Strangeness Enhancement: Challenges and Successes

July 2, 2007, Zimányi 75, Budapest

0) **Motivation: Vacuum and the Early Universe, QGP experiments**
1) **Proposal of signatures of QGP**
2) **J. Zimányi challenge: is there s-chemical equilibrium in QGP?**
3) **Antibaryons and sudden hadronization challenge**
4) **Analysis of present day data**
5) **Strangeness and entropy enhancement today**
6) **QGP at LHC: role of strangeness**

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

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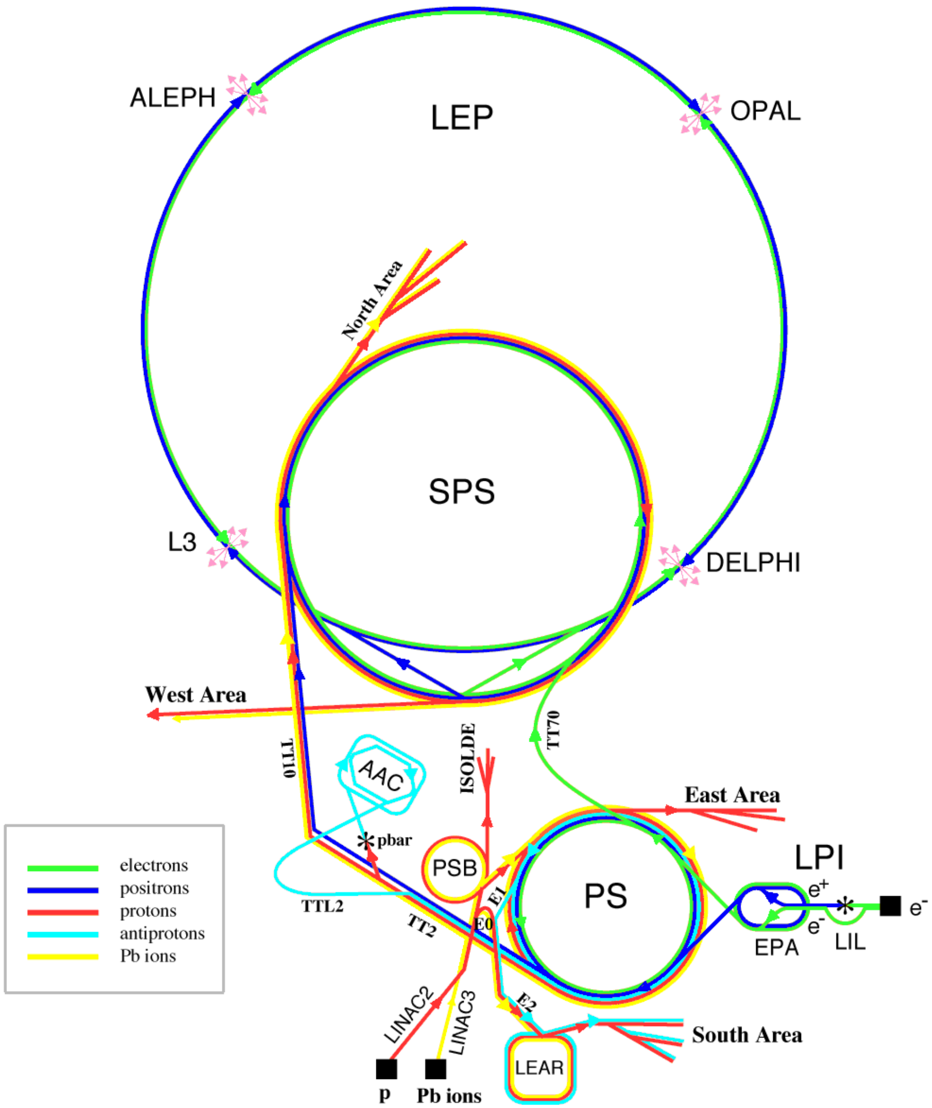
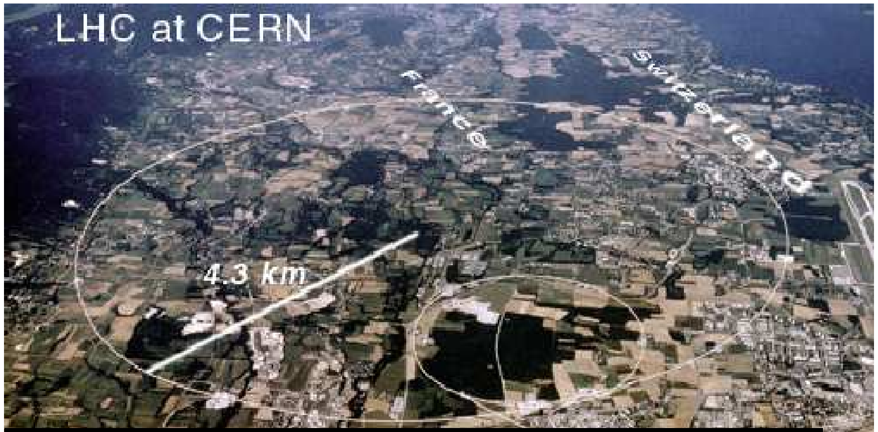
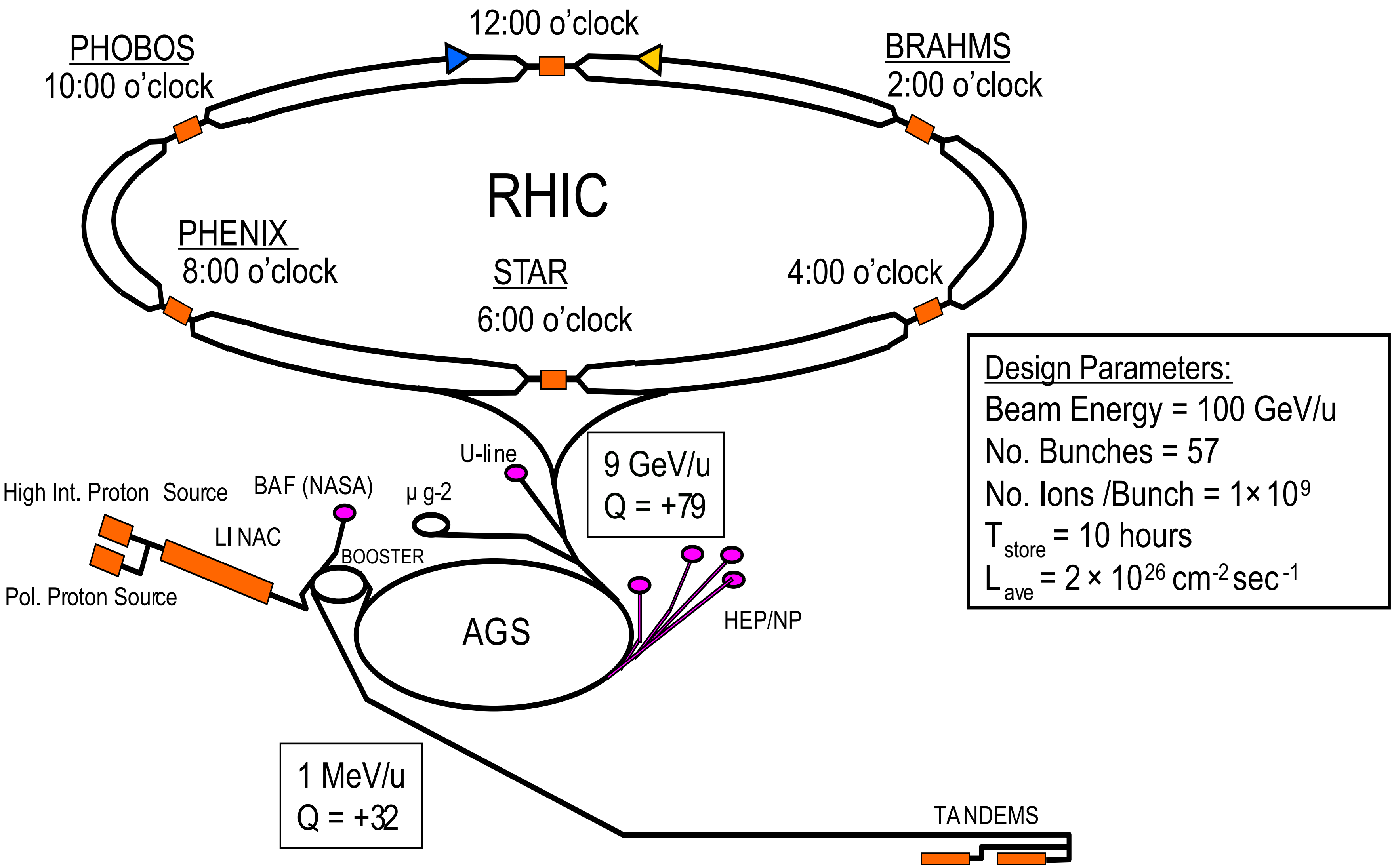
EXPERIMENTAL PROGRAM AT CERN and at . . .





SPS in the past and and in the near future LHC

BROOKHAVEN NATIONAL LABORATORY



Relativistic Heavy Ion Collider: RHIC

Foundations of QGP/RHI Collisions Research

RECREATE THE EARLY UNIVERSE IN LABORATORY:
Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 25 μs after big bang.

QGP-Universe hadronization led to nearly matter-antimatter symmetric state, ensuing matter-antimatter annihilation yields 10^{-10} *matter asymmetry, the world around us.*

STRUCTURED VACUUM (Einsteins 1920+ Aether/Field/Universe)
The vacuum state determines prevailing fundamental laws of nature. Demonstrate by changing the vacuum from hadronic matter ground state to quark matter ground state, and finding the changes in laws of physics.

ORIGIN OF MASS OF MATTER –DECONFINEMENT
The confining quark vacuum state is the origin of 99.9% of mass, the Higgs mechanism applies to the remaining 0.1%. We want to show that the quantum zero-point energy of confined quarks is the mass of matter. To demonstrate we 'melt' the vacuum structure setting quarks free.

Vacuum structure

Quantum vacuum is polarizable: see atomic vac. pol. level shifts

Quantum gluon-quark fluctuations:

Permanent fluctuations in 'space devoid of matter':

$$\textbf{even though}\quad \langle V|G^a_{\mu\nu}|V\rangle = 0, \quad \langle V|\Psi_{u,d,s,\ldots}|V\rangle = 0,$$

$$\textbf{we have}\quad \langle V|\frac{\alpha_s}{\pi}G^2|V\rangle \simeq (2.3\pm 0.3)10^{-2}\mathrm{GeV}^4 = [390(12)\,\mathrm{MeV}]^4\,,$$

$$\textbf{and}\quad \langle V|\bar{u}u+\bar{d}d|V\rangle = -2[225(9)\,\mathrm{MeV}]^3\,.$$

Vacuum and Laws of Physics

Vacuum structure controls early Universe properties

Vacuum is thought to generate color charge confinement:
hadron mass originates in QCD vacuum structure.

Vacuum determines inertial mass by confinement or for 'elementary' particles, by the way of the Higgs mechanism,

$$m_i = g_i\langle V|h|V\rangle\,,$$

Vacuum determines interactions, symmetry breaking, etc.....

QGP has fleeting presence in laboratory
Discover / Diagnosis / Study properties at 10^{-23} s scale

- Deep probes (diletpons and photons), weakly coupled probes of the entire history of collision, including the initial moments (!) – suffer from large background
- J/Ψ suppression: one measurement per energy/centrality, ongoing and evolving interpretation
- Jet suppression: spectacular measurement, interpretation reminds me of above J/Ψ issues
- Dynamics of quark matter flow: promising new research direction to demonstrate presence of collective quark matter dynamics

We will today look in depth at the strongly interacting probes of last 3fm/c of QGP expansion/hadronization:

- **Strangeness enhancement**
- **Strange antibaryon enhancement**

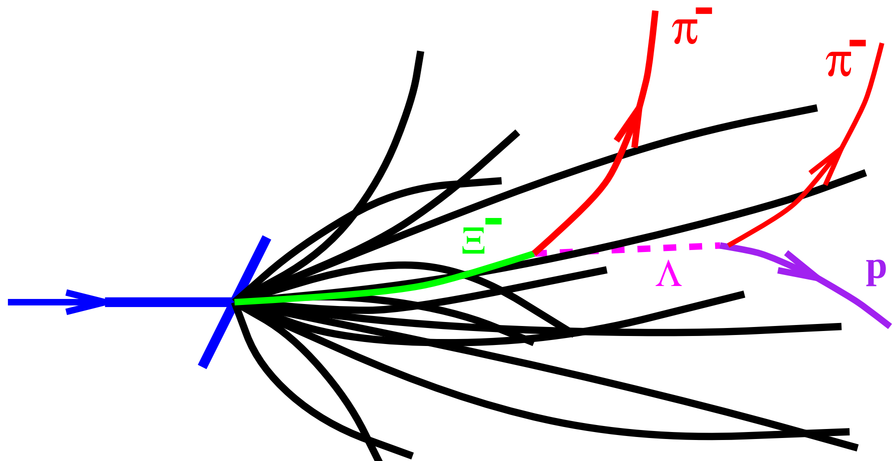
Strangeness: a popular QGP/dense matter diagnostic tool

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

$$\phi(s\bar{s}), \quad K(q\bar{s}), \quad \overline{K}(\bar{q}s), \quad \Lambda(qqs), \quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),$$

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

- **Several strange hadrons subject to a self analyzing decay within a few cm from the point of production**



- **Production rates hence statistical significance is high**

A few slides on the history of the subject:

Strangeness

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):

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

(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:

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

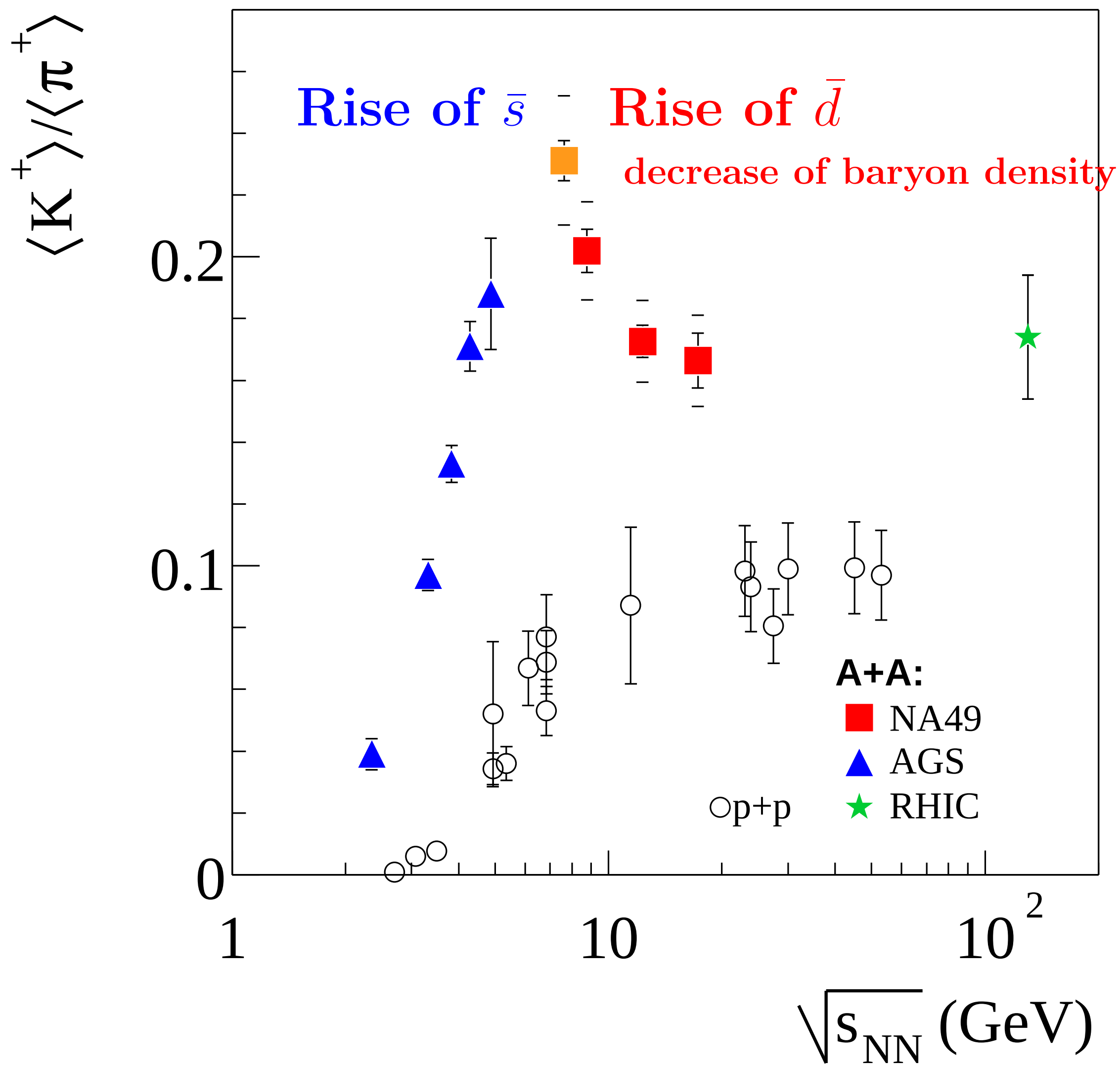
The function $x^2K^2(x)$ is, for example, tabulated in Ref. 15). For $x = m_s/T$ between 1.5 and 2, it varies between 1.3 and 1. Thus, we almost always have more $\bar{s}$ than $\bar{q}$ quarks and, in many cases of interest, $\bar{s}/\bar{q} \sim 5$. As $\mu \to 0$ there are about as many $\bar{u}$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

First published literature mention of strange particle production as probe of quark-gluon plasma and as signature of phase transition appears in the preprint CERN-TH-2969 of October 1980 (Rafelski & Hagedorn). Published in "Statistical Mechanics of Quarks and Hadrons", H. Satz, editor, Elsevier 1981. Strangeness enhancement $\bar{s}/\bar{q} \to K^+/\pi^+$, and strange antibaryons $\bar{s}/\bar{q} \to \overline{\Lambda}/p$ 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, originating in a challenge from J. Zimányi

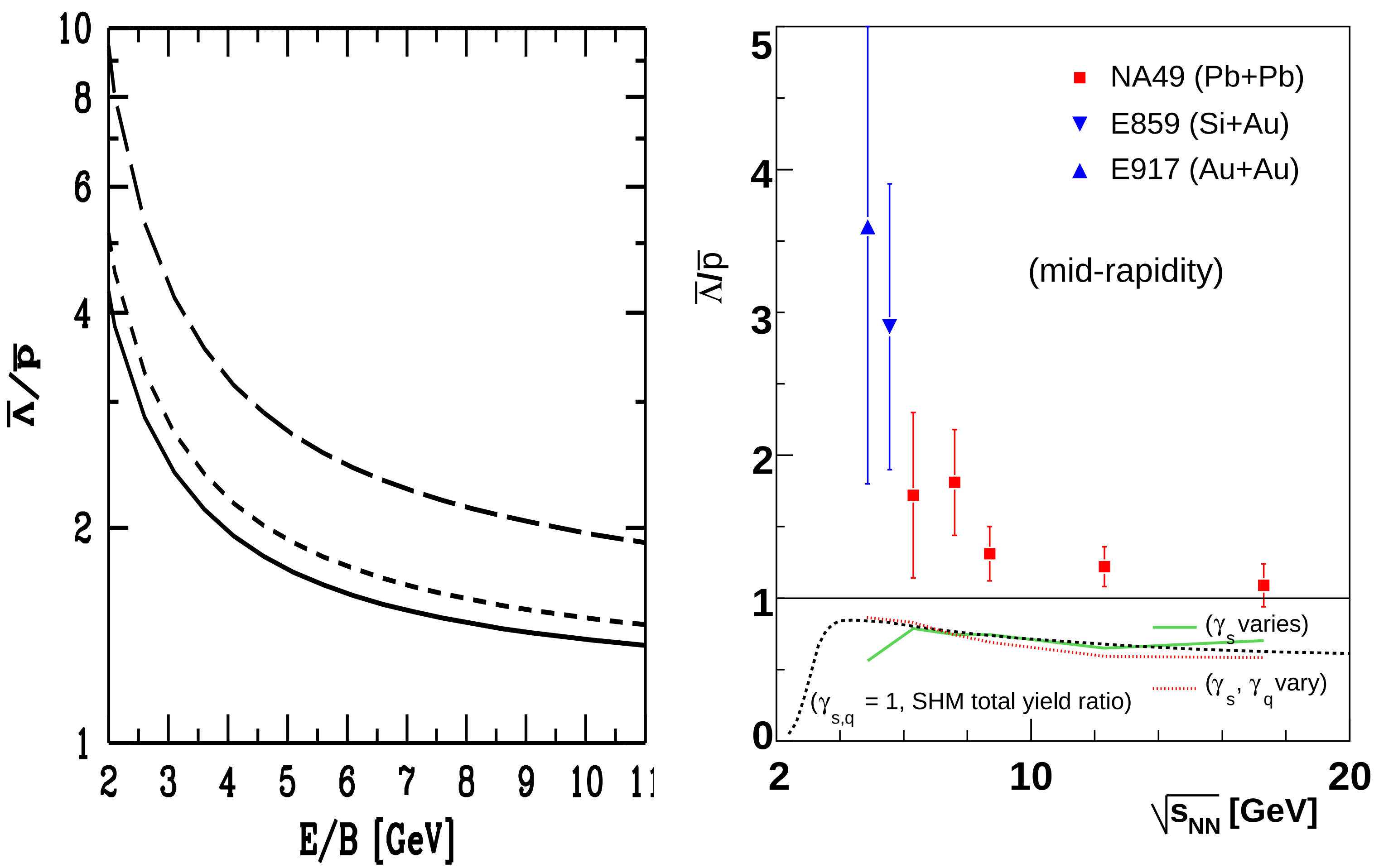
K^+/π^+ ratio anomaly predicted 1980: today status



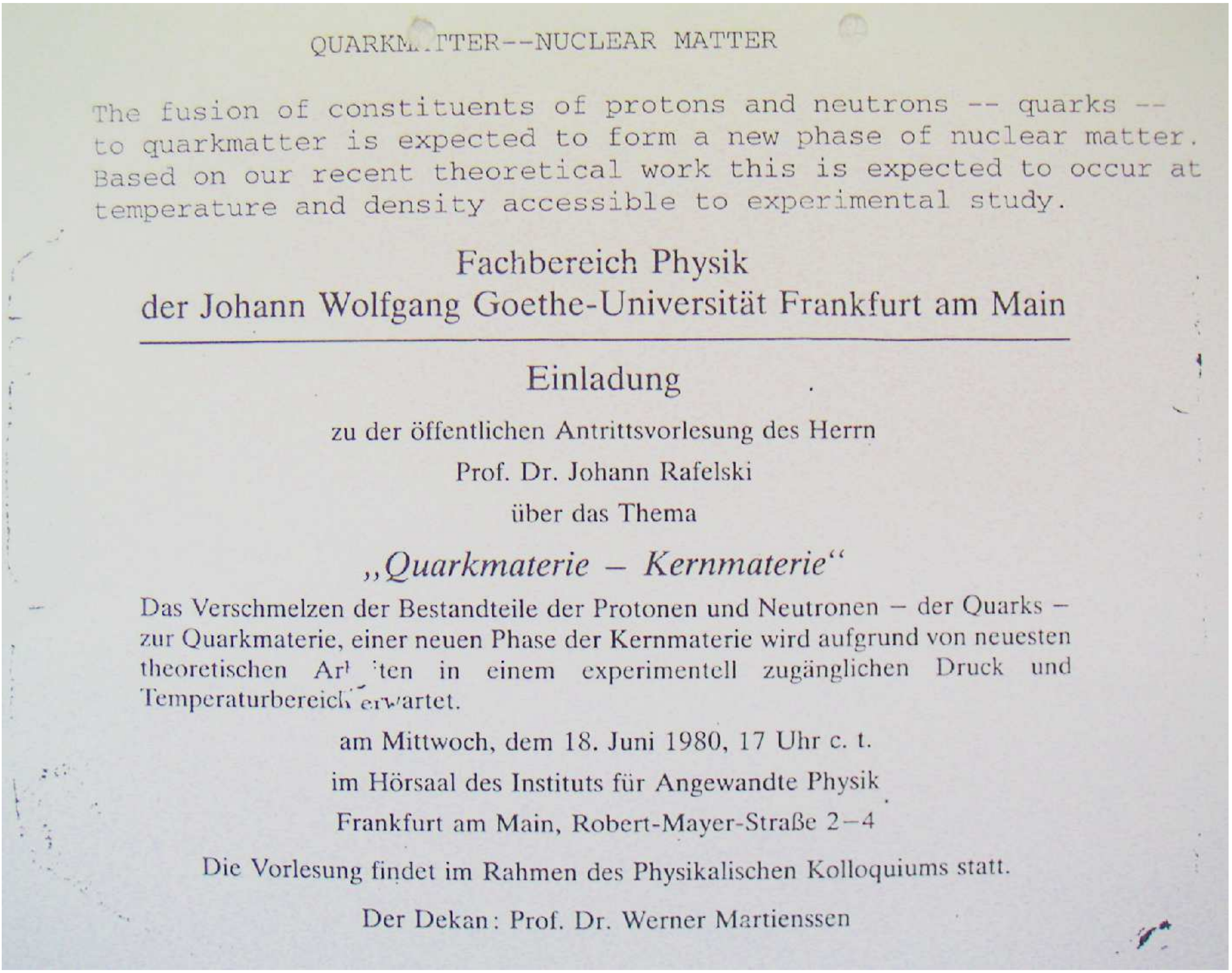
The NA49 (Marek Gaździcki) HORN

$\overline{\Lambda}/\bar{p} > 1$ 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**


QUARKMATTER--NUCLEAR MATTER

The fusion of constituents of protons and neutrons -- quarks -- to quarkmatter is expected to form a new phase of nuclear matter. Based on our recent theoretical work this is expected to occur at temperature and density accessible to experimental study.

Fachbereich Physik
der Johann Wolfgang Goethe-Universität Frankfurt am Main

Einladung

zu der öffentlichen Antrittsvorlesung des Herrn
Prof. Dr. Johann Rafelski
über das Thema

„Quarkmaterie – Kernmaterie“

Das Verschmelzen der Bestandteile der Protonen und Neutronen – der Quarks – zur Quarkmaterie, einer neuen Phase der Kernmaterie wird aufgrund von neuesten theoretischen Arbeiten in einem experimentell zugänglichen Druck und Temperaturbereich erwartet.

am Mittwoch, dem 18. Juni 1980, 17 Uhr c. t.
im Hörsaal des Instituts für Angewandte Physik
Frankfurt am Main, Robert-Mayer-Straße 2–4

Die Vorlesung findet im Rahmen des Physikalischen Kolloquiums statt.

Der Dekan: Prof. Dr. Werner Martienssen

Inaugural lecture presentation – Prof. Janos Zimányi was at the time a good friend of my boss, InstitutsDirektor Prof. Dr. Walter Greiner. It is possible that I also knew him and, we discussed at CERN or Frankfurt, but I have no recollection of these interactions, prior the fate full events of Summer/Fall 1981:

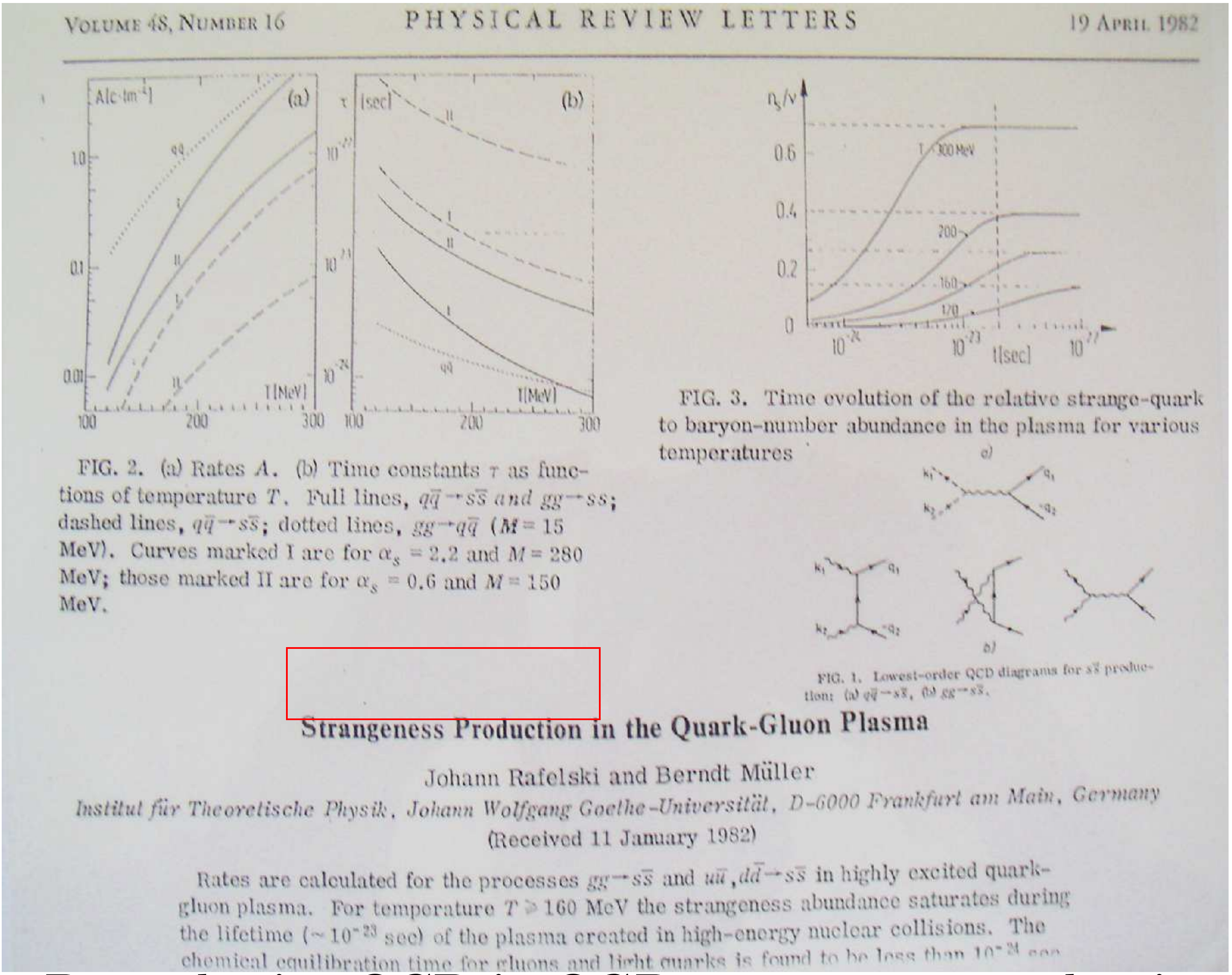
Prof. J. Zimányi and chemical equilibrium

illustration of scientific group dynamics: where there are a few good people and pressure from outside, interesting results follow

While I was away in Summer/Fall 1981 in Seattle, a lecture has been presented in Frankfurt.Prof. J. Zimányi presented the thesis work of T. Biró. As soon as Walter saw me first time in late September, he told me that there were grave objections "Johann, your strangeness enhancement signature of QGP is BS, Zimányi has proved you are wrong".

Walters misgivings about CERN and QGP, and insistence that I return to work on positron lines instead of wasting my time on fantasies prompted me to send a request for a preprint of Biro-Zimányi work to Budapest. Even before I got my copy, Walter presented me this "end of QGP in Frankfurt" paper.

I discussed the situation how Walter treated me and QGP-strangeness with Berndt Müller, whom I was supposed to help solve the positron line mysteries. Since I had to explain to Berndt, a novice in the field the Biro-Zimányi paper I read it much more carefully than I would have done otherwise. This was the first time I saw a master equation for particle population. It was an interesting and important lesson in physical chemistry. I never had taken such a class. Instead, I was well prepared in use of QCD:



VOLUME 48, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1982

FIG. 2. (a) Rates A. (b) Time constants τ as functions of temperature T. Full lines, $q\bar{q}\to s\bar{s}$ and $gg\to ss$; dashed lines, $q\bar{q}\to s\bar{s}$; dotted lines, $gg\to q\bar{q}$ ($M = 15$ MeV). Curves marked I are for $\alpha_s = 2.2$ and $M = 280$ MeV; those marked II are for $\alpha_s = 0.6$ and $M = 150$ MeV.

FIG. 3. Time evolution of the relative strange-quark to baryon-number abundance in the plasma for various temperatures

FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q}\to s\bar{s}$, (b) $gg\to s\bar{s}$.

Strangeness Production in the Quark-Gluon Plasma

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(Received 11 January 1982)

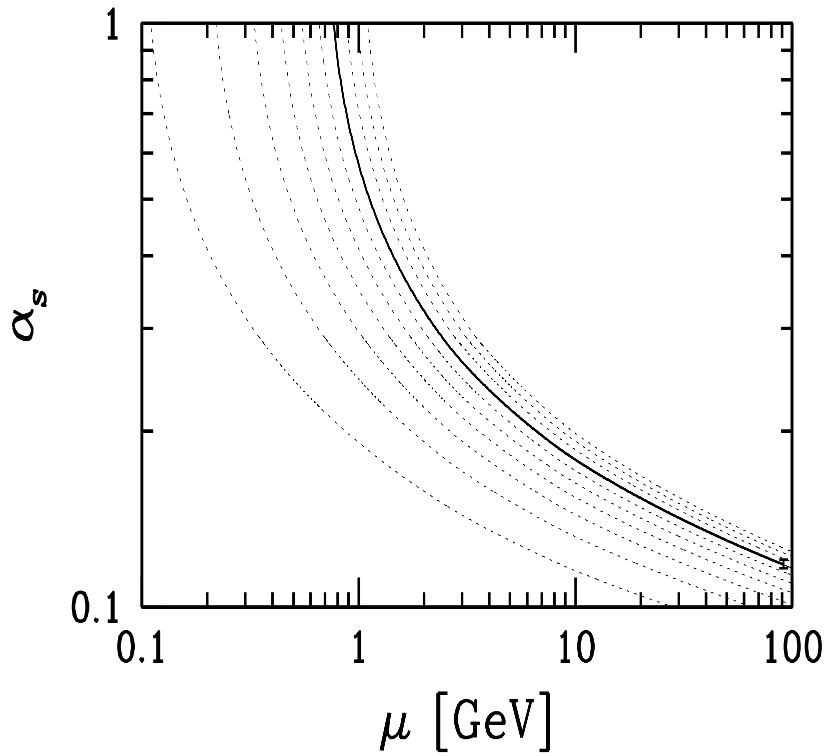
Rates are calculated for the processes $gg\to s\bar{s}$ and $u\bar{u}, d\bar{d}\to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \geq 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec

Perturbative QCD in QGP strangeness production

When at CERN 1977-79 I shared with Brian Combridge an office. He wrote several papers on perturbative QCD charm production, which were essential for the development of the thermal glue based process.

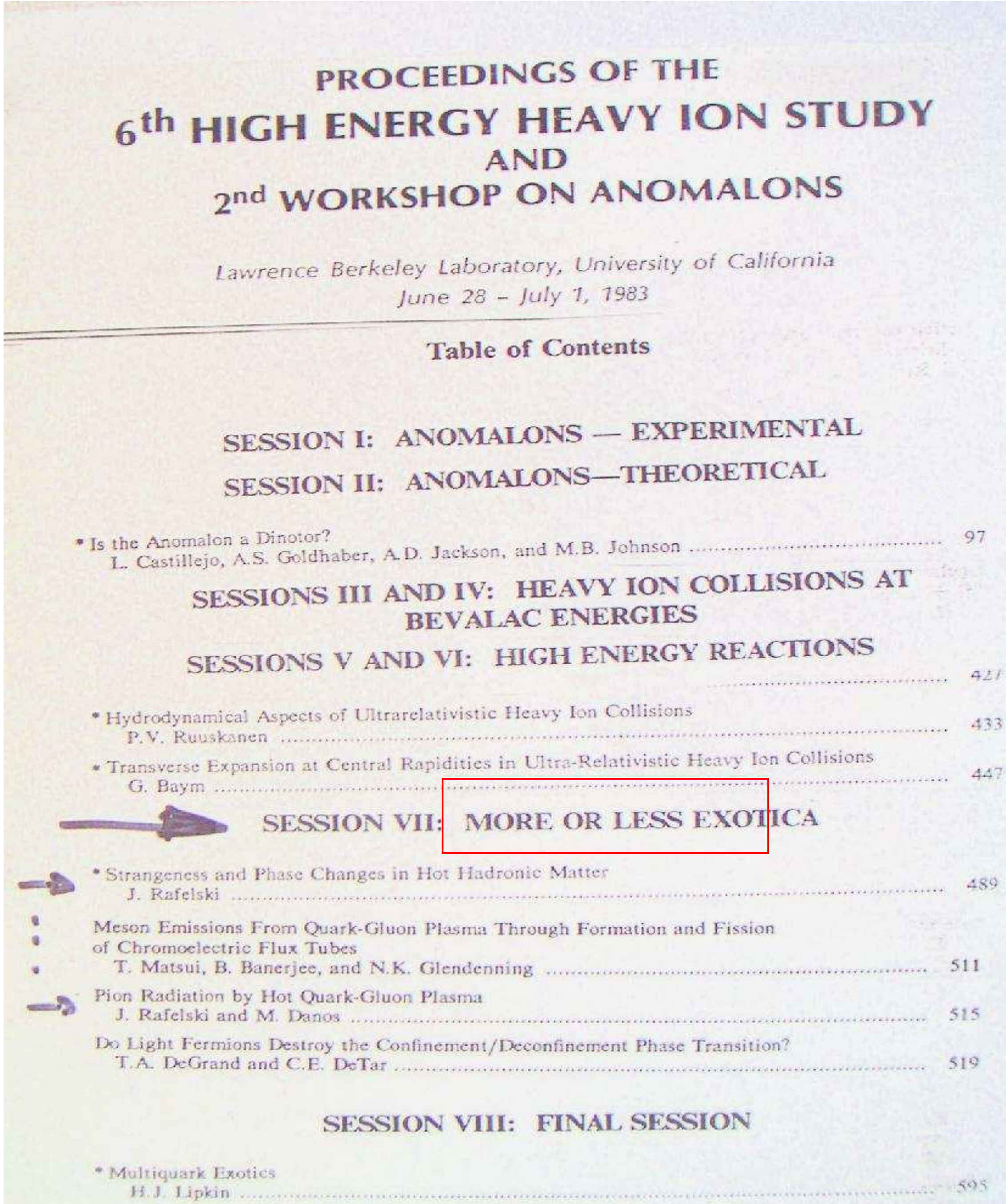
WHY Perturbative QCD in QGP strangeness production works

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. For this reason, at the energy scale $\mu \simeq 5T \simeq$1–3 GeV where typically thermal strangeness production in lab-QGP occurs, perturbative theory makes good sense.



$\alpha_s^{(4)}(\mu)$ 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 $\mu = M_Z$). Had $\alpha_s(M_Z) > 0.125$ been measured (that is 5% greater value in days where 50% precision at best ruled) than our perturbative strangeness production approach from 1982 would have been invalid.

Exotic Strangeness



PROCEEDINGS OF THE

6th HIGH ENERGY HEAVY ION STUDY

AND

2nd WORKSHOP ON ANOMALONS

Lawrence Berkeley Laboratory, University of California

June 28 – July 1, 1983

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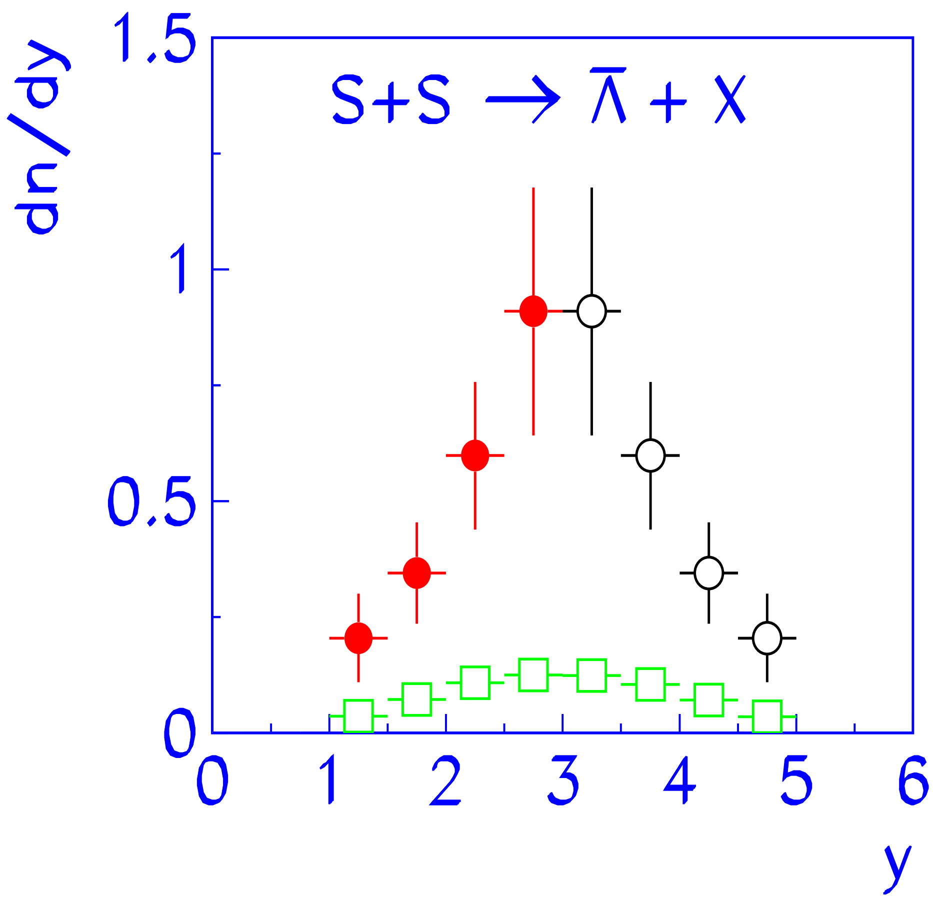
It was difficult to publish in refereed journals on strangeness. QGP was exotic, and strangeness in QGP was double exotic. One of the papers took in the end 2.5 years from submission in one journal to publication in another. I keep the transparencies from the LBL 6th heavy ion study where I presented individual particle yields, I do recall that I was laughed out of the room, maybe it was Miklos Gyulassy who placed this fantasy in the "Exotica session" of the proceedings. A couple years back I reminded **J. Zimanyi** of the situation, he said something to the extend, "O, that it right, ..." silence followed.

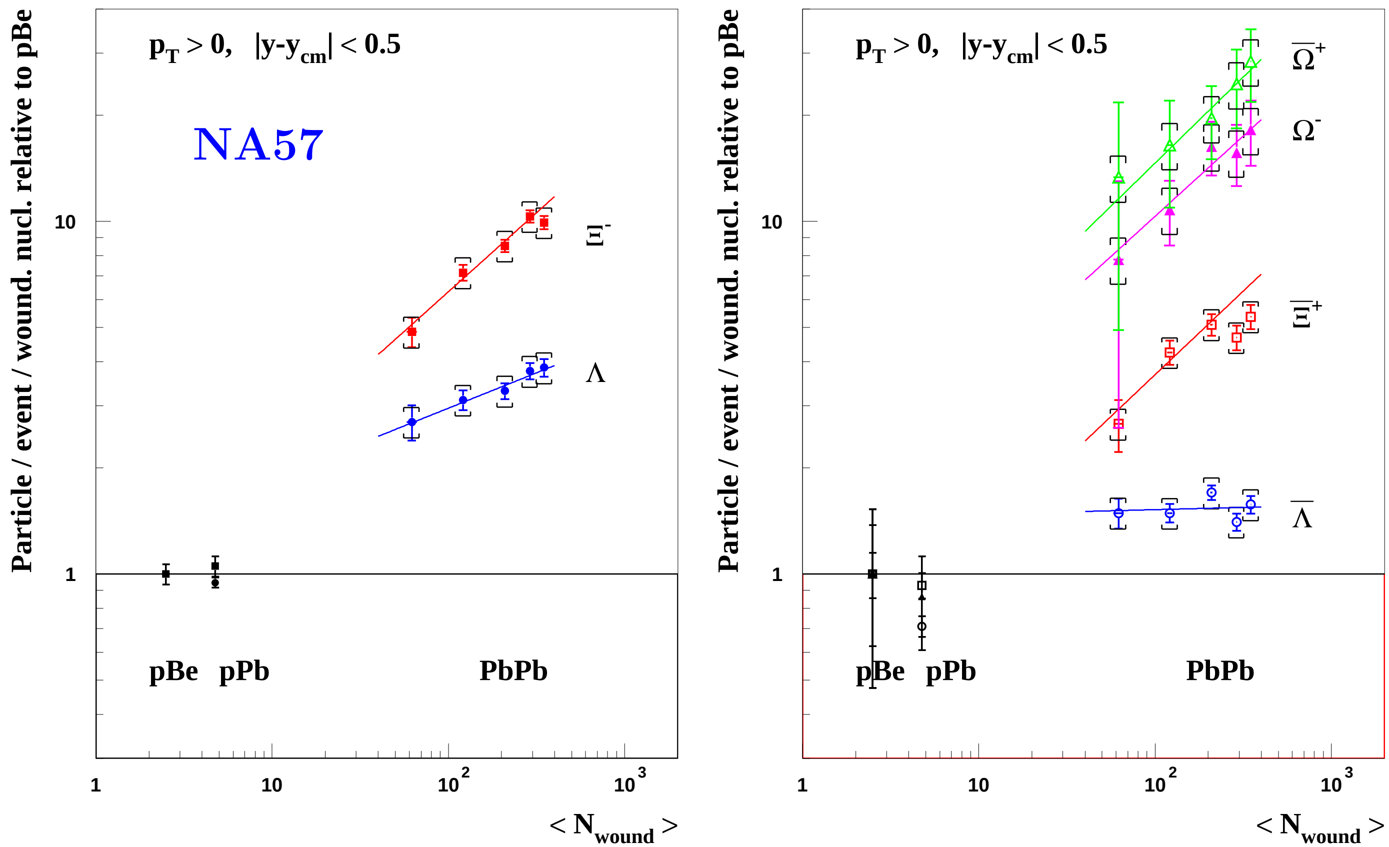
Strange Antibaryon CHALLENGE

Around mid 1985 Howell Pugh, in midst of experiment preparation for CERN, called me in Cape Town. Joe Kapusta has shown that hadronization of QGP took 50-100 fm/c. According to Miklos Guylassy the strange antibaryon enhancement could never happen since strange antibaryons would annihilate in the mixed phase. "He thinks the entire strangeness topic was dead". And if so, the bet placed by LBL nuclear science (both NA35 and NA36 were mainly strangeness experiments) was bad.



First antibaryon enhancement result, 1990, SPS-NA35II EXCESS $\overline{\Lambda}$ emitted from a central well localized source. Background (squares) from multiplicity scaled NN reactions.

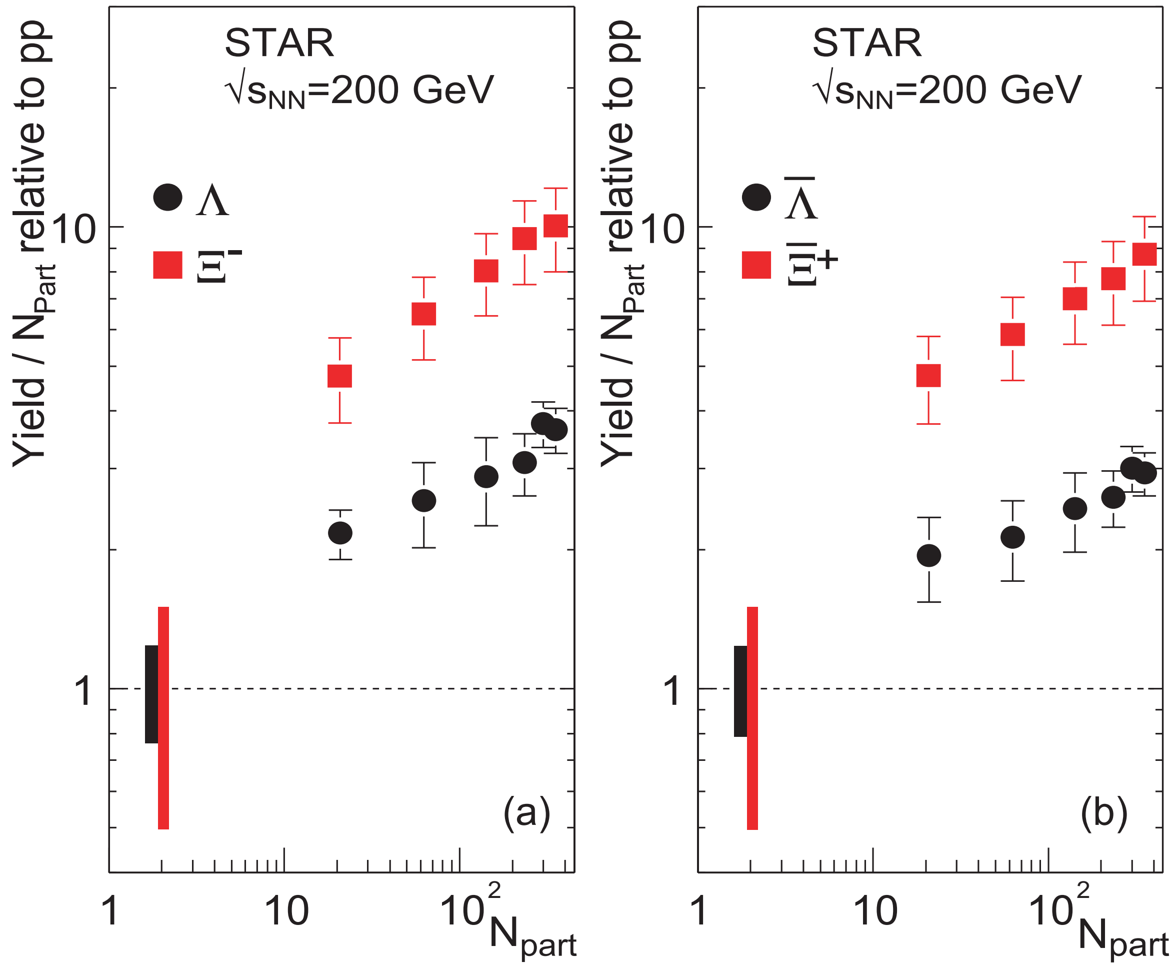
SPS MULTI STRANGE HYPERON ENHANCEMENT



<u>Another challenge here:</u> Instead to kinetic theory, such as string breaking model use equilibrium statistical models for the reference yields. This takes us back to pre 1981 <u>Biro-Zimányi</u> days, to the canonical phase space introduced in heavy ion physics by Rafelski and Danos, PLB97B, p279 (1980).

The systematic behavior as function of reaction energy, and of centrality, excludes this challenge on experimental grounds. In small systems, even more so than in large systems, kinetic theory determines yields.

RHIC MULTI STRANGE HYPERON ENHANCEMENT



Results of the STAR collaboration. More available.

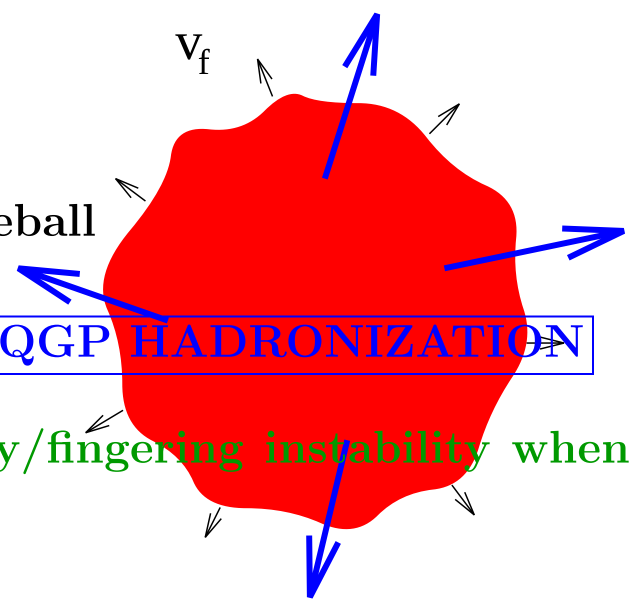
Fast hadronization Challenge:
MATTER-ANTIMATTER SPECTRAL SYMMETRY

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.

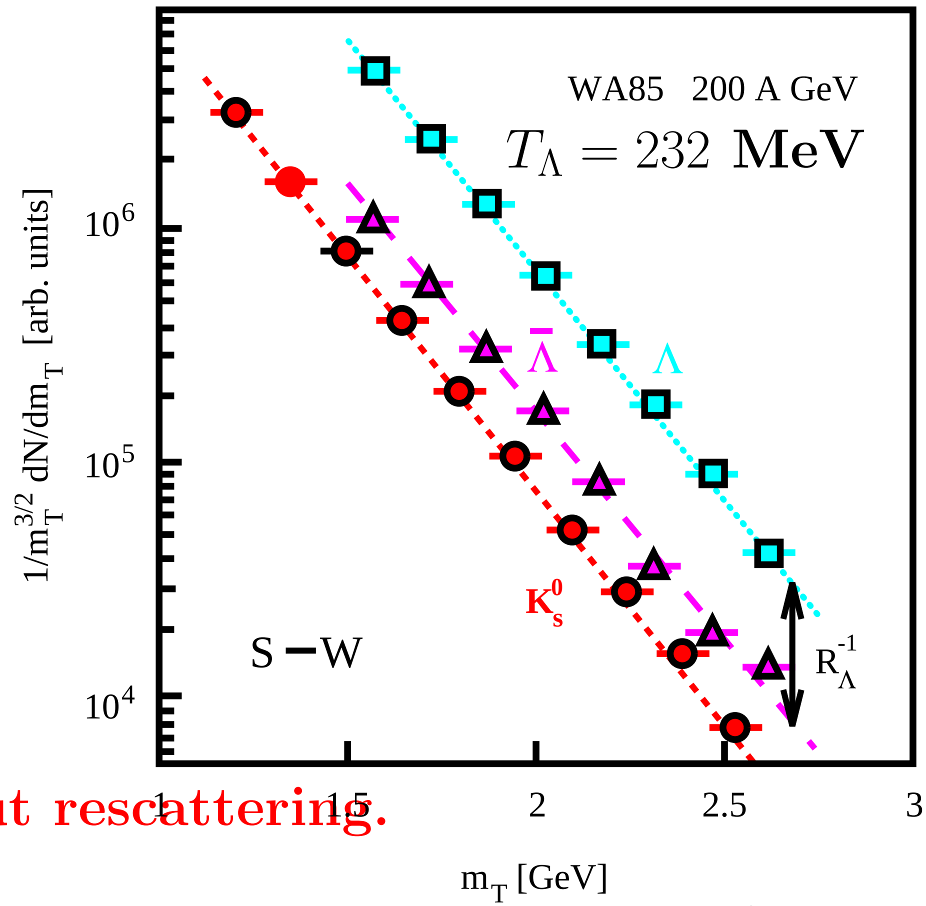
High $m_\perp$ slope universality

Discovered in S-Pb collisions, by WA85, very pronounced in Pb-Pb Interactions.

Why is the slope of baryons and antibaryons precisely the same?

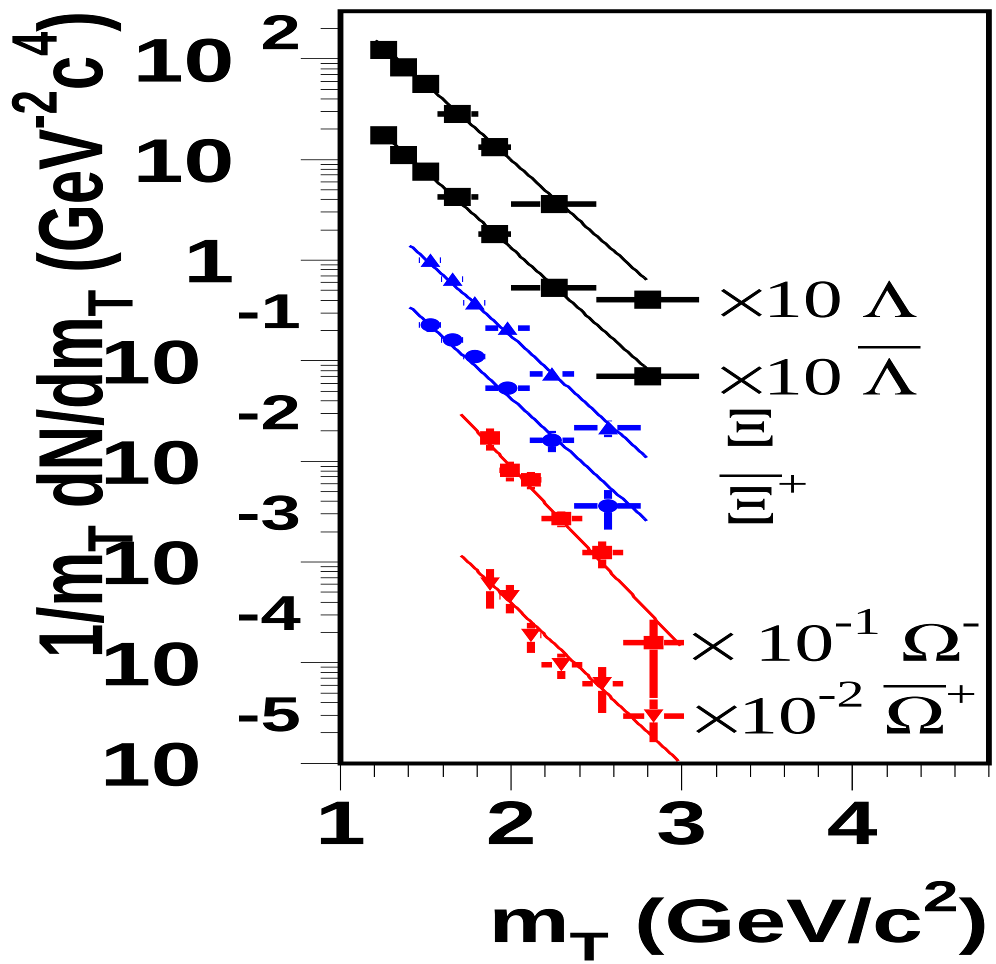
Why is the slope of different particles in same m_t range the same?

Analysis+Hypothesis 1991: QGP quarks coalescing in SUDDEN hadronization without rescattering.



This allows to study ratios of particles measured only in a fraction of phase space

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**



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

Kaon – hyperon difference:

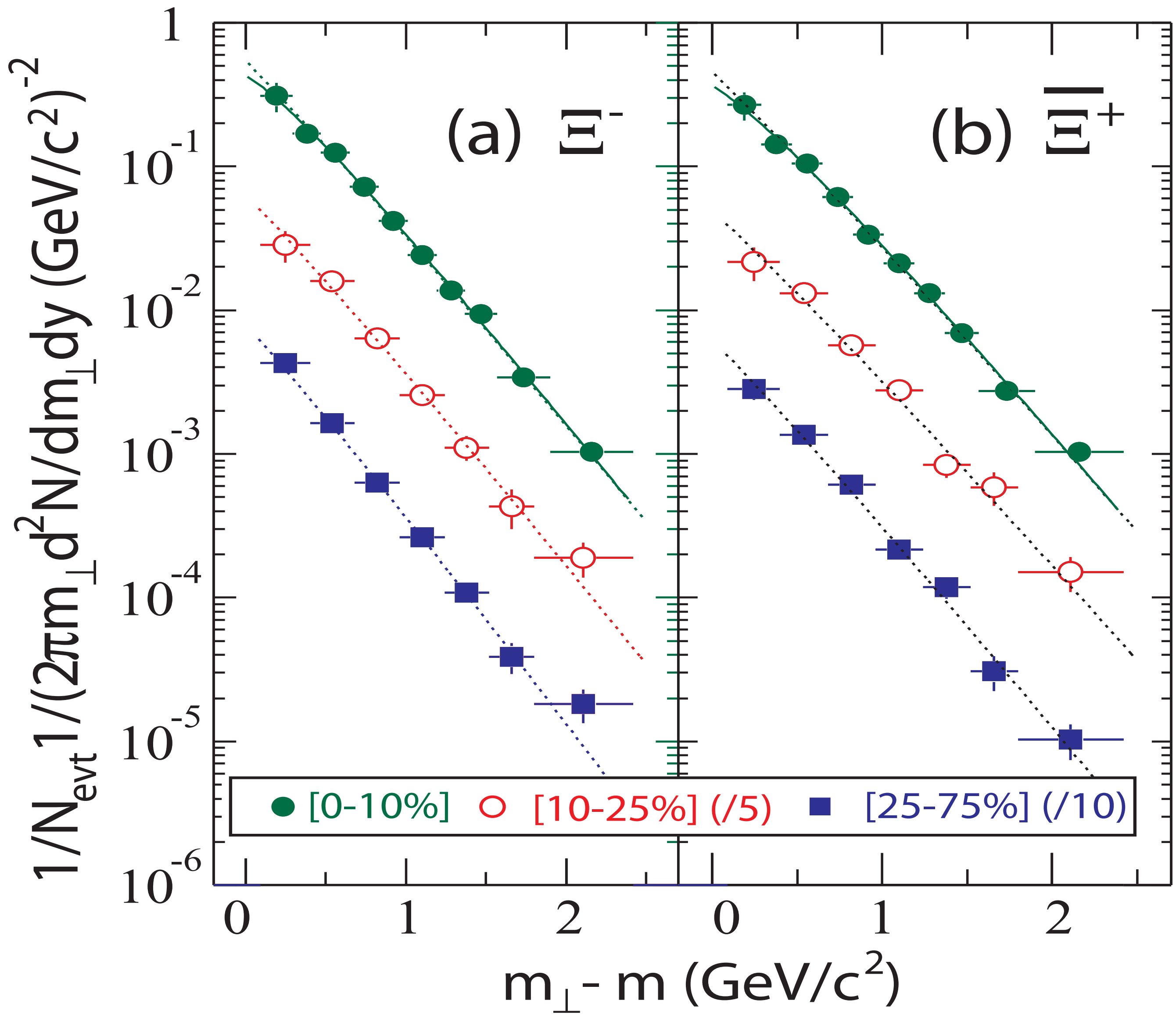
EXPLOSIVE FLOW effect

Difference between $\Omega + \overline{\Omega}$:

presence of an excess of low $p_\perp$ particles

we will return to study this in spectral analysis

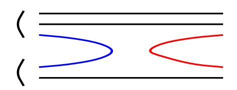
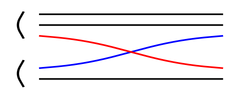
$\Xi^-, \overline{\Xi^-}$ Spectra RHIC-STAR 130+130 A GeV



ANALYSIS OF DATA

If QGP near/at chemical equilibrium prior to SUDDEN hadronization we must expect that a different phase, the hadron matter, will be in ABSOLUTE chemical non-equilibrium.

In general: 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**	**HG production** 
λ_i	$= e^{\mu_i/T}$ **controls difference between strange and light quarks $(i = q, s)$**	**Relative chemical equilibrium**	**HG exchange** 

See Physics Reports 1986 Koch, Müller, JR

Boltzmann gas: $\gamma \equiv \frac{\rho(T,\mu)}{\rho^{\rm eq}(T,\mu)}$

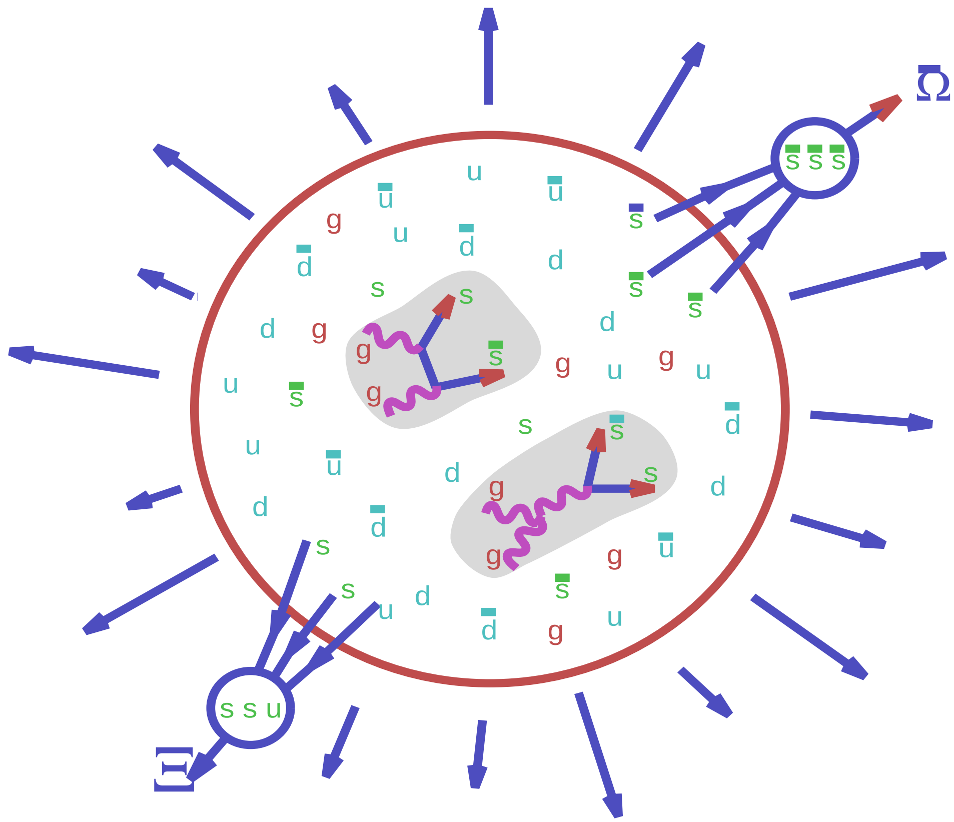
DISTINGUISH: hadron 'h' phase space and QGP phase parameters: micro-canonical variables such as baryon number, strangeness, charm, bottom, etc flavors are continuous, and entropy is almost continuous across phase boundary:

$$\gamma_s^{\rm QGP} \rho_{\rm eq}^{\rm QGP} V^{\rm QGP} = \gamma_s^{\rm h} \rho_{\rm eq}^{\rm h} V^{\rm h}$$

Equilibrium distributions are different in two phases and hence are densities:

$$\rho_{\rm eq}^{\rm QGP} = \int f_{\rm eq}^{\rm QGP}(p) dp \neq \rho_{\rm eq}^{\rm h} = \int f_{\rm eq}^{\rm h}(p) dp$$

Q-RECOMBINATION: A NEW HADRON FORMATION MECHANISM

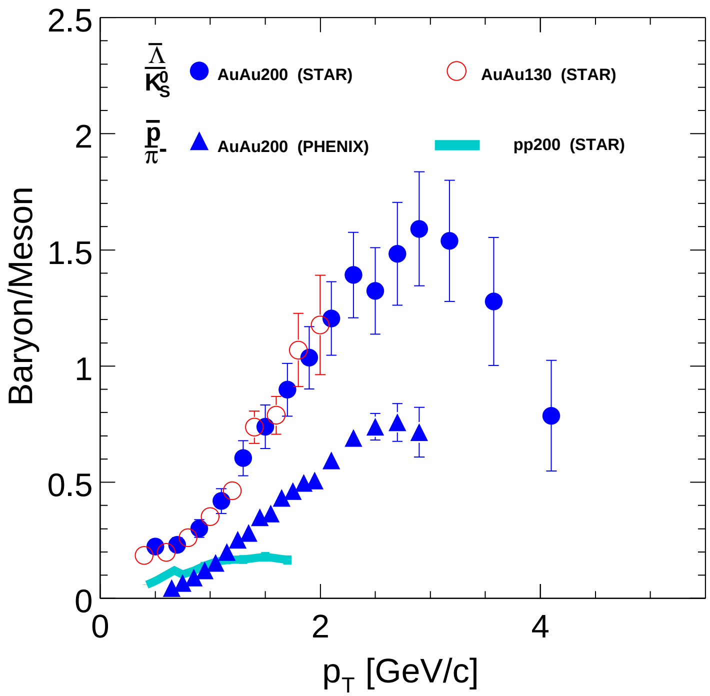


1. $GG \to s\bar{s}$ (thermal gluons collide)
   $GG \to c\bar{c}$ (initial parton collision)
   $GG \to b\bar{b}$ (initial parton collision)
   gluon dominated reactions
2. RECOMBINATION of pre-formed
   s, $\bar{s}$, c, $\bar{c}$, b, $\bar{b}$ quarks

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. See: P. Koch, B. Muller and J. Rafelski, *Strangeness In Relativistic Heavy Ion Collisions,* **Phys. Rept. 142, 167 (1986), and references therein.**

Indeed, a 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: non-equilibrium 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:**

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

Counting hadronic particles

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

$$\Upsilon_i \equiv \Pi_i \gamma_i^{n_i} \lambda_i^{k_i} = e^{\sigma_i/T}; \qquad \lambda_q \equiv e^{\frac{\mu_q}{T}} = e^{\frac{\mu_b}{3T}}, \qquad \lambda_s \equiv e^{\frac{\mu_s}{T}} = e^{\frac{[\mu_b/3-\mu_S]}{T}}$$

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

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

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

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

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

NOTE: For $\gamma_N \to 1$ **the pair terms vanishes, the** μ_b **term remains, it costs** $dE = \mu_B$ **to add to baryon number.**

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 $\rightarrow 0$ 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

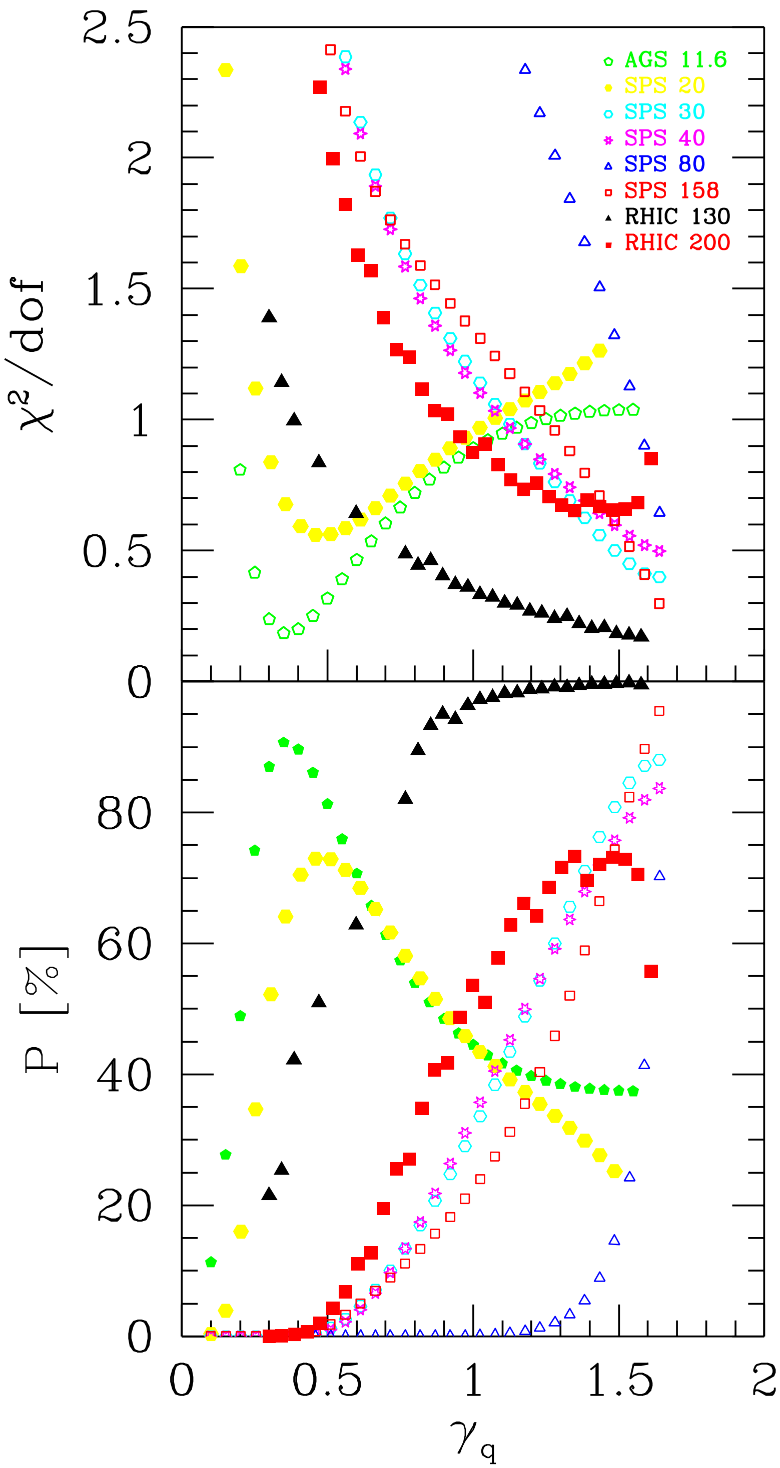
Lead author: Giorgio Torrieri,
W. Broniowski, W. Florkowski, J. Letessier, et al
nucl–th/0404083 Comp. Phys. Com. 167, 229 (2005)

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

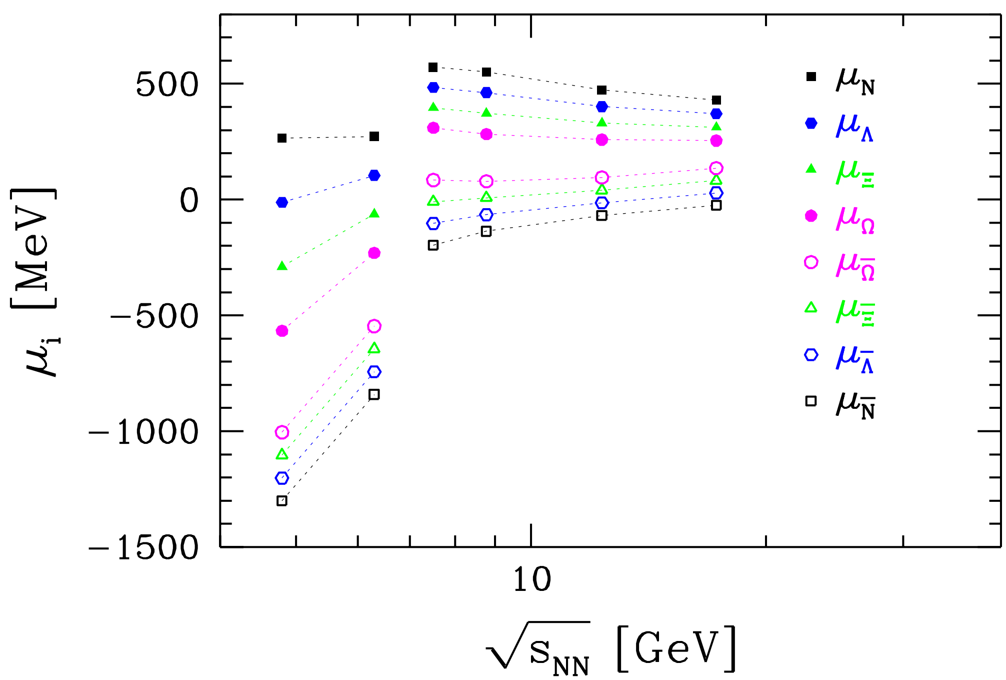
We will next do Energy-dependence for latest NA49 complete data sample.

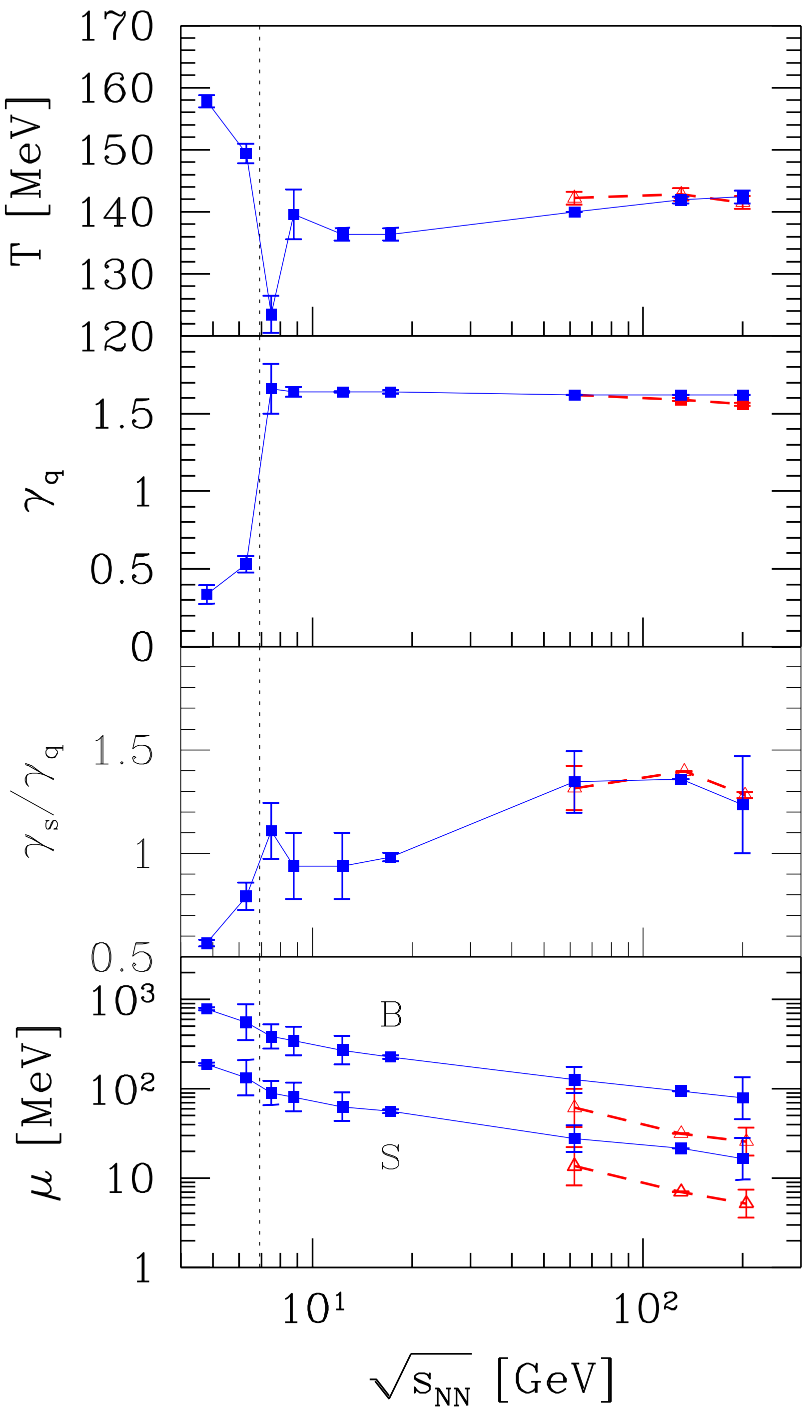
E[A**GeV**]	**11.6**	**20**	**30**	**40**	**80**	**158**
$\sqrt{s_{\rm NN}}$ [**GeV**]	**4.84**	**6.26**	**7.61**	**8.76**	**12.32**	**17.27**
$y_{\rm CM}$	**1.6**	**1.88**	**2.08**	**2.22**	**2.57**	**2.91**
$N_{4\pi}$ **centrality**	**most central**	7%	7%	7%	7%	5%
$R = p/\pi^+$, N_W	$R = 1.23 \pm 0.13$	**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**
$R = \mathrm{K}^+/\mathrm{K}^-$,$\mathrm{K}^+$	$R = 5.23 \pm 0.5$	**40±2.8**	**55.3±4.4**	**59.1±4.9**	**76.9±6**	**103±10**
K^-	**3.76±0.47**	**10.4±0.62**	**16.1±1**	**19.2±1.5**	**32.4±2.2**	**51.9±4.9**
$R = \phi/\mathrm{K}^+$, 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**		
$\mathrm{K_S}$						**81±4**
$V[\mathrm{fm}^3]$	**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**



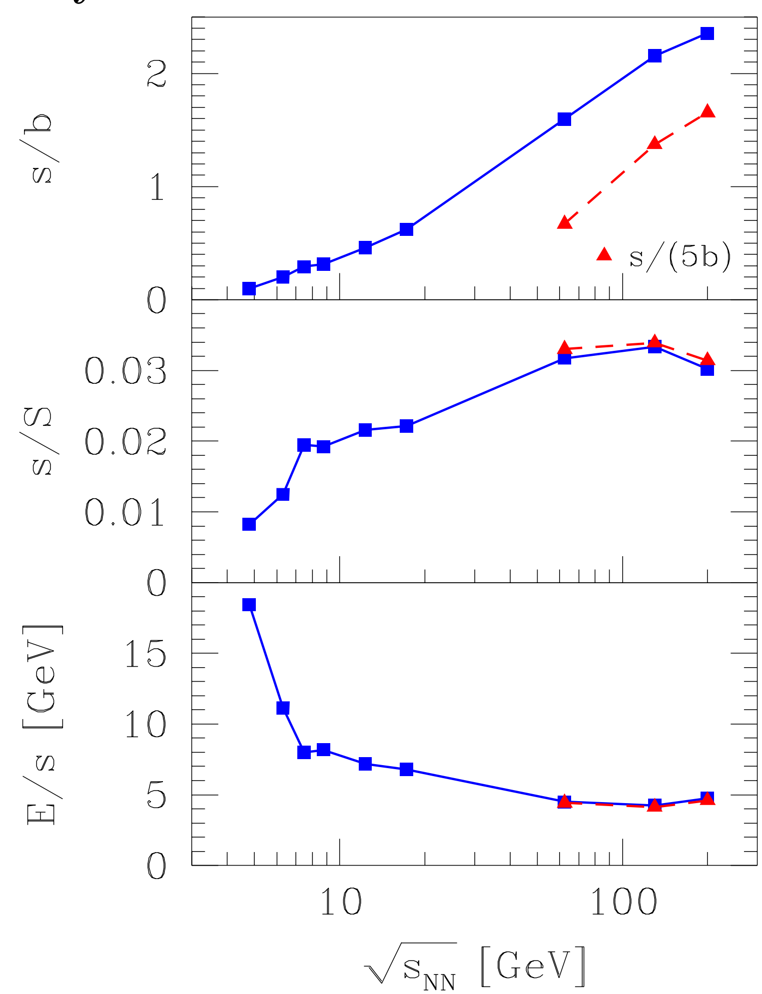
How good is the fit? χ^2/dof and confidence level P[%] as function of γ_q. For lowest two energies (AGS/SPS): small $\gamma_q < 1$ preferred, for other energies $\gamma_q \to e^{m_\pi/2T}$, maximum of entropy. If only one reaction energy is considered one may think $\gamma_q = 1$ is useful.

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......

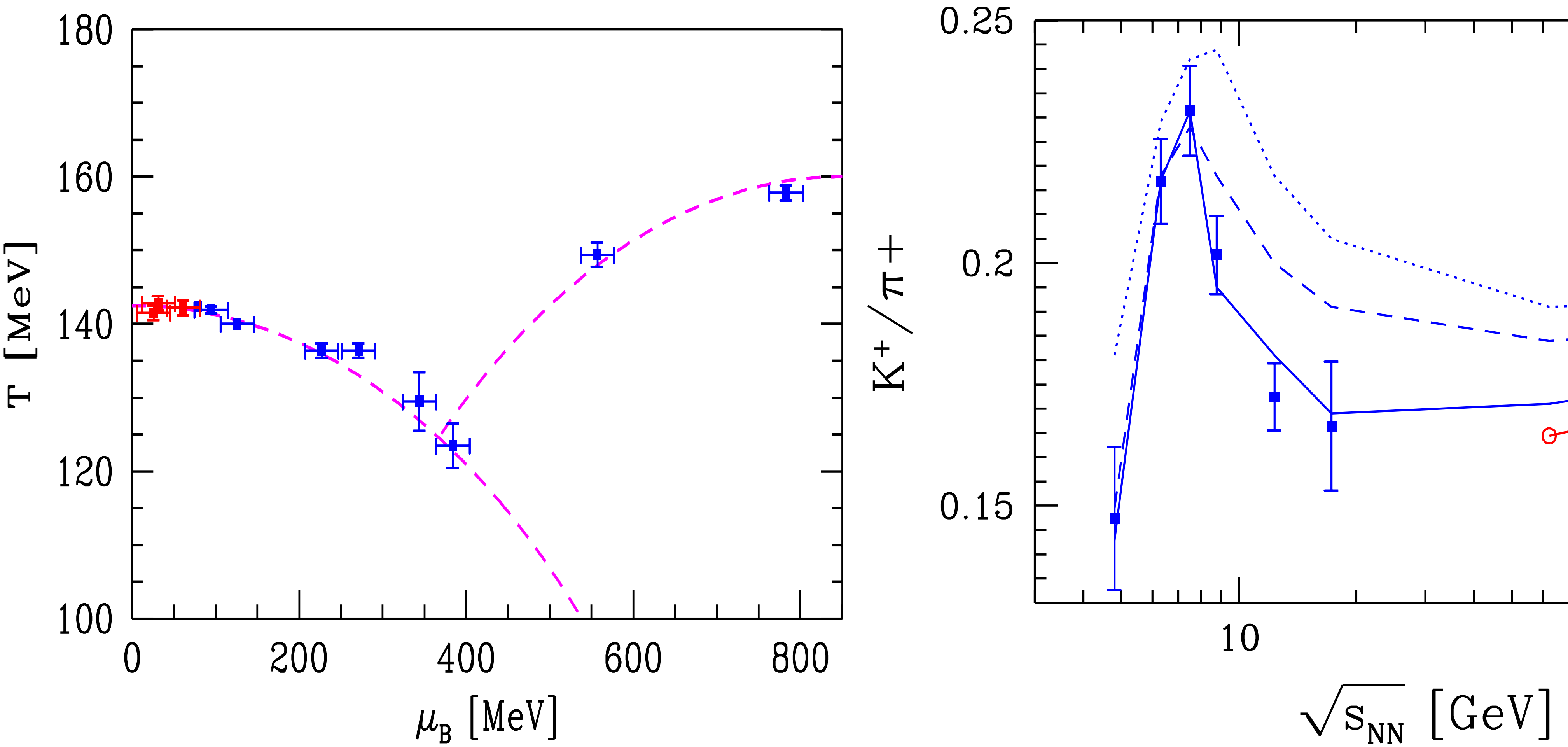




Statistical parameter results for $N_{4\pi}$ (blue online, square). Same for dN/dy at RHIC (red triangles). The lines guide the eye.



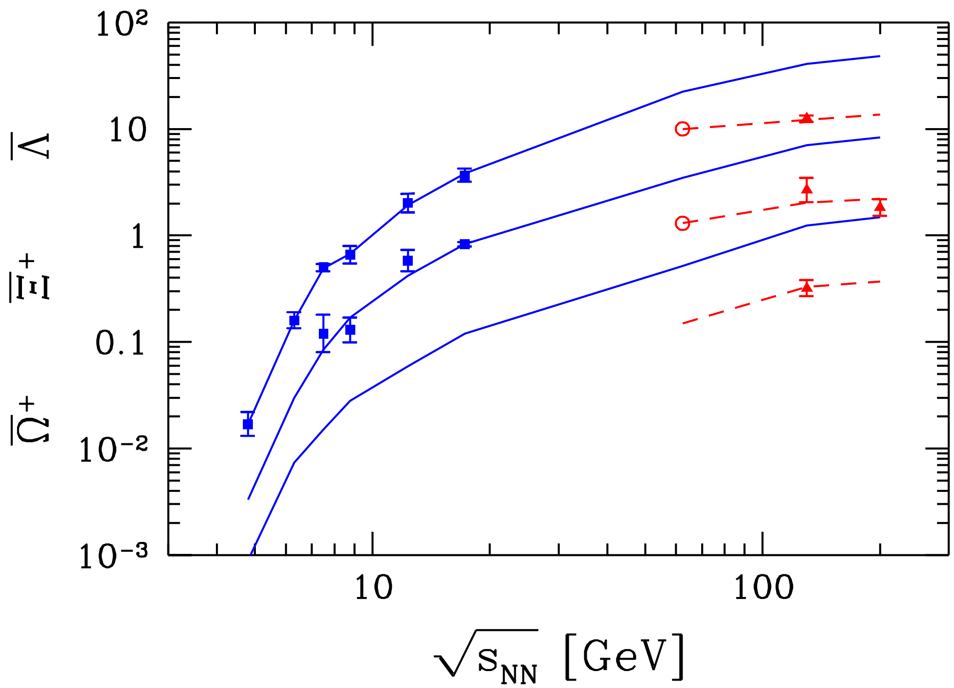
strangeness yield as function of reaction energy: s/b, s/S, s/E_{th}



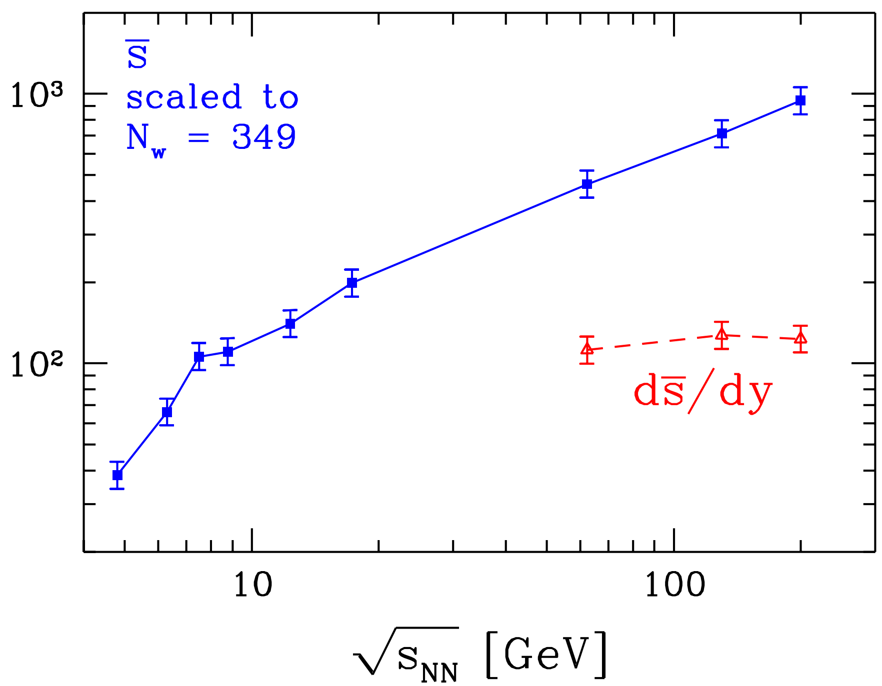
Features: **Reduced T (by 15 MeV), we think due to fast expansion. K^+/π^+ peak at the minimum of μ_B.**

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.

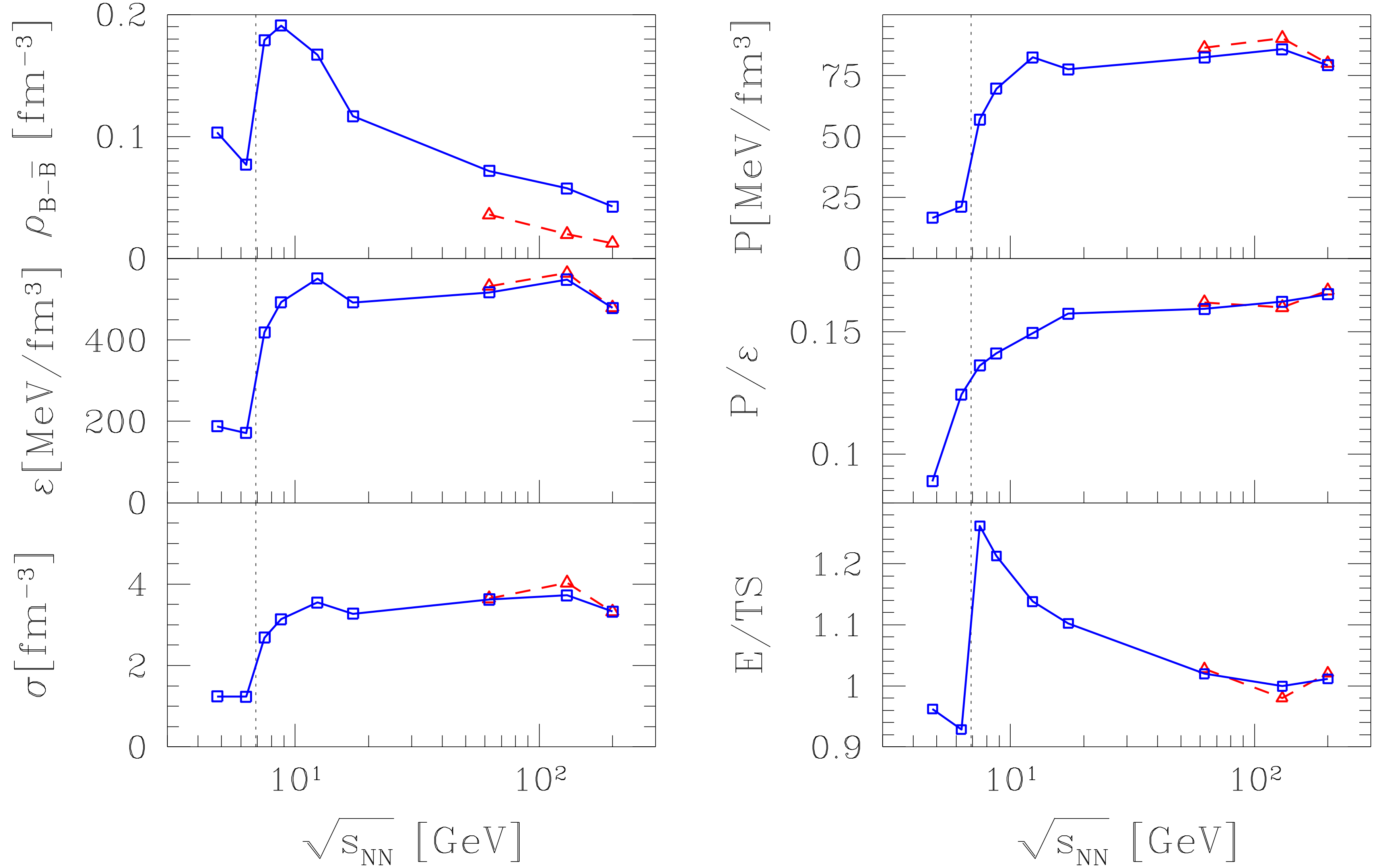
Antibaryon i.e. $\bar{u}, \bar{d}, \bar{s}$ yields



Strangeness Yield



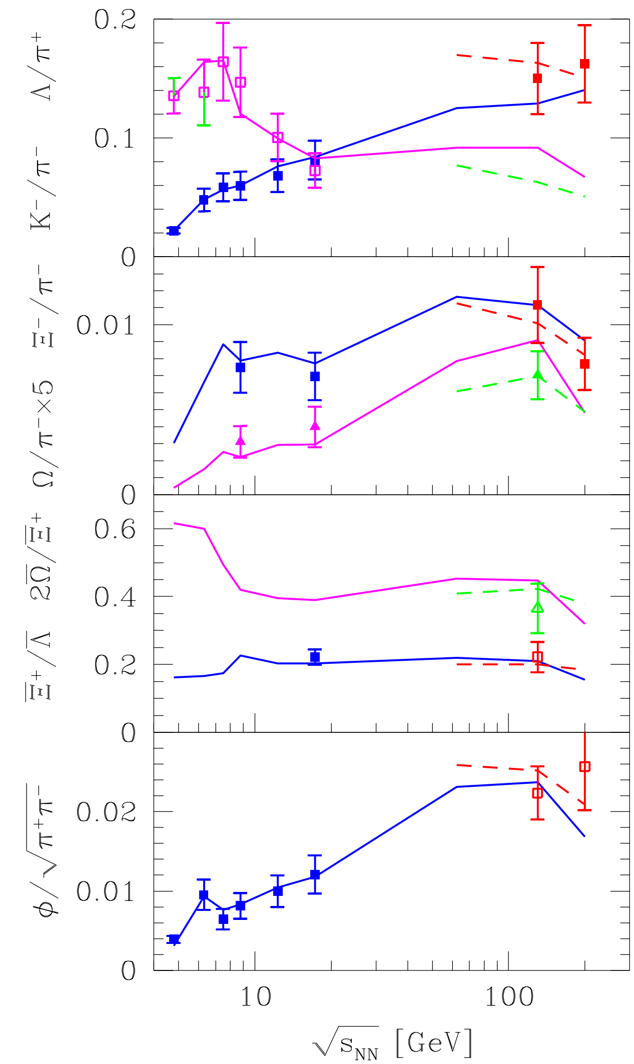
Antibaryons suppressed at low energies. Strangeness yield rises rapidly, slowdown at 30 GeV ($\sqrt{s_{\rm NN}} = 7.61$ GeV)



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
K^+	17.2	39.4	55.2	56.7	77.1	109.7
K^-	3.58	10.4	15.7	19.6	35.1	54.1
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
$K^0(892)$	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



TODAY STRANGENESS ENHANCEMENT: Strangeness / Entropy

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

For chemical equilibrium IN PLASMA:

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

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

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

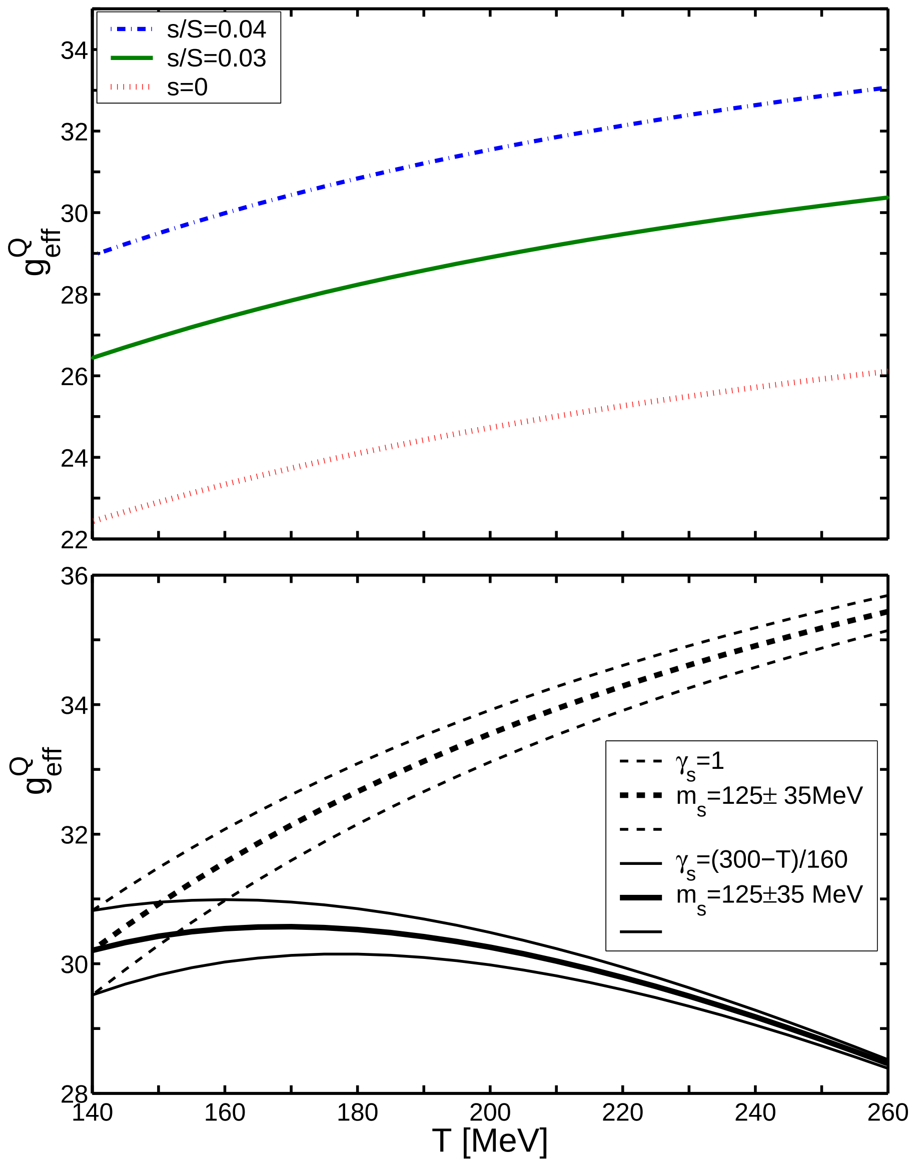
Chemical non-equilibrium occupancy of strangeness $\gamma_s^{\rm Q}$

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

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:

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

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



defined to reproduce the entropy content of QGP

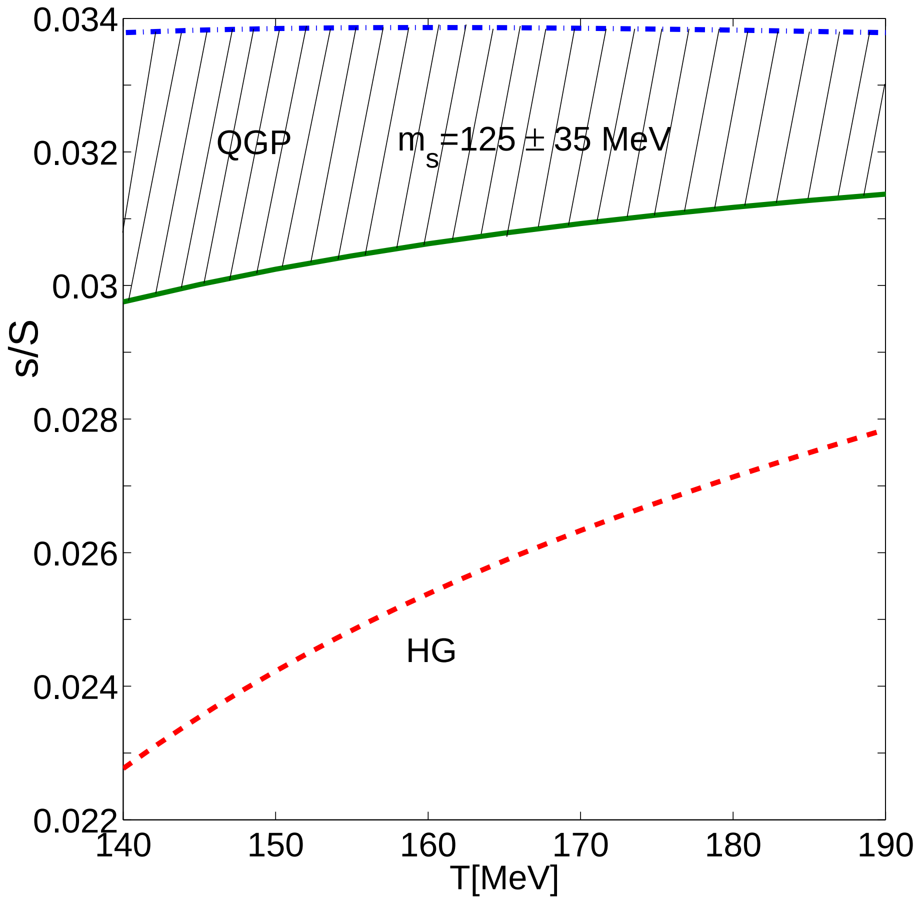
$$\sigma = \frac{4\pi^2}{90} g_{\rm eff}^Q T^3,$$

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

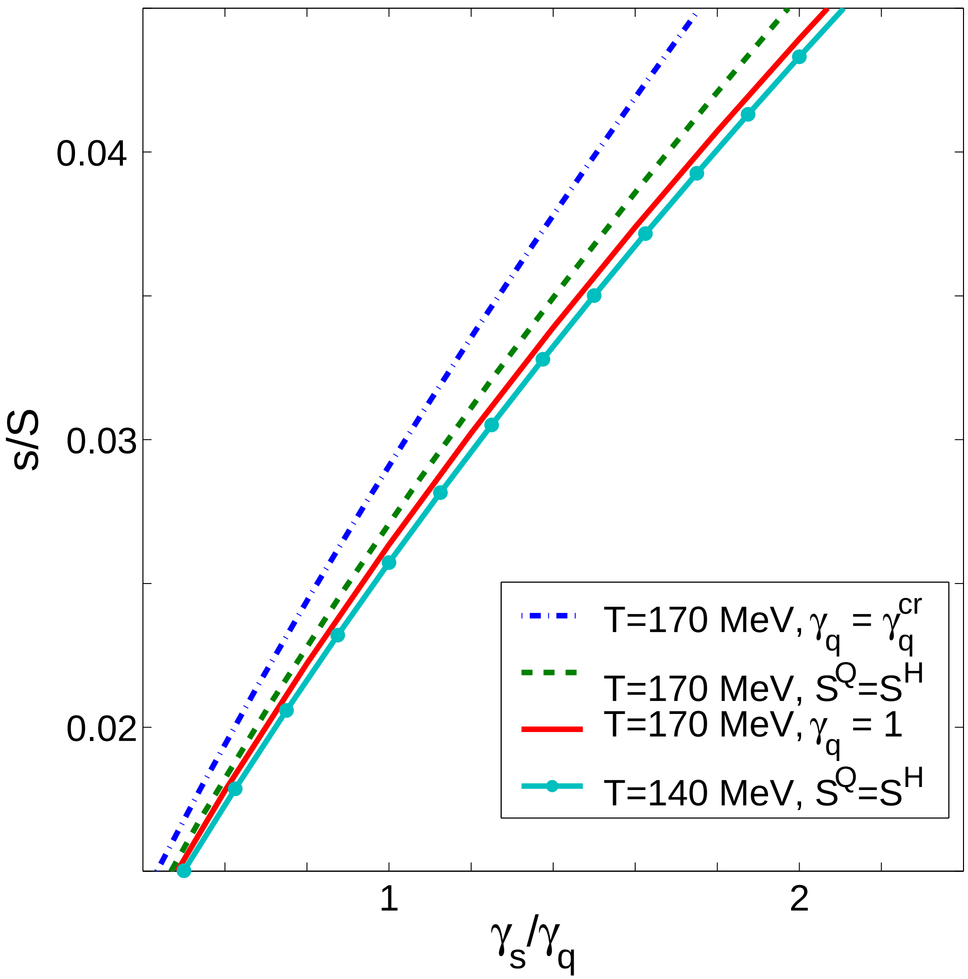
We compare deconfined quark-gluon plasma with hadron gas at common measured T.



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.

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.**

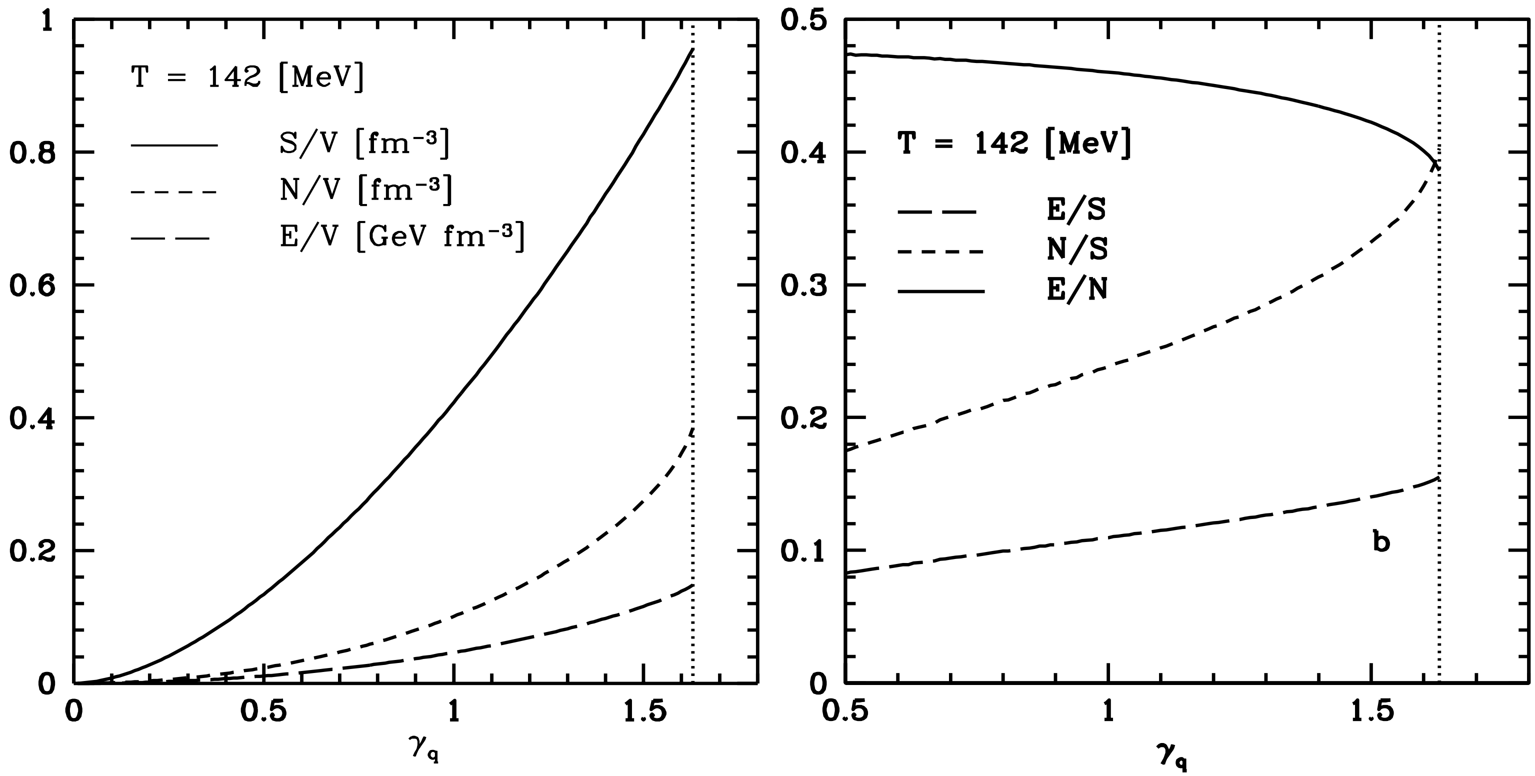
ENTROPY ENHANCEMENT CONSEQUENCE: $\gamma_q^{\rm H} > 1$ at breakup

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

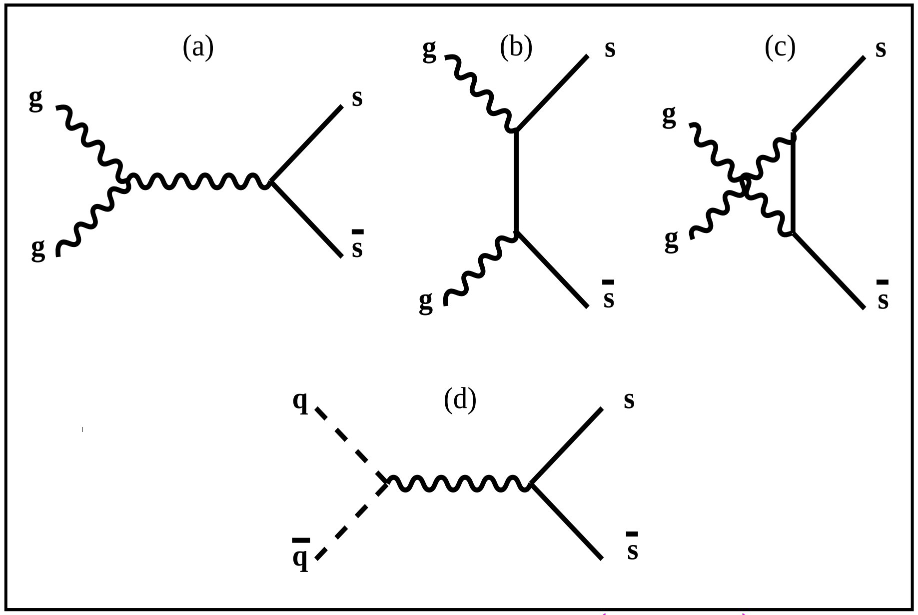
Example:maximization of entropy density in pion gas $E_\pi = \sqrt{m_\pi^2 + p^2}$

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

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



Kinetic 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 resummation: 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 $m_s(1\textbf{GeV})\simeq 2.1m_s(M_Z)\simeq 200\textbf{MeV}$.

Thermal average of (strangeness 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:

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

$1/(1+\delta_{1,2})$ **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

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

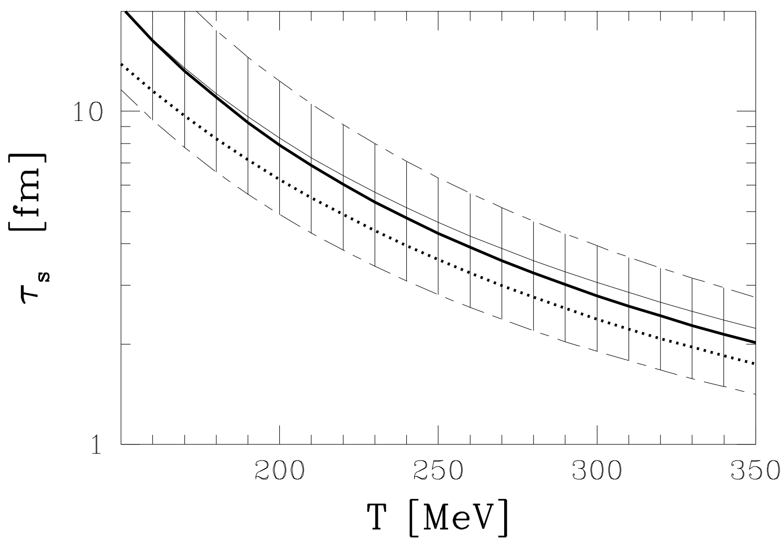
Time evolution of $s^{\rm Q}/S^{\rm Q}$, $\gamma_s^{\rm Q}$ (*drop henceforth superscript Q*)

strangeness production dominated by thermal gluon fusion $\boxed{GG \to s\bar{s}}$
at 10% level also: quark-antiquark fusion, primary parton/string dynamics; outcome depends on initial entropy content.

Kinetic equations for time evolution os s/S and γ_s

$$\frac{d}{d\tau}\frac{s}{S} = \frac{\tilde{g}_s}{g^{\rm QGP}} z^2 K_2(z) \left[\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d\ln[\tilde{g}_s z^2 K_2(z)/g^{\rm QGP}]}{d\tau}\right] \qquad z = \frac{m_s}{T}, \quad \sigma = \frac{4\pi^2}{90} g^{\rm QGP} T^3$$

$$\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d\ln[\tilde{g}_s z^2 K_2(z)/g^{\rm QGP}]}{d\tau} = \frac{A_G}{2n_s^\infty}\left[\gamma_{\rm G}^2 - {\gamma_s}^2\right] + \frac{A_q}{2n_s^\infty}\left[\gamma_{\rm q}^2 - {\gamma_s}^2\right]$$



pQCD invariant production rate A:

$$A^{12\to 34} \equiv \frac{1}{1+\delta_{1,2}} \rho_1^\infty \rho_2^\infty \langle \sigma_s v_{12} \rangle_T^{12\to 34}.$$

and the related characteristic time constant τ_s:

$$2\tau_s \equiv \frac{\rho_s(\infty)}{A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} + \ldots}$$

To integrate the equation for s/S we need to understand $T(\tau)$. Hydrodynamic expansion with Bjørken scaling motivates simple model assumptions.

Fireball volume time evolution model

To integrate the equation for s/S we need to understand $T(\tau)$.

The integration stops at the final observed conditions: $S(\tau_f)$, $T(\tau_f)$ and, the volume per rapidity, $\Delta V/\Delta y|_{\tau_f}$, available as normalizer of particle yields $dN_i/dy = n_i dV/dy$.

Theory (lattice) further provides Equations of State here mainly number of degrees of freedom in entropy $\sigma(T) = (dS/dy)/(dV/dy)$.

Hydrodynamic expansion with Bjørken scaling implies strictly $dS/dy = \sigma(T)dV/dy = \mathrm{Const.}$ as function of time.

This means that $dV/dy(\tau)$ expansion fixes $T(\tau)$.

$\frac{dV}{dy} \propto A_\perp(\tau) dz/dy|_{\tau,y}$

a) we need transverse area expansion, $A_\perp(\tau)$. We assume $R_\perp(\tau) = R_0 + v_\perp(\tau)\tau$ and consider two geometries:

i) $A_\perp = \pi R_\perp^2(\tau)$ **bulk expansion**

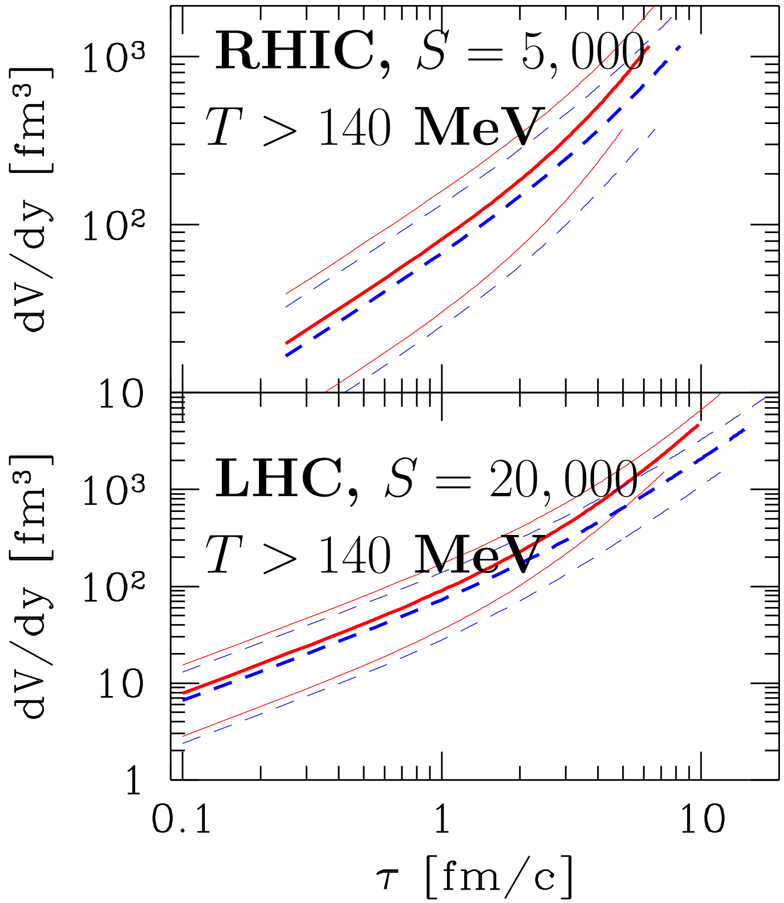
ii) $A_\perp = \pi\left[R_\perp^2(\tau) - (R_\perp^2(\tau) - d)^2\right] = 2\pi d\left[R_\perp(\tau) - \frac{d}{2}\right]$ **and**

b) we need to associate with the domain of observed rapidityΔy a geometric region at the source Δz. We take scaling Bjørken hydrodynamical solution:

$\frac{dz}{dy} = \tau \cosh y$.

Early time behavior $\gamma_G(tau)$ and $v(\tau)$ can be shown to be of minimal relevance. Strangeness looks back at times $\tau \simeq 2-3$ fm. Beyond, for yet earlier τ there is little, if any, memory.

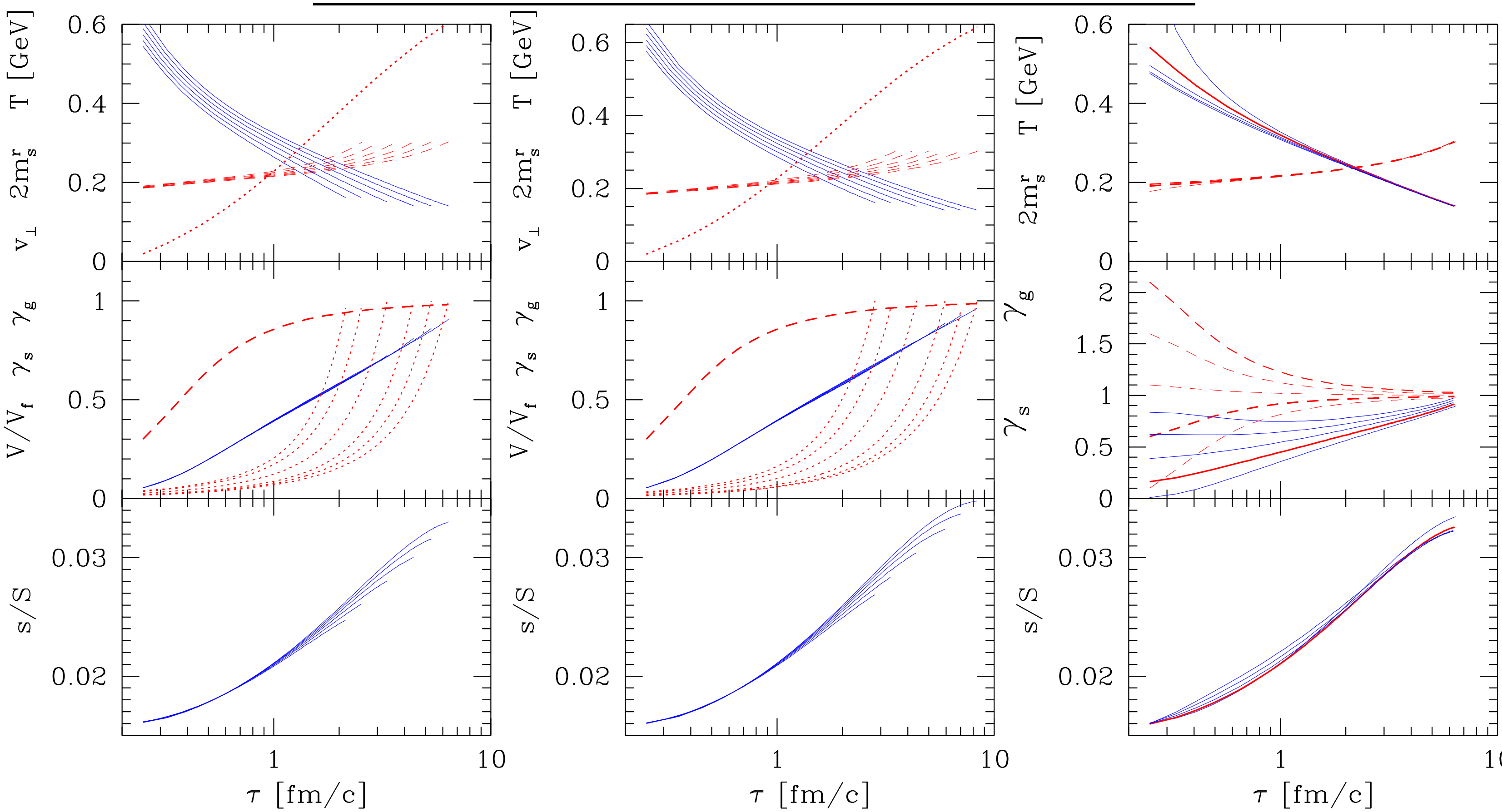
Typical examples of volume evolution



Three centralities: middle $R_\perp = 5$ fm and the upper/lower lines corresponding to $R_\perp = 7$, and, $R_\perp = 3$ fm/c. dashed lines for donut geometry $d = 2.1,\ 3.5$ and 4.9 fm.

Main difference LHC to RHIC, lifespan much longer, despite increase of average final expansion velocity from 0.6 to 0.8 c.

s/S and γ_s at RHIC: centrality dependence



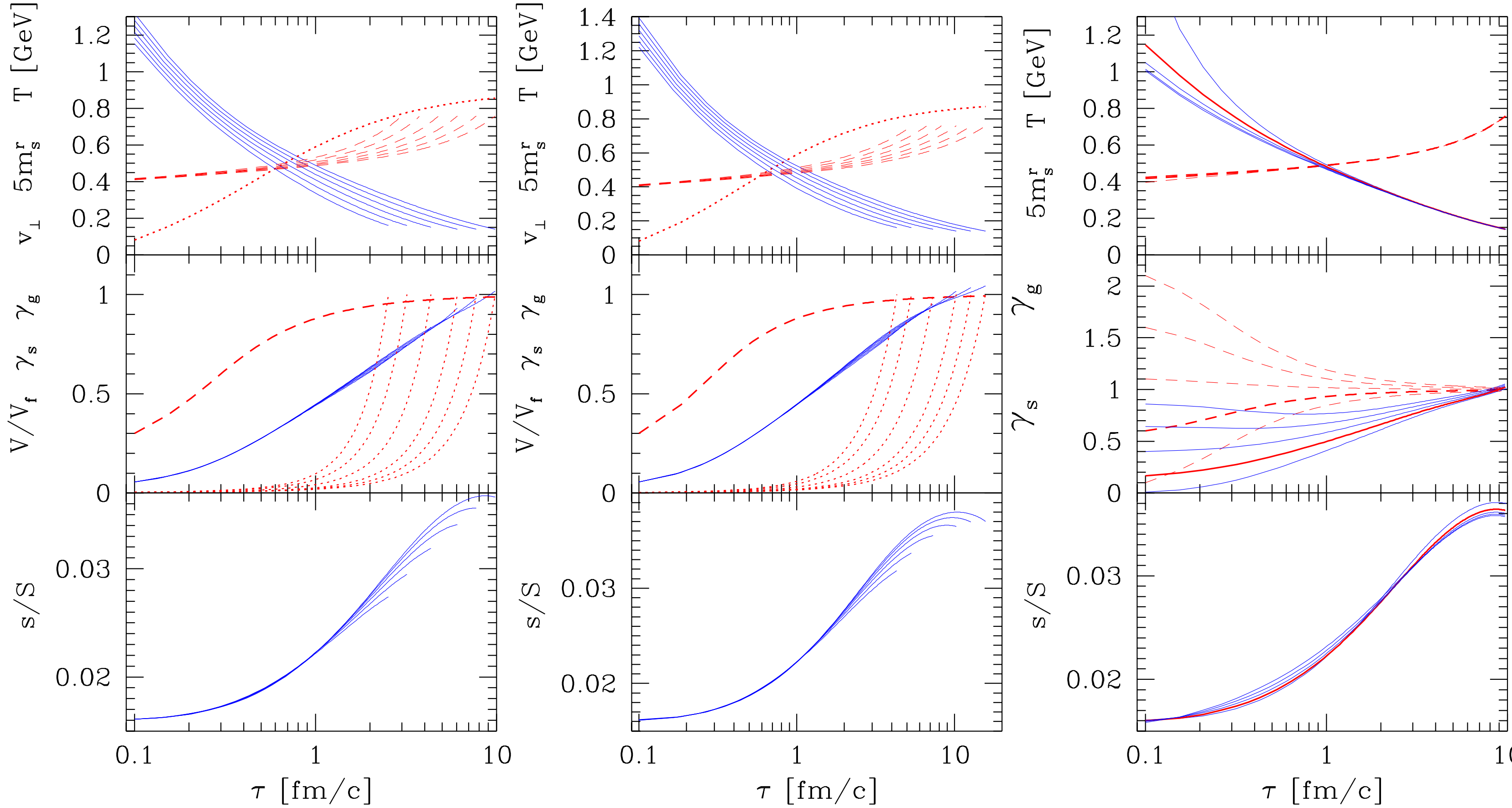
The two left panels: Comparison of the two transverse expansion models, bulk expansion (left), and wedge expansion. Different lines correspond to different centralities. On right: study of the influence of the initial density of partons.

Top: T, middle γ_s and bottom s/S

Assumptions:

dotted top panel: profile of $v_\perp(\tau)$, the transverse expansion velocity; middle panel: dashed $\gamma_g(\tau)$,(which determines slower equilibrating γ_q dotted: normalized $dV/dy(\tau)$ normalized by the freeze-out value.

Strangeness production at LHC after tuning RHIC, with $dS/dy|_{\rm LHC} = 4dS/dy|_{\rm RHIC}$

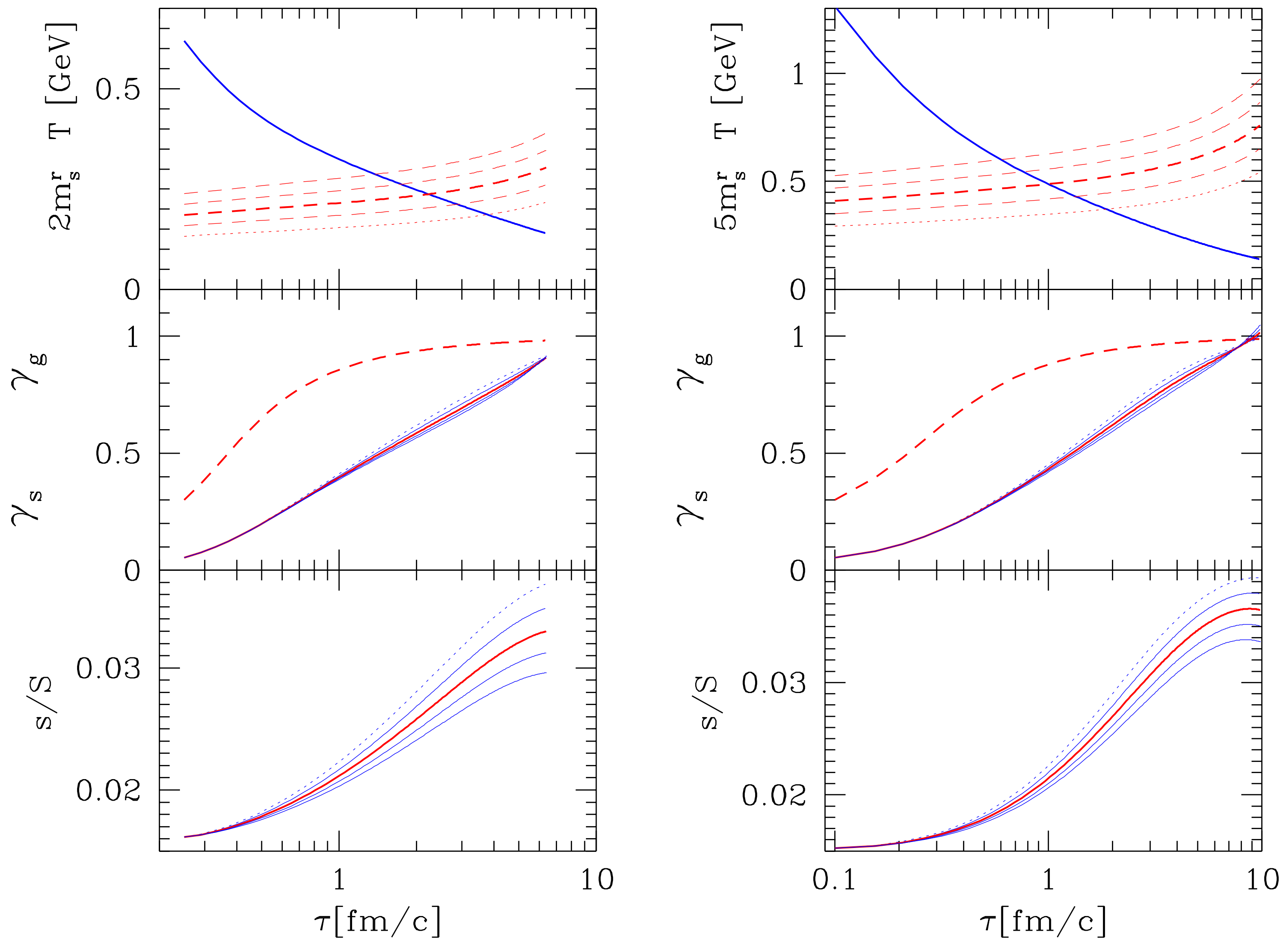


LHC differences to RHIC

- **There is a significant increase in initial temperature and gluon occupancy γ_g to accommodate increased initial pre-thermal evolution entropy.**
- **There is a about twice longer expansion time to the freeze-out condition, since there is 4 times entropy content at similar hadronization T_h.**
- **There is over saturation of $s/S, \gamma_s$ in QGP, and thus a much greater over-saturation in hadron phase space (for $T_h < 240$ MeV)**

NOTE: s/S measures chemical equilibration in QGP and number of strange to all degrees of freedom. Study as function of centrality to see saturation.

Strange quark mass matters



Left RHIC, right LHC, bulk volume expansion. m_s varies by factor 2.

γ_s overlays: Accidentally two effects cancel: for smaller mass more strangeness production, but by definition γ_s smaller. s/S of course bigger for smaller mass.

WHAT THAT MEANS FOR LHC BULK HADRONS

For computation of soft hadron production at LHC we need:

1) the entropy content: $dS/dy \equiv$ multiplicity,

not (yet) predictable, straight line exptrap.

2) strangeness content ds/dy and/or s/S

strangeness computable within pQCD given entropy

3) nett baryon stopping $\frac{d(b-\bar{b})}{dy}$, $\quad \frac{b-\bar{b}}{b+\bar{b}} \simeq 0$

unknown, very difficult to measure

Other Constraints and Inputs

a) Strangeness balance $\langle s\rangle = \langle \bar{s}\rangle$ at any rapidity

b) Net charge per net baryon ratio $Q/b = 0.4$

c1) $T = 140$ for hadronization at fixed V,T (Chemical non-equilibrium approach) and

c1) $T = 162$ for final hadron chemical equilibrium requiring re-heating/inflation (change in V,T).

d) bias to assure that SHARE 2 is looking for $\pi^+/\pi^- \simeq 1$, with $E/TS \simeq 1$.

The entropy content: $dS/dy \equiv$ hadron multiplicity

1) A straight line extrapolation as function of $\ln\sqrt{s_{\rm NN}}$ implies an increase of dS/dy by only a factor 1.65 from RHIC-200 to the LHC-ion top energy of $\sqrt{s_{\rm NN}} = 5520$ GeV.

2) BUT: We will also evaluate the case with 3.4-fold increase, with TPC visible $h = 2924$, in entropy/multiplicity content per unit of rapidity. We favor a 4-fold increase.

3) This $h = 2924$-value has been fine-tuned such that the visible charged hadron yield is just as in chemical equilibrium model, where the hadronization volume was set to be $V = 6200\,\mathrm{fm}^3$). This allows to compare the yields of both models normalized to same hadron yield. (Clever use of SHARE 2 allows to use h as input).

T[MeV]	140*	140*	161*
dV/dy[fm^3]	**2126**	**4223**	**6200***
dS/dy	**7457**	**16278**	**18790**
$b-\bar{b}$	**2.6**	**5.5**	**6.4**
$dh_{\rm ch}/dy$ **(PHOBOS)**	1150*	2435	2538
$dh^{\rm vis}_{\rm ch}/dy$ **(STAR)**	1350	2924* →	2924
$(b+\bar{b})/h^-$	**0.334**	**0.353**	**0.370**
$1000\cdot(\lambda_{\rm q,s}-1)$	5.6*, 2.1*	5.6*, 2.1*	5.6*, 2.0*
$\mu_{\rm B,S}$[MeV]	2.3*, 0.5*	2.3*, 0.5*	2.7*, 0.6*
$\gamma_{q,s}$	1.6*, 2.35	1.6*, 2.8	1*, 1*
s/S	0.034*	0.038*	0.0255
$E/(b-\bar{b})$	423	**431**	**404**
E/TS	**1.04**	**1.04**	**0.86**
P/E	**0.165**	**0.162**	**0.162**
E/V[MeV/fm^3]	**509**	**560**	**420**
S/V[1/fm^3]	**3.51**	**3.86**	**3.03**
$(s+\bar{s})/V$[1/fm^3]	**0.119**	**0.147**	**0.077**
P[MeV]	**84**	**91**	**68**

LHC predictions, our non-equilibrium two variants on left differing mainly by entropy/multiplicity contents, the chemical equilibrium model results are stated for comparison in the right column. Star '*' indicates a fixed input value, violet: 50% difference to equilibrium model.

T[MeV]	140*	140*	161*
$dh^{\rm vis}_{\rm ch}/dy$	1350	2924* →	2924
$0.1\cdot\pi^{\pm}$	**49/61**	**102/132**	**115/132**
p	25/45	50/101	71/111
Λ	**19/27**	**45/70**	**40/53**
K$^{\pm}$	**94**	**226**	**183**
ϕ	**14**	**38**	**25**
Ξ^-	**3.9**	**11**	**6.2**
Ω^-	**0.78**	**2.6**	**0.98**
$\Delta^0,\ \Delta^{++}$	**4.7**	**9.4**	**14.6**
$K^*_0(892)$	**22**	**52**	**55**
η	**62**	**149**	**133**
η'	**5.2**	**13.2**	**12.1**
ρ	**36**	**74**	**119**
ω	**32**	**65**	**109**
f_0	**2.8**	**5.6**	**10.2**
$\mathbf{K}^+/\pi^+_{\rm vis}$	**0.164**	**0.184**	**0.148**
$\Xi^-/\Lambda_{\rm vis}$	**0.143**	**0.159**	**0.116**
$\Lambda(1520)/\Lambda_{\rm vis}$	**0.044**	**0.041**	**0.060**
$\Xi(1530)^0/\Xi^-$	**0.33**	**0.33**	**0.36**
$1000\phi/h^{\rm vis}_{\rm ch}$	**10**	**13**	**8.4**
$K^*_0(892)/K^-$	**0.237**	**0.232**	**0.303**

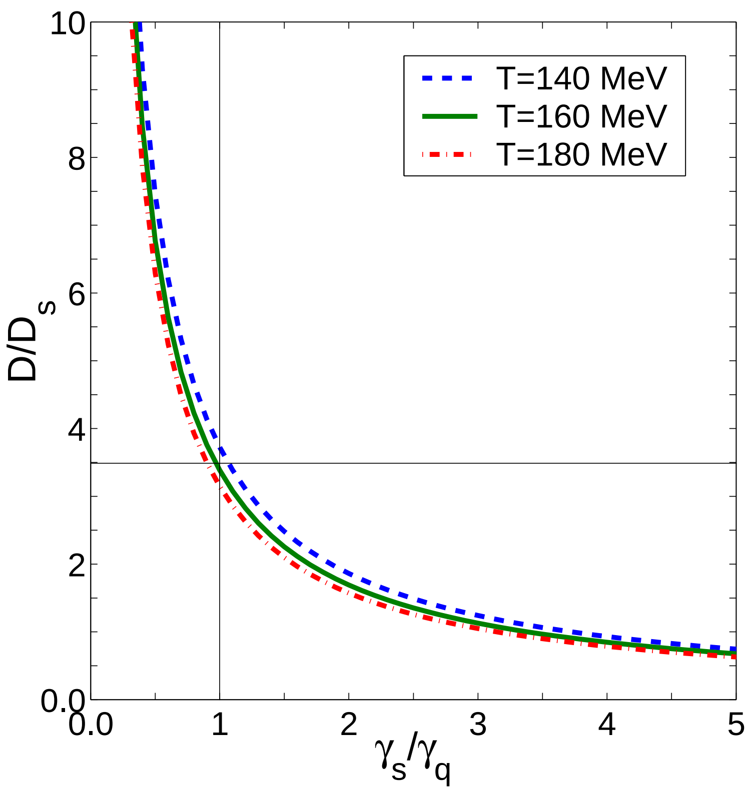
Charm and strangeness

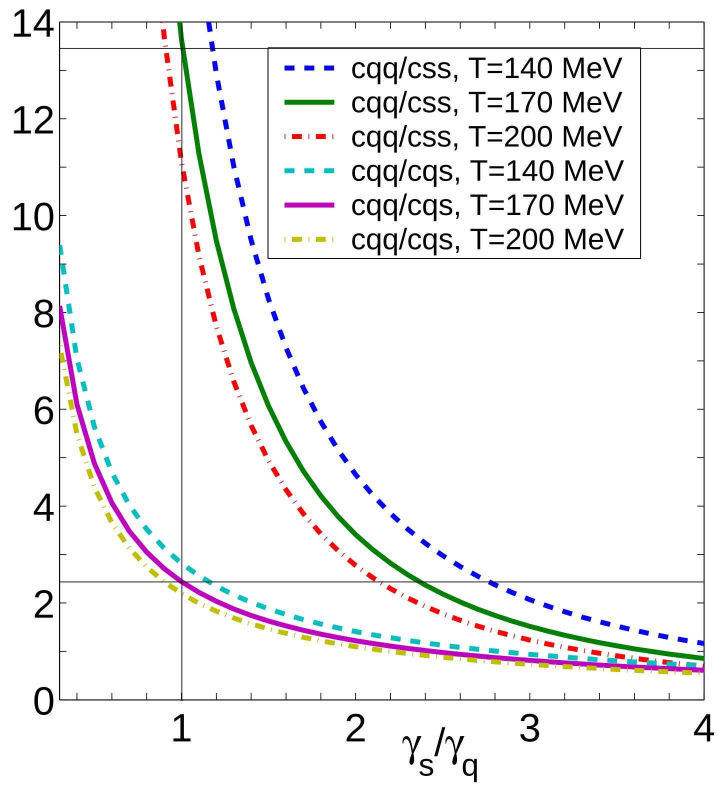
There is considerable energetic advantage for a charm quark to bind with a strange quark – most, if not all, charmonium–strange meson/baryon reactions of the type

$$c\bar{c} + sX \to cX + \bar{c}s, \quad X \equiv \bar{q} = \bar{u}, \bar{d}; X \equiv qq, qs, ss$$

are strongly exothermic.

In statistical hadronization this phase space effect favors formation of D_s which is greatly enhanced by $\gamma_s^{\rm H} > 1$.





Charmonium and strangeness

In the non-equilibrium statistical hadronization model we balance total yield of charmed particles within a given volume dV/dy to the level available in the QGP phase

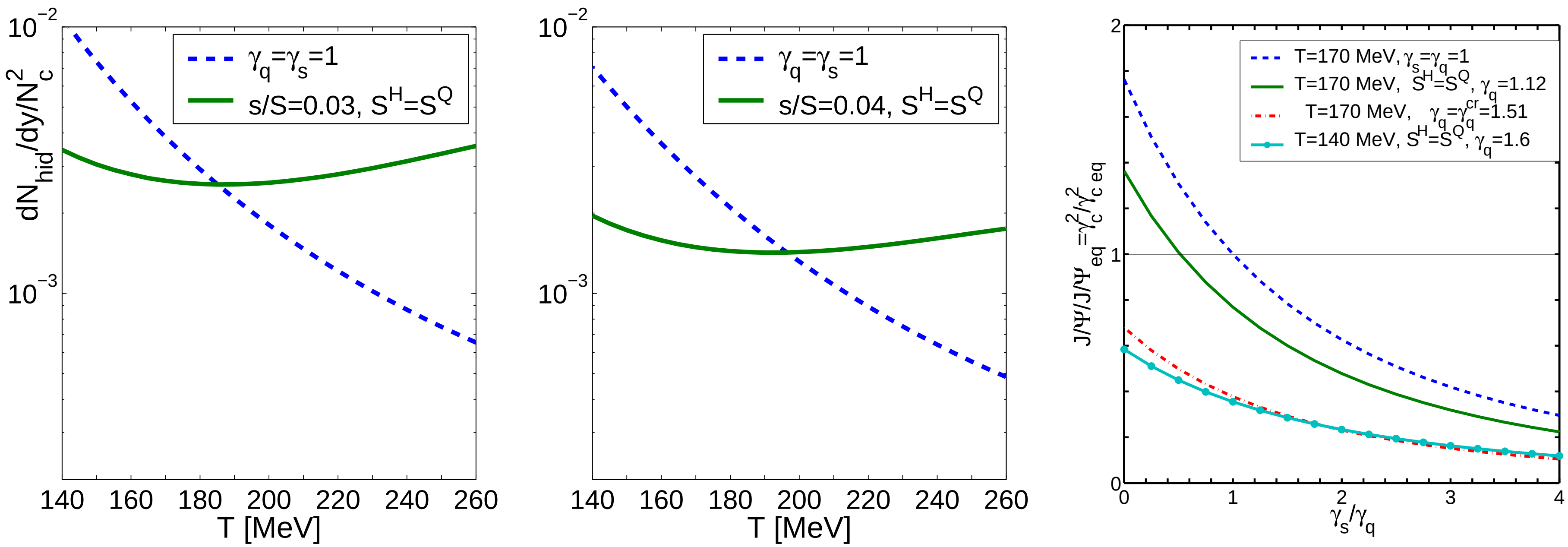
$$\frac{dN_c}{dy} \propto \frac{dV}{dy}(\gamma_c^{\rm H}\gamma_i^H + \ldots)$$

a few percent of the yield is in multi-charm baryons and charmonium involving higher powers of $\gamma_c^{\rm H}$. This constraint determines a value of $\gamma_c^H >> 1$, at LHC.

Therefore, the hadronization yields we compute for hidden charm mesons:

$$\frac{dN_{c\bar c}}{dy} \propto \frac{dV}{dy}\gamma_c^{H\,2} \propto \frac{\left(\frac{dN_c}{dy}\right)^2}{\gamma_i^{H\,2}\frac{dV}{dy}}$$

depends on the inverse of the model dependent reaction volume, and scales with the square of the total charm yields. For the case that $\gamma_i^H > 1$ a hereto unexpected suppression of 'onium yield is predicted. This effect of course CAN OPERATE also at SPS, if charmonium is made in recombination.



Left two panels: $c\bar{c}/N_c^2$ relative yields as a function of hadronization temperature T, right panel ratio $J/\Psi/J/\Psi_{eq}$ as a function of $\gamma_s^{\rm H}/\gamma_q^{\rm H}$. The yield of all hidden charm $c\bar{c}$ (sum over all $c\bar{c}$ mesons) is shown, normalized by the square of $dN_c/dy = 10$. Result for $s/S = 0.03$ with $dV/dy = 600\,$fm^3, $T = 200$ MeV (solid line, left panel) and for $s/S = 0.04$ with $dV/dy = 800\,$fm^3, $T = 200$ MeV (solid line, middle panel). Results shown for chemical equilibrium case (dashed lines) are for the values $\gamma_s = \gamma_q = 1$. For the chemical non-equilibrium hadronization (solid lines $\gamma_i^H > 1, i = q, s$), the QGP and hadron phase space is evaluated conserving entropy $S^Q = S^H$ and strangeness $s^Q = s^H$ between phases.

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.**

INSIGHTS FOR LHC

Strangeness production slightly over-saturates LHC-QGP phase space if it nearly saturates (QGP equilibrium) the RHIC-QGP phase space, expect $s/S \simeq 0.36 \pm 0.04$. Note that s/S changes little in last phase of expansion, so it can be computed at $T = 1.5T_{\rm cr}$, QGP equilibrium is nearly reliable.

The measurement of p, Λ, π suffers from significant weak decay contribution, differs relatively little between models (also since there is adjustment to fit total hadron yields), not very characteristic and because of WD must be used with caution

Strangeness/entropy enhancement can be easily observed in multi-strange hadron Ξ, ω and ϕ yields

Non-strange heavy resonances suppressed, not the resonances with strangeness content

Strange D$_s$ mesons enhanced, $c\bar{c}$ charmonium suppressed in over-saturated HG phase.

In fact all the above exactly true at RHIC as well.