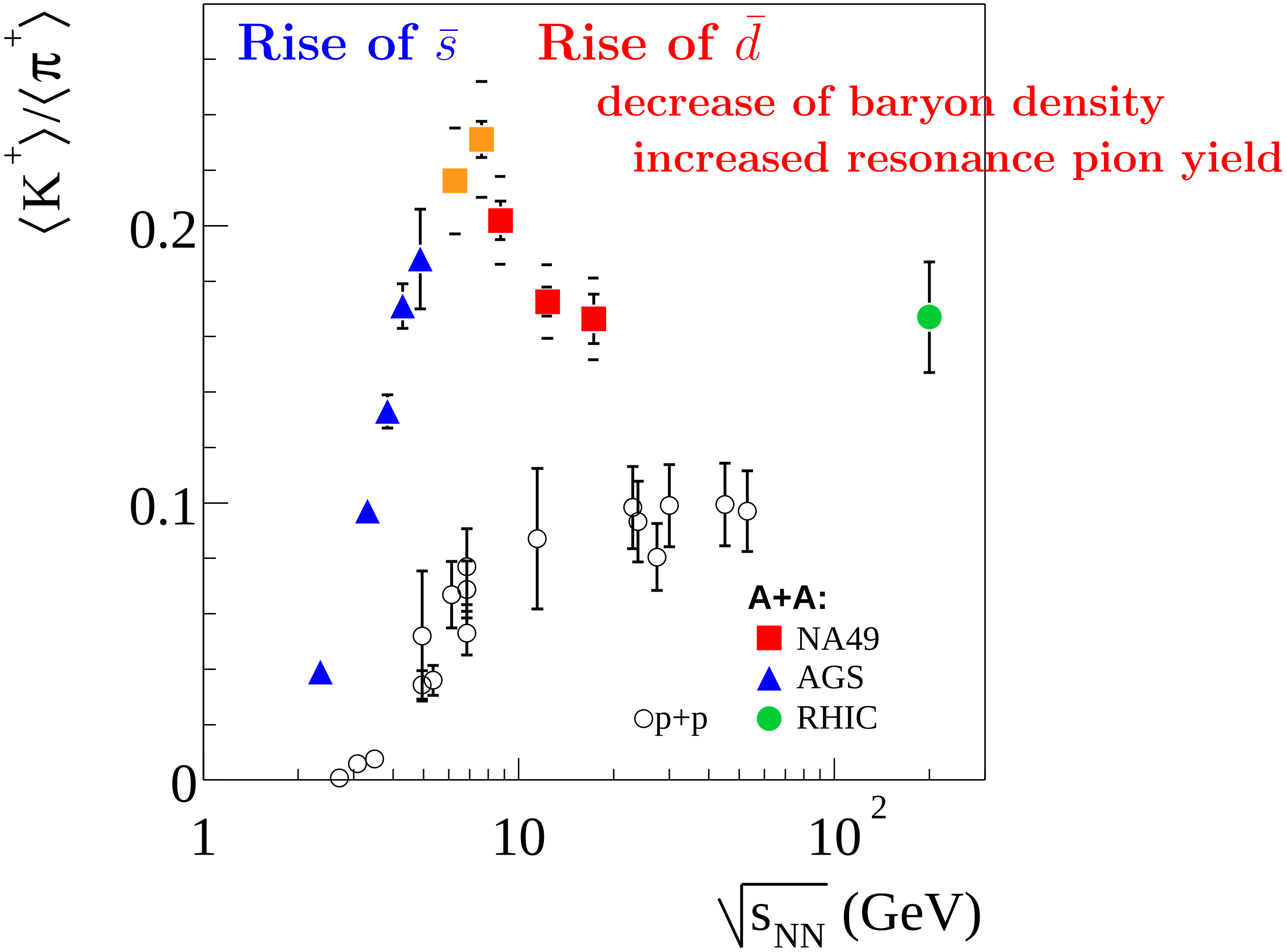
STRANGENESS EXCITATION FUNCTION



Green: C–C and Violet: Si–Si, other Au–Au, Pb–Pb Count $\bar{s}$ quarks in all hadrons. At low energy practically $2K^+$.

No change in reaction mechanism visible, neither as function of energy, nor reaction volume, in this simple yield observable

More SPECTACULAR: NA49 horn in final state $\bar{s}/\bar{d}$



Rise of $\bar{s}$

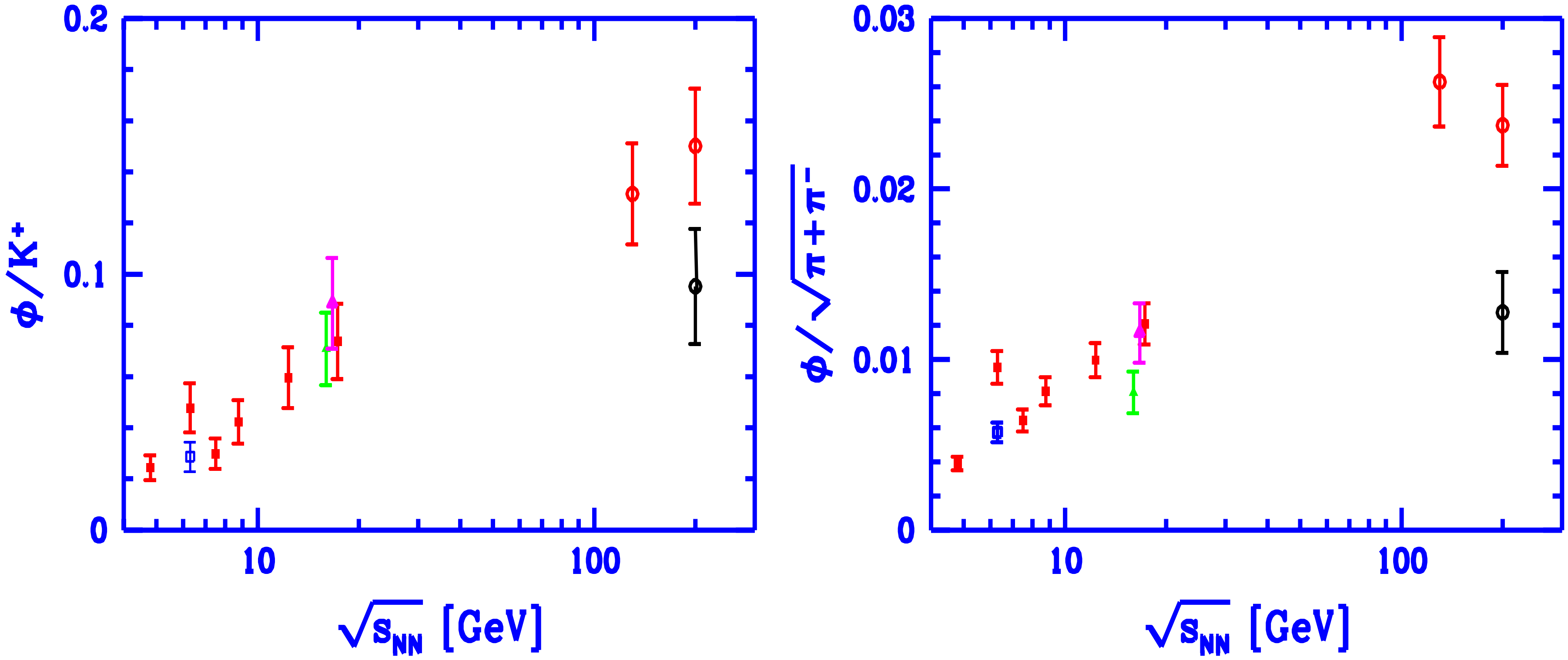
Rise of $\bar{d}$

decrease of baryon density

increased resonance pion yield

The 'Gaździcki-horn' is result of two effects: left side of peak, strangeness approach to saturation and a right hand of peak, reduction of baryon density which allows growth of $\bar{d}$. Statistical Hadronization Model (SHM) with chemical nonequilibrium allows to understand how such a rapid change occurs. A spectacular change in physics will be demonstrated.

A more difficult ϕ observable



Issues:

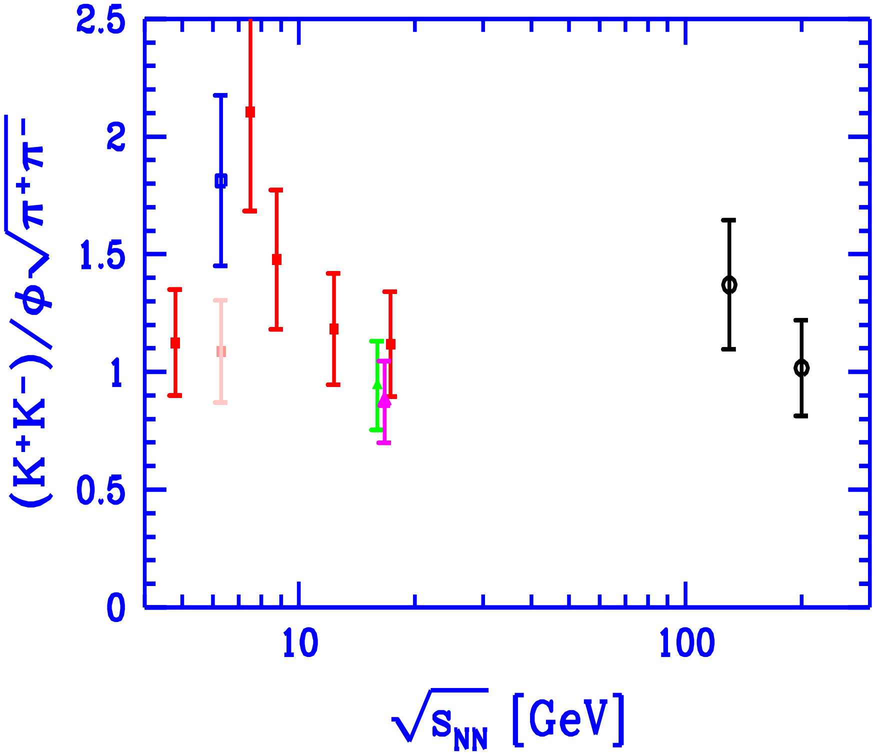
1) The SPS 20GeV ϕ-yield is out of systematics, requires factor 0.6,

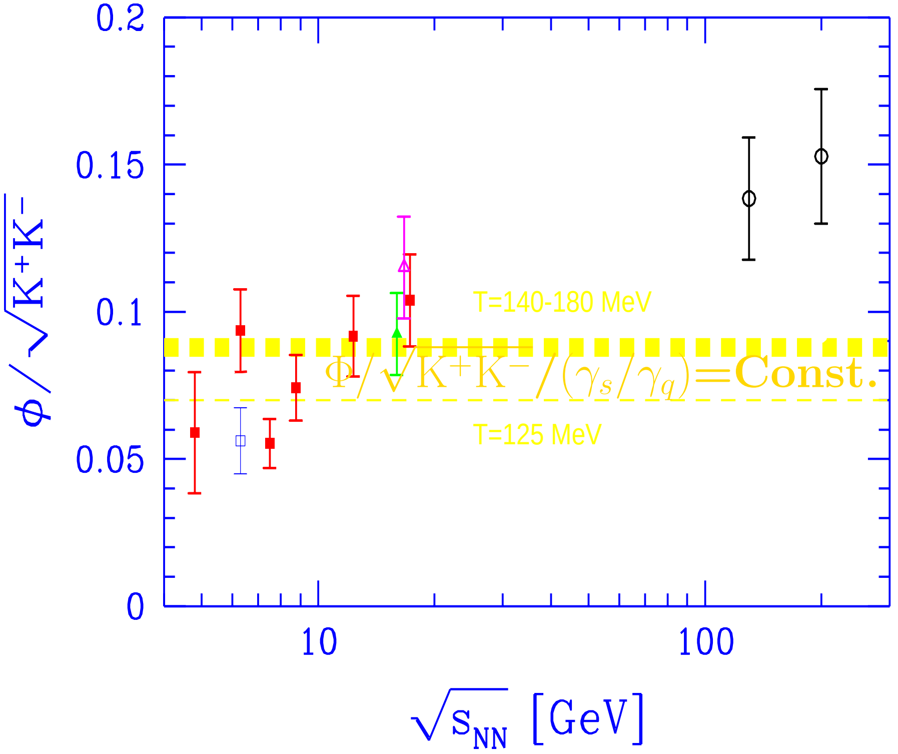
2) at RHIC the reconciliation between STAR (red) and PHENIX (black) will decide if relative ϕ yield saturates or increases.

3) The small Si–Si system shows same behavior as Pb–Pb.

There is a ϕ peak even after we eliminate baryon density effects

The ‘horn’ is real, reappears in another observable

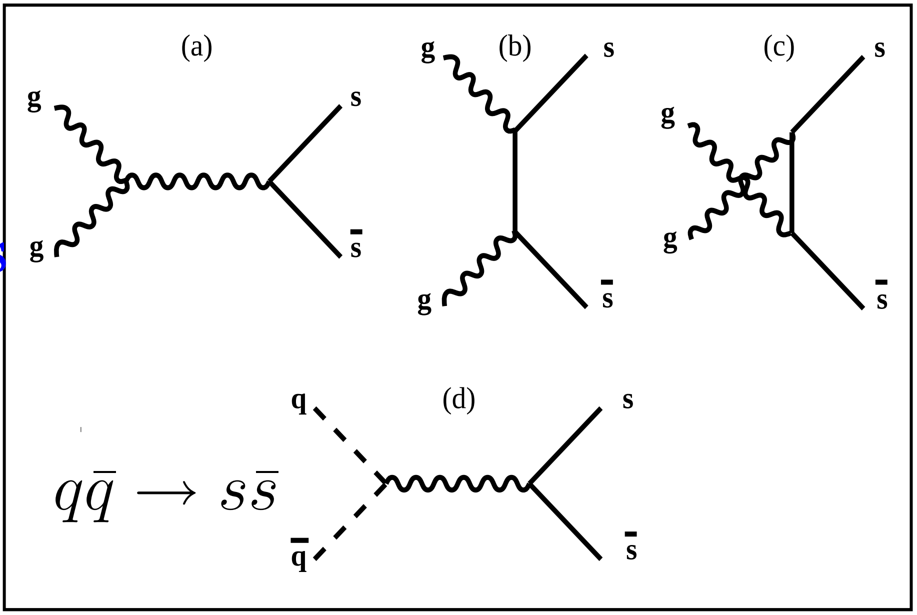




The combination of $\mathrm{K^+K^-}$, $\pi^+\pi^-$ **limits baryon density effects: this is a strangeness, strangeness coalescence and entropy peak. As shown on right, the relative yield** $\phi/\sqrt{\mathrm{K^-K^+}}$ **rises with energy. In Stat. Had. Model.** $\Phi/\sqrt{\mathrm{K^+K^-}} \simeq \mathrm{Const.}\gamma_s/\gamma_q$**: Ratio directly measures** γ_s/γ_q

WHY s: THEORETICAL CONSIDERATIONS

- **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:**

$$\boxed{m_s \simeq T_c} \rightarrow \boxed{\tau_s \simeq \tau_{\rm QGP}} \rightarrow$$

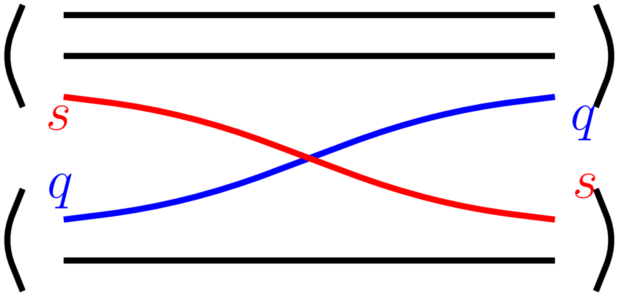
strangeness a clock for QGP phase

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

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

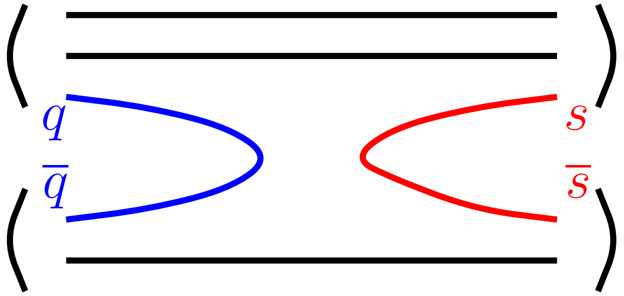
γ_i controls overall abundance of quark $(i = q, s)$ pairs	Absolute chemical equilibrium
λ_i (μ_B, μ_S) controls difference between strange and non-strange quarks $(i = q, s)$	Relative chemical equilibrium

HG-EXAMPLE: redistribution,
Relative chemical equilibrium



EXCHANGE REACTION
λ_i

production of strangeness
Absolute chemical equilibrium



PAIR PRODUCTION REACTION
γ_i

STATISTICAL MODEL STRANGENESS YIELD IN QGP

$$\frac{\rho_{\rm s}}{\rho_{\rm b}}=\frac{s}{q/3}=\frac{\gamma_{\rm s}^{\rm QGP}\ \frac{3}{\pi^2}T^3(m_{\rm s}/T)^2K_2(m_{\rm s}/T)}{\gamma_{\rm q}^{\rm QGP}\ \frac{2}{3}\left(\mu_{\rm q}T^2+\mu_{\rm q}^3/\pi^2\right)}\,,\rightarrow\ \frac{s}{b}\simeq\frac{\gamma_{\rm s}^{\rm QGP}}{\gamma_{\rm q}^{\rm QGP}}\ \frac{0.7}{\ln\lambda_{\rm q}+(\ln\lambda_{\rm q})^3/\pi^2}\,.$$

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

We consider $m_{\rm s}=200$ MeV and hadronization $T=150$ MeV,

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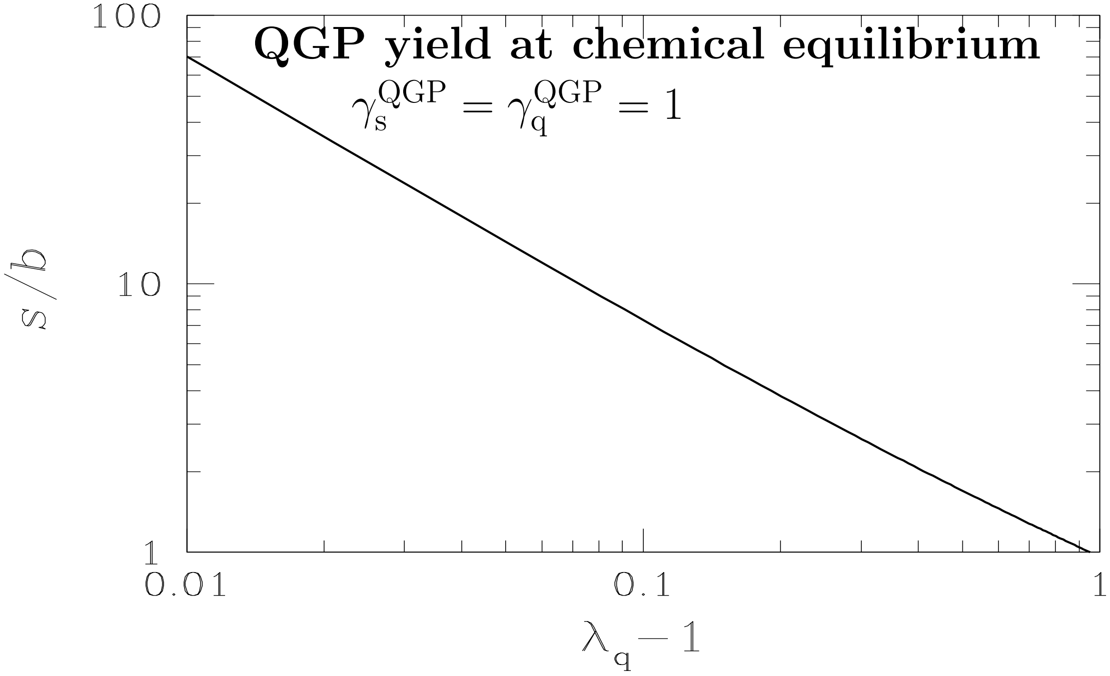
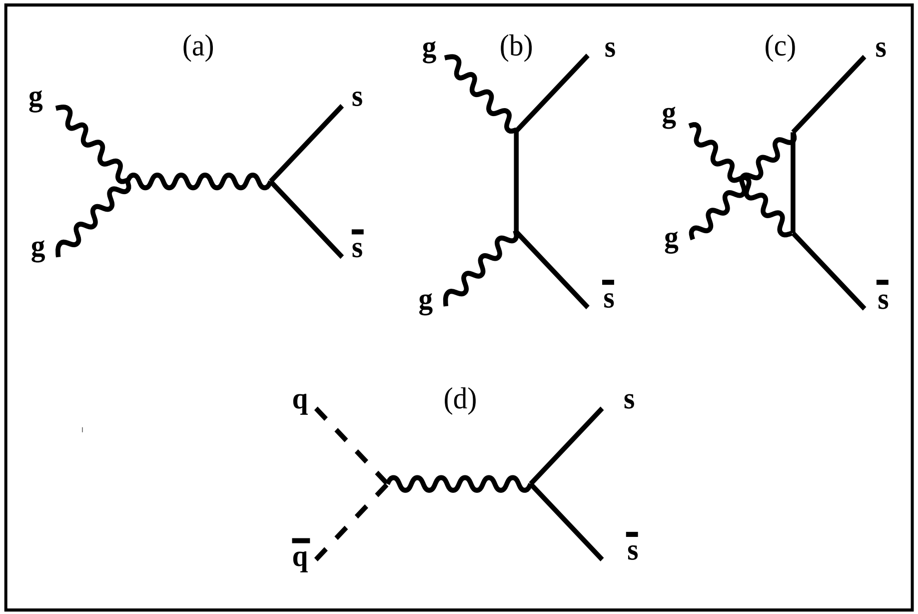


At SPS, λ_q=1.5–1.6, thus $s/b\simeq1.5$ in equilibrium; for $s/b\simeq0.75\rightarrow\gamma_{\rm s}^{\rm QGP}/\gamma_{\rm q}^{\rm QGP}=0.5$

At central RHIC-200 we have $\lambda_q\simeq1.06$

Comparison with the actual $s/b=9.6\pm1$ yields $\gamma_{\rm s}^{\rm QGP}/\gamma_{\rm q}^{\rm QGP}$=0.8.

Kinetic description of strangeness production



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:

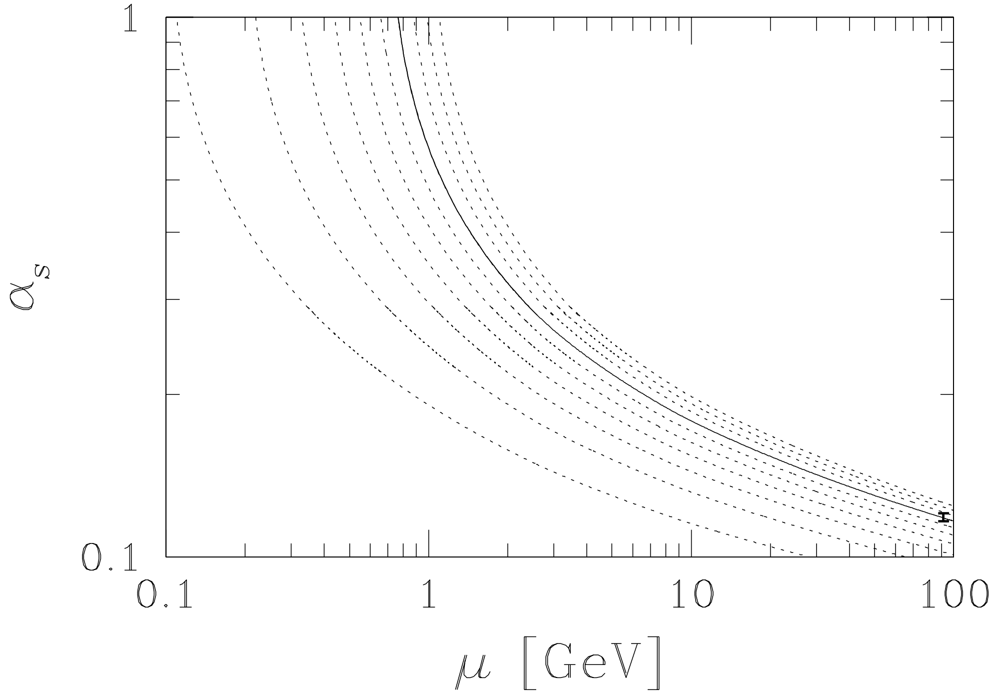
$$\bar{\sigma}_{gg\to s\bar{s}}(s)=\frac{2\pi\alpha_{\rm s}^2}{3s}\left[\left(1+\frac{4m_{\rm s}^2}{s}+\frac{m_{\rm s}^4}{s^2}\right)\tanh^{-1}W(s)-\left(\frac{7}{8}+\frac{31m_{\rm s}^2}{8s}\right)W(s)\right],$$

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

Infinite QCD re-summation: running $\alpha_{\rm s}$ and $m_{\rm s}$ taken at the energy scale $\mu\equiv\sqrt{s}$.
USED: $m_s(M_Z)=90\pm20\%$ MeV $m_s(1\textbf{GeV})\simeq 2.1m_s(M_Z)\simeq 200$**MeV.**

WHY PERTURBATIVE STRANGENESS WORKS

An essential pre-requirement for the perturbative theory of strangeness production in QGP, is the relatively small experimental value $\alpha_s(M_Z) \simeq 0.118$, which has been experimentally established in recent years.



$\alpha_s^{(4)}(\mu)$ as function of energy scale μ for a variety of initial conditions. Solid line: $\alpha_s(M_Z) = 0.1182$ (experimental point, includes the error bar at $\mu = M_Z$).

At the scale of just above 1 GeV where typically thermal strangeness production in RHIC QGP occurs, perturbative theory makes good sense but is not completely reliable. Had $\alpha_s(M_Z) > 0.125$ been measured 1996 than our approach from 1982 would have been invalid.

Thermal average of (strangeness p[production) reaction rates

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

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

Invariant reaction rate in medium:

$$A^{gg\to s\bar{s}} = \frac{1}{2}\rho_g^2(t)\,\langle \sigma v\rangle_T^{gg\to s\bar{s}}\,, \quad A^{q\bar{q}\to s\bar{s}} = \rho_q(t)\rho_{\bar{q}}(t)\langle \sigma v\rangle_T^{q\bar{q}\to s\bar{s}}\,, \quad A^{s\bar{s}\to gg,q\bar{q}} = \rho_s(t)\,\rho_{\bar{s}}(t)\,\langle \sigma v\rangle_T^{s\bar{s}\to gg,q\bar{q}}.$$

$1/(1+\delta_{1,2})$ **introduced for two gluon processescompensates the double-counting of identical particle pairs, arising since we are summing independently both reacting particles.**

This rate enters the momentum-integrated Boltzmann equation which can be written in form of current conservation with a source term

$$\partial_\mu j_s^\mu \equiv \frac{\partial \rho_s}{\partial t} + \frac{\partial \vec{v} \rho_s}{\partial \vec{x}} = A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} - A^{s\bar{s}\to gg,q\bar{q}}$$

Strangeness density time evolution

in local restframe ($\vec{v}$) we have :

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

Evolution for s and $\bar{s}$ identical, which allows to set $\rho_s(t)=\rho_{\bar{s}}(t)$.
Use detailed balance to simplify

$$\frac{d\rho_s}{dt} = A\left(1 - \frac{\rho_s^2(t)}{\rho_s^2(\infty)}\right), \qquad A = A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}}$$

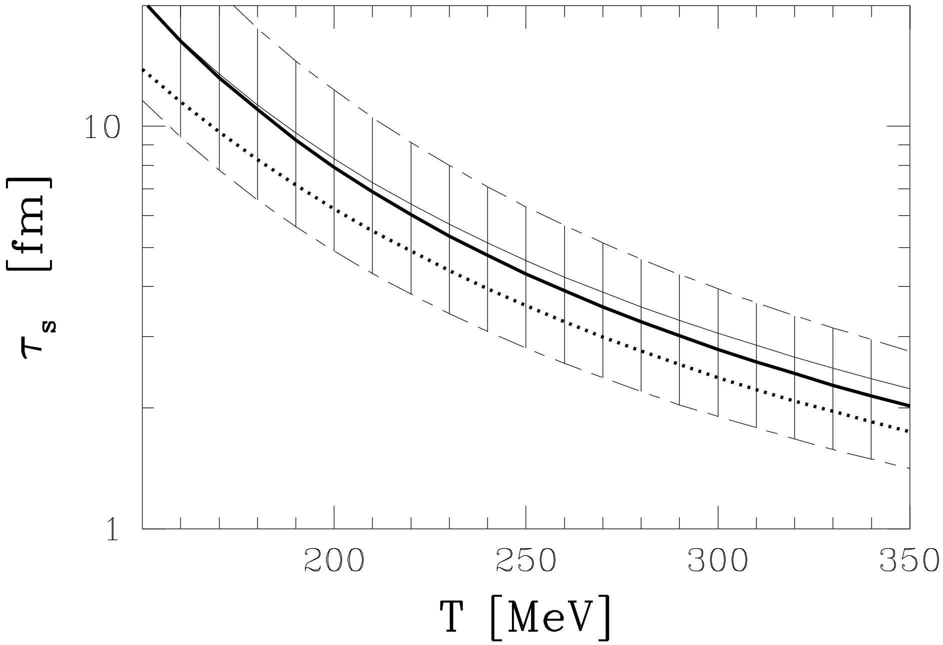
The generic solution at fixed T ($\rho \propto \tanh$) implies that in all general cases there is an exponential approach to chemical equilibrium

$$\frac{\rho_s(t)}{\rho_s^\infty} \longrightarrow 1 - e^{-t/\tau_s}$$

with the characteristic time constant τ_s:

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

Characteristic time constant and γ_s-evolution



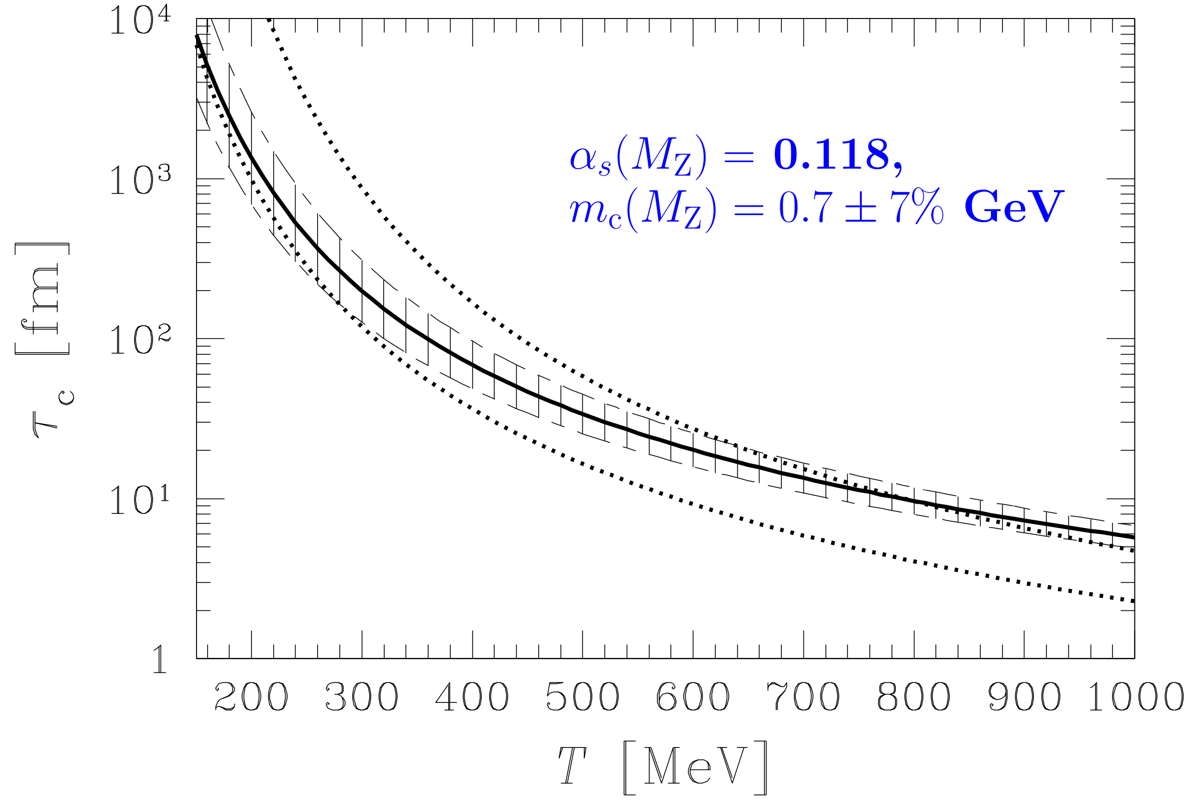
$\sigma_{\rm QCD}^{\to s\bar s}$ **gives τ_s similar to lifespan of the plasma phase!**
Strange quark pair production dominated by gluon fusion: $G+G\to s\bar s$, also some (10%) $q\bar q\to s\bar s$, present; this is due to gluon collision rate.
ENTROPY CONSERVING expansion i.e. at SPS T^3V =Const. (not yet long. scaling):

$$2\tau_s\frac{dT}{dt}\left(\frac{d\gamma_s}{dT}+\frac{\gamma_s}{T}z\frac{K_1(z)}{K_2(z)}\right)=1-{\gamma_s}^2\,,\qquad \gamma_s(t)\equiv n_s(t)/n_s^\infty\,,\qquad z=\frac{m_s}{T}\,,\qquad K_i:\mathrm{Besself.}$$

Once γ_s known, $\langle\rho_s(t)\rangle=\langle\bar\rho_s(t)\rangle=\int dx^3\rho_s^\infty(T(t,x))\gamma_s(T(t,x),\dot T(t,x))$;
evolution till $t\to t_f$,but effectively production stops for $T<180$ MeV.

What about charm? $m_s \to m_c$

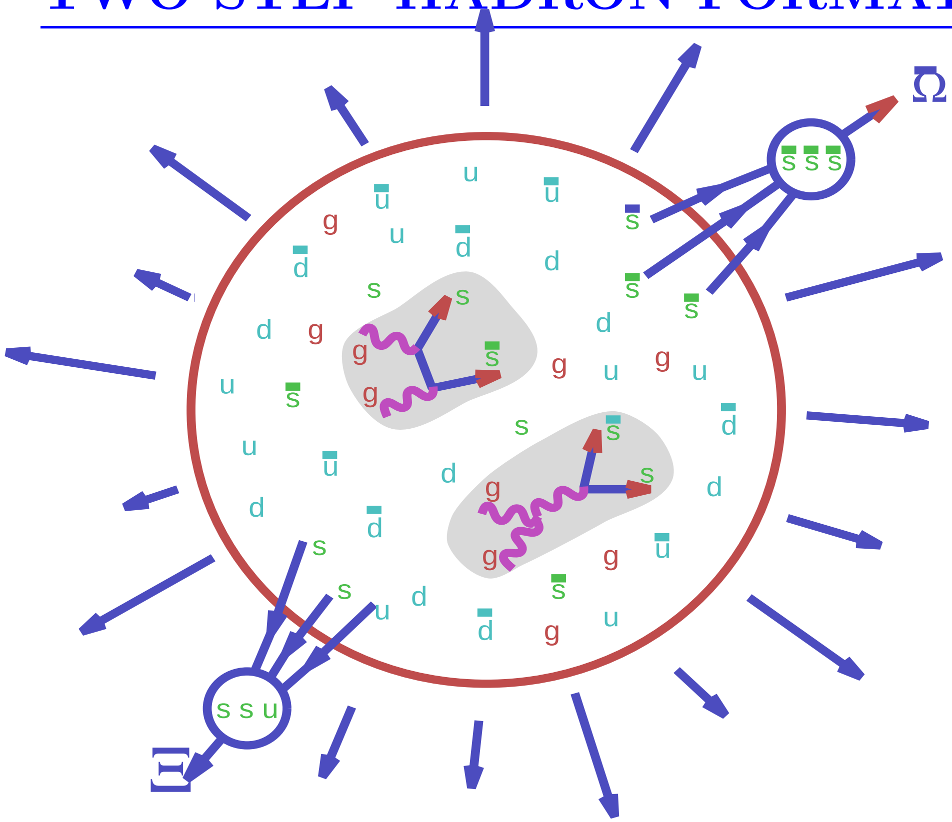
We expect that thermal charm production is of relevance only for $T \to m_c(1\,\mathbf{GeV}) \simeq 1.5\,\mathbf{GeV}$, probably not accessible.



Lower dotted line: for fixed $m_c = 0.9\,\mathbf{GeV}$, $\alpha_s = 0.35$;
upper doted line: for fixed $m_c = 1.5\,\mathbf{GeV}$, $\alpha_s = 0.4$.
Equilibrium density for $\rho_c^\infty(m_c \simeq 1.5\,\mathbf{GeV})$.

Charm is produced relatively abundantly in first parton collisions. Benchmark: 10 $c\bar{c}$ pairs in central Au–Au at RHIC-200. This yield is greater than the expected thermal equilibrium yield at hadronization of QGP. Charmonium enhancement by recombination.

TWO STEP HADRON FORMATION MECHANISM IN QGP



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. hadronization of pre-formed

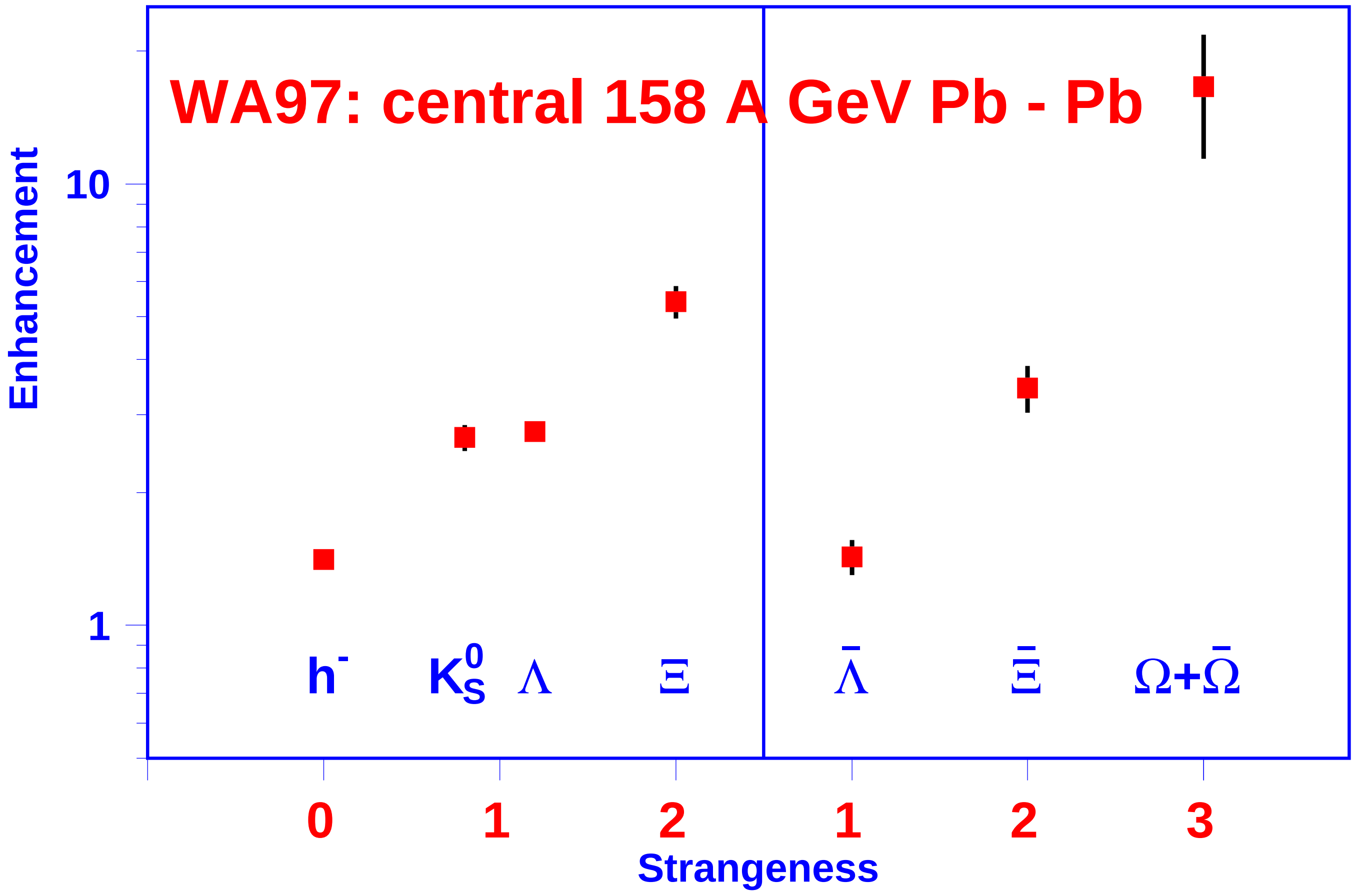
   s, $\bar{s}$, c, $\bar{c}$, b, $\bar{b}$ quarks

Formation of complex rarely produced (multi)exotic flavor (anti)particles from QGP 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. Enhancement of flavored (strange, charm,...) antibaryons progressing with 'exotic' flavor content.

Available results (SPS, RHIC):

Enhancement of strange (anti)baryons progresses with strangeness content.

(MULTI)STRANGE (ANTI)HYPERON ENHANCEMENT

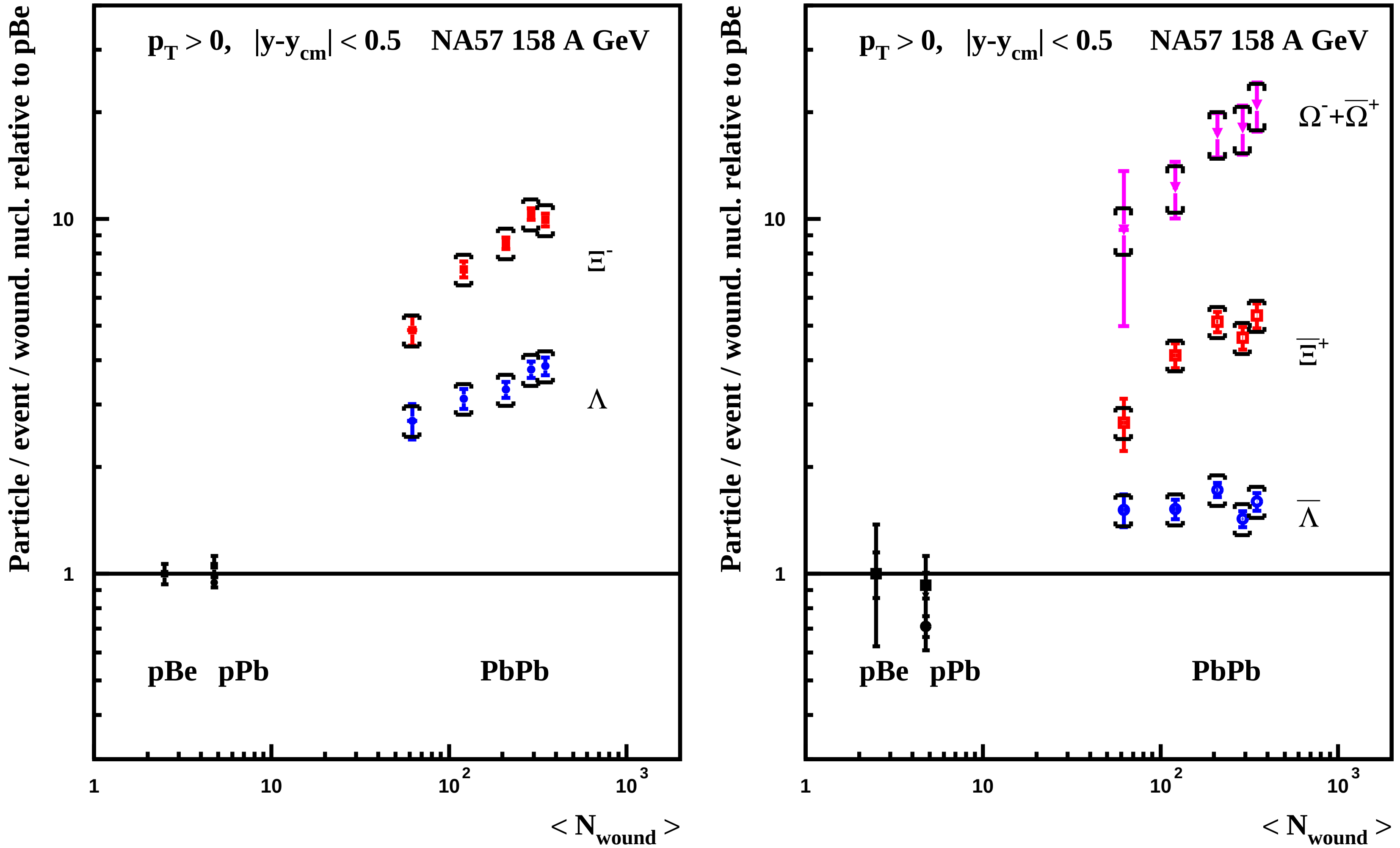


Enhancement GROWTH with

strangeness antiquark content.

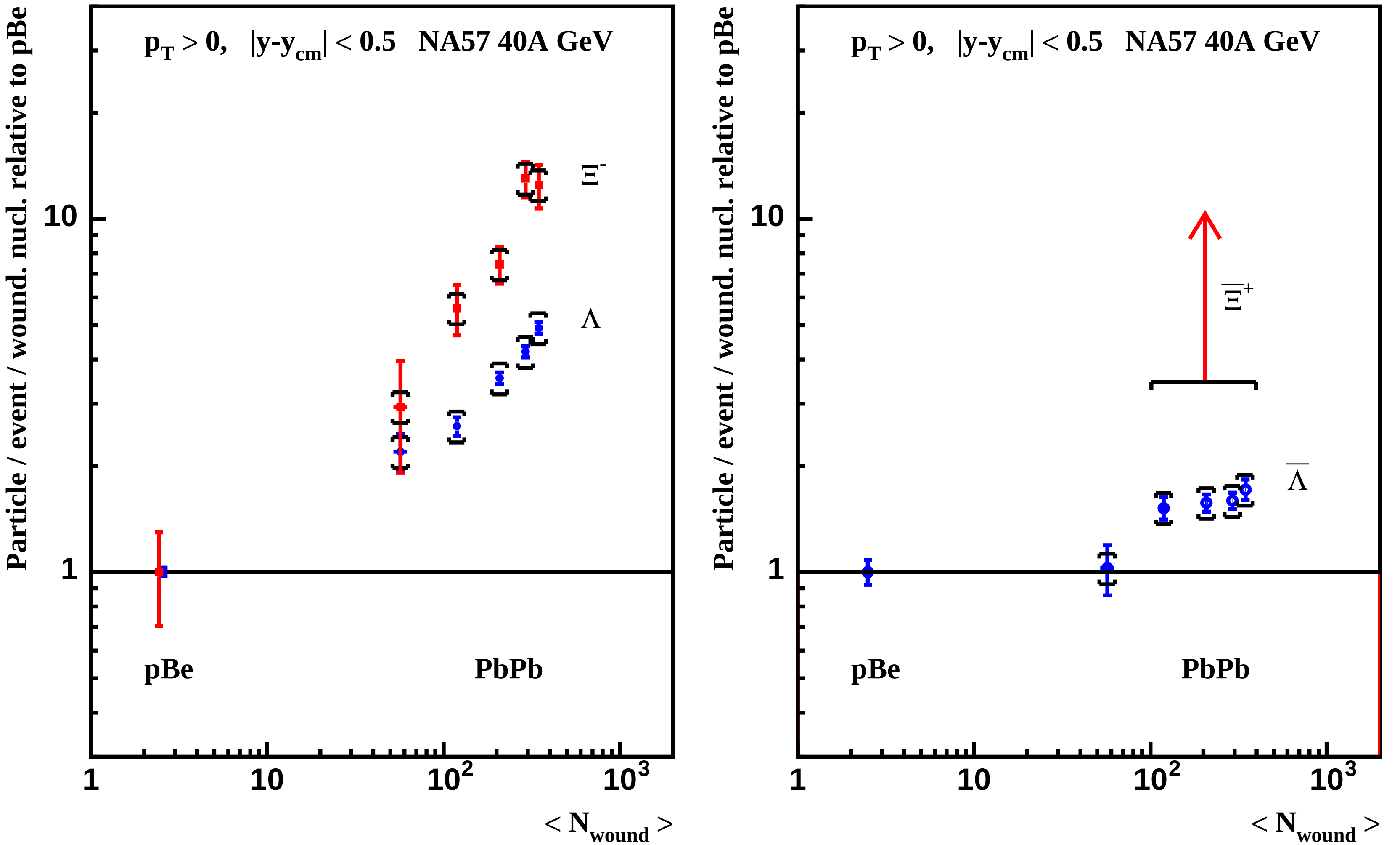
Enhancement is here defined with respect to the yield in p–Be collisions, scaled up with the number of collision 'wounded' nucleons.

ENHANCEMENT AS FUNCTION OF REACTION VOLUME



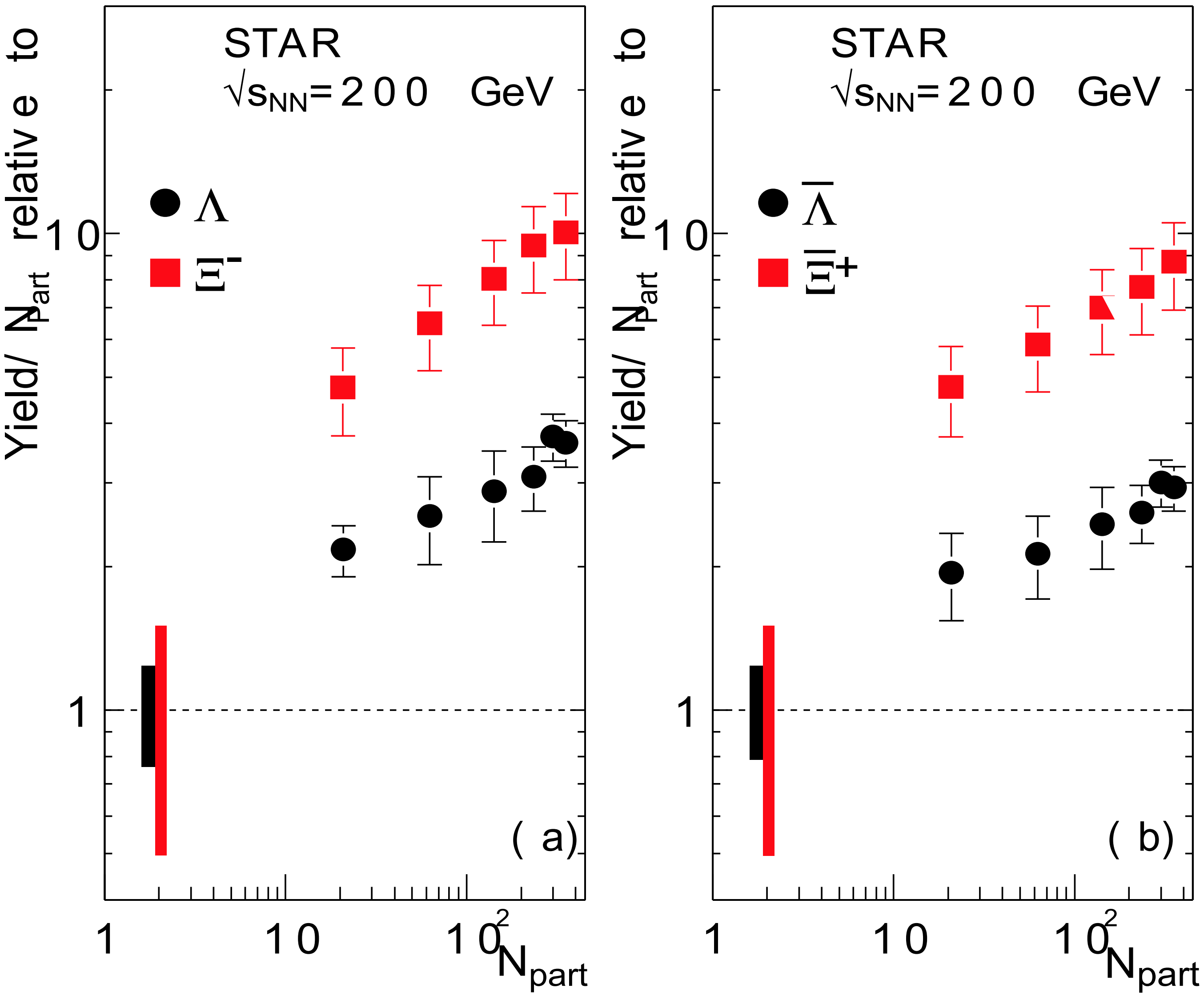
The gradual onset of enhancement with reaction volume predicted within kinetic strangeness production models, see e.g. Phys.Lett.B389:586-594,1996, also in Acta Physica Polonica Review p1116 Fig 37. "Canonical enhancement" (an equilibrium model) predicts wrong A and $\sqrt{s}$ dependence

ENHANCEMENT at low SPS Energy



At 40A GeV we still see a strong volume dependent hyperon enhancement, in agreement with expectations for deconfined state formation.

RHIC (ANTI)HYPERON ENHANCEMENT



RHIC-STAR 200 GeV enhancement

REACTION MECHANISM OF PARTICLE PRODUCTION

several experiments since 1991 demonstrated symmetry of $m_\perp$ spectra of strange baryons and antibaryons in baryon rich environment, also observed at RHIC.

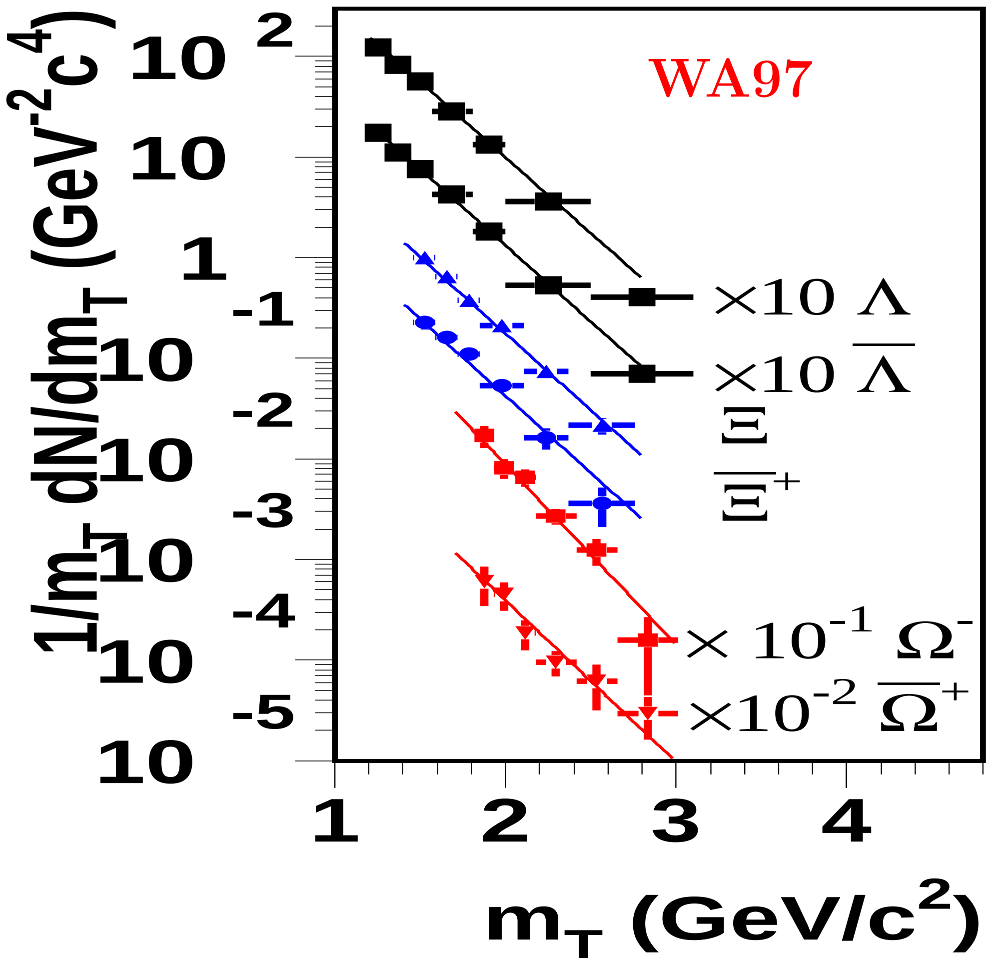
Interpretation:

1. **Common matter-antimatter particle formation mechanism,**
2. **No reannihilation in sequel evolution: free streaming hadrons.**

Appears to be direct final state hadron emission by a quark source.
Fast hadronization confirmed by abundant yield of hadron resonances at RHIC and HBT particle correlation analysis: same size pion source at all energies

High $m_\perp$ slope universality

WA97	$T_\perp^{\rm Pb}$ [MeV]
$T^{\rm K^0}$	**230 ± 2**
T^{Λ}	**289 ± 3**
$T^{\overline{\Lambda}}$	**287 ± 4**
T^{Ξ}	**286 ± 9**
$T^{\overline{\Xi}}$	**284 ± 17**
$T^{\Omega+\overline{\Omega}}$	**251 ± 19**



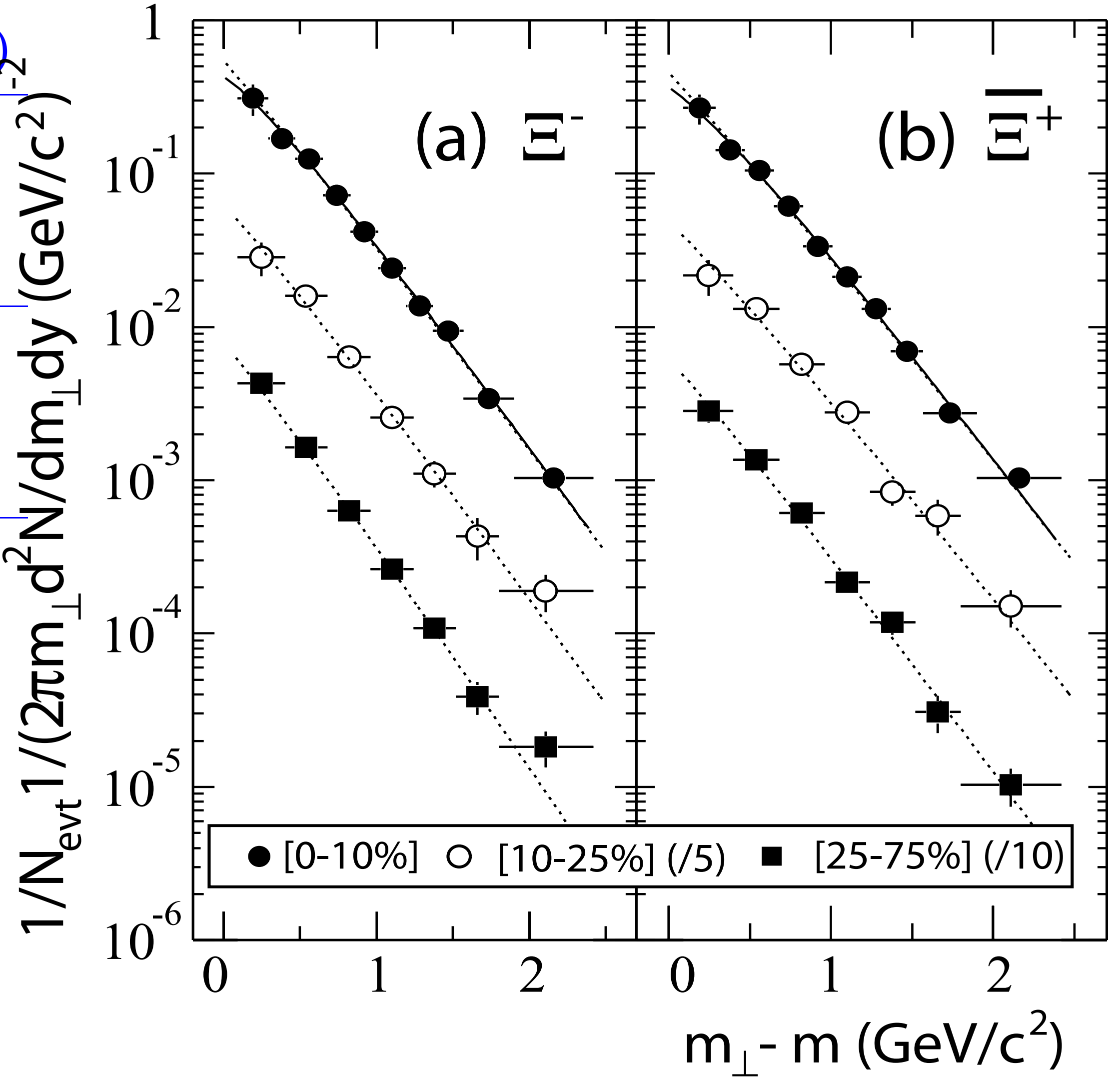
Λ within 1% of $\overline{\Lambda}$

Kaon – hyperon difference: collective FLOW effect.

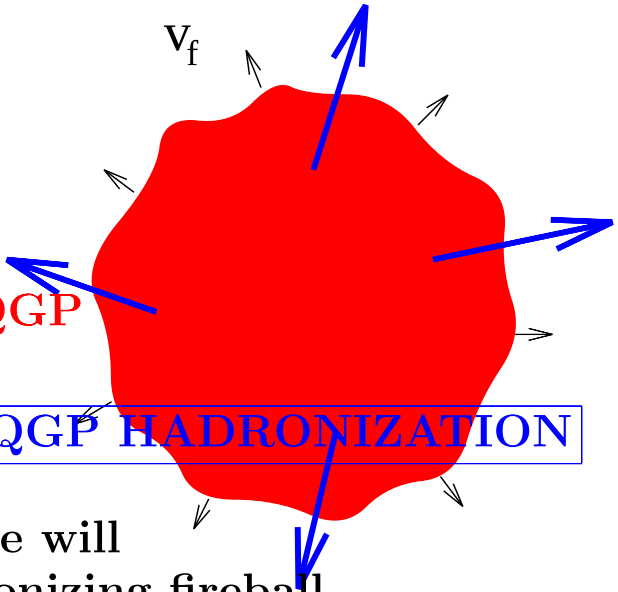
$\Xi^-, \overline{\Xi^-}$ Spectra RHIC-STAR 130+130 A GeV

h^-		$T_{\rm E}$(MeV)	$T_{\rm B}$(MeV)
260.3±7.5	Ξ^-	**338±6**	**296±5**
	$\bar{\Xi}^+$	**339±7**	**297±5**
163.6±5.2	Ξ^-	**335±16**	**291±13**
	$\bar{\Xi}^+$	**349±17**	**302±13**
42.5±3.0	Ξ^-	**312±12**	**273±10**
	$\bar{\Xi}^+$	**320±11**	**280±9**

STAR Collaboration
PRL92 (2004) 182301



REACTION MECHANISM OF PARTICLE PRODUCTION



CONCLUSION

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

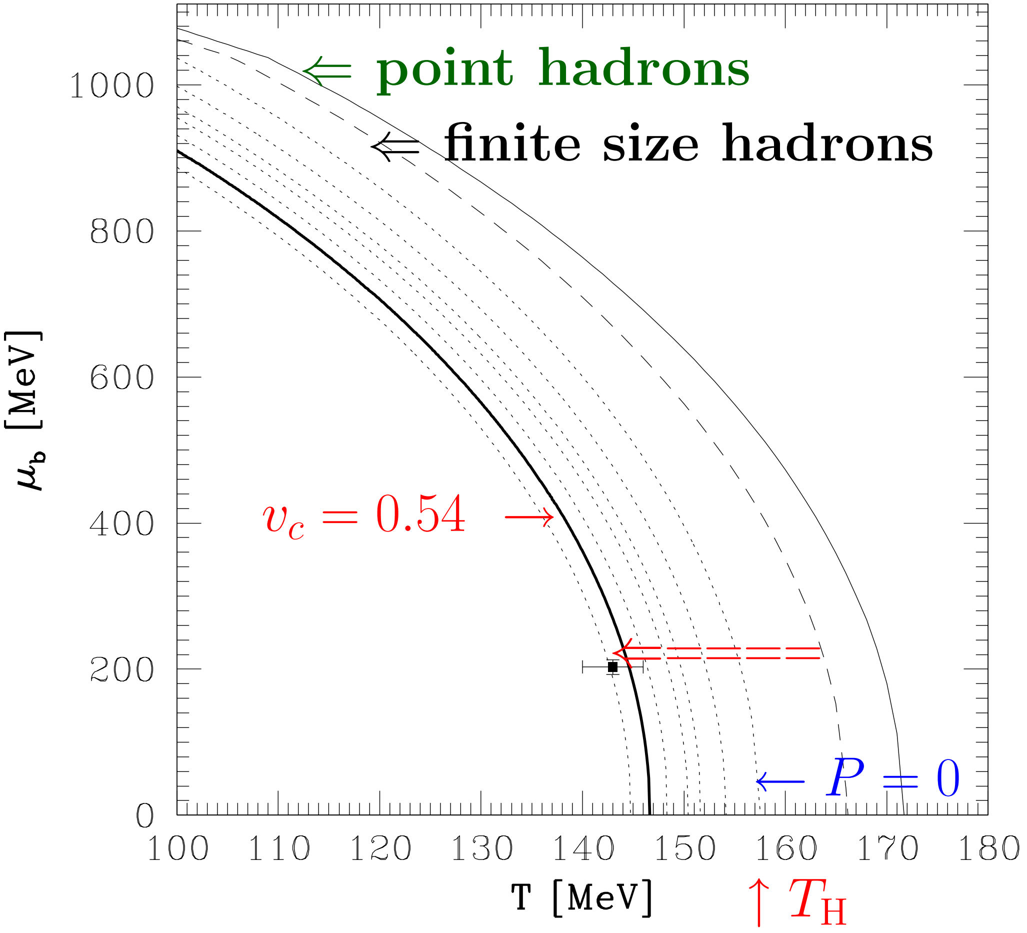
Develop analysis tools viable in SUDDEN QGP HADRONIZATION

This means that study of hadronic particle will
a) allow to understand properties of hadronizing fireball
b) consideration of (semi)conserved quantities (baryon number, entropy) allow us to look deeper into the early history of the fireball.

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

Fast expansion of the fireball will lead to super cooling which in turn helps us understand the sudden nature of the fireball breakup.
NEXT: see magnitude of supercooling.
Than turn to understanding of the data using Statistical Hadronization Model: will talk about resonances and a bit more on quark chemistry, and SHARE model, before showing some results.

Phase boundary and ‘wind’ of flow of matter



Solid: point hadrons T_p

Dashed: finite size

Dotted: $T_c(\mu_{\rm b})|_{P_{eff}-\mathcal{B}=0}$ **for** $v^2 = 0, 1/10, 1/6, 1/5, 1/4, 1/3$**.**

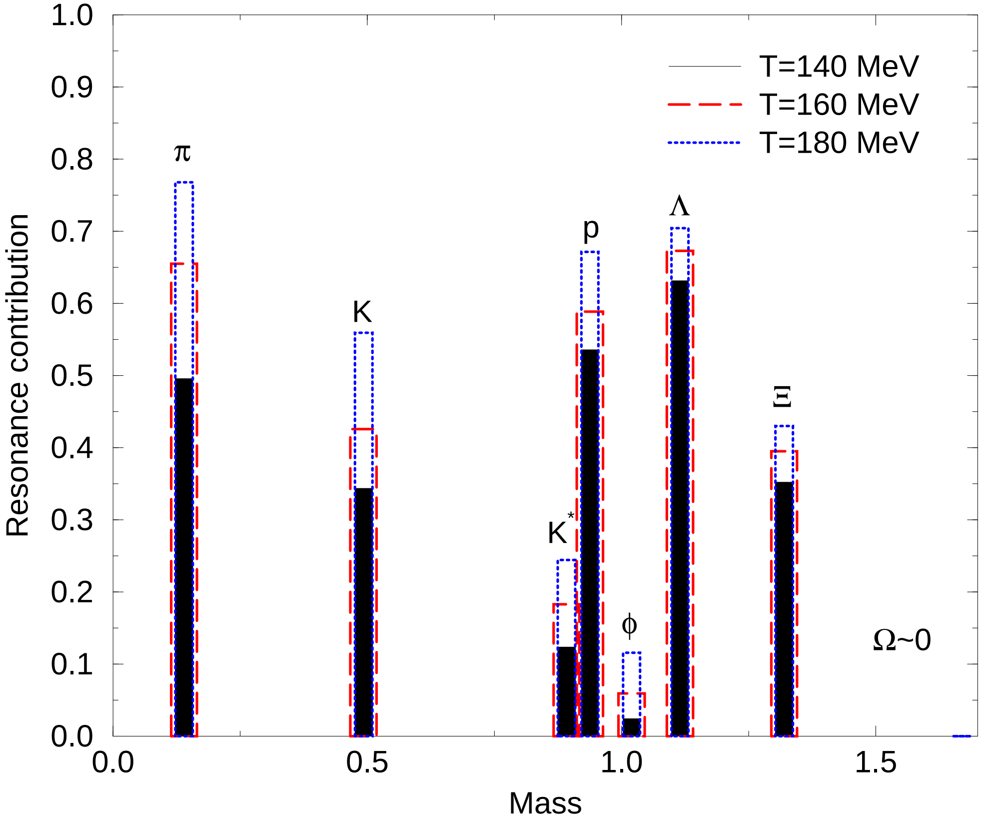
Thick solid: breakup with $v = 0.54$ **(**$\kappa = 0.6$**)**
PRL 85 (2000) 4695

DEEP 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 is at $\simeq 166$**.**

STATISTICAL HADRONIZATION AND RESONANCES

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.

OBSERVABLE RESONANCE YIELDS

Invariant mass method: construct invariant mass from decay products:

$$M^2 = \left(\sqrt{m_a^2+\vec{p}_a^{\,2}}+\sqrt{m_b^2+\vec{p}_b^{\,2}}+\ldots\right)^2-(\vec{p}_a+\vec{p}_b+\ldots)^2$$

If one of decay products rescatter the reconstruction not assured.

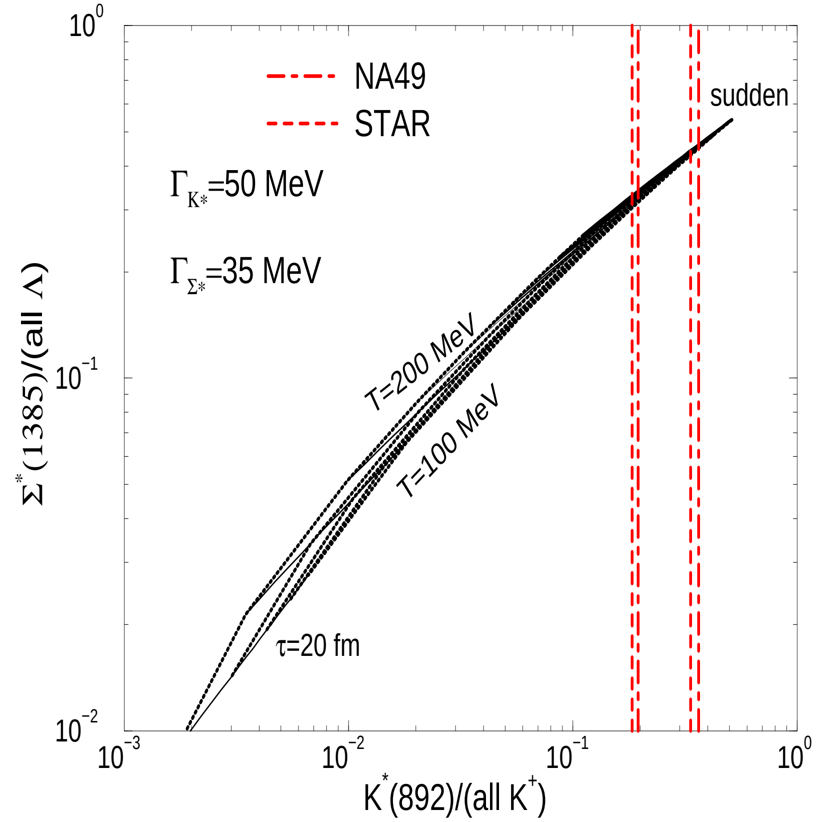
Strongly interacting matter essentially non-transparent. Simplest model: If resonance decays $N^*\to D+\ldots$ within matter, resonance can disappear from view. Model implementation:

$$\frac{dN^*}{dt}=-\Gamma N^*+R,\qquad \frac{dD}{dt}=\Gamma N^*,\qquad \frac{dN^*_{\rm rec}}{dt}=\Gamma N^*-D\sum_j\langle\sigma_{Dj}v_{Dj}\rangle\rho_j(t)$$

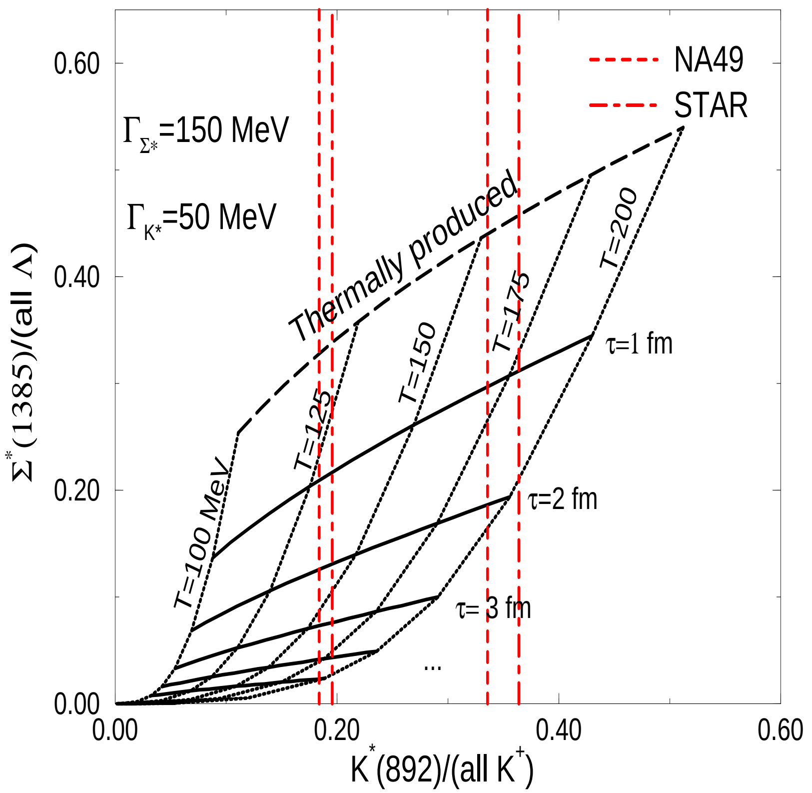
To obtain the observable resonance yield $N^*_{\rm rec}$ we integrate to the time $t=\tau$ spend by N^* in the opaque matter, and add the remainder from free space decay. Regeneration term $R\propto\langle\sigma_{Di}^{INEL}v_{Di}\rangle\rho_i$ negligible since production reactions very much weaker than total scattering.Hadronic matter acts as black cloud, practically all in matter decays cannot be reconstructed.

TWO resonance ratios combined

natural widths



spread $\Gamma_{\Sigma^*} = 150$ MeV



Dependence of the combined Σ^*/(all Λ) with $K^*(892)$/(all K) signals on the chemical freeze-out temperature and HG phase lifetime.

Even the first rough measurement of K^*/K indicates that there is no long lived hadron phase. In matter widening makes this conclusion stronger.
Await forthcoming STAR Σ^* yields.

Resonances are difficult

Measurement of hadronic resonances is very difficult. Preliminary results are often not final. Consider STAR at QM2004:

$$\frac{\Delta^{++}}{p+\mathrm{Resonances}+\mathrm{Br}\Lambda+\mathrm{Br}\Sigma+\mathrm{Br}\Xi}=0.24\pm0.06$$

Stripping the weak decay contributions this means

$$\frac{\Delta^{++}}{p+\mathrm{Resonances}}\simeq 0.5$$

Now we recall that there are $\Delta^{++},\Delta^{+},\Delta^{0},\Delta^{-}$ but only two nucleons.

$$\frac{\Delta^{++}+\Delta^{+}+\Delta^{0}+\Delta^{-}}{p+n+\mathrm{Resonances}}\simeq 1$$

This means that all nucleons are descendants of Δ, so no direct production of nucleons, no other resonances... CAN HIS BE TRUE?

In my opinion: The final value will be 2–3s.d. smaller

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.

Particle yields in chemical (non)equilibrium

The counting of hadrons is conveniently done by counting the valence quark content $(u, d, s, \ldots)$, and it leads to characterization of HG equivalent to QGP phase. There is a natural relation of quark fugacities with hadron fugacities, for particle 'i'

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

but for one complication: for historical reasons hyperon number is opposite to strangeness, thus $\mu_S = \frac{\mu_b}{3} - \mu_s$, where $\lambda_q^3 = e^{\mu_b/T}, \lambda_q^2 = \lambda_u \lambda_d$.

Example of NUCLEONS:

two particles $N, \overline{N}$ → two chemical factors, with $\lambda_q^3 = e^{\mu_b/T}, \gamma_N = \gamma_q^3$;

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

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

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

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

The (baryo)chemical potential μ_b controls the particle difference = baryon number. γ regulates the number of particle-antiparticle pairs present.

Some issues in description of hadron yields

1. **FAST phase transformation implies chemical nonequilibrium, see 'Gaździcki 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 not only for yields but also most important for** **please note: spectra.**
3. **OPTION: Production weight with width of the resonances accounts for experimental reaction rates**

Full analysis of experimental results requires a significant numerical effort. Shortcut projects produce results which alter physical conclusions. **For this reason the 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. Online SHARE: Steve Steinke

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

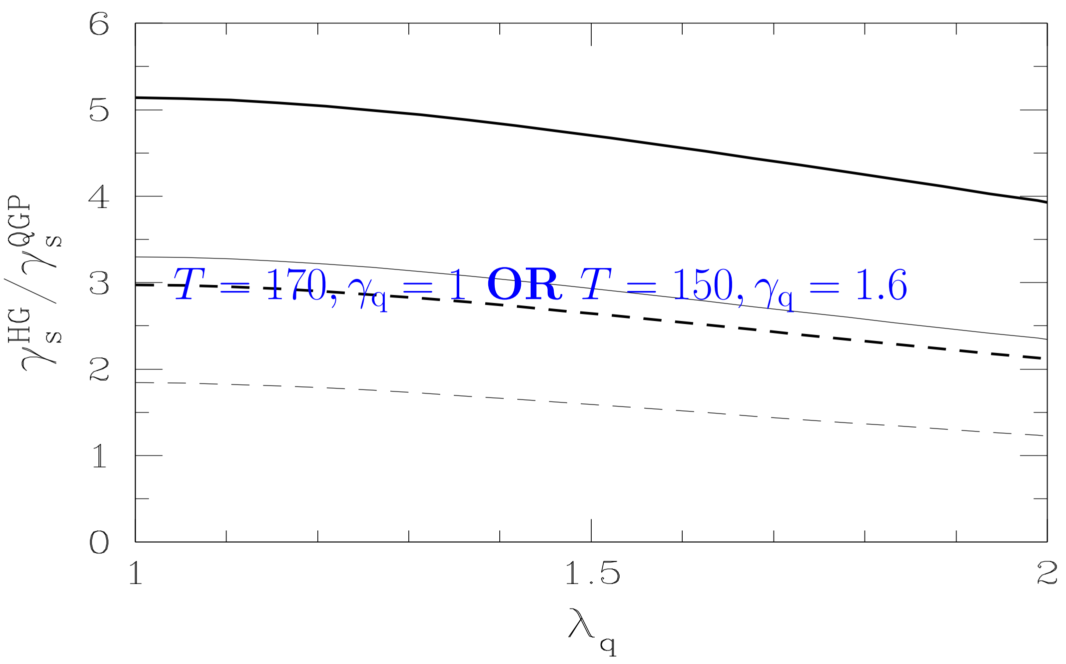
Aside of particle yields, also PHYSICAL PROPERTIES of the source are available, both in SHARE and ONLINE. No fitting online (server too small), just check your program.

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

COMPUTE EXPECTED RATIO OF $\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$

In sudden hadronization, $V^{\rm HG} \simeq V^{\rm QGP}$, $T^{\rm QGP} \simeq T^{\rm HG}$,
the chemical occupancy factors accommodate the different magnitude of particle phase space.

→

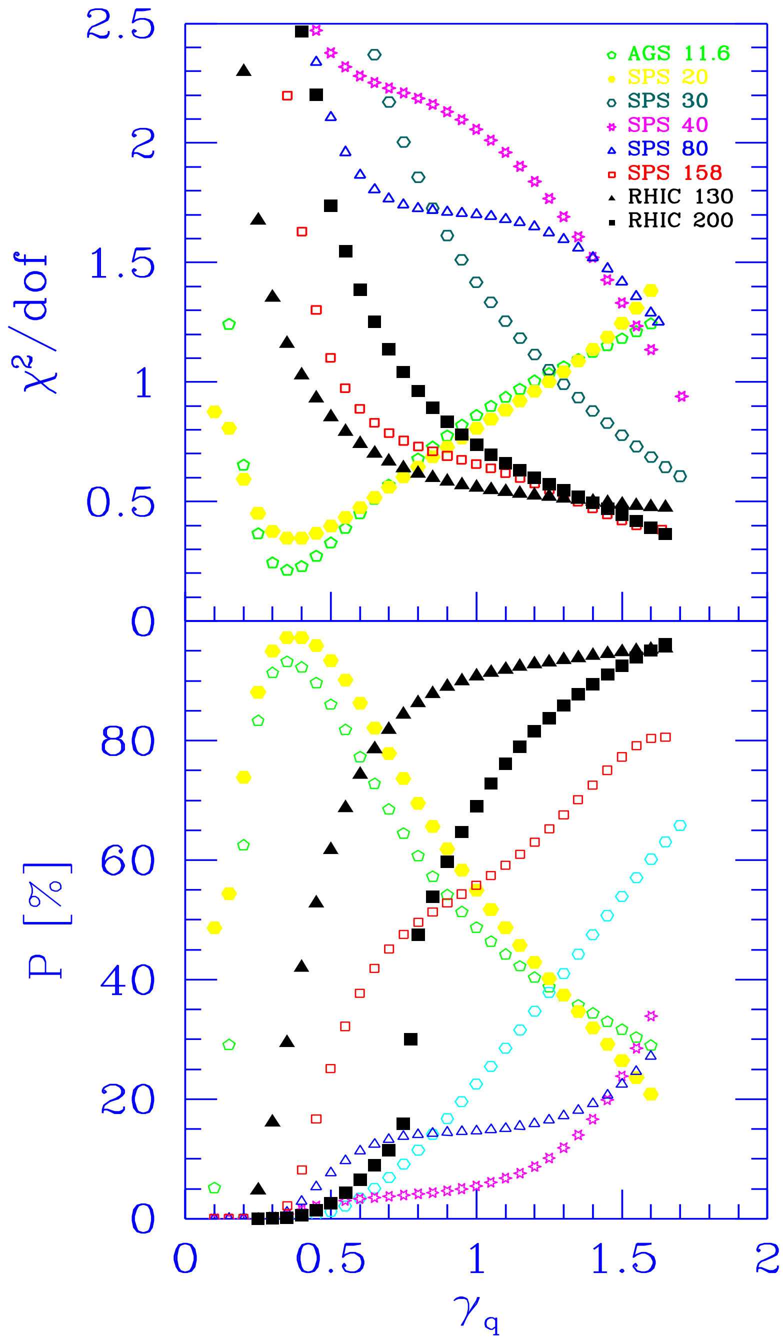


$T = 170$, $\gamma_{\rm q} = 1$ **OR** $T = 150$, $\gamma_{\rm q} = 1.6$

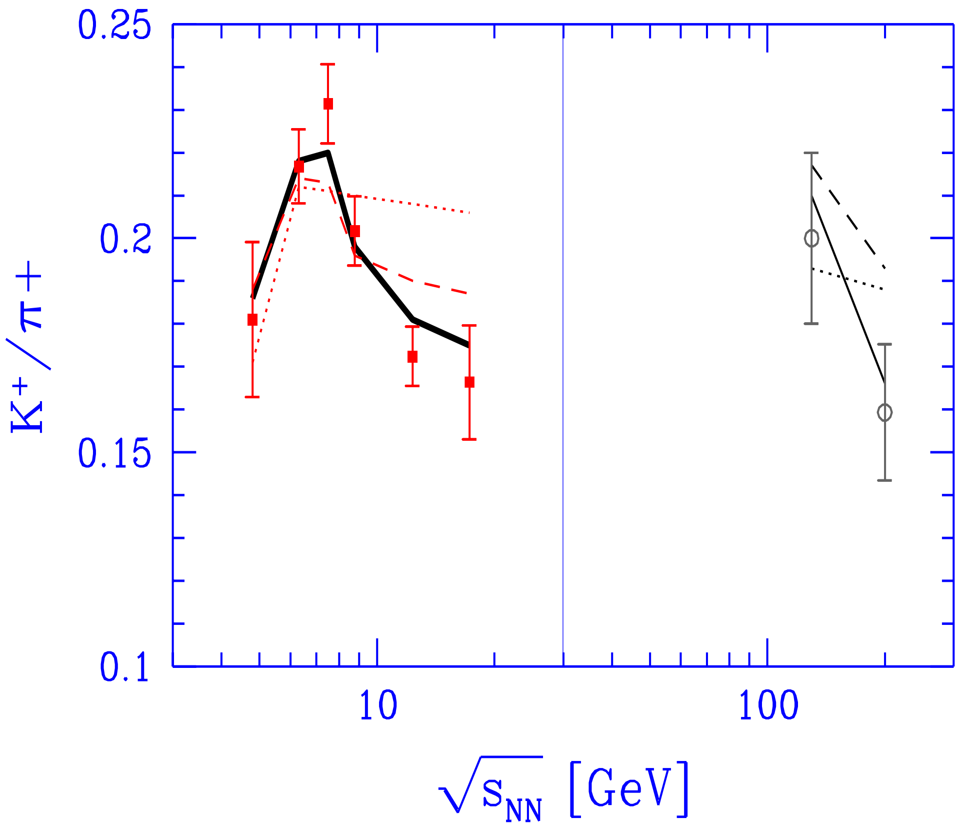
$\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$ in sudden hadronization as function of $\lambda_{\rm q}$. Solid lines $\gamma_{\rm q} = 1$, and short dashed $\gamma_{\rm q} = 1.6$. Thin lines for $T = 170$ and thick lines $T = 150$ MeV, common to both phases.

$$\boxed{\gamma_s^{\rm HG} \simeq 2...5\gamma_s^{\rm QGP}}$$

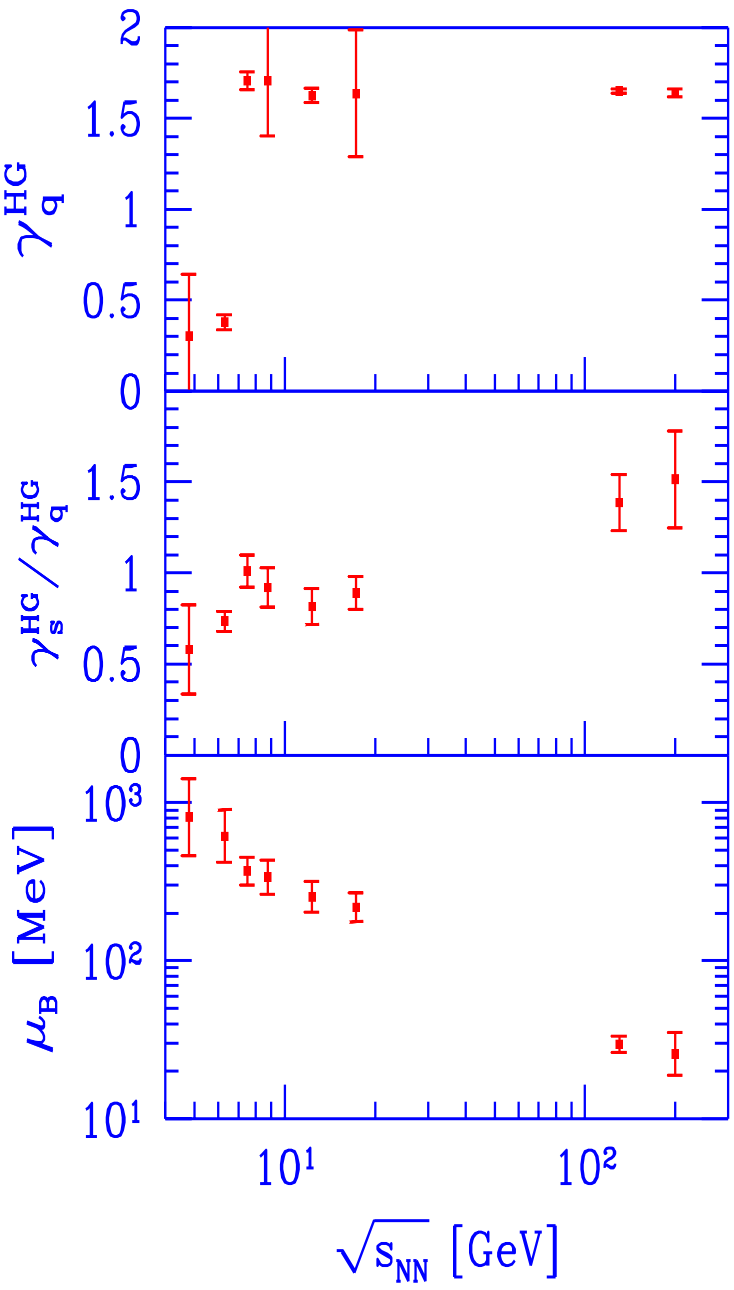
STRANGE PARTICLE EXCITATION FUNCTION: WE CAN

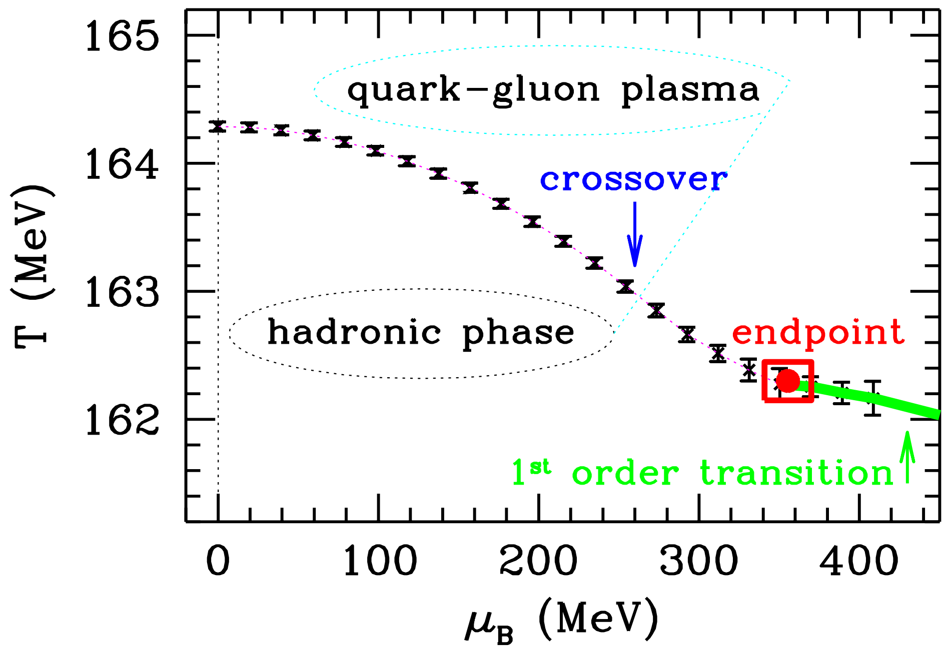


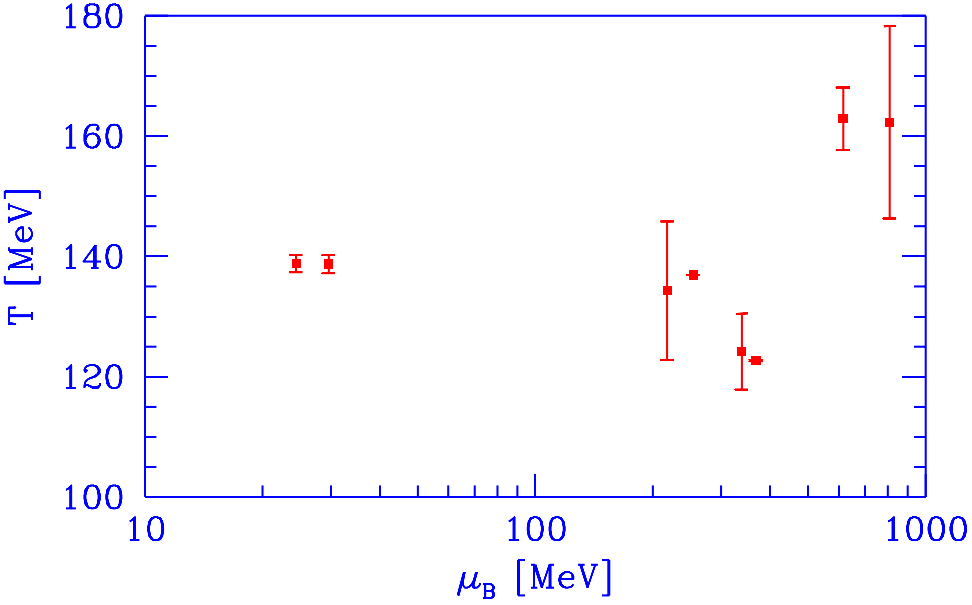
Allowing chemical nonequilibrium we see that between 20 and 30GeV the fit jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The fits have reasonable quality, in particular those relevant to understanding how the horn is created.



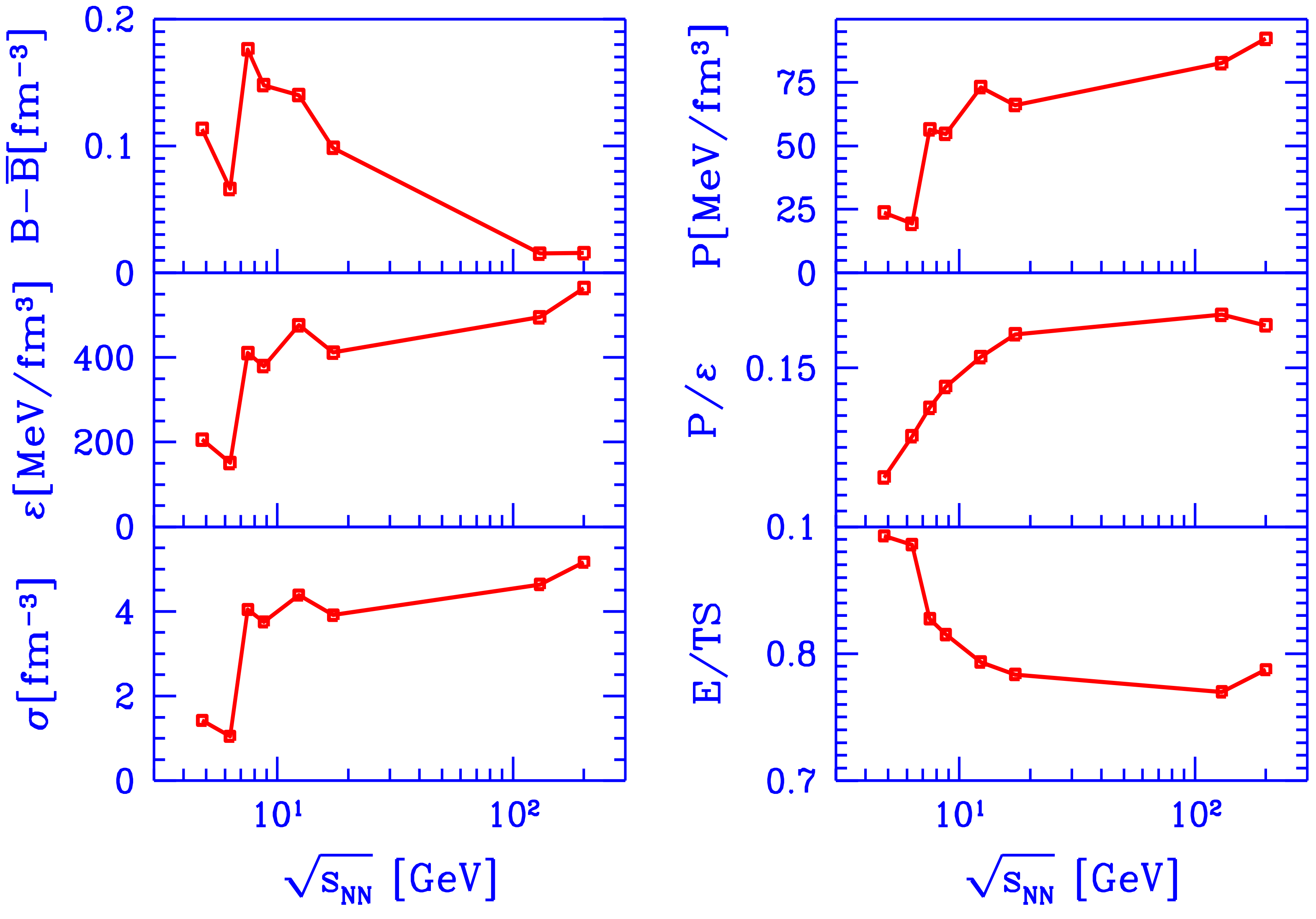
SUMMARY OF FIT RESULTS





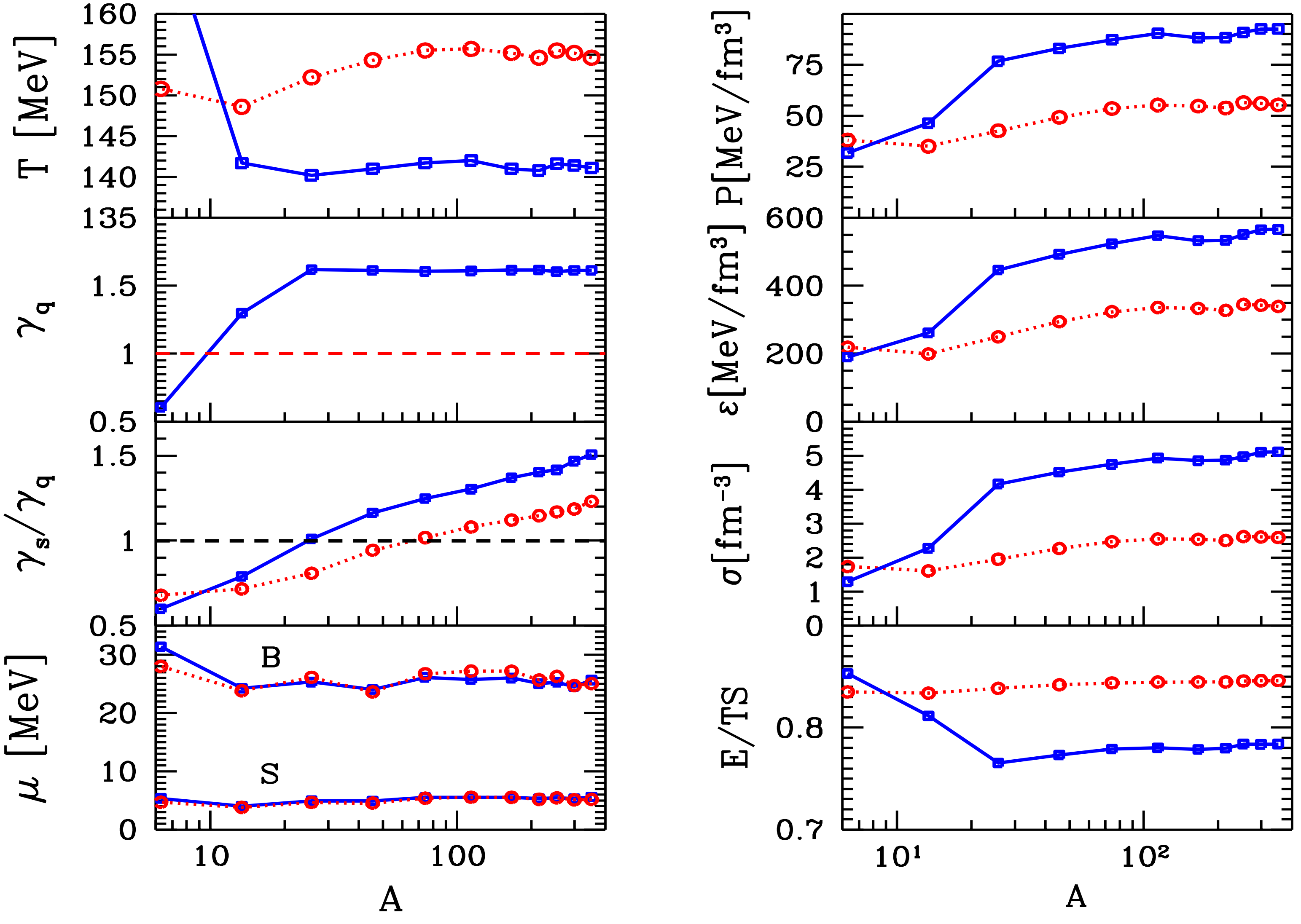


PHYSICAL PROPERTIES



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.

RHIC200 dependence on centrality=dependence on energy



$\gamma_s \neq 1$ $\gamma_s, \gamma_q \neq 1$ **Note:** γ_q **moves from under-saturated to over-saturated value,** P, σ, ϵ **increase by factor 2–3,** E/TS **decreases, just as we saw it as function of** $\sqrt{s}$**.**

STRANGENESS PRODUCTION: quantities of interest

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 CONTENT s/S

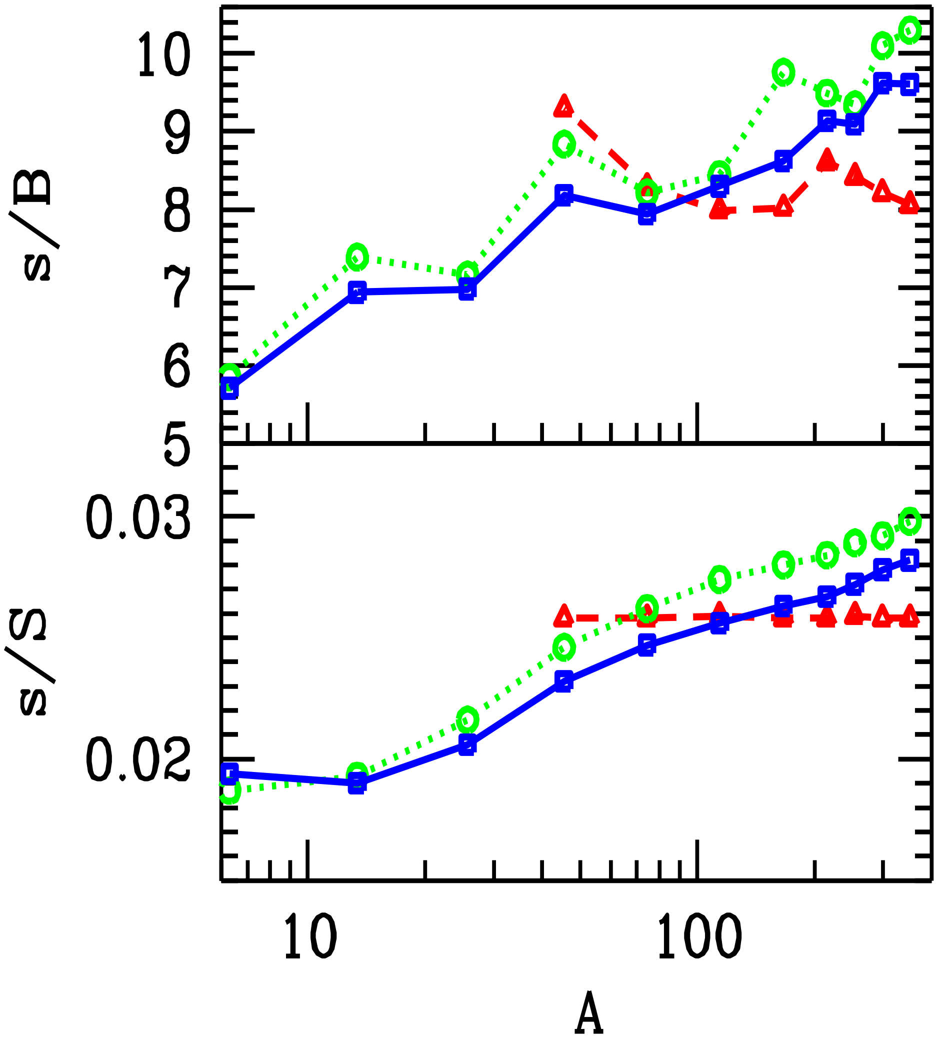
Strangeness s and entropy S produced predominantly in early hot parton phase. Ratio eliminates dependence on reaction geometry. Strangeness and entropy could increase slightly in hadronization. s/S relation to K^+/π^+ is not trivial when precision better than 25% needed.

HADRON PHASE SPACE OVERPOPULATION

$\gamma_s,\ \gamma_q$ allow correct measure of yields of strangeness and baryon number, probe dynamics of hadronization, allow fast breakup without 'mixed phase'.

and much more......

RHIC200 s/b and s/S dependence on centrality



Chemical equilibrium fit has limited validity; $\gamma_s \neq 1$, $\gamma_q, \gamma_s \neq 1$

Charm and bottom at LHC

Given high energy threshold charm (and certainly bottom)heavy flavor is believed to be produced predominantly in initial parton collisions and not in thermal relatively soft collisions. Will it thermalize?

$$Y_{c\bar{c}} \simeq 150 - 300; \qquad Y_{b\bar{b}} \simeq 5 - 15$$

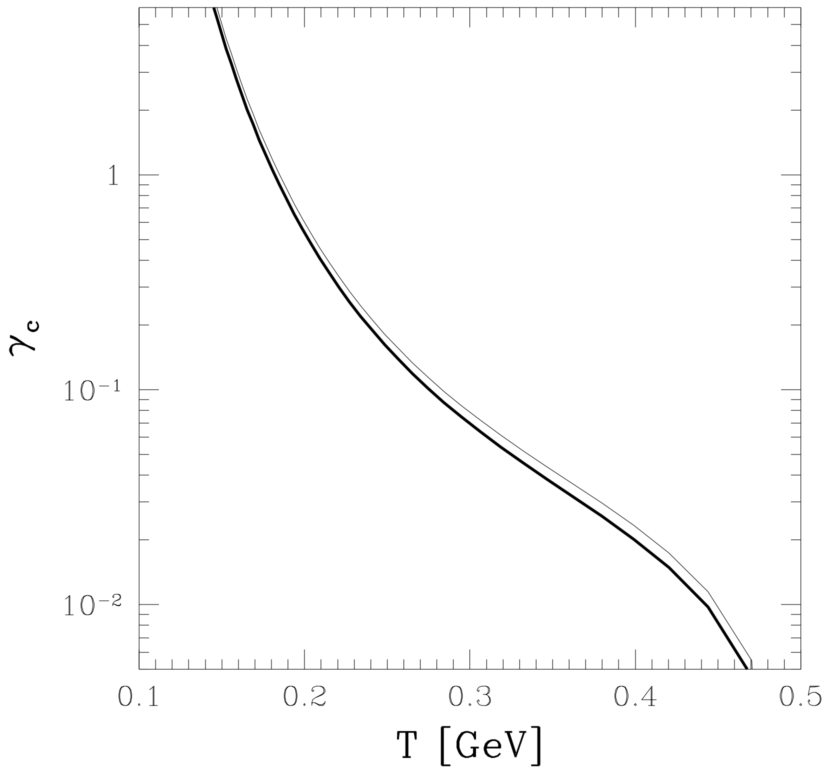
Precise prediction is a challenge to nLO pQCD since it requires parton distribution and initial time evolution within colliding nuclei. Thermal yields are at 10-30% for charm, negligible for $b\bar{b}$.

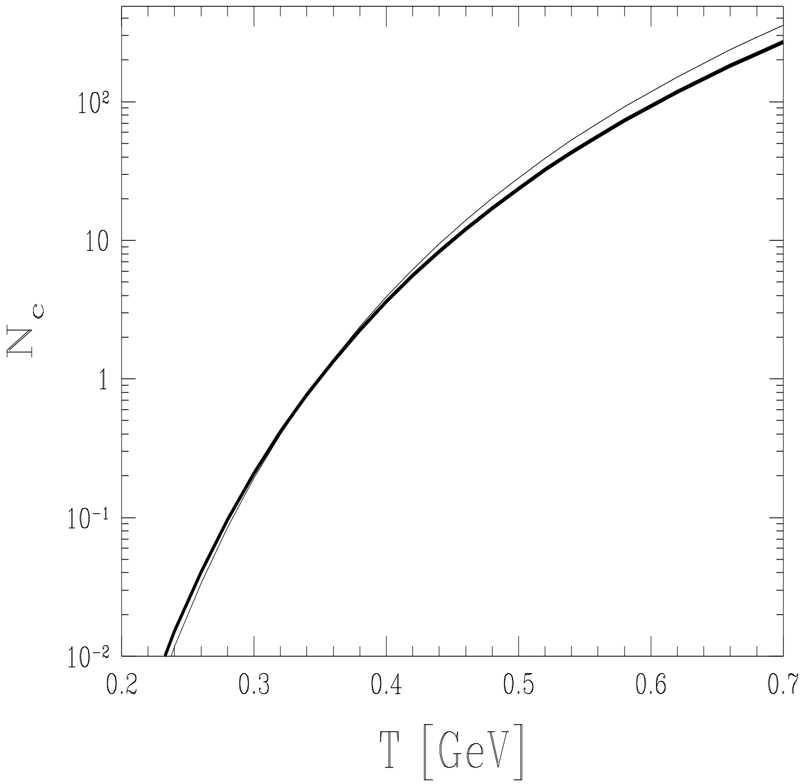
No significant reannihilation expected in dense matter evolution. The phase space occupancy rises rapidly. The way it works: assuming effective thermalization of local distributions, the integral of the Boltzmann spectrum yields at each local temperature T:

$$N_c = k\, VT^3\, \gamma_c(t) \sqrt{\left(\frac{m}{T(t)}\right)^3}\, e^{m/T(t)}, \qquad VT^3 = \textbf{Const.}, \qquad k = \frac{g}{2\pi^2}\sqrt{\frac{\pi}{2}}.$$

Since at hadronization $m_c/T \simeq 10$ and $m_b/T \simeq 30$ the thermal yields need to be multiplied by large γ_c, or resp. γ_b to maintain the initially produced yield. We expect ABOVE equilibrium yields. Since e.g. $J/\Psi \propto \gamma_c^2$ we expect multi charmed meson, baryon production enhancement.

Thermal Charm Example at LHC





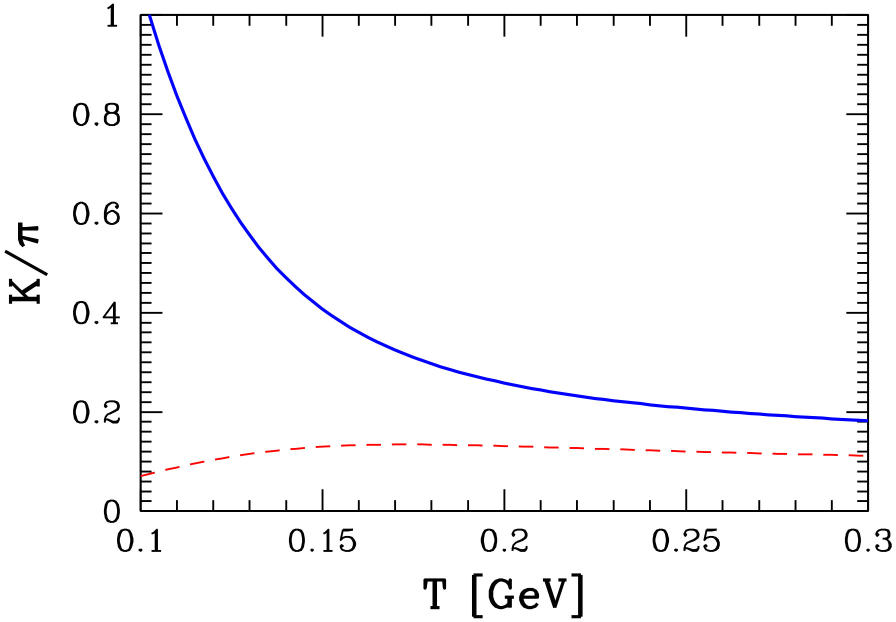
thermal charm as function T, the time dependent local temperature.

Total thermal charm yield as function of initial temperature.

SHARE online version allows computation of thermal charm yields of all particles

Strangeness at LHC has some surprises

At LHC fast dilution of initial high density phase. Strangeness is slower to reequilibrate chemically. Initial high yield preserved, this leads to overpopulation of phase space at hadronization. Here, let us estimate the maximum possible. Limits generated by condensation boundary. For pions, an kaons limits are: $\pi\ :\ \gamma_q^2 \ \leq\ e^{\frac{m_\pi}{T}}$, $K\ :\ \gamma_s\gamma_q \ \leq\ e^{\frac{m_K}{T}} \ \to\ \gamma_s/\gamma_q \ \leq\ e^{\frac{m_K-m_\pi}{T}} \ \to\ K/\pi$



Expect a shift toward strange meson production. Aside of K/π **shown, the enhanced** γ_s/γ_q **will enhance other strange particles.**

STRANGENESS AND QGP DISCOVERY

1. **Energy excitation functions and centrality dependence is now available**
2.

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

The winner **poor looser**

3. **If QGP fireball: strangeness nearly equilibrated at hadronization. Overpopulates HG phase space.**
4. **Features of strange baryon and antibaryon spectra demonstrate sudden breakup, absence of reequilibration, suggest super-cooling**
5. **Resonances help probe the dynamics of hadronization, test SHM.**
6. **Standarized programs and online web page available for SHARE (statistical hadronization with resonances)**
7. **Charm emerges as the next flavor signature of QGP**

Have we found QGP: as much as Columbus discovered WestIndies. Further study will show, but there is a lot of 'gold' to be found anyway.
My opinion: 'valon' quark deconfinement at AGS, transition to pQGP at SPS.