Strangeness Yield and Charm Chemistry In an expanding QGP

Erice, Alice Physics, December 7, 2005

in Collaboration with: Jean Letessier, and Inga Kouznetsova; EJP and papers in prep

OBJECTIVES:

1. **Understand the dynamics of s production at RHIC-200 and extrapolate to LHC**
2. **Understand the possible range of soft hadron production;**
3. **Understand how yield of strangeness impacts redistribution of charm/bottom into hadrons.**

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

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

Chemical Non-equilibrium in Heavy Ions Collision

MOTIVATION: QGP fireball subject to rapid expansion, expect chemical nonequilibrium. "So What" at LHC?

- **Strangeness yield chemistry alters yields of CHARMED HADRONS;**
- **Chemical non-equilibrium quark 'occupancy' can favor /disfavor presence of a phase transition. What $\mu_{\rm B}$ can do, γ_i can do better as both quark and antiquark number increase/decrease together.**
- **Shift in hadron yields (recent EJP paper)**

REMINDER:

μ_b controls the particle difference = baryon number.

γ_i regulates the number of particle-antiparticle pairs present.

DISTINGUISH HG and QGP parameters: micro-canonical variables such as baryon number, strangeness, charm, bottom, etc flavors are continuous and entropy is almost continuous across any phase boundary encountered in HI collisions, even in presence of a rapid change in STRUCTURE of the phase.

THEREFORE γ_i will in general be discontinuous: e.g. $\gamma_s^{\rm QGP} \neq \gamma_s^{\rm HG}$. However, μ_i are continuous, with the proviso that by definition $3\mu_q = \mu_{\rm B},\ \mu_s = \mu_{\rm B}/3 - \mu_S$.

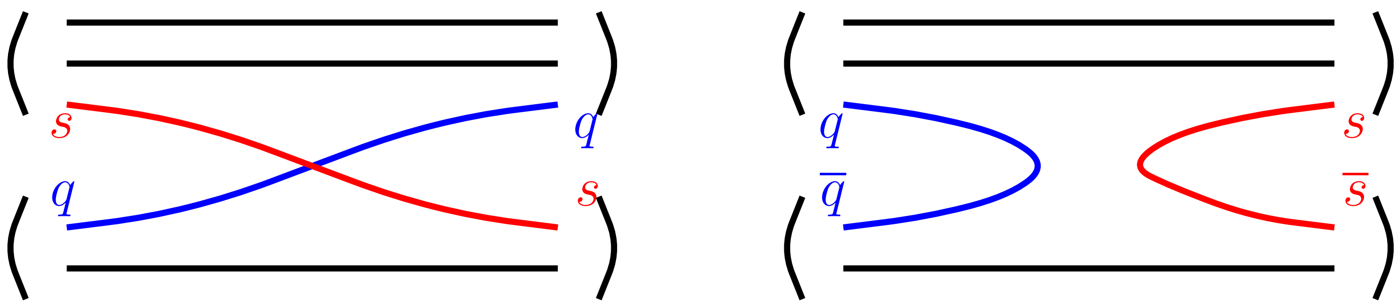
A SHORT TUTORIAL FOLLOWS:

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

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

HG-EXAMPLE: redistribution, production of strangeness

Relative chemical equilibrium **Absolute chemical equilibrium**



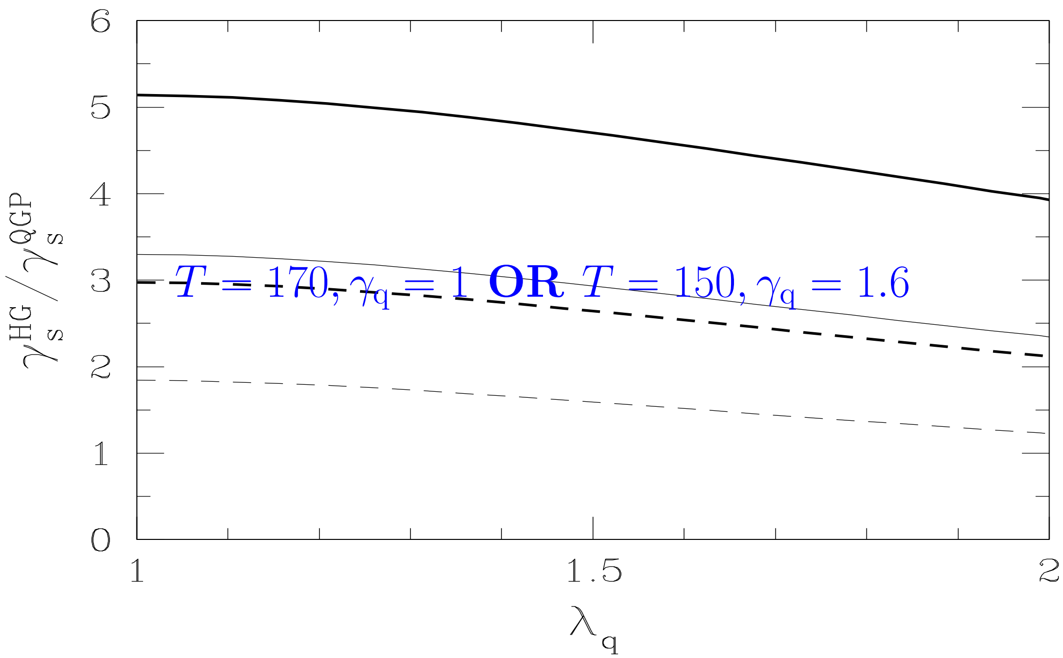
EXCHANGE REACTION λ_i **PAIR PRODUCTION REACTION** γ_i

See Physics Reports 1986 Koch, Müller, JR

$\gamma_s^{\rm HG}$; EXPECTED INCREASE QGP → HG

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

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

→ 

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

$$\gamma_s^{\rm HG} \simeq 2 - 4\gamma_s^{\rm QGP}$$

When we fix s/S (strangeness/entropy), see below, factor follows exactly.

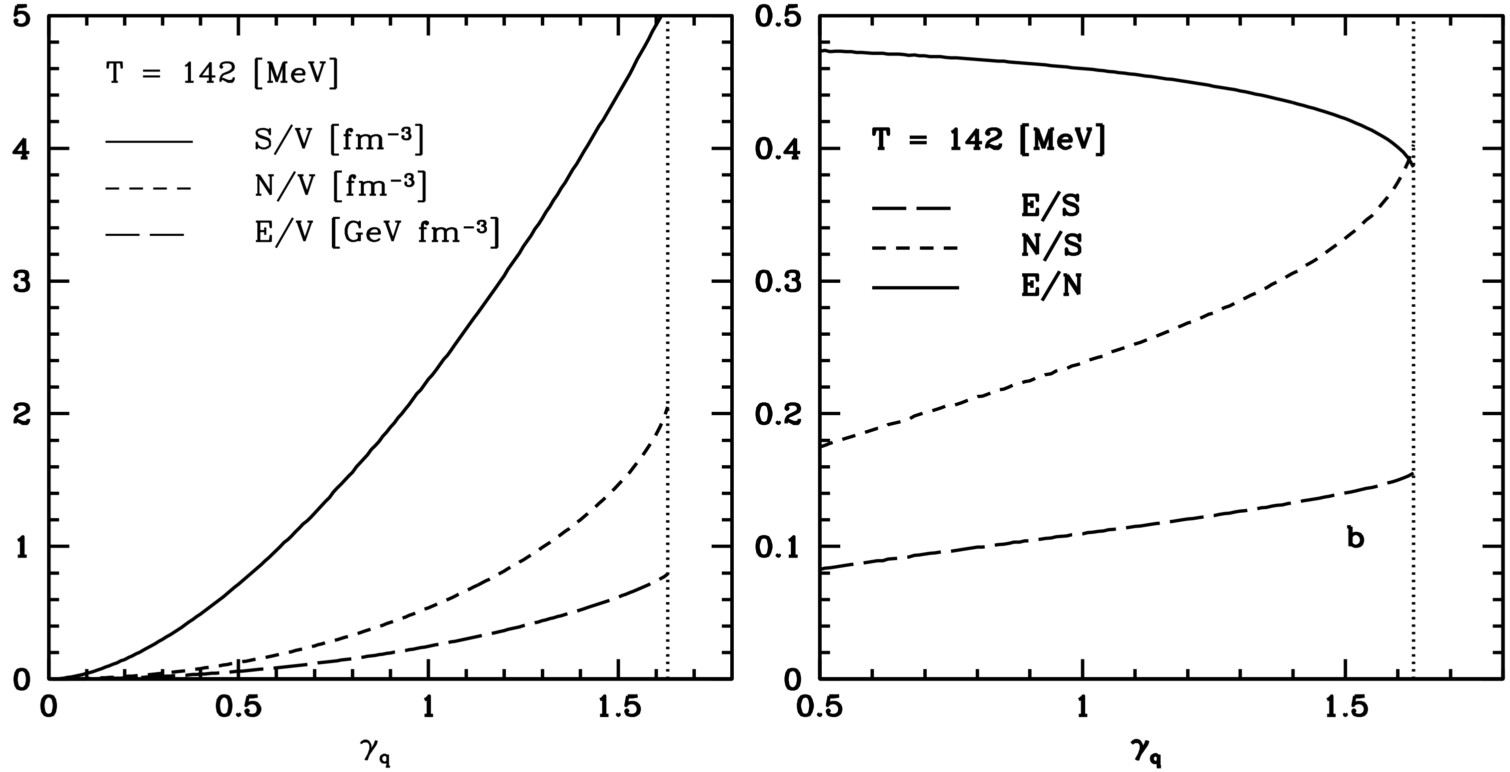
HIGH ENTROPY STATE AND THE EXPECTED $\gamma_q^{\rm HG}$

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

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

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

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



Counting particles

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

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

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.**

For fixed $\tilde{\gamma}_s \equiv \gamma_s/\gamma_q$ **and fixed other statistical parameters** $(T, \lambda_i, \ldots)$**:**

$$\frac{\text{baryons}}{\text{mesons}} \propto \frac{\gamma_q^3}{\gamma_q^2} = \gamma_q \,.$$

$\gamma_s > 1$? in HG at RHIC, in QGP maybe at LHC (depends on T_f):

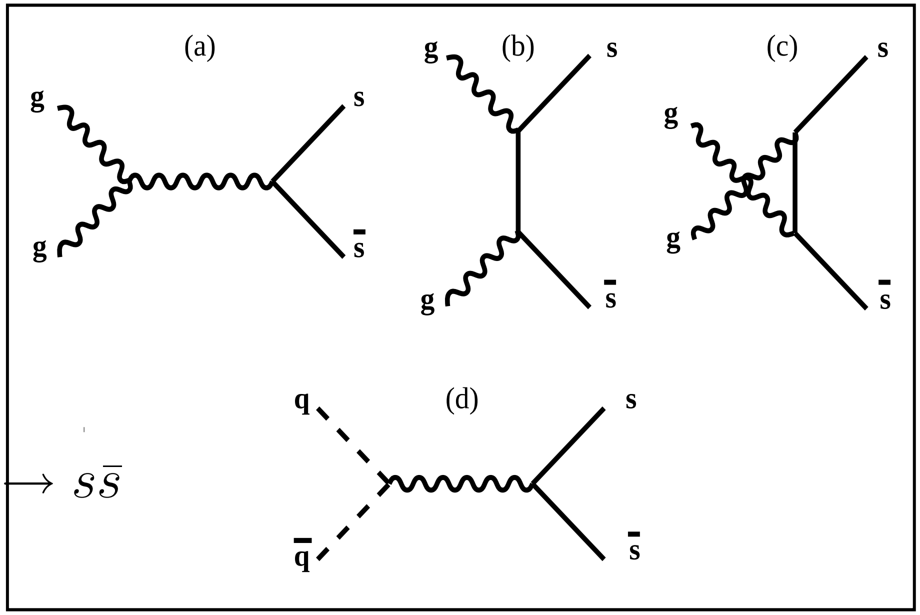
- **production of strangeness in gluon fusion** $\boxed{GG \to s\bar{s}}$
  strangeness linked to gluons from QGP;

dominant processes:

$$GG \to s\bar{s}$$

abundant strangeness
=evidence for gluons

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



- **coincidence of scales:**

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

strangeness a clock for QGP phase

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

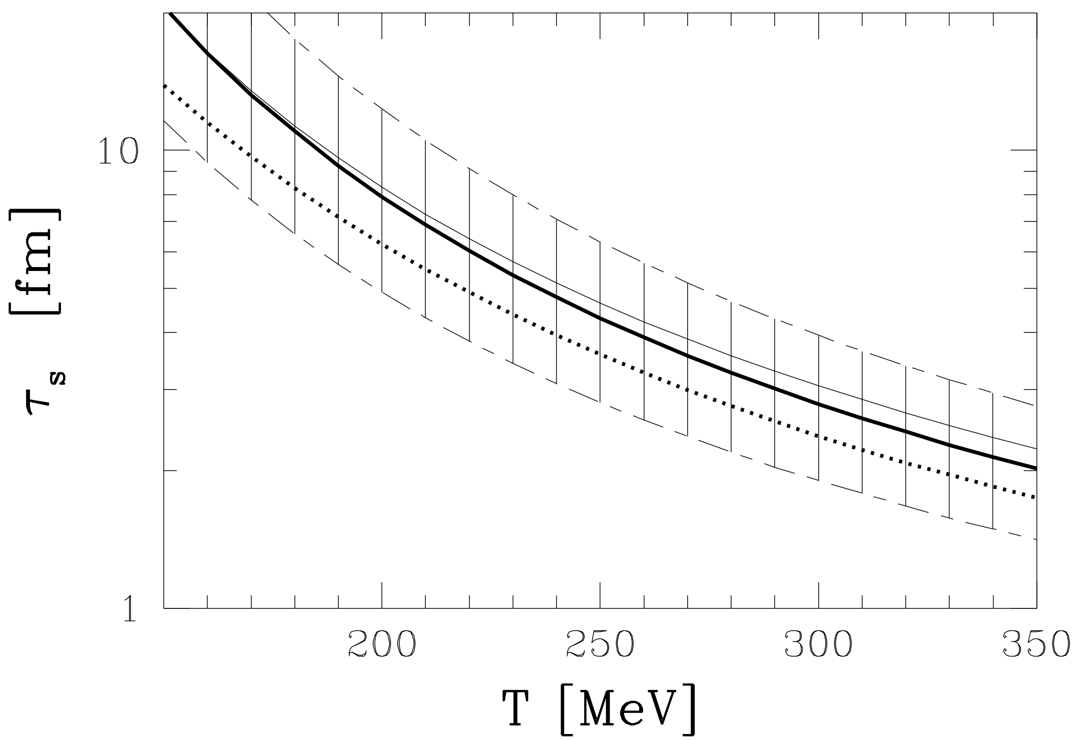
Strangeness relaxation to chemical equilibrium

Strangeness density time evolution in local rest frame:

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

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

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



STRANGENESS IN ENTROPY CONSERVING EXPANSION

QGP expansion is adiabatic i.e. $(g_G = 2_s 8_c = 16, g_q = 2_s 3_c n_{\rm f})$

$$S = \frac{4\pi^2}{90} g(T) V T^3 = \textbf{Const.} \quad g = g_G\left(1 - \frac{15\alpha_s(T)}{4\pi} + \ldots\right) + \frac{7}{4} g_q \left(1 - \frac{50\alpha_s(T)}{21\pi} + \ldots\right) \ .$$

The volume, temperature change such that $\delta(gT^3V) = 0$**. Strangeness phase space occupancy,** $g_s = 2_s 3_c \left(1 - \frac{k\alpha_s(T)}{\pi} + \ldots\right), k = 2$ **for** $m_s/T \to 0$**:**

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

evolves due to production and dilution, keeping entropy fixed:

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

For $m_s \to 0$ **dilution effect decreases, disappears, and** $\gamma_s \le \gamma_{G,q}$**, importance grows with mass of the quark,** $z = m_s(T)/T$**, which grows near phase transition boundary. From this we can obtain the time evolution of** s/S**, the specific strangeness per entropy:**

$$\frac{d}{d\tau}\frac{s}{S} = \frac{g_s}{g} z^2 K_2(z) \left[\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d \ln[g_s z^2 K_2(z)/g]}{d\tau}\right]$$

We have considerable information on s/S**.**

Thermal average rate of strangeness production

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

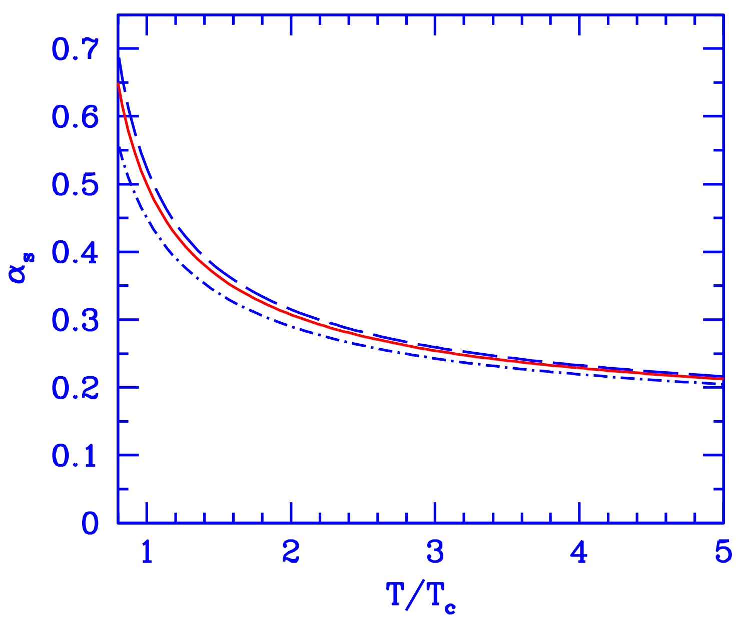
$$\langle \sigma v_{\rm rel} \rangle_T \equiv \frac{\int d^3p_1 \int d^3p_2 \sigma_{12} v_{12} f(\vec{p}_1, T) f(\vec{p}_2, T)}{\int d^3p_1 \int d^3p_2 f(\vec{p}_1, T) f(\vec{p}_2, T)} \, .$$

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

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

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

RESUMMATION



The relatively small experimental value $\alpha_{\rm s}(M_Z) \simeq 0.118$, established in recent years helps to achieve QCD resummation with running $\alpha_{\rm s}$ and $m_{\rm s}$ taken at the energy scale $\mu \equiv \sqrt{s}$.

Effective T-dependence:

$$\alpha_s(\mu = 2\pi T) \equiv \alpha_s(T) \simeq \frac{\alpha_s(T_c)}{1 + (0.760 \pm 0.002) \ln(T/T_c)}$$

with $\alpha_s(T_c) = 0.50 \pm 0.04$ and $T_c = 0.16$ GeV.

α_s^2 **varies by factor 10**

Strangeness / Entropy

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

$$\frac{s}{S} = \frac{\frac{g_s}{2\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{(g2\pi^2/45)T^3 + (g_s n_{\rm f}/6)\mu_q^2 T} \simeq 0.03$$

much of $\mathcal{O}(\alpha_s)$ interaction effect cancels out

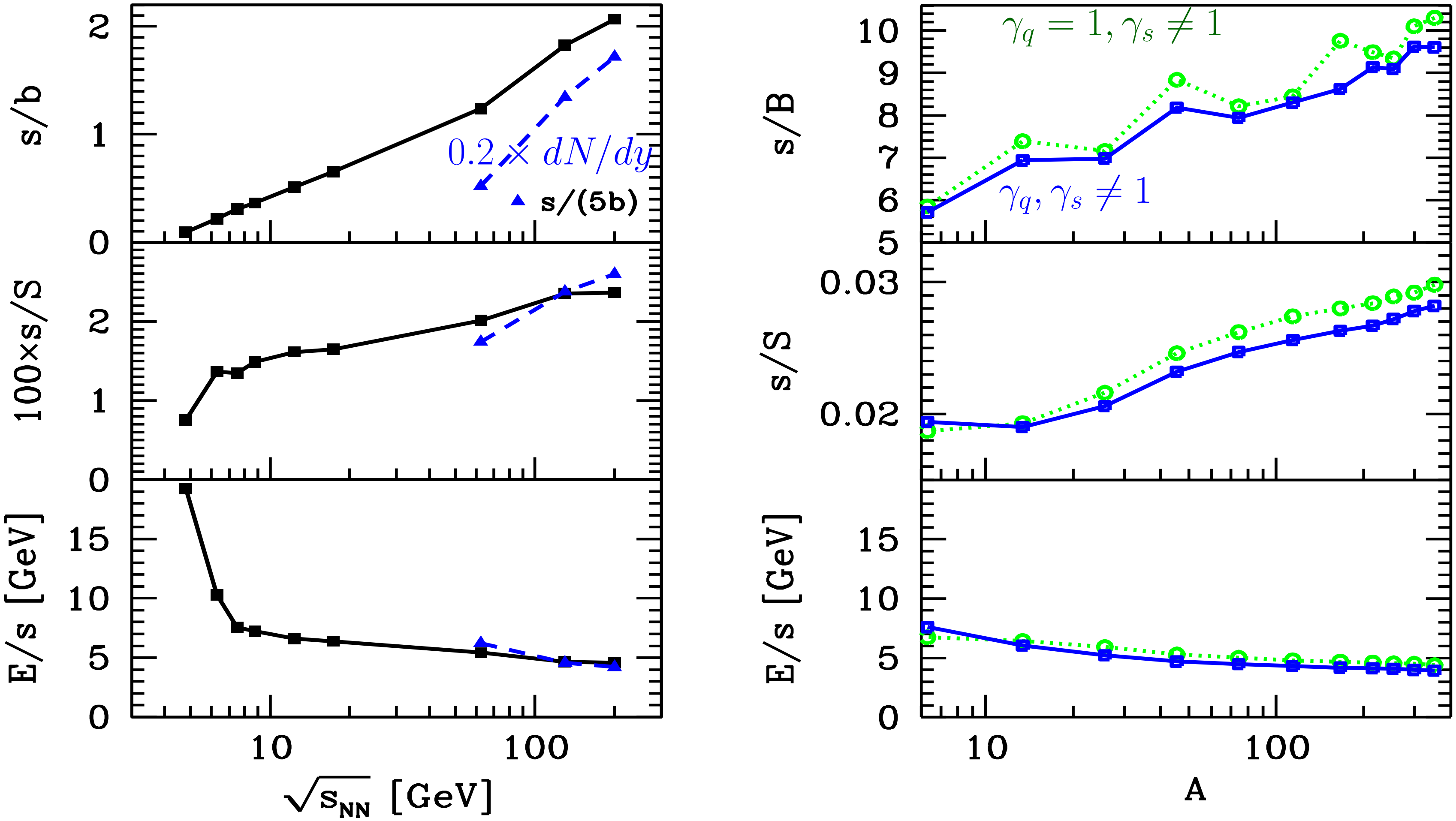
Allow for chemical non-equilibrium of strangeness $\gamma_s^{\rm QGP}$, and possible quark-gluon pre-equilibrium:

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

We expect the yield of gluons and light quarks to approach chemical equilibrium fast and first: $\gamma_{\rm G} \to 1$ and $\gamma_q^{\rm QGP} \to 1$, thus $s/S \simeq 0.03\gamma_s^{\rm QGP}$.

CHECK: FIT YIELDS OF PARTICLES, EVALUATE STRANGENESS AND ENTROPY CONTENT AND COMPARE WITH EXPECTED RATIO,

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



On left: Full 4π and central rapidity results. On right: central rapidity Interestingly, $s/S \to 0.027$, as function of $\sqrt{s_{\rm NN}}$ and V: Fit results suggests that at RHIC energy in most central collisions $\gamma_s^{\rm QGP} \to 0.9$. Peripheral reactions at RHIC suggest the pre-thermal direct yield $s/S|_{\rm direct} < 0.02$.

Energy/strangeness E/s cost drop at $\sqrt{s_{\rm NN}^{\rm cr}}$, suggests appearance of a new (e.g. thermal $GG \to s\bar{s}$) production mechanism.

Time evolution of s/S

$$\frac{d}{d\tau}\frac{s}{S} = \frac{g_s}{g} z^2 K_2(z) \left[\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d \ln[g_s z^2 K_2(z)/g]}{d\tau}\right] \qquad z = \frac{m_s}{T}$$

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

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

We have at our disposal the final conditions: $S(\tau_f)$, $T(\tau_f)$ and since particle yields $dN_i/dy = n_i dV/dy$ the volume per rapidity, $\Delta V/\Delta y|_{\tau_{\rm f}}$. Theory (lattice) further provides Equations of State $\sigma(T) = S/V$. Hydrodynamic expansion with Bjørken scaling implies strictly $dS/dy = \sigma(T) dV/dy = \mathrm{Const.}$ as function of time.

$dV/dy(\tau)$ expansion completes the model.

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

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**

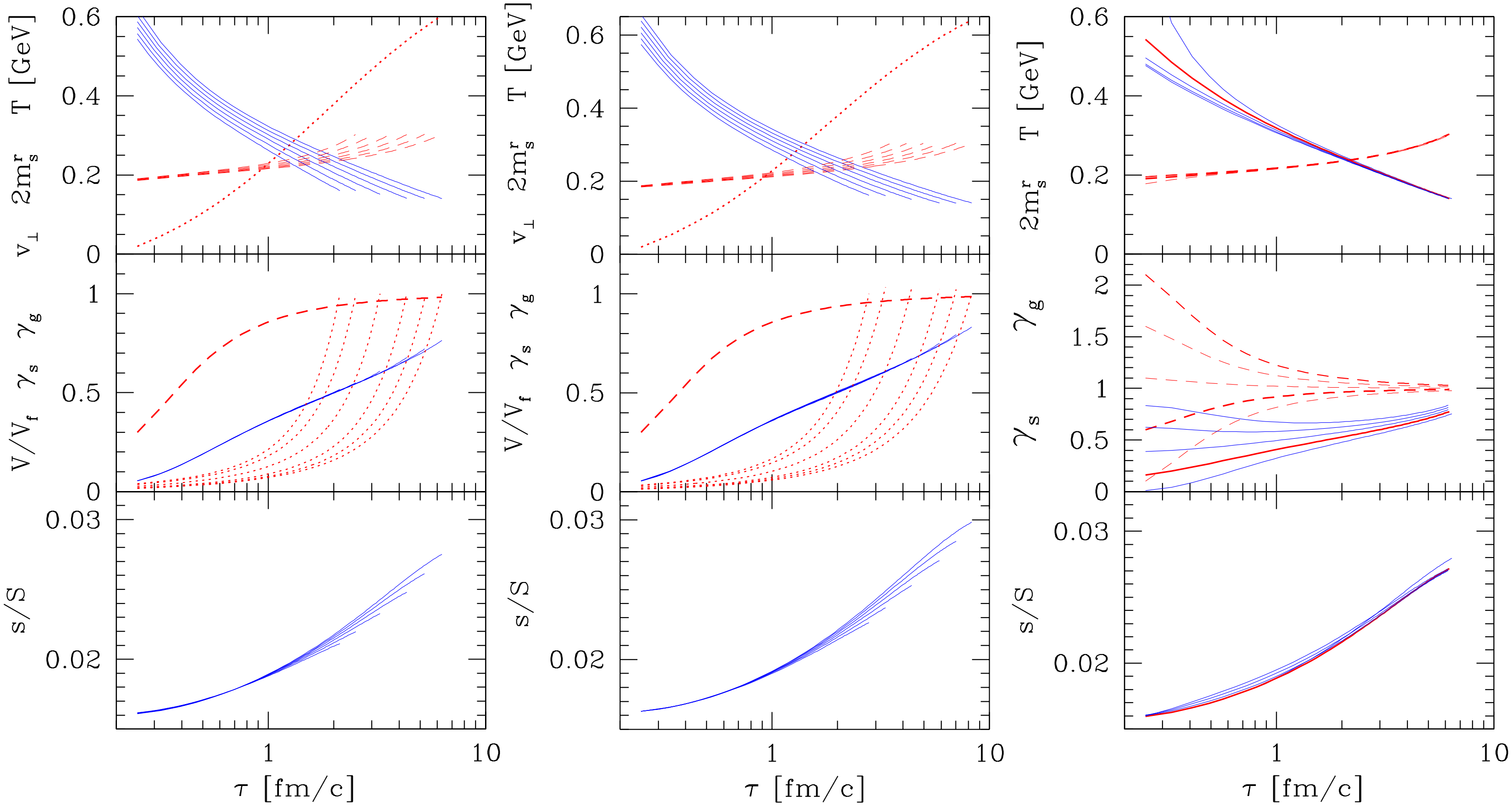
ii) $A_\perp = \pi\left[R_\perp^2(\tau) - (R_\perp^2(\tau) - d)^2\right] = 2\pi d\left[R_\perp(\tau) - \frac{d}{2}\right]$ **and**

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

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

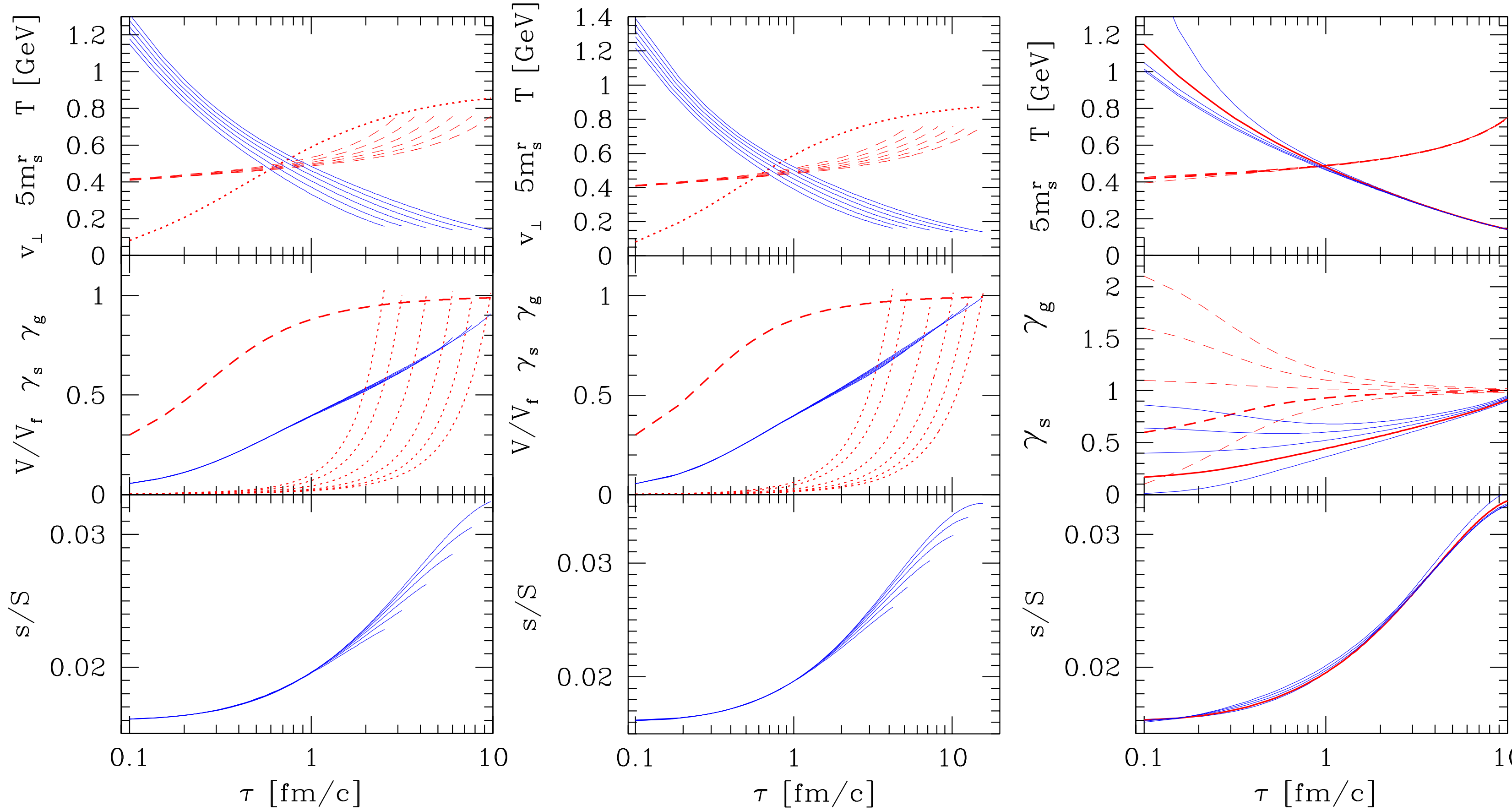
Early time behavior $\gamma_G(tau)$ and $v(\tau)$ can be shown to be of minimal relevance. Strangeness looks back at times $\tau \simeq 2 - 3$ fm. Beyond, for yet earlier τ there is little, if any, memory.

Understanding s/S and γ_s at RHIC



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 panel: temperature T, running mass m^r_s, dotted: the assumed profile of $v_\perp(\tau)$, the transverse expansion velocity; middle panel: dashed assumed $\gamma_g(\tau)$, dotted the assumed normalized $dV/dy(\tau)$ normalized by the freeze-out value. Solid line(s): resulting γ_s for different centralities coincide; and bottom panel: resulting s/S for different centralities, with R_0 stepped down for each line by factor 1.4 . The end points at maximum τ allow to find corresponding centrality curves. Initial temperatures change slightly to accommodate an observed change in $dS/dy|_{\rm f}$ beyond participant scaling. **Lifespan of system for most central reactions consistently $\tau_f = 7 \pm 1$ fm. Freeze-out condition at $T_f = 140$ MeV (higher T_f implies proportionally shorter τ_f).**

What this means for LHC



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.

Notable LHC differences to RHIC: (we assumed $dS/dy|_{\rm LHC} = 4dS/dy|_{\rm RHIC}$)

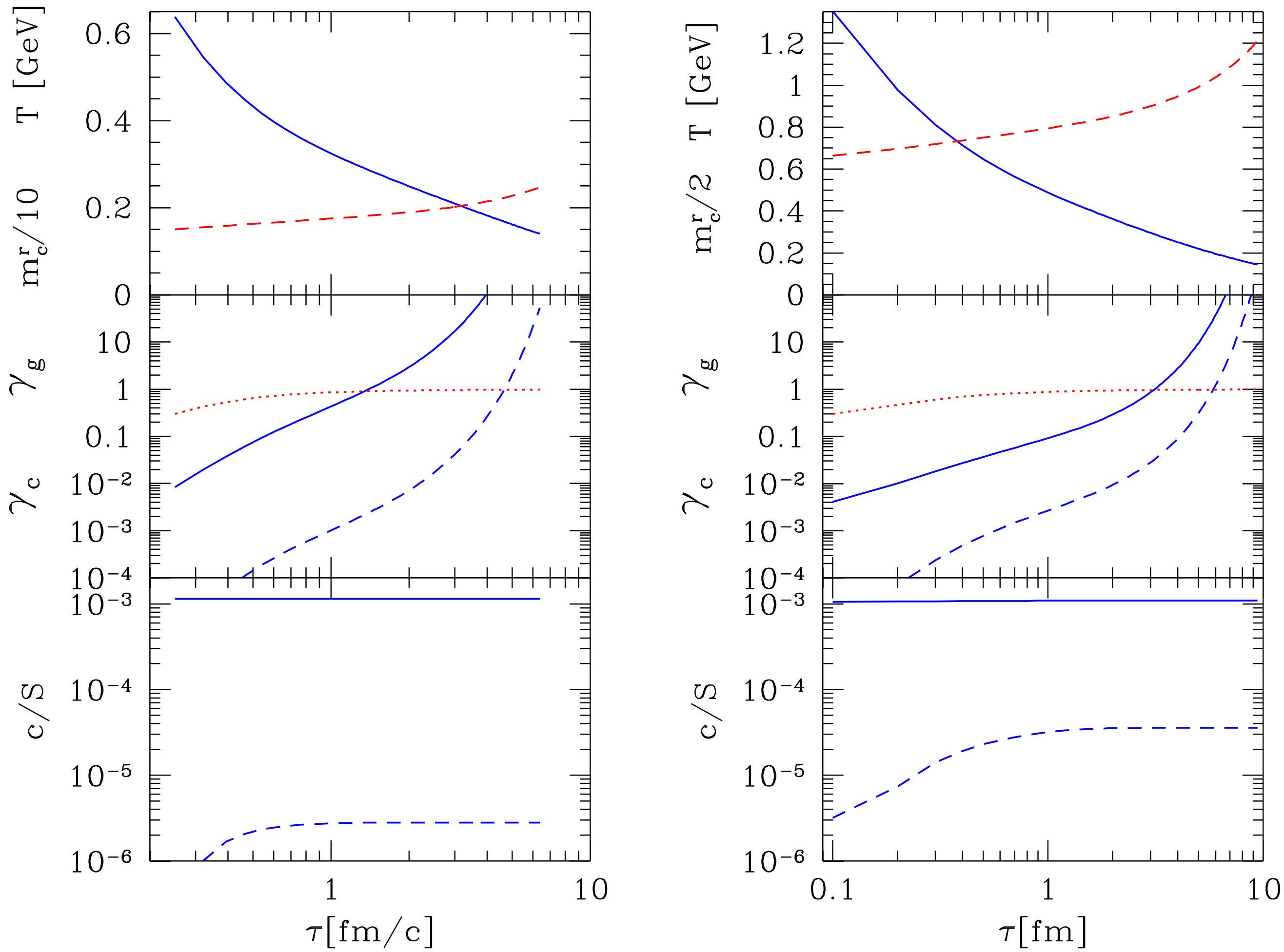
• There is a significantly longer expansion time to the freeze-out condition (factor 2).

• There is a 20% growth in s/S implying corresponding growth in K/π. More generally, there is a steady growth of s/S and γ_s with $\ln dS/dy$.

• There is a significant increase in initial temperature to accommodate increased entropy density.

Reconsider thermal charm production:

Thermal charm at LHC - comparison with direct charm production



Left RHIC and right LHC: Top panel: Solid lines T , dashed lines, running m_c (scaled with 10 for RHIC on left and with 2 on right for LHC); middle panel: Dotted line γ_g, solid lines total charm γ_c, dashed lines γ_c corresponding to thermal charm production; and bottom panel: specific charm yield per entropy, solid lines for all charm, and dashed lines for thermally produced charm.

Thermal charm production alone exceeds significantly chemical equilibrium!

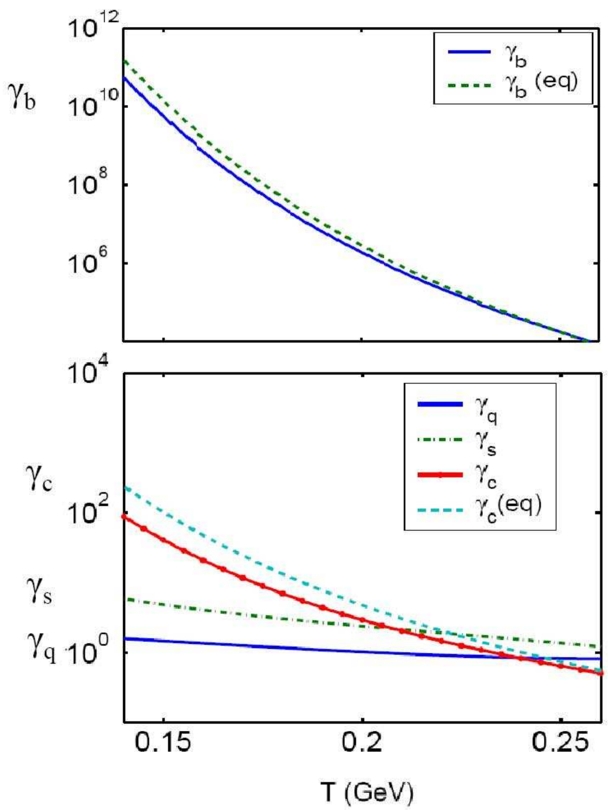
Direct production yield (to see assumed values multiply with $dS/dy = 5000$ on left (RHIC) and =20,000 on right (LHC)) remains significantly (300 at RHIC and 60 times at LHC) above thermal production (compare lines in bottom panel).

Charm chemistry in presence of high s/S

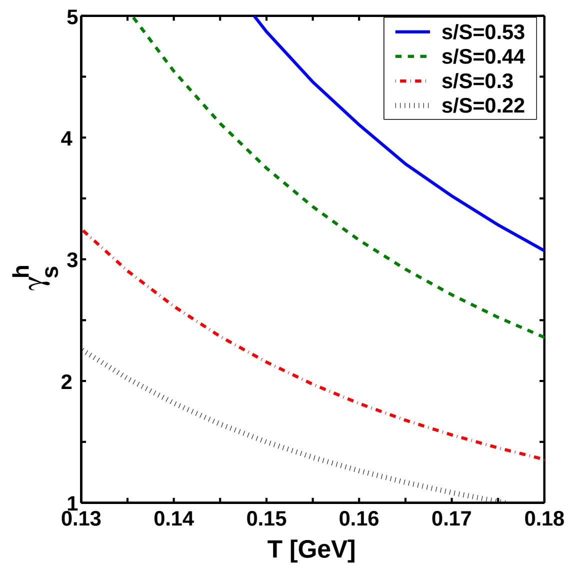
Recombination hadronization of charm has to be considered at a given s and S created in the dynamics of RHIC collision rather than for prescribed statistical yields. Charm distribution among particles according to:

$$\frac{dN_c}{dy} = \frac{dV}{dy}\left[\gamma_c^{\rm h} n^c_{\rm open} + \gamma_c^{\rm h\,2}(n^c_{\rm hidden} + 2\gamma_q^{\rm h} n^{\rm eq}_{ccq} + 2\gamma_s^{\rm h} n^{\rm eq}_{ccs})\right];$$

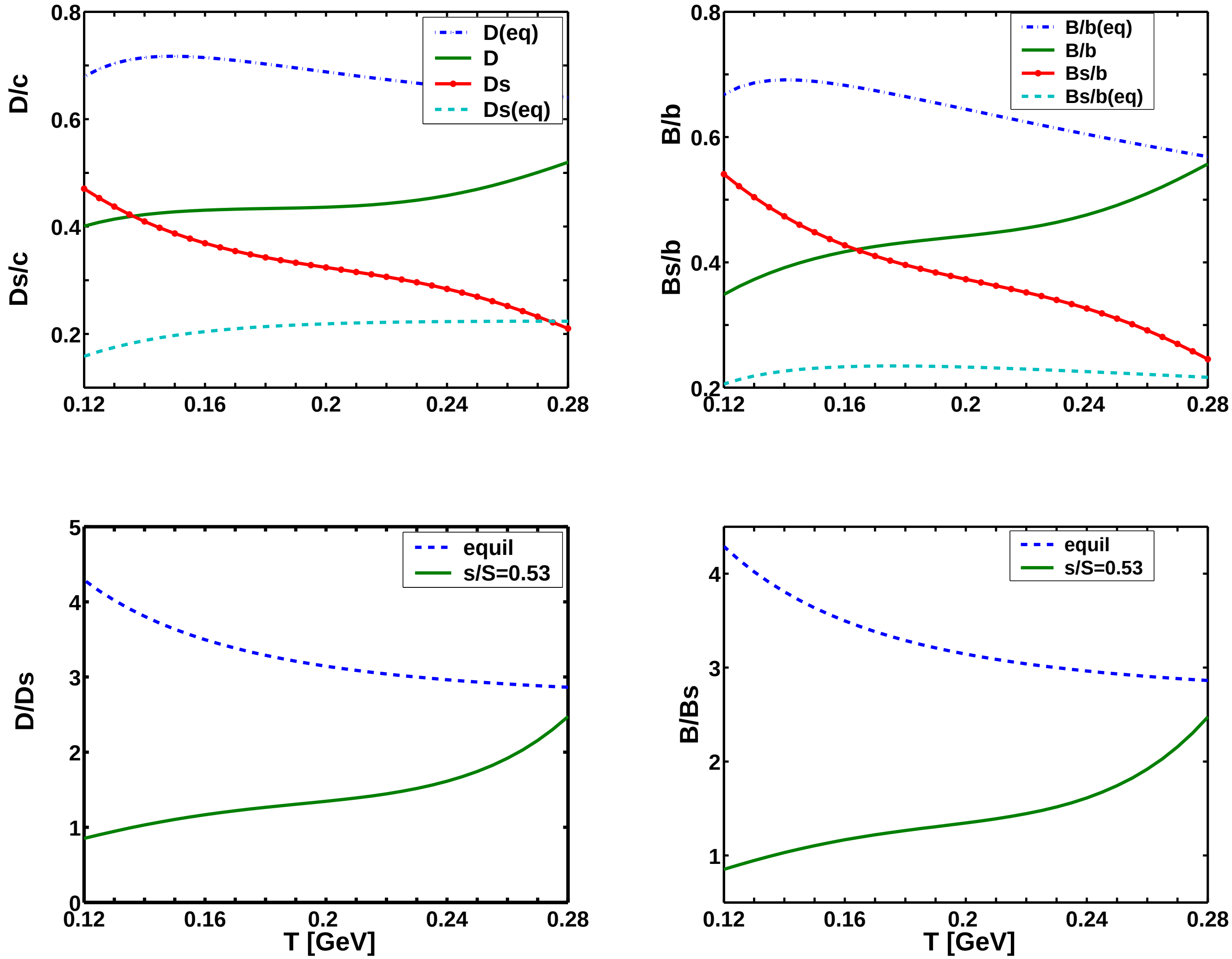
$$n^c_{\rm open} = \gamma_q^{\rm h} n_D^{\rm eq} + \gamma_s^{h} n^{\rm eq}_{Ds} + \gamma_q^{\rm h\,2}\, n^{\rm eq}_{qqc} + \gamma_s^{\rm h}\gamma_q^{h} n^{\rm eq}_{sqc} + \gamma_s^{\rm h\,2}\, n^{\rm eq}_{ssc}\,; \qquad n^c_{\rm hidden} = \gamma_c^{\rm h\,2}\, n^{\rm eq}_{c\bar c}$$



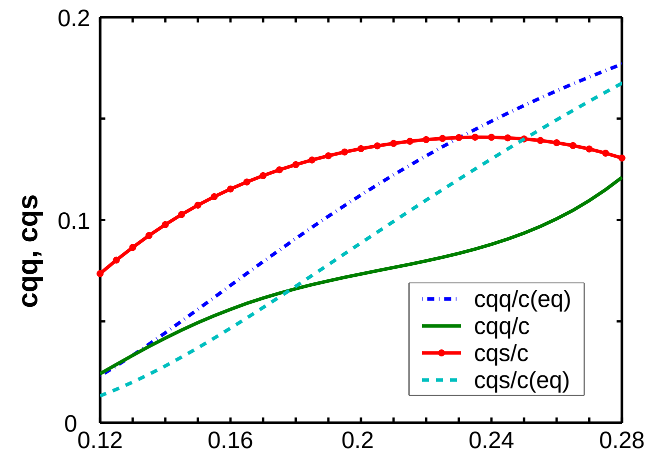
For $db/dy = 1$, $dc/dy = 10$, $ds/dy = 650$ and $dS/dy = 12,000$ (only 2.5 times RHIC) the hadron occupancies were obtained (equilibrium values for $\gamma_i^{\rm QGP} = 1$ for freeze-out at T).

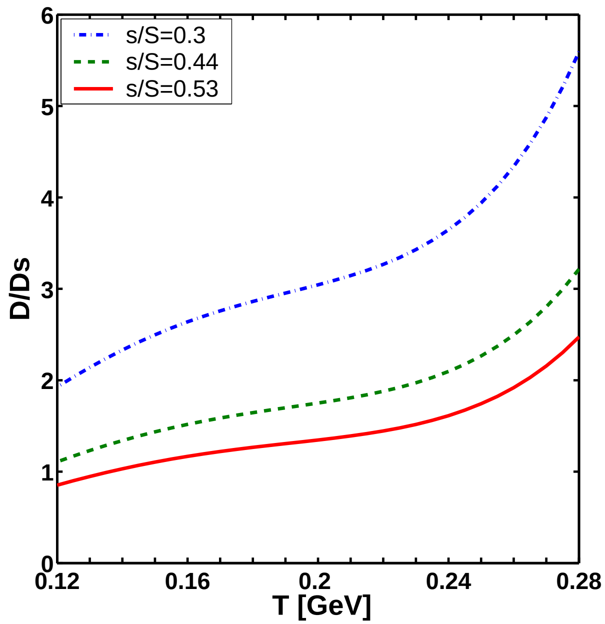


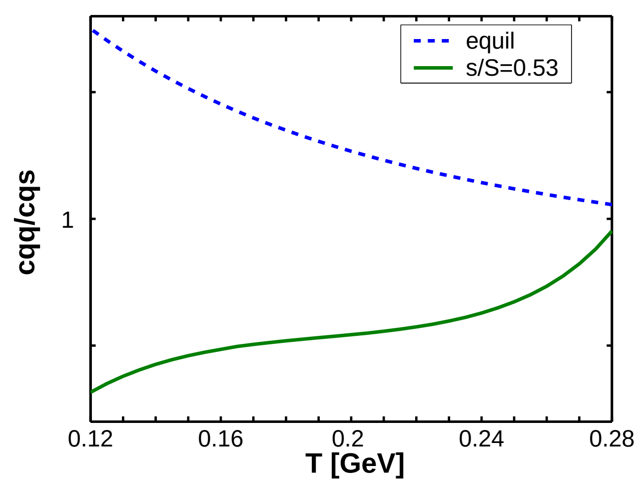
Yields of D, D_s and B, B_s at $s/S = 0.053$



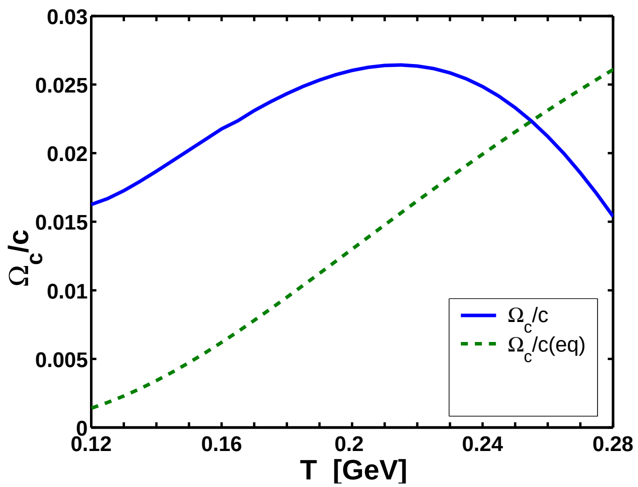
Yields of D, D_s and c-baryons at variable s/S

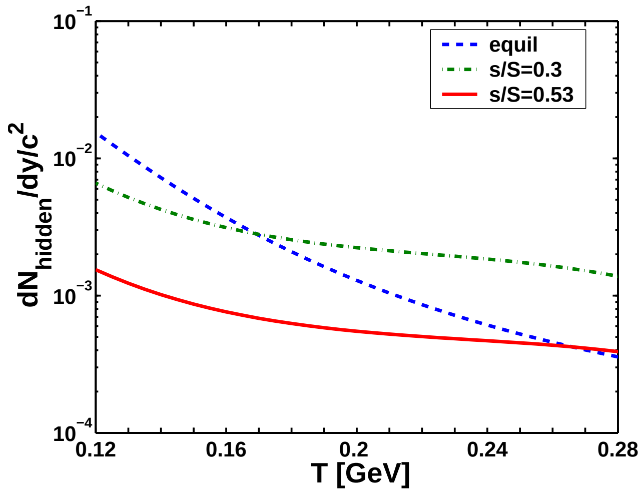


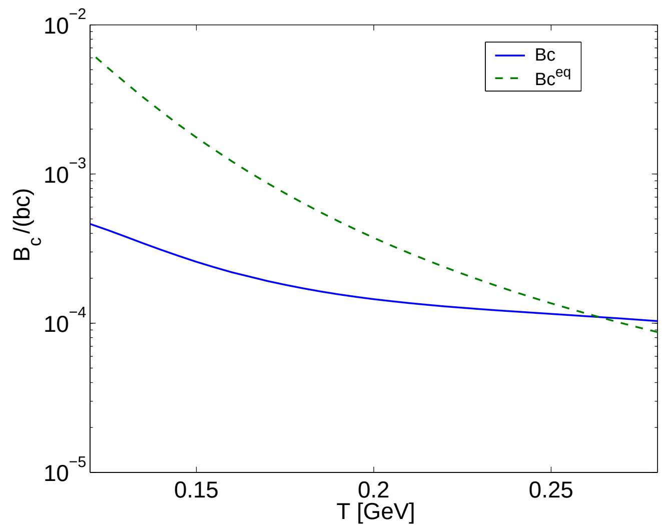




Yields of charmonium, css-baryons and B_c







Further work on heavy flavor chemistry on the way. Return now to discuss relevance of understanding of strangeness at LHC and phase transition dynamics.

SOFT HADRONS: Parameters at LHC

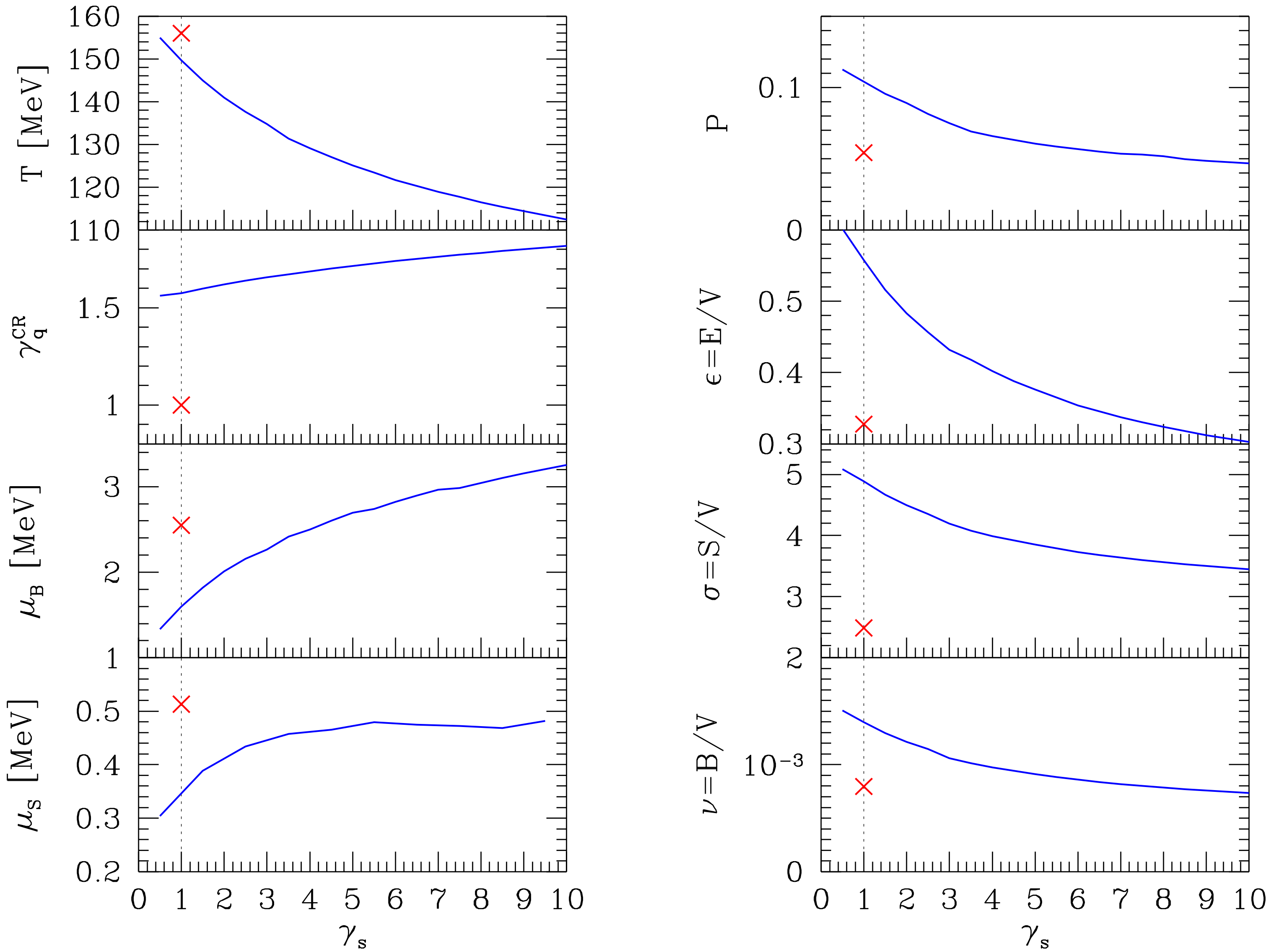
Assuming that statistical hadronization model applies, we have 7 parameters needing fixing:

1) $\mu_b \equiv T\ln(\lambda_u\lambda_d)^{3/2}$**, the baryon and**
2) $\mu_S \equiv T\ln[\lambda_q/\lambda_s]$**, hyperon chemical potentials;**
3) $\lambda_{I3} \equiv \lambda_u/\lambda_d$**, a fugacity distinguishing the up from the down quark flavor;**
4) γ_s **the strangeness phase space occupancy;**
5)γ_q **the light quark phase space occupancy;**
6) T**, the (chemical) freeze-out temperature;**
7) dV/dy**, the volume related a given rapidity to the particle yields;**

There are several constraints and physical conditions:

1) What is baryon stopping? use $dE/db = 412 \pm 20\,\mathrm{GeV}$, μ_b **is hard to measure .**
2) Strangeness conservation, we set $(\bar{s}-s)/(\bar{s}+s) = 0 \pm 0.01$**, this fixes** μ_S **given** μ_b**.**
3) The electrical charge to net baryon ratio, we set $Q/b = 0.39 \pm 0.01$**. Fixes** λ_{I3}
4-5) The value of γ_s^{h} **will be varied, the value of** γ_q^{h} **set either to unity (for equilibrium) or max allowed value 1.6–1.7.**
6) We rely on $E/TS \to 0.78$ **for non-equilibrium and** $\to 0.845$ **for equilibrium**
7) particle ratios limit need for volume normalization.

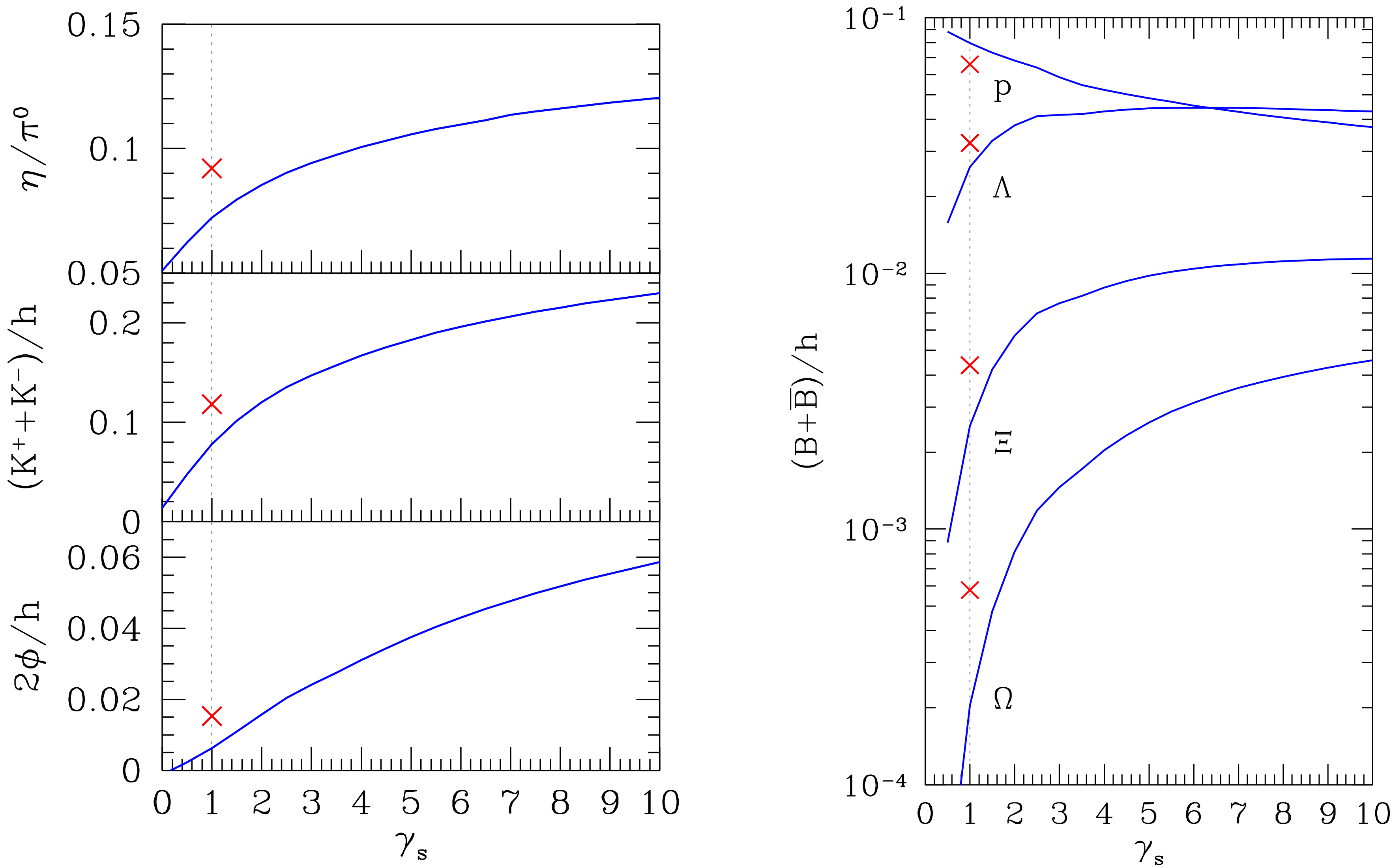
Range of Parameters / Physical Freeze-out Conditions at LHC



On left: The values of T, γ_q^{CR}, μ_B, and μ_S as function of varying γ_s, the equilibrium model results are crosses at $\gamma_s = 1$ for $\gamma_q = 1$.

On right : Pressure P [GeV/fm^3], energy density ϵ [GeV/fm^3], entropy density $\sigma = S/V$ [1/fm^3], net baryon density $\nu = (B - \overline{B})/V = b/V$ [1/fm^3], for non-equilibrium SHM. Cross at γ_s for chemical equilibrium.

Particle ratios at LHC



All yields after weak decay of hyperons and $K_{S,L}$, crosses denote chemical equilibrium result. $h = h^+ + h^- \equiv p + \bar{p} + \pi^+ + \pi^- + K^+ + K^-$,

$dV/dy =$ $=$**3600 fm**^{3} dN/dy	$T = 156$ $\gamma_s^{\rm H} = \gamma_q^{\rm H} = 1$ $\mu_{\rm B} = 2.57, \mu_{\rm S} = 0.51$	$T = 145$ $\gamma_s^{\rm H} = \gamma_q^{\rm H} = 1.62$ $\mu_{\rm B} = 1.83, \mu_{\rm S} = 0.40$	$T = 135$ $\gamma_s^{\rm H} = 3, \gamma_q^{\rm H} = 1.67$ $\mu_{\rm B} = 2.28, \mu_{\rm S} = 0.45$	$T = 125$ $\gamma_s^{\rm H} = 5, \gamma_q^{\rm H} = 1.73$ $\mu_{\rm B} = 2.70, \mu_{\rm S} = 0.48$
s/S	**0.025**	**0.021**	**0.029**	**0.034**
π^+	**466.22**	**866.24**	**655.12**	**506.6**
π^-	**480.48**	**889.48**	**682.24**	**535.6**
π^0	**524.98**	**966.74**	**751.16**	**598.4**
$\rm K^+$	**84.60**	**137.62**	**163.48**	**176.9**
$\rm K^-$	**84.16**	**136.98**	**162.54**	**175.8**
$\rm K_S$	**81.96**	**133.42**	**156.82**	**168.1**
ϕ	**10.95**	**15.73**	**26.86**	**36.54**
p	**32.80**	**64.98**	**36.12**	**19.98**
$\bar{p}$	**31.76**	**63.42**	**34.96**	**19.18**
Λ	**16.76**	**32.24**	**28.34**	**21.9**
$\overline{\Lambda}$	**16.33**	**31.62**	**27.58**	**21.1**
Ξ^-	**3.12**	**5.94**	**8.46**	**9.46**
$\overline{\Xi}^+$	**3.06**	**5.86**	**8.28**	**9.20**
Ω	**0.416**	**0.724**	**1.634**	**2.56**
$\overline{\Omega}$	**0.410**	**0.718**	**1.610**	**2.52**
$\rm K^0(892)$	**24.78**	**35.58**	**35.34**	**31.2**
$\Delta^0 = \Delta^{++}$	**6.16**	**11.66**	**5.68**	**2.70**
$\Lambda(1520)$	**1.29**	**2.220**	**1.66**	**1.08**
$\Sigma^-(1385)$	**2.14**	**3.98**	**3.28**	**2.34**
$\Xi^0(1530)$	**0.914**	**1.656**	**2.26**	**2.46**
η	**59.6**	**95.2**	**93.4**	**90.2**
η'	**5.32**	**7.62**	**7.78**	**7.06**
ρ^0	**53.8**	**79.2**	**48.4**	**29.8**
$\omega(782)$	**49.8**	**72.2**	**42.4**	**25.0**
$f_0(980)$	**4.50**	**6.42**	**6.28**	**5.44**

In lieu of conclusions: A few questions with answers

Is there chemical nonequilibrium near to hadronization point?

In QGP: strangeness. For a fast change to HG no absolute s, q equilibrium

Can chemical nonequilibrium impact physical observables? and even phase transition properties?

Simple observables such as K/π depend decisively on s/S. We have discussed here the influence on charm chemistry, and argued that $\gamma_s^{QGP} > 1$ helps establish a true 1st order phase transition for $\mu_{\rm B} \to 0$.

Is there $\gamma_s^{\rm QGP} > 1$ (that is $\gamma_s^{\rm h} > 3$) at LHC?

Yield study suggests 'perhaps', depends on many technical assumptions. So it is certainly still an open issue, experiment will show.

What is strangeness content, compare CERN-SPS to RHIC-200 to LHC?

Not discussed today, but we find a gradual rise as function of collision energy of the yield s/S (per entropy).

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

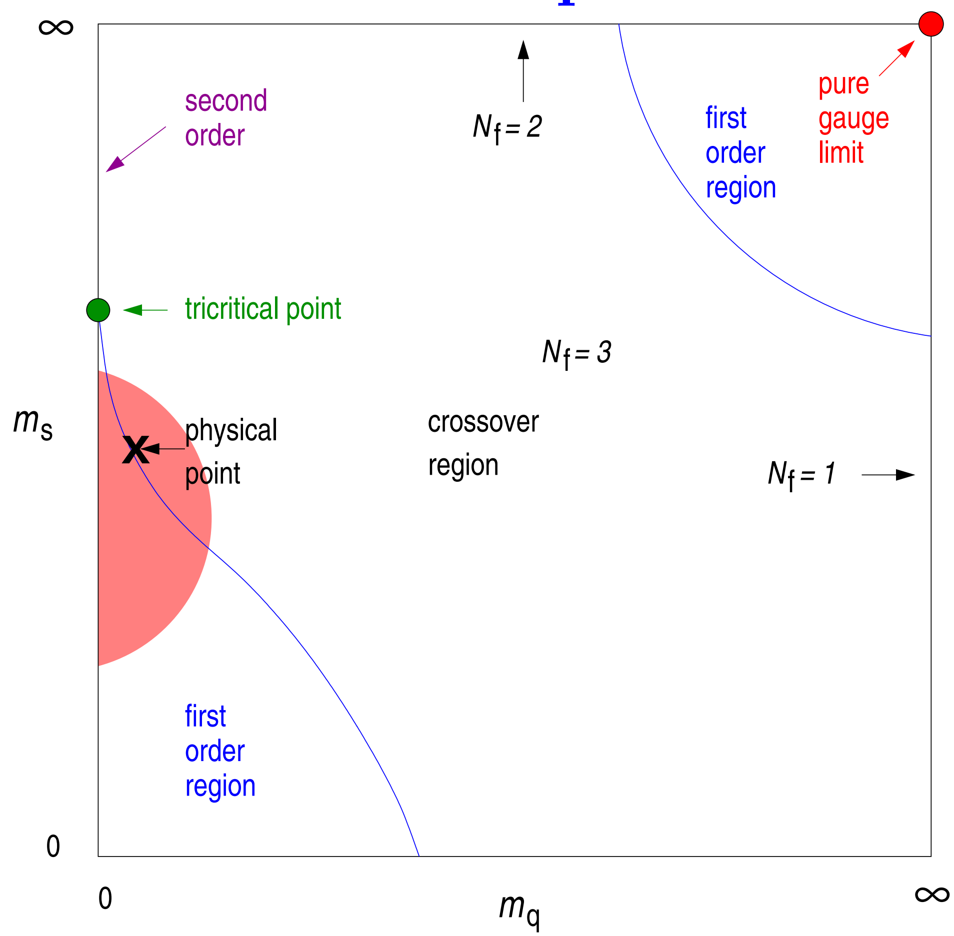
Our particle yield analysis shows excitation energy threshold seen in s/S, s/b and E/s.

Why low/high PHASE BOUNDARY Temperature?

- **Degrees of freedom**
  - **Temperature of phase transition depends on available degrees of freedom.**
    - **For 0 flavor theory $T > 200$ MeV**
    - **For 2 flavors: $T \to 170$ MeV**
    - **For 2+1 flavors: $T = 162 \pm 3$ and appearance of minimum $\mu_{\rm B}$**
    - **For 3, 4 flavors further drop in T.**

    what happens when $\gamma_s > 1$?
  - **The nature of phase transition/transformation changes when number of flavors rises from 2+1 to 3 is effect of $\gamma_i > 1$ creating a real phase transition?**
- **Dynamical effects of expansion:**
  colored partons like a wind, displace the boundary

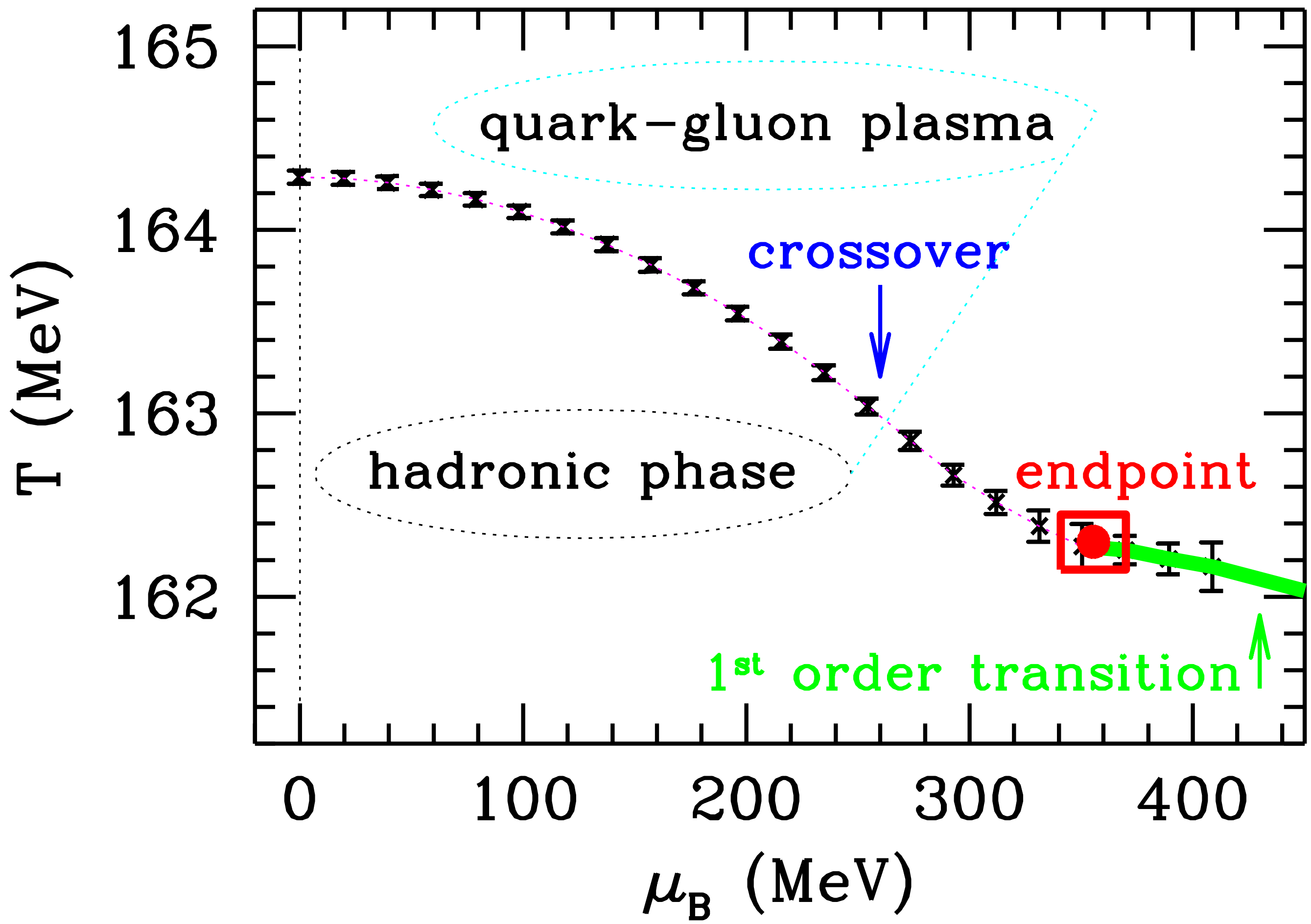
Fermi degrees of freedom and phase transitions in QCD



adapted from: THE THREE FLAVOR CHIRAL PHASE TRANSITION WITH AN IMPROVED QUARK AND GLUON ACTION IN LATTICE QCD. By A. Peikert, F. Karsch, E. Laermann, B. Sturm, (LATTICE 98), Boulder, CO, 13-18 Jul 1998. in Nucl.Phys.Proc.Suppl.73:468-470,1999.

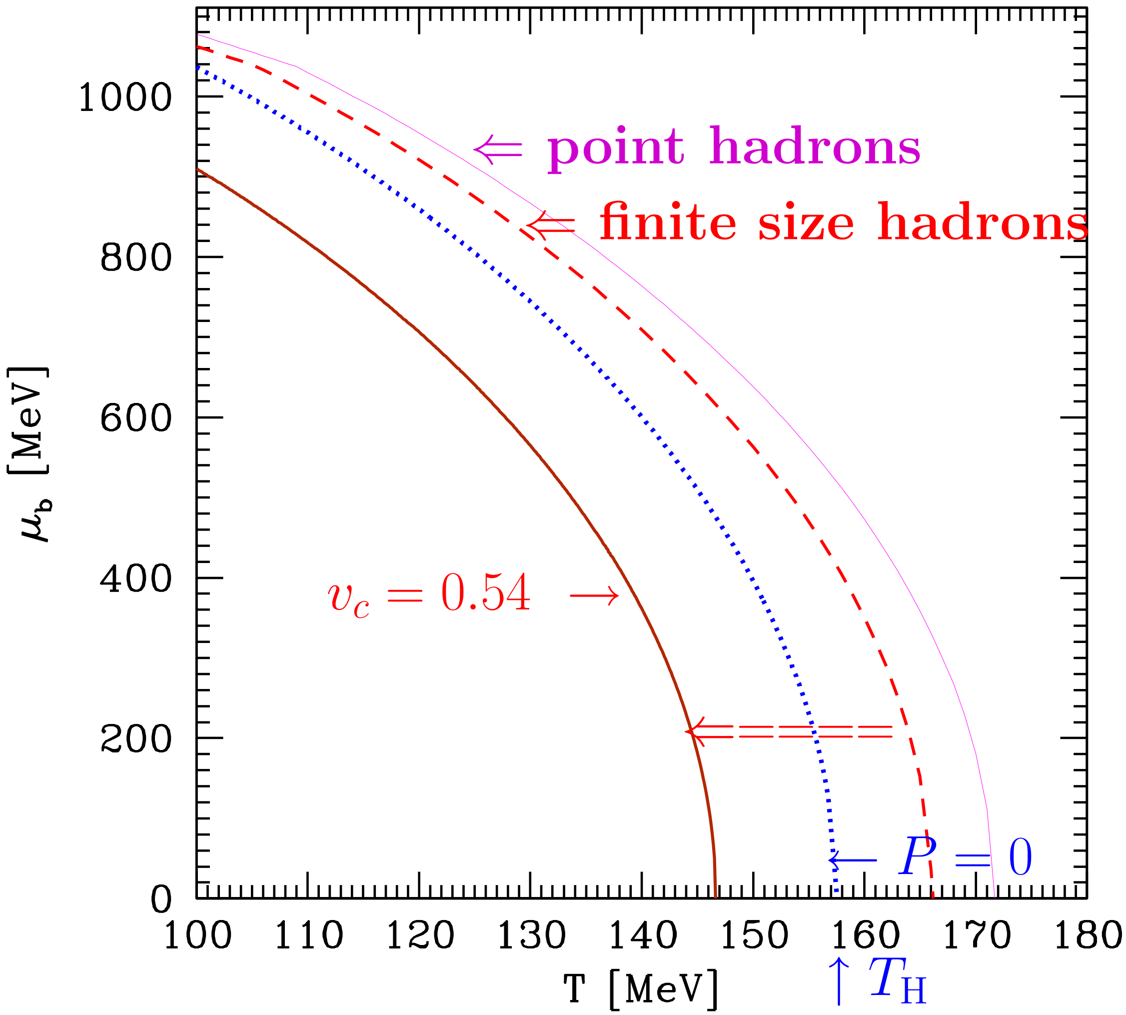
Note that we need some additional quark degrees of freedom to push the system over to phase transition. Conventional wisdom: baryon density:

....and considering the baryochemical potential



adapted from: CRITICAL POINT OF QCD AT FINITE T AND MU, LATTICE RESULTS FOR PHYSICAL QUARK MASSES. By Z. Fodor, S.D. Katz (Wuppertal U.), JHEP 0404:050,2004; hep-lat/0402006. **However, at LHC the baryochemical potential at level of 1-3 MeV. Better hope for γ_s, and MOTION:**

(dynamical)Phase boundary and 'wind' of flow of matter



Solid: point hadrons T_p
Dashed: finite size hadrons

Thick solid: breakup with $v = 0.54$ $(\kappa = 0.6)$
Expansion
SUPERCOOLING
by 20 MeV

$T_{\rm H} = 158$ **MeV Hagedorn temperature where** $P = 0$**, no hadron** P
$T_f \simeq 0.9 T_H \simeq 143$ **MeV is where supercooled QGP fireball breaks up**
equilibrium phase transformation used here was at $T \simeq 166$**.**