

Strangeness Enhancement and Charm Hadronization

June 28, 2007, SQM07 Levoca

Jean Letessier and **JR** *Strangeness chemical equilibration in QGP at RHIC and LHC.* arXiv:nucl-th/0602047, Phys.Rev.C75:014905,2007.

JR and **Jean Letessier**, *Soft hadron ratios at the LHC* arXiv:hep-ph/0506140, Eur.Phys.J.C45:61-72,2006.

Inga Kouznetsowa and **JR** *Heavy Flavor Hadrons in Statistical Hadronization of Strangeness-rich QGP* arXiv:hep-ph/0607203, Eur.Phys.J.C51:113-133, 2007 .

- 1) Charm and Beauty from Strangeness-rich QGP at LHC
- 2) Charmonium Suppression in Strangeness-rich QGP

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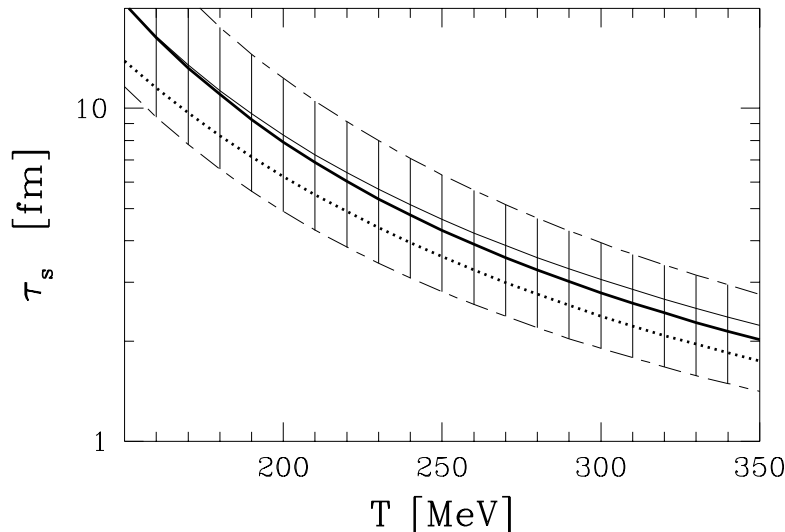
Time evolution of s^Q/S^Q , γ_s^Q (drop henceforth superscript Q)

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

Kinetic equations for time evolution of s/S and γ_s

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

$$\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d \ln[\tilde{g}_s z^2 K_2(z)/g^{\text{QGP}}]}{d\tau} = \frac{A_G}{2n_s^\infty} [\gamma_G^2 - \gamma_s^2] + \frac{A_q}{2n_s^\infty} [\gamma_q^2 - \gamma_s^2]$$



pQCD invariant production rate A :

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

and the related characteristic time constant

τ_s :

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

To integrate the equation for s/S we need to understand $T(\tau)$. Hydrodynamic expansion with Bjorken 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 $dS/dy = \sigma(T)dV/dy = \text{Const.}$ 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

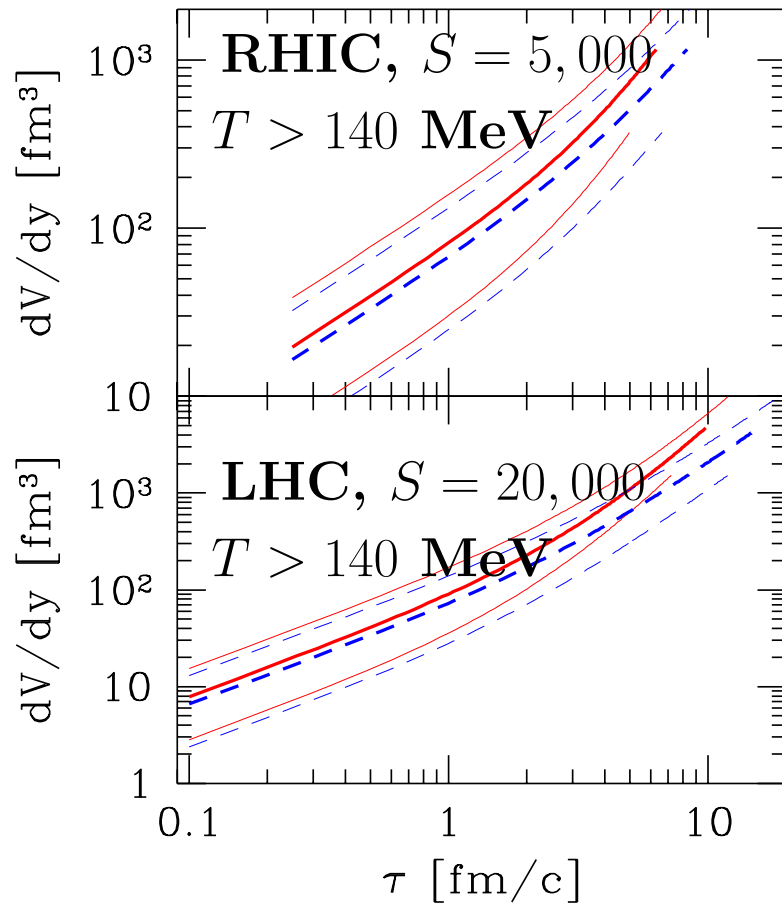
ii) $A_{\perp} = \pi [R_{\perp}^2(\tau) - (R_{\perp}^2(\tau) - d)^2] = 2\pi d [R_{\perp}(\tau) - \frac{d}{2}]$ and

b) we need to associate with the domain of observed rapidity Δy 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.

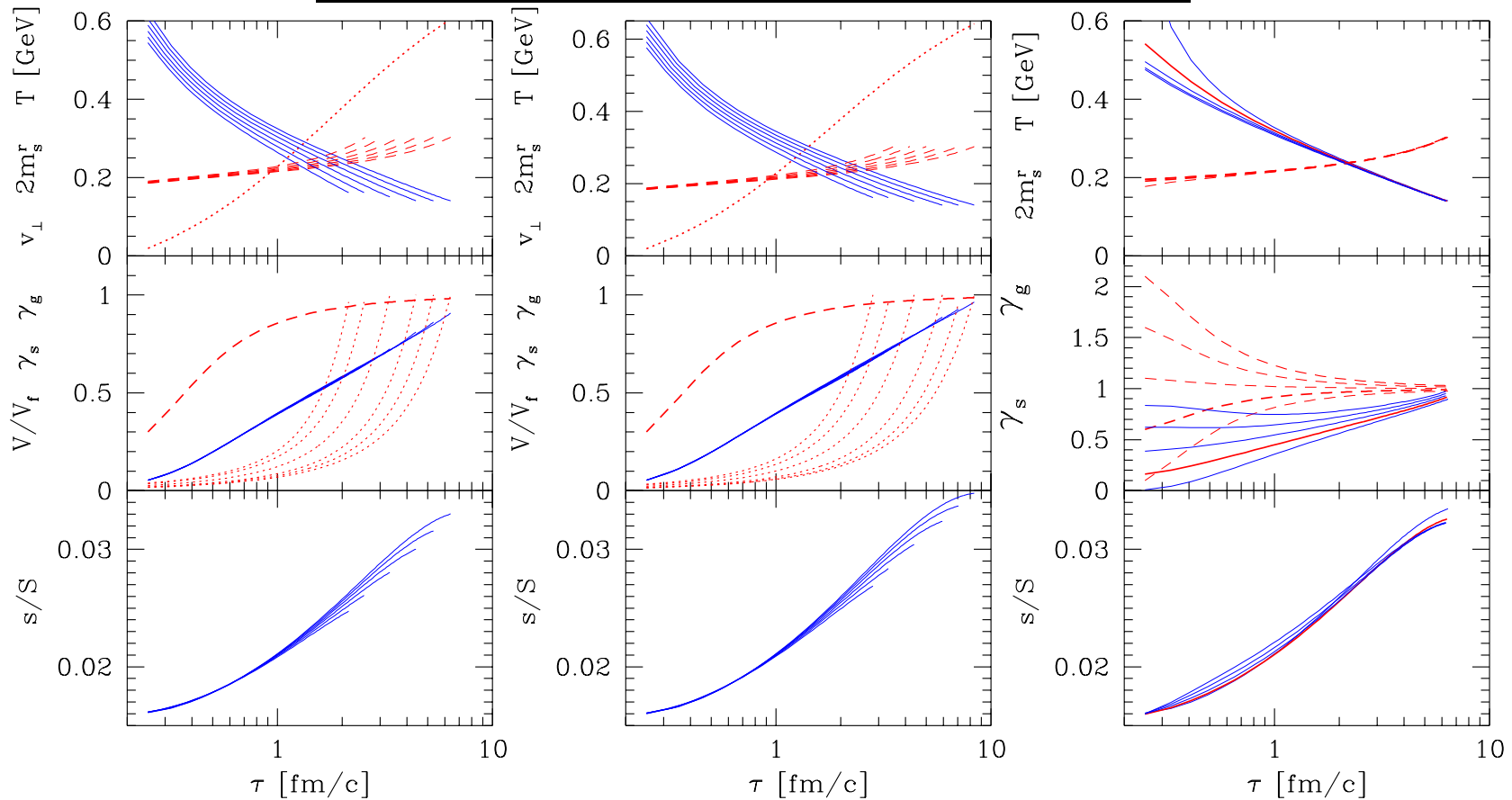
Typical examples of volume evolution



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



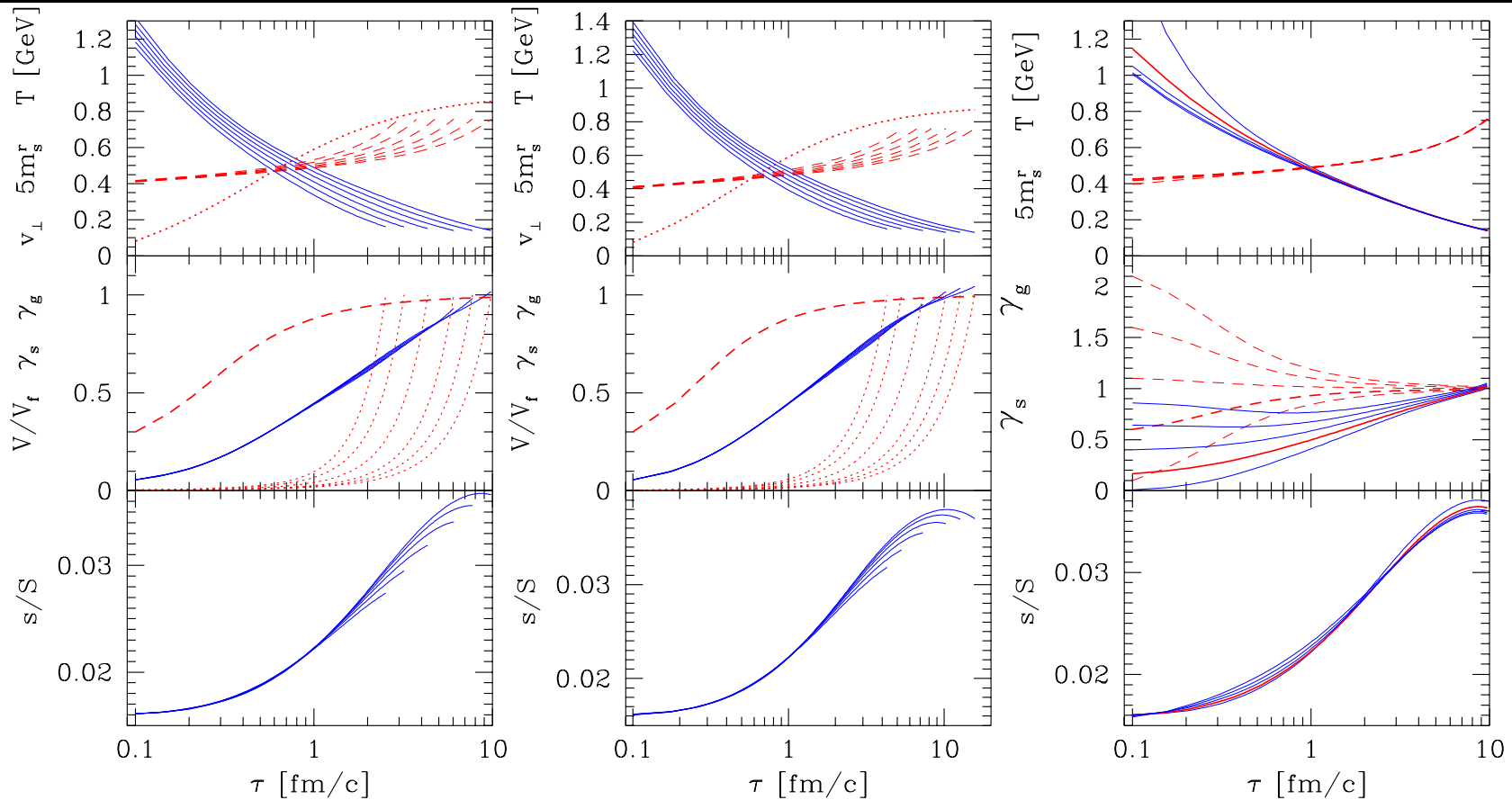
The two left panels: Comparison of the two transverse expansion models, bulk expansion (left), and wedge expansion. Different lines correspond to different centralities. **On right: study of the influence of the initial density of partons.**

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 $dS/dy|_{\text{LHC}} = 4dS/dy|_{\text{RHIC}}$

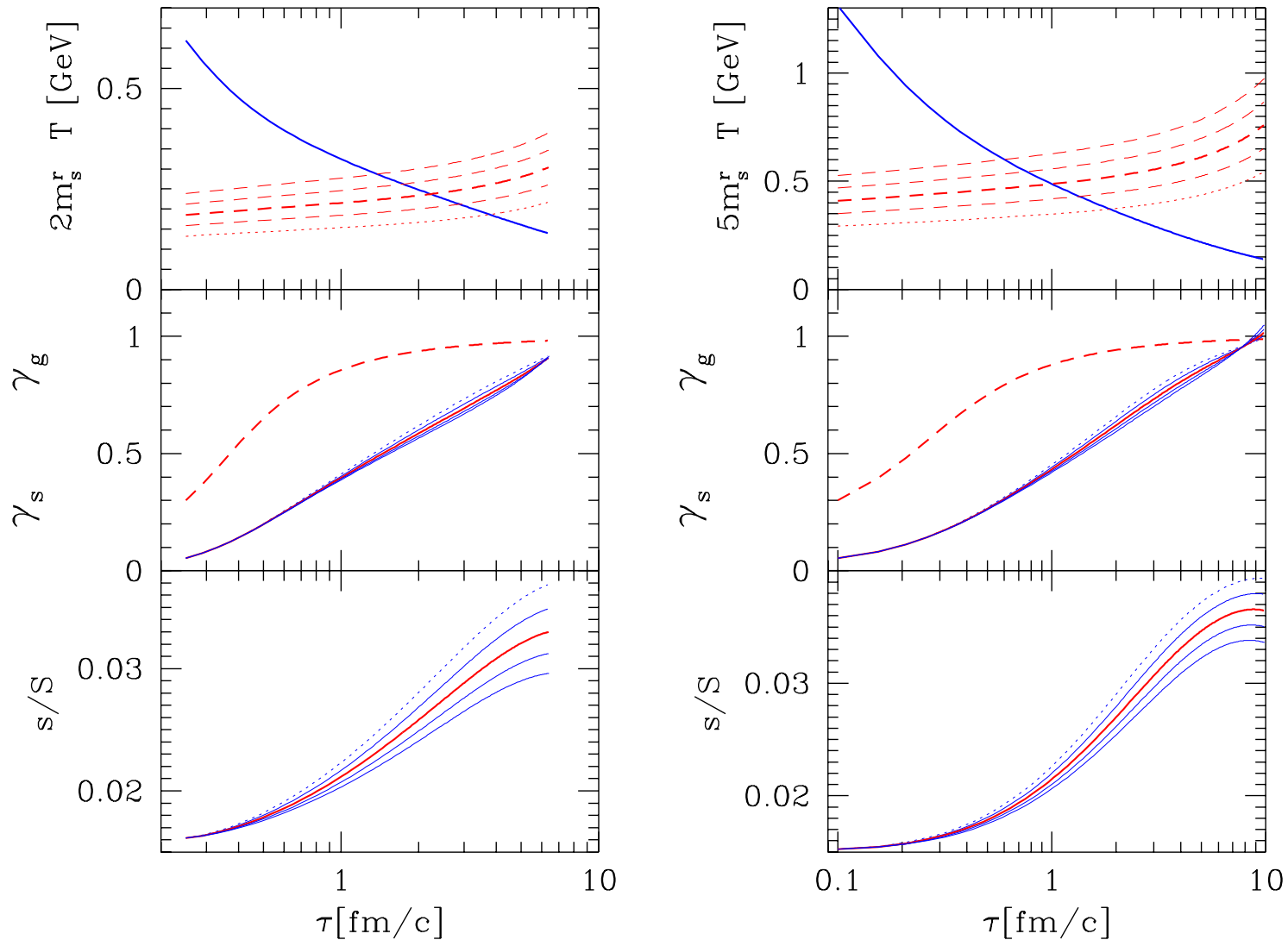


LHC differences to RHIC

- 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 $\frac{d(b-\bar{b})}{dy}$, $\frac{b-\bar{b}}{b+\bar{b}} \simeq 0$

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 reheating/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 $\ln \sqrt{s_{\text{NN}}}$ implies an increase of dS/dy by **only a factor 1.65** from RHIC-200 to the LHC-ion top energy of $\sqrt{s_{\text{NN}}} = 5520$ 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.

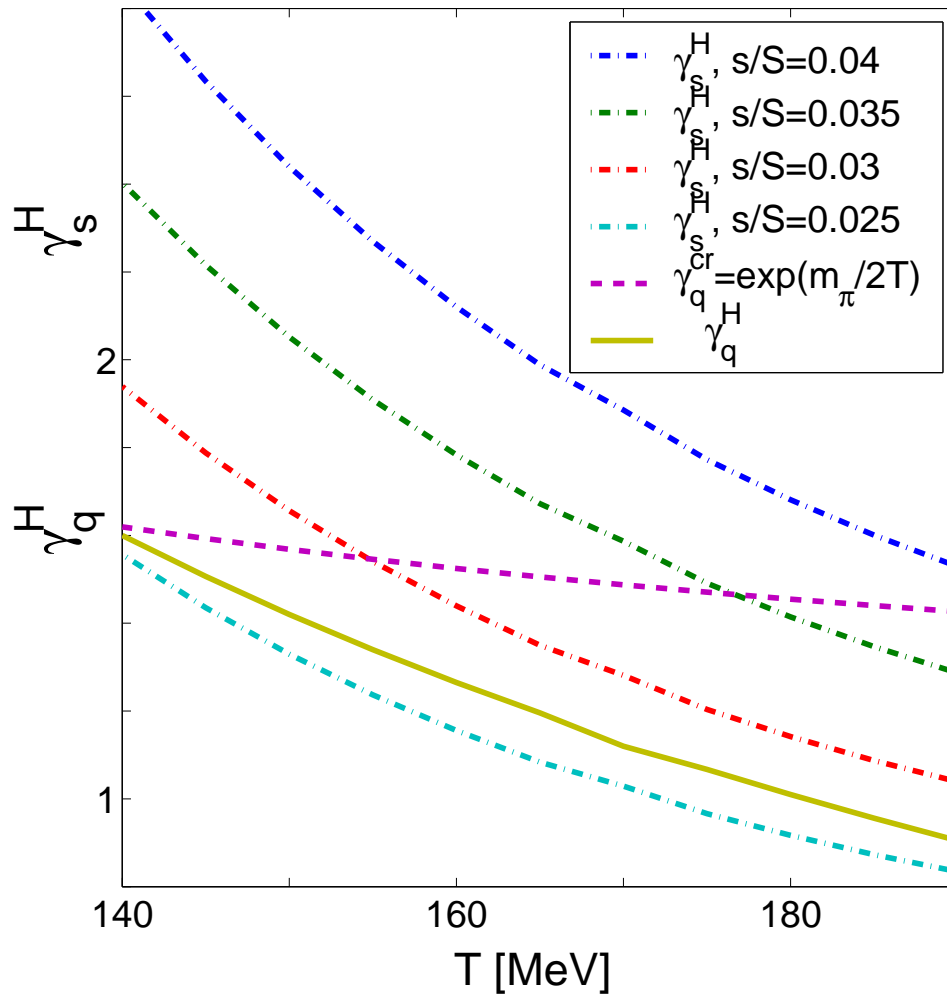
3) This $h = 2924$ -value has been fine-tuned such that the visible charged hadron yield is just as in chemical equilibrium model, where the hadronization volume was set to be $V = 6200 \text{ fm}^3$). This allows to compare the yields of both models normalized to same hadron yield. (Clever use of SHARE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

| | | | |
|---|------------|---------------------|------------|
| $T[\text{MeV}]$ | 140* | 140* | 161* |
| $dV/dy[\text{fm}^3]$ | 2126 | 4223 | 6200* |
| dS/dy | 7457 | 16278 | 18790 |
| $b - \bar{b}$ | 2.6 | 5.5 | 6.4 |
| dh_{ch}/dy (PHOBOS) | 1150* | 2435 | 2538 |
| $dh_{\text{ch}}^{\text{vis}}/dy$ (STAR) | 1350 | 2924* \rightarrow | 2924 |
| $(b + \bar{b})/h^-$ | 0.334 | 0.353 | 0.370 |
| $1000 \cdot (\lambda_{q,s} - 1)$ | 5.6*, 2.1* | 5.6*, 2.1* | 5.6*, 2.0* |
| $\mu_{B,S}[\text{MeV}]$ | 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 |
| $E/V[\text{MeV}/\text{fm}^3]$ | 509 | 560 | 420 |
| $S/V[1/\text{fm}^3]$ | 3.51 | 3.86 | 3.03 |
| $(s + \bar{s})/V[1/\text{fm}^3]$ | 0.119 | 0.147 | 0.077 |
| $P[\text{MeV}]$ | 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.

| | | | |
|---------------------------------------|-------|---------------------|---------|
| $T[\text{MeV}]$ | 140* | 140* | 161* |
| $dh_{\text{ch}}^{\text{vis}}/dy$ | 1350 | 2924* \rightarrow | 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 |
| Δ^0, Δ^{++} | 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 |
| K^+/π_{vis}^+ | 0.164 | 0.184 | 0.148 |
| $\Xi^-/\Lambda_{\text{vis}}$ | 0.143 | 0.159 | 0.116 |
| $\Lambda(1520)/\Lambda_{\text{vis}}$ | 0.044 | 0.041 | 0.060 |
| $\Xi(1530)^0/\Xi^-$ | 0.33 | 0.33 | 0.36 |
| $1000\phi/h_{\text{ch}}^{\text{vis}}$ | 10 | 13 | 8.4 |
| $K_0^*(892)/K^-$ | 0.237 | 0.232 | 0.303 |

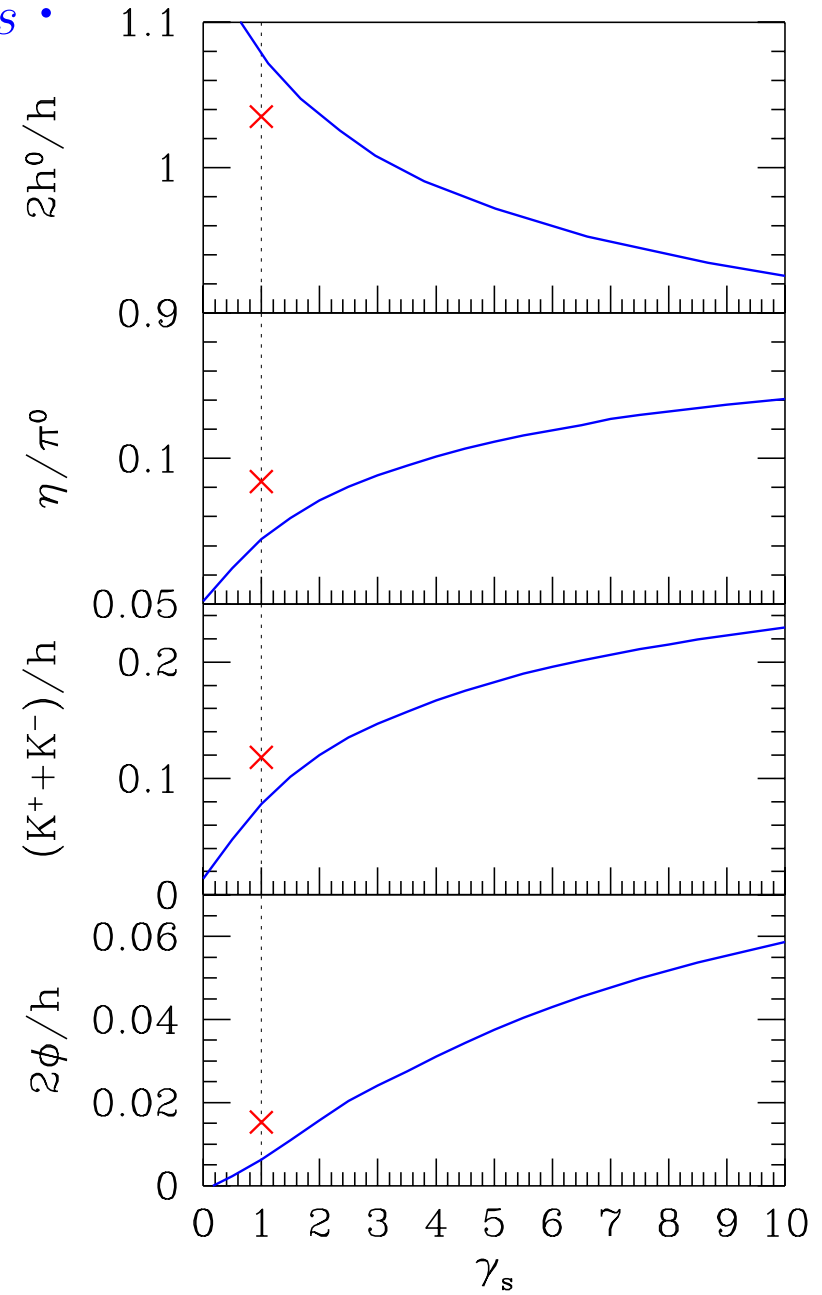
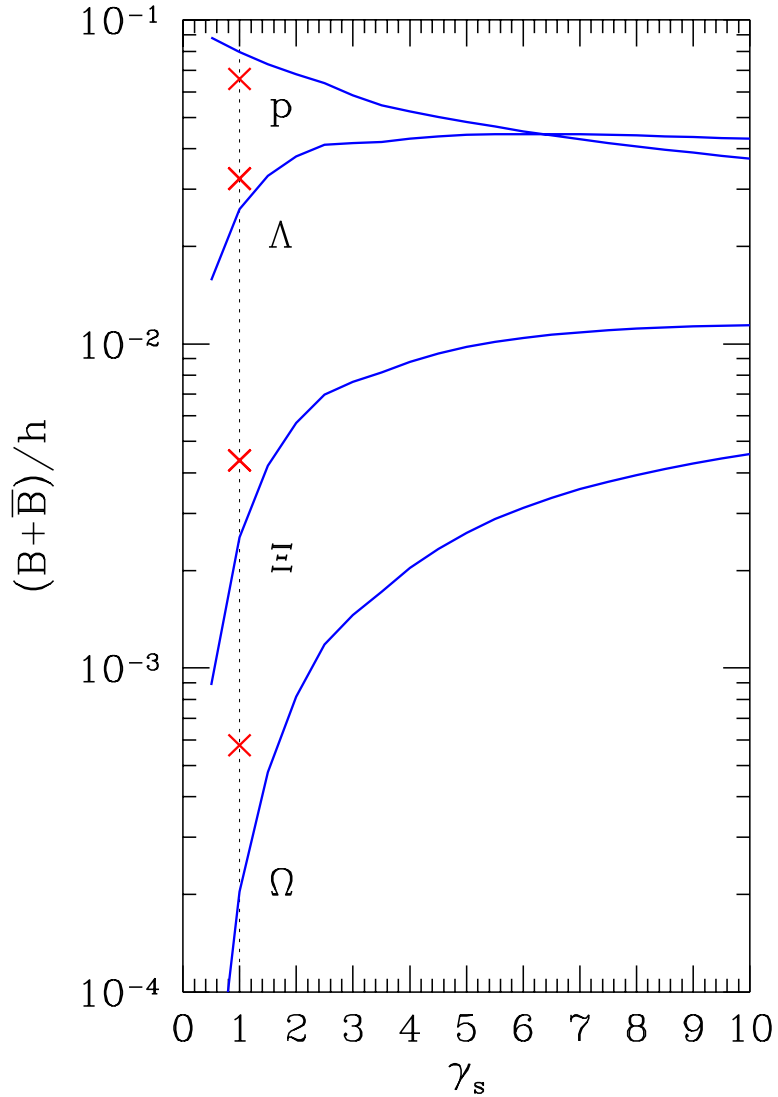
Cross-Check: QGP-HG balance of strangeness and entropy?



Estimate properties of QGP gas and compare to hadron resonance gas. For the parameter set $T = 140$ MeV, $\gamma_q = 1.6$ and $\gamma_s \simeq 2.2-2.4$ good match of properties.

For $T = 161$ MeV entropy density 27% too low and strangeness nearly half as dense, see table

EPJ-C ratios as function of γ_s^H :
Fixed: γ_q at max,
 $E/b = 412 \pm 20$ GeV,



INSIGHTS

Strangeness production slightly oversaturates 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 $T = 1.5T_{\text{cr}}$, 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

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