Heavy Flavor Hadrons in Statistical Hadronization of Strangeness-rich QGP

CERN, Alice Heavy Flavor and Quarkonia WG, March 14, 2006

We study c (and b) quark hadronization from QGP. We obtain the yields of charm and bottom flavored hadrons within statistical hadronization model. The important feature is that we take into account the high strangeness content of QGP, conserving strangeness, charm, bottom, entropy yield at hadronization.

OBJECTIVES:

1. **Introduction: Does Strangeness Chemical Non-equilibrium Matter?**
2. **Statistical hadronization**
3. **Charm hadronization**
4. **First results and conclusions**

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

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1. Does Chemical Non-equilibrium Matter?

- **Is there chemical equilibrium in QGP:**

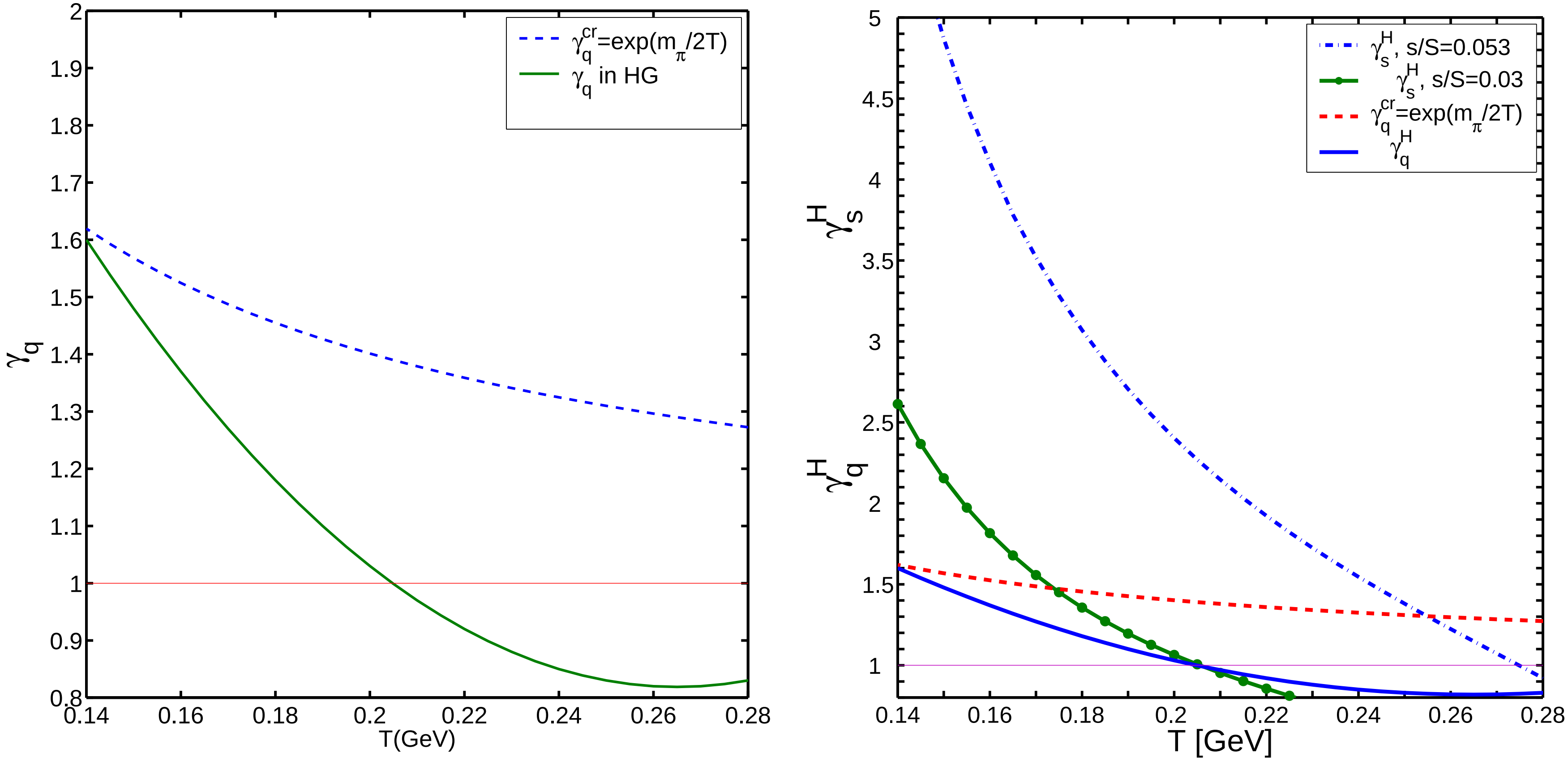
$$\gamma_g = 1,\ \ \gamma_q^{\mathrm{Q}} = 1,\ \ \gamma_s^{\mathrm{Q}} \simeq 1?,\ \ \gamma_c^{\mathrm{Q}} >> 1, \gamma_b^{\mathrm{Q}} >>> 1$$

LHC: Charm and bottom overproduced in initial parton reactions. Strangeness cooked to some over-saturation, quarks and gluons could also be slightly over-saturated, due to fast expansion.

- **Is there chemical equilibrium after QGP breakup in the yields of hadrons? Note: composite particle fugacities are made of constituent quark fugacities, for example:**

$$\gamma_{D_s}^{\mathrm{h}} = \gamma_c^{\mathrm{h}}\gamma_s^{\mathrm{h}}, \quad \gamma_D^{\mathrm{h}} = \gamma_c^{\mathrm{h}}\gamma_q^{\mathrm{h}}.$$

QGP breakup at fixed V, S, and s



Thermal equilibrium distributions are different in two phases and hence are densities:

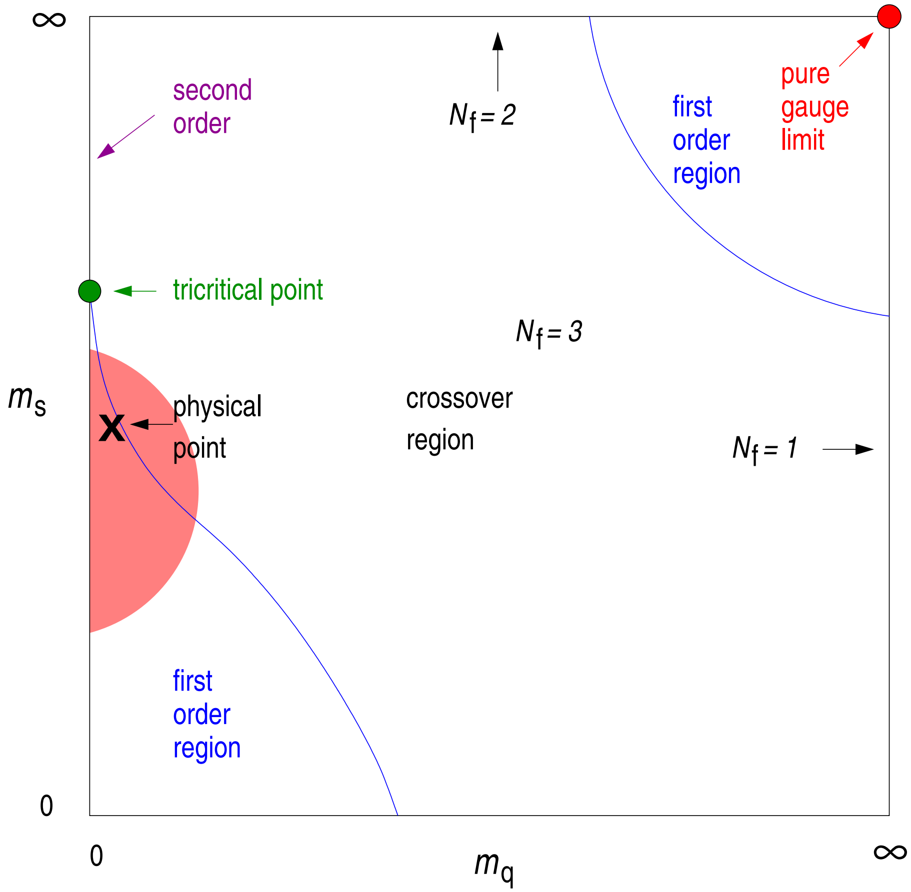
$$\rho_{\rm eq}^{\rm Q} = \int f_{\rm eq}^{\rm Q}(p)dp \neq \rho_{\rm eq}^{\rm h} = \int f_{\rm eq}^{\rm h}(p)dp$$

flavors are continuous, and entropy is almost continuous across phase boundary:

$$\langle (s,c,b,S)_{\rm TOT}^{\rm Q}\rangle = \gamma_{(s,c,b,S)}^{\rm Q}\rho_{(s,c,b,S){\rm eq}}^{\rm Q}V^{\rm Q} = \gamma_{(s,c,b,S)}^{\rm h}\rho_{(s,c,b,S){\rm eq}}^{\rm h}V^{\rm h} = \langle (s,c,b,S)_{\rm TOT}^{\rm h}\rangle$$

If $V^{\rm Q} = V^{\rm h}$ (sudden hadronization) we must have $\gamma_i^{\rm Q} \neq \gamma_i^{\rm h}$

Physics issues related to chemical nonequilibrium



- **Shift in hadron yields between**
  a) baryons $\propto \gamma_q^{h\,3}$ and mesons $\propto \gamma_q^{h\,2}$:

  $$\frac{\text{baryons}}{\text{mesons}} \propto \gamma_q^{h}; \quad \frac{\text{strange hadrons}}{\text{non}-\text{strange hadrons}} \propto \frac{\gamma_s^h}{\gamma_q^h}$$

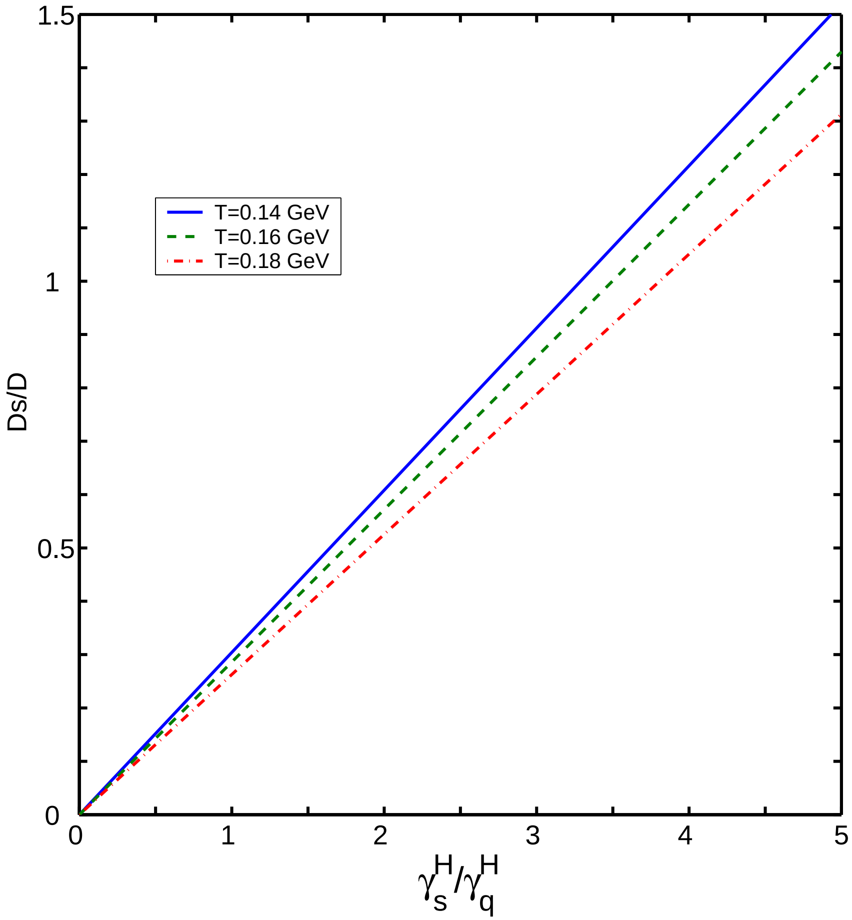
  b) shift in relative yields of CHARMED HADRONS;

- **Strangeness over-saturation $\gamma_s^h > 1$ is a diagnostic signature of deconfinement.**

- **Chemical non-equilibrium quark 'occupancy' γ_s can favor /disfavor onset of phase transition –Not 2+1 but 2+γ_s^{QGP} flavor lattice.**

adapted from: "The three flavor flavor chiral phase transition with an improved quark and gluon action in lattice QCD", **A. Peikert, F. Karsch , E. Laermann, B. Sturm,**(LATTICE 98), in Nucl.Phys.Proc.Suppl.73:468-470,1999.

Example of strangeness influence on charmed hadron yields

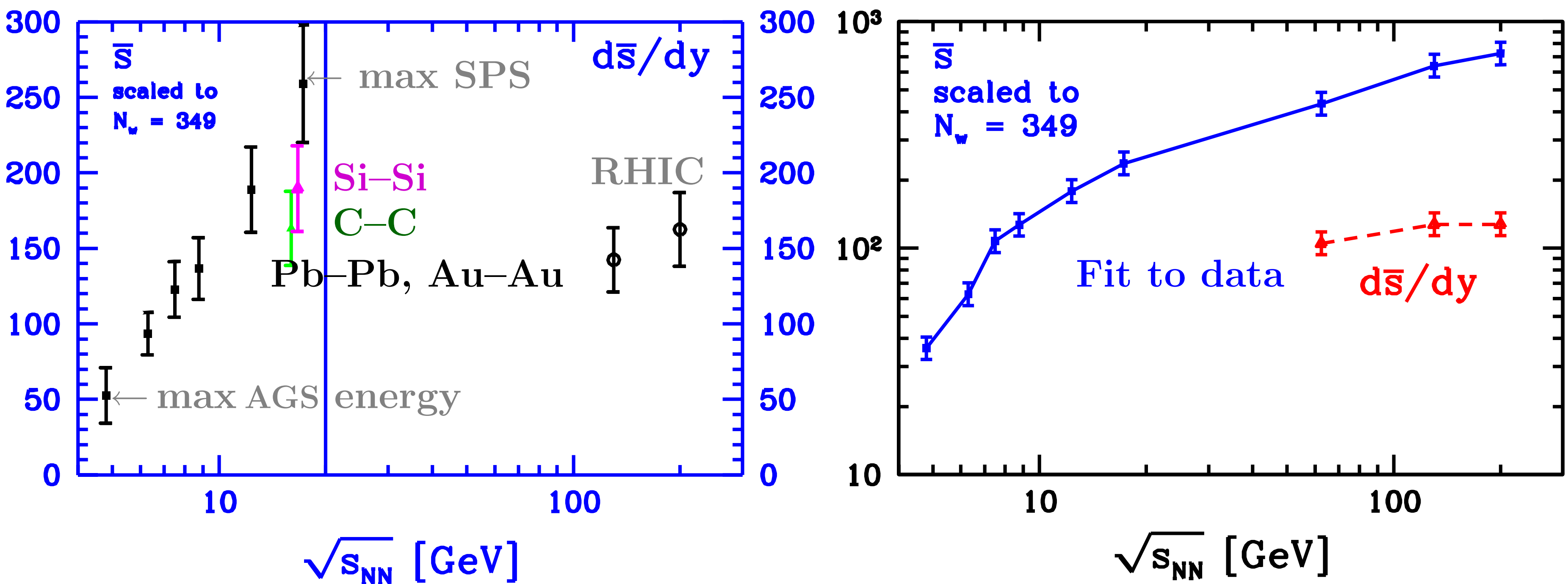


hadron		M[GeV]	hadron		M[GeV]	g
$D^0(0^-)$	$c\bar{u}$	**1.8646**	$B^0(0^-)$	$b\bar{u}$	**5.279**	**1**
$D^+(0^-)$	$c\bar{d}$	**1.8694**	$B^+(0^-)$	$b\bar{d}$	**5.279**	**1**
$D^{*0}(1^-)$	$c\bar{u}$	**2.0067**	$B^{*0}(1^-)$	$b\bar{u}$	**5.325**	**3**
$D^{*+}(1^-)$	$c\bar{d}$	**2.0100**	$B^{*+}(1^-)$	$b\bar{d}$	**5.325**	**3**
$D^0(0^+)$	$c\bar{u}$	**2.352**	$B^0(0^+)$	$b\bar{u}$	**5.697**	**1**
$D^+(0^+)$	$c\bar{d}$	**2.403**	$B^+(0^+)$	$b\bar{d}$	**5.697**	**1**
$D_1^{*0}(1^+)$	$c\bar{u}$	**2.4222**	$B_1^{*0}(1^+)$	$b\bar{u}$	**5.720**	**3**
$D_1^{*+}(1^+)$	$c\bar{d}$	**2.4222**	$B_1^{*+}(1^+)$	$b\bar{d}$	**5.720**	**3**
$D_2^{*0}(2^+)$	$c\bar{u}$	**2.4589**	$B_2^{*0}(2^-)$	$b\bar{u}$	**(5.730)**	**5**
$D_2^{*+}(2^+)$	$c\bar{d}$	**2.4590**	$B_2^{*+}(2^+)$	$b\bar{d}$	**(5.730)**	**5**
$D_s^+(0^-)$	$c\bar{s}$	**1.9868**	$B_s^0(0^-)$	$s\bar{b}$	**5.3696**	**1**
$D_s^{*+}(1^-)$	$c\bar{s}$	**2.112**	$B_s^{*0}(1^-)$	$s\bar{b}$	**5.416**	**3**
$D_{sJ}^{*+}(0^+)$	$c\bar{s}$	**2.317**	$B_{sJ}^{*0}(0^+)$	$s\bar{b}$	**5.716**	**1**
$D_{sJ}^{*+}(1^+)$	$c\bar{s}$	**2.4593**	$B_{sJ}^{*0}(1^+)$	$s\bar{b}$	**5.760**	**3**
$D_{sJ}^{*+}(2^+)$	$c\bar{s}$	**2.573**	$B_{sJ}^{*0}(2^+)$	$s\bar{b}$	**(5.850)**	**5**

$$\frac{Ds}{D} \approx \frac{\gamma_s^{\rm H}}{\gamma_q^{\rm H}} \frac{\Sigma_i g_{Dsi} m_{Dsi}^{3/2} \exp(-m_{Dsi}/T)}{\Sigma_i g_{Di} m_{Di}^{3/2} \exp(-m_{Di}/T)} = f(T) \frac{\gamma_s^{\rm H}}{\gamma_q^{\rm H}}, \qquad \gamma_{D_s}^{\rm H} = \gamma_c^{\rm H}\gamma_s^{\rm H}, \quad \gamma_D^{\rm H} = \gamma_c^{\rm H}\gamma_q^{\rm H}.$$

Note that overabundance of strangeness ‘binds’ charm (bottom) and fewer heavy quarks are left to make other states. This explains many results shown below.

Experimental STRANGENESS EXCITATION FUNCTION



Strangeness production increases with energy, expected to continue to LHC energy. A measure of the increase is Strangeness / Entropy in QGP.

Relative s/S yield measures the number of active degrees of freedom and degree of relaxation when strangeness production freezes-out.

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

much of $\mathcal{O}(\alpha_s)$ interaction effect cancels out. When considered $s/S \to 1/31 = 0.0323$

Allow for $\gamma_s^{\rm QGP}$,

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

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2. Statistical Hadronization:

Hypothesis (Fermi, Hagedorn): particle production can be described by evaluating the accessible phase space.

BIG Print Disclaimer: **Fermi: worked with hadron phase space, not a "hadron gas phase": for 'strong' interactions when all matrix elements are saturated ($|M|^2 \to 1$), rate of particle production according to the Fermi golden rule is the n-particle phase space. Micro canonical picture used by Fermi. With time begun to use (grand) canonical phase space, since number of particles and energy content sufficiently high (Hagedorn). WE HADRONIZE A QGP FIREBALL, nobody ever saw a hadron fireball except perhaps at lowest 20-SPS and AGS energies.**

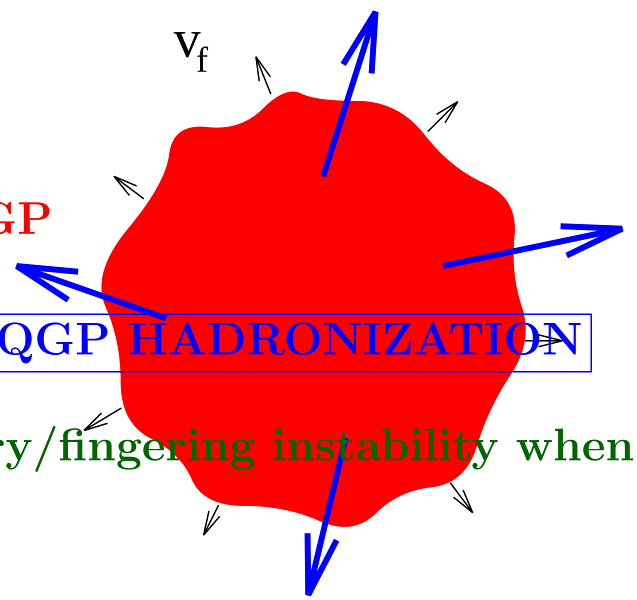
QGP fireball subject to rapid expansion and fast hadronization

For the past 15 years experiments demonstrate symmetry of $m_\perp$ spectra of strange baryons and antibaryons in baryon rich environment.

Interpretation: Common matter-antimatter particle formation mechanism, little antibaryon re-annihilation in sequel evolution.

Appears to be free-streaming particle emission by a quark source into vacuum. Such fast hadronization confirmed by other observables: e.g. reconstructed yield of hadron resonances. Note: within HBT particle correlation analysis: nearly same size pion source at all energies. **WHERE IS ONSET OF fast hadronization as function of $\sqrt{s_{\rm NN}}$? At the NA49 K^+/π^+ horn?**

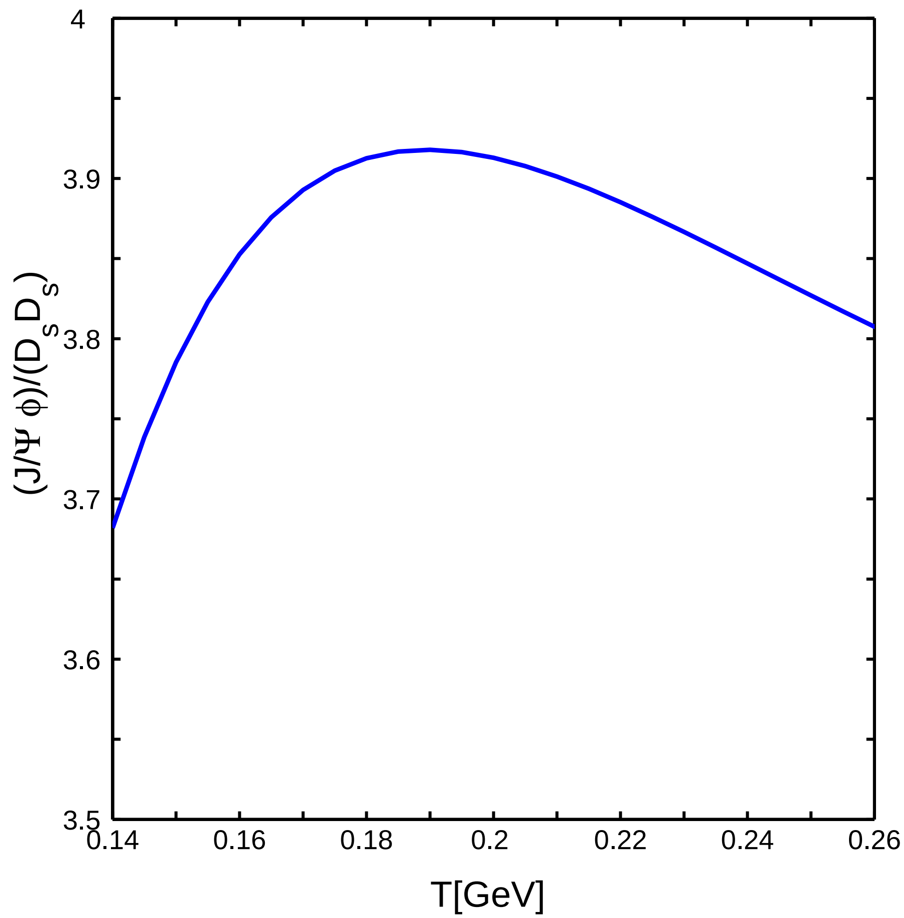
Practically no hadronic 'phase'!
No 'mixed phase' either!
Direct emission of free-streaming
hadrons from exploding filamentary QGP

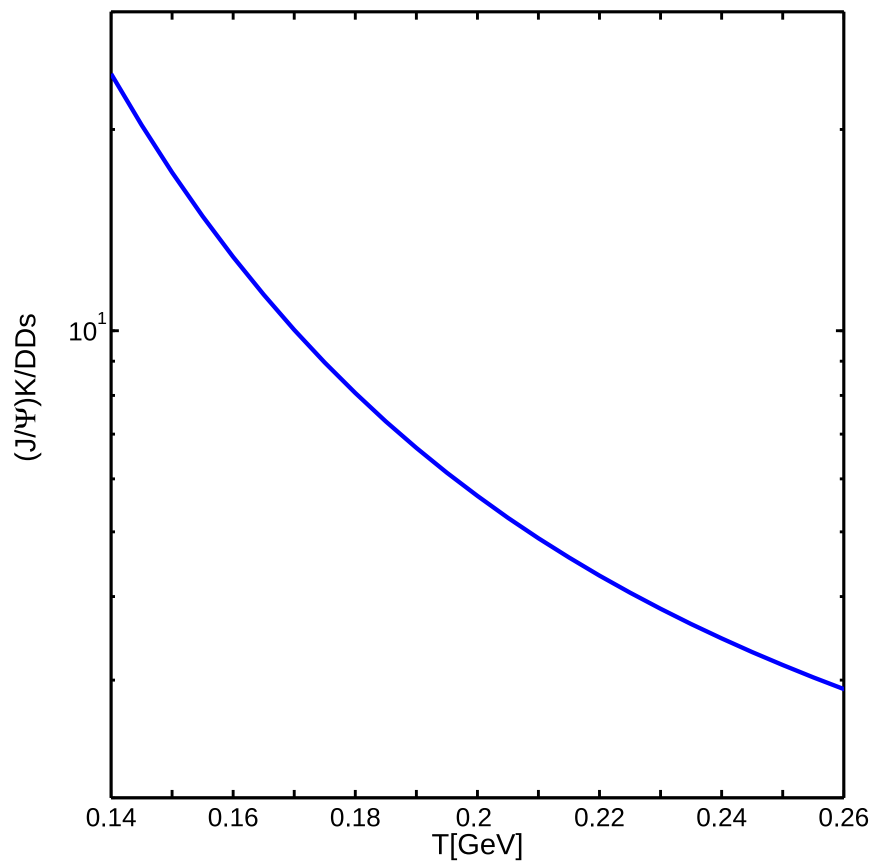


Develop analysis tools viable in SUDDEN QGP HADRONIZATION

Proposed reaction mechanism: filamentary/fingering instability when in expansion pressure reverses.

First amusing results: ratios in which all γ_i cancel:





COMMON FREEZE-OUT OF STRANGE AND CHARMED PARTICLES??
SUBJECT UNDER STUDY, will be an interesting experimental finding

3. Charm hadronization: determine charm and bottom occupancy $\gamma_c^{\rm H}, \gamma_b^{\rm H}$

The number of particles with mass m_i per unit of rapidity is:

$$\frac{dN_i}{dy} = \gamma_i \lambda_i n_i^{eq} \frac{dV}{dy}.$$

γ_i, λ_i products of constituent quark factors, dV/dy is system volume associated with the unit of rapidity, n_i^{eq} is a Boltzmann particle density in chemical equilibrium.

$$n_i^{eq} = g_i\lambda_i \int \frac{d^3p}{(2\pi)^3} e^{-\sqrt{p^2+m_i^2}/T} \to \frac{g_i\lambda_i}{2\pi^2}\sqrt{\frac{\pi}{2}}(m_iT)^{3/2}e^{-m_i/T}\left(1+\frac{15T}{8m_i}+\frac{105}{128}\left(\frac{T}{m_i}\right)^2\ldots\right).$$

We will use as a reference a QGP which at some instance will have $dV/dy = 1000\mathrm{fm}^3$ at $T = 0.2\,\mathrm{GeV}$ with $\alpha_s = 0.5$. Perturbative QCD allows to find $dS/dy \sim 13,810$ and this yields $dN^{\rm Q}/dy \sim 3,500$ and a total hadron multiplicity after hadronization $dN^{\rm H}/dy \sim 4000$, and we use:

$$\frac{dN_c}{dy} = 10; \qquad \frac{dN_b}{dy} = 1 \quad \text{MOSTLY FROM DIRECT PRODUCTION}$$

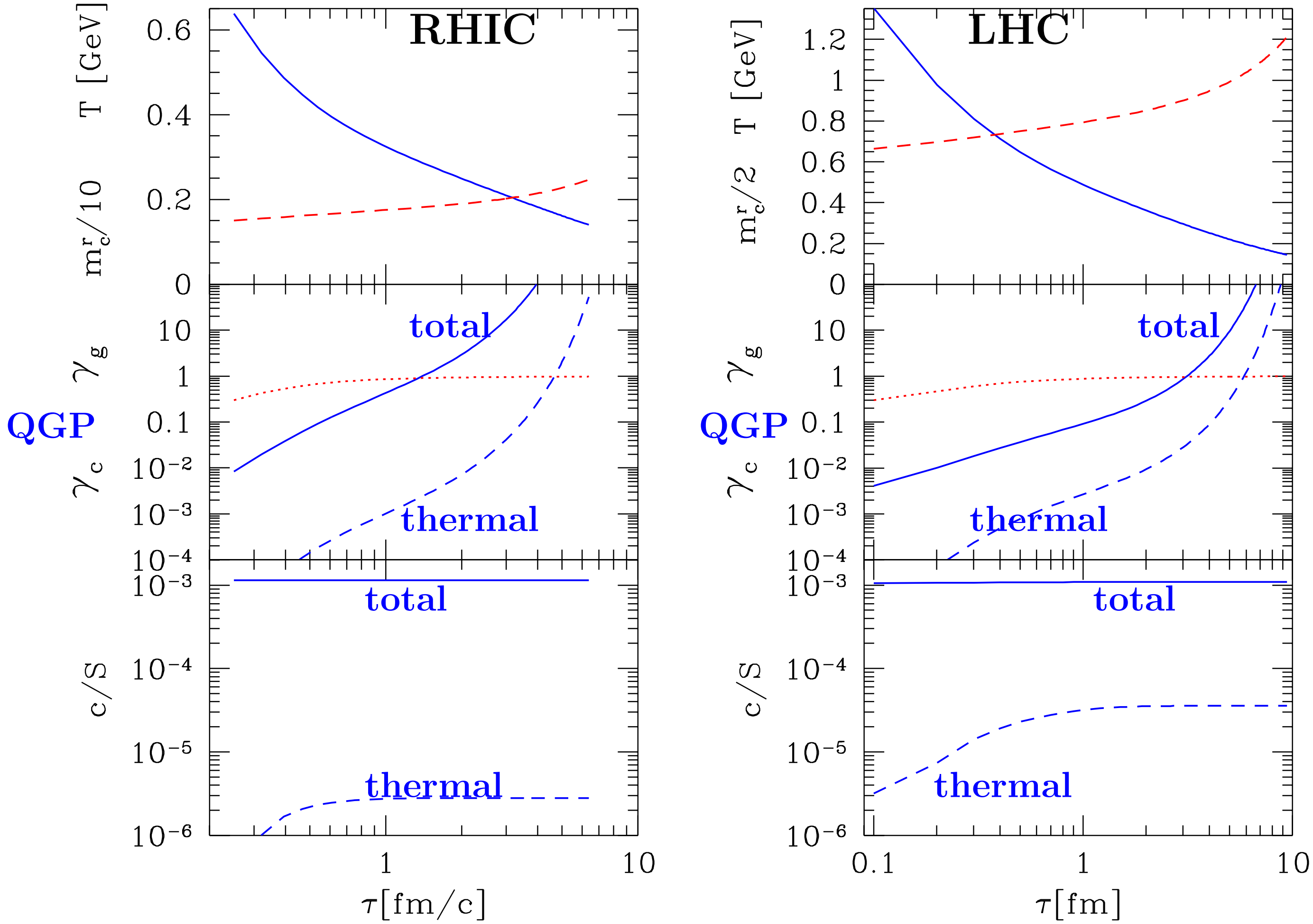
Note that by forming yields per abundance e.g. $\frac{D}{dN_c/dy}$ the assumed absolute yield becomes insignificant for most particle yields.

$$\frac{dN_c}{dy} = \frac{dV}{dy}\left[\gamma_c^{\rm H} n_{\rm op}^c + \gamma_c^{\rm H\,2}(n_{\rm hid}^c + 2\gamma_q^{\rm H} n_{ccq}^{\rm eq} + 2\gamma_s^{\rm H} n_{ccs}^{\rm eq})\right];$$

$$n_{\rm op}^c = \gamma_q^{\rm H} n_D^{\rm eq} + \gamma_s^{\rm H} n_{Ds}^{\rm eq} + \gamma_q^{\rm H\,2} n_{qqc}^{eq} + \gamma_s^{\rm H}\gamma_q^{H} n_{sqc}^{\rm eq} + \gamma_s^{\rm H\,2} n_{ssc}^{\rm eq}; \;\; n_{\rm hid}^c = \gamma_c^{\rm H\,2} n_{c\bar c}^{\rm eq}.$$

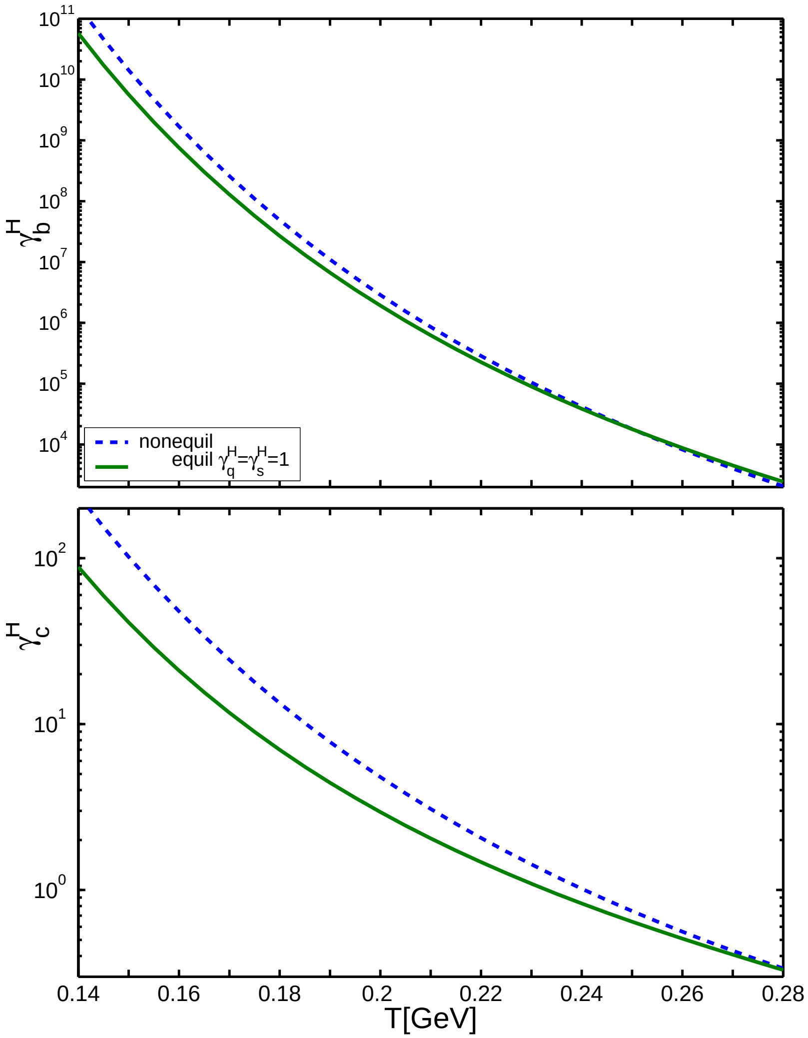
and similar for bottom.

Thermal charm - small but noticeable at LHC



Thermal charm production alone exceeds AT HADRONIZATION the chemical equilibrium yield! **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). However, initial $T(\tau)$ matters a lot and thermal production could increase. Also, the direct production maybe not momentum equilibrated with light particles.**

$\gamma_c^{\rm h}$ and $\gamma_b^{\rm h}$ LARGE



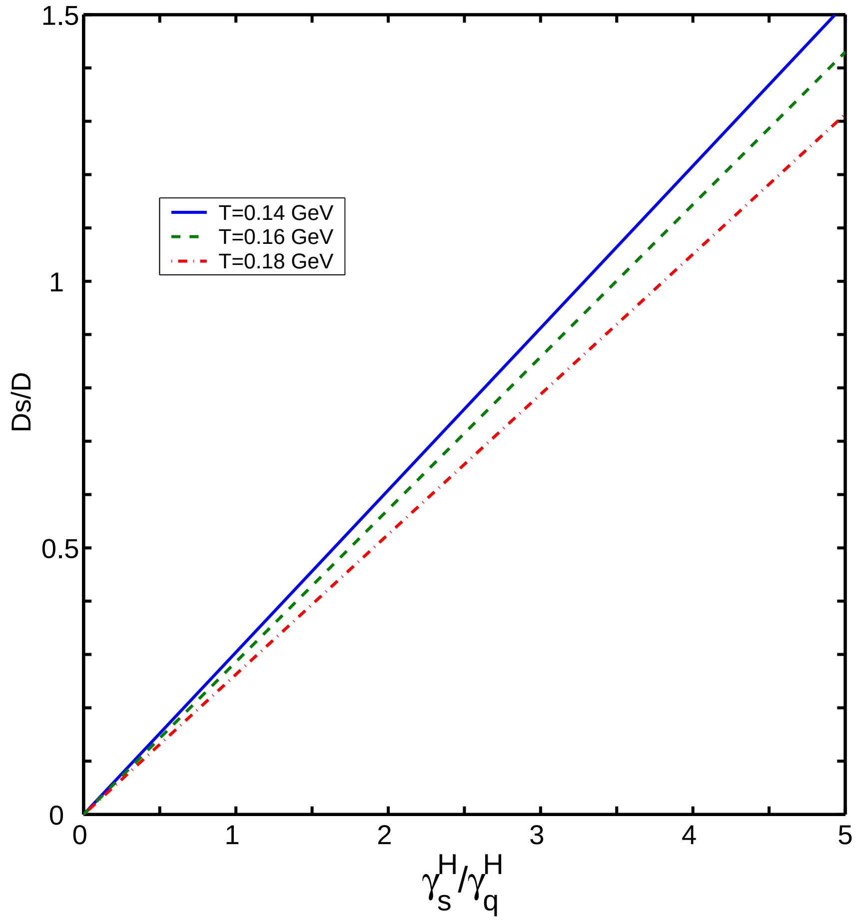
$\gamma_b^{\rm h}(dN_b/dy = 1)$ **and** $\gamma_c^{\rm h}(dN_c/dy = 10)$**, Nonequilibrium (solid line) and equilibrium case** $\gamma_s=\gamma_q=1$ **(dashed line). Nonequilibrium case is considered for** $s/S = 0.053$**.**

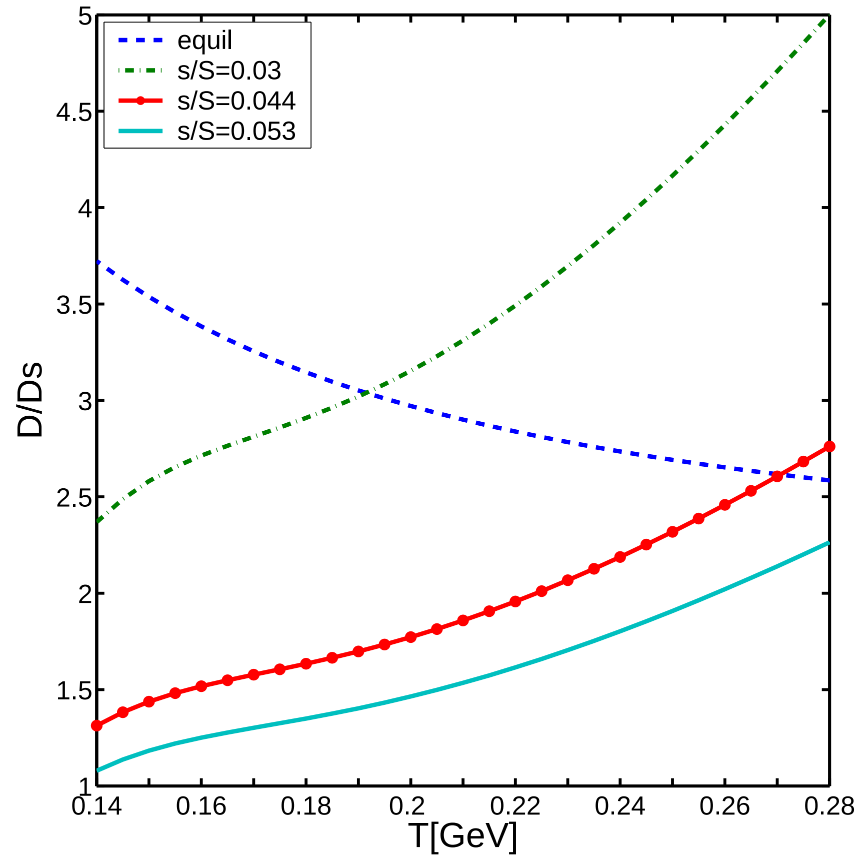
heavy mesons already shown, here are the heavy baryons used (Keep Charm and Bottom hadron spectra SYMMETRIC):

hadron		M[GeV]	hadron		M[GeV]	g
$\Lambda_c^+(1/2^+)$	udc	2.285	$\Lambda_b0(1/2^+)$	udb	5.624	2
$\Lambda_c^+(1/2^-)$	udc	2.593	$\Lambda_b0(1/2^-)$	udb	(6.000)	2
$\Lambda_c^+(3/2^-)$	udc	2.6266	$\Lambda_b0(1/2^-)$	udb	(6.000)	2
$\Sigma_c^+(1/2^+)$	qqc	2.452	$\Sigma0_b(1/2^+)$	qqb	(5.770)	6
$\Sigma_c^*(3/2^+)$	qqc	2.519	$\Sigma_b^{0*}(3/2^+)$	qqb	(5.780)	12
$\Xi_c(1/2^+)$	qsc	2.4663	$\Xi_b(1/2^+)$	qsb	(5.760)	4
$\Xi_c'(1/2^+)$	qsc	2.4718	$\Xi_b'(1/2^+)$	qsb	(5.900)	4
$\Xi_c(3/2^+)$	qsc	2.5741	$\Xi_b'(3/2^+)$	qsb	(5.900)	8
$\Omega_c(1/2^+)$	ssc	2.700	$\Xi_b(1/2^+)$	ssb	(6.000)	2
$\Omega_c(3/2^+)$	ssc	(2.700)	$\Xi_b(3/2^+)$	ssb	(6.000)	4

Note that the value of $\gamma_s^{\rm h}, \gamma_q^{\rm h}$ **here used was obtained considering entropy and strangeness conservation at the given** T **.**

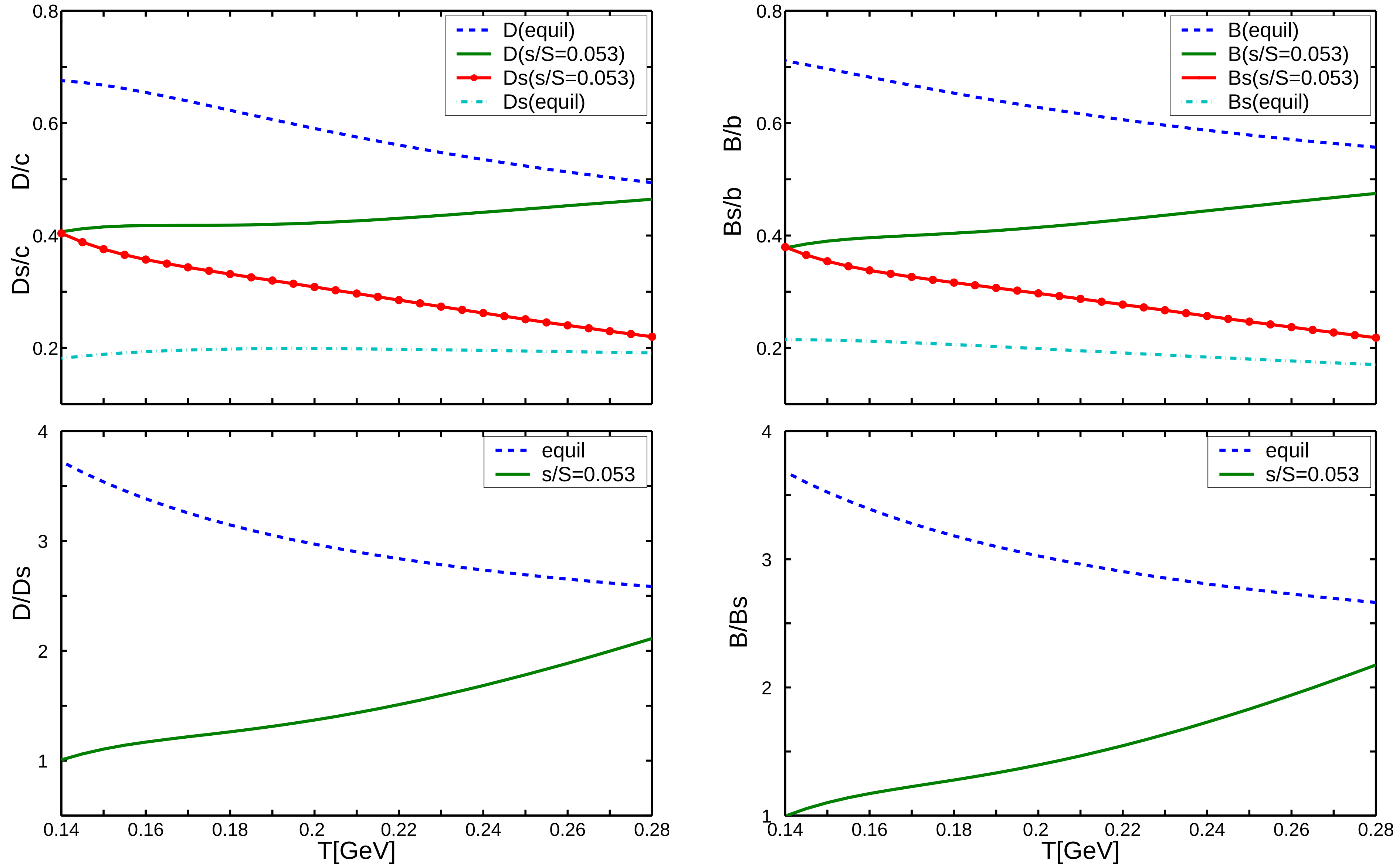
4. Results: Strange charmed – charmed meson ratio determine s/S



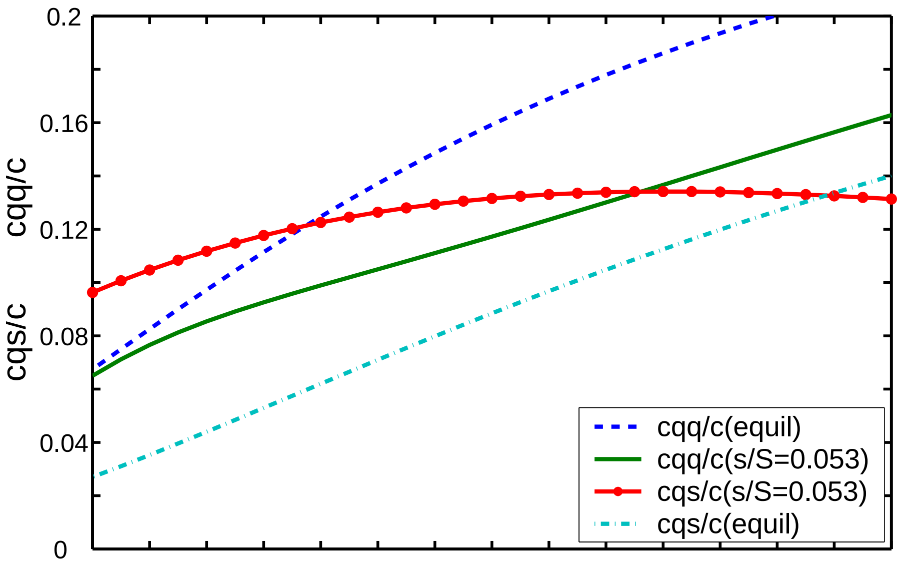


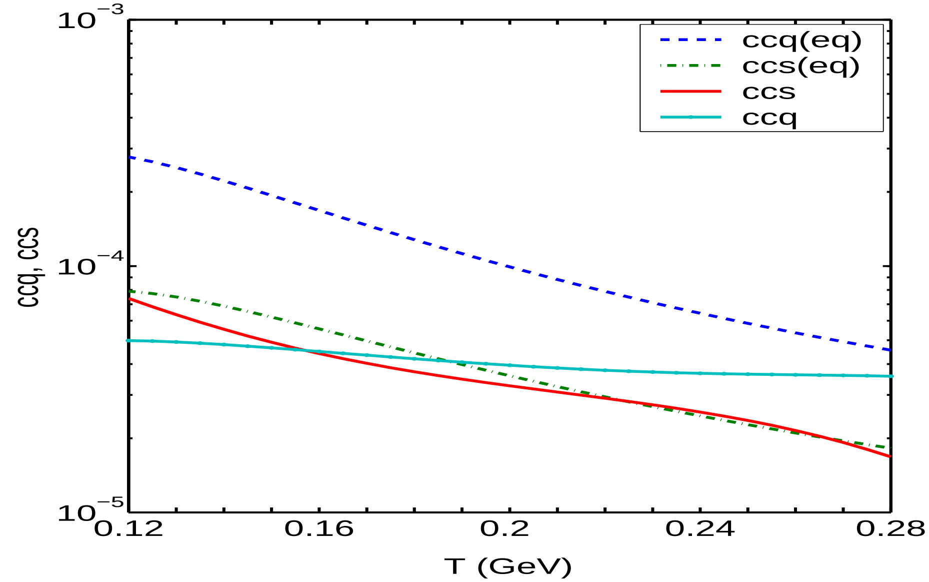
Chemical equilibrium hadronization at high T not much different to non-equilibrium with low T unless s/S noticeably larger than expected in QGP equilibrium. Reference $D/D_s \simeq 3$. Other observables more sensitive.

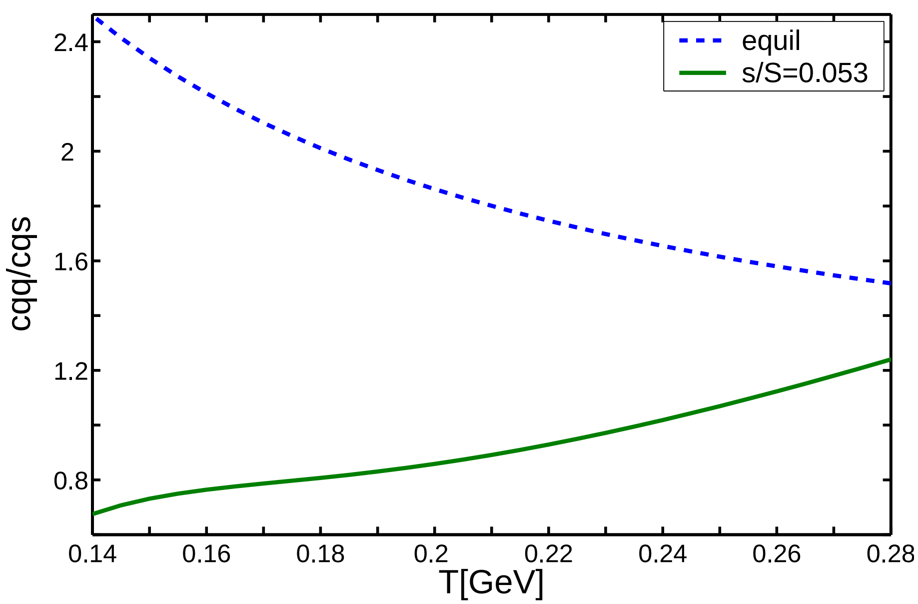
Compare charm and bottom meson ratio, absolute yield

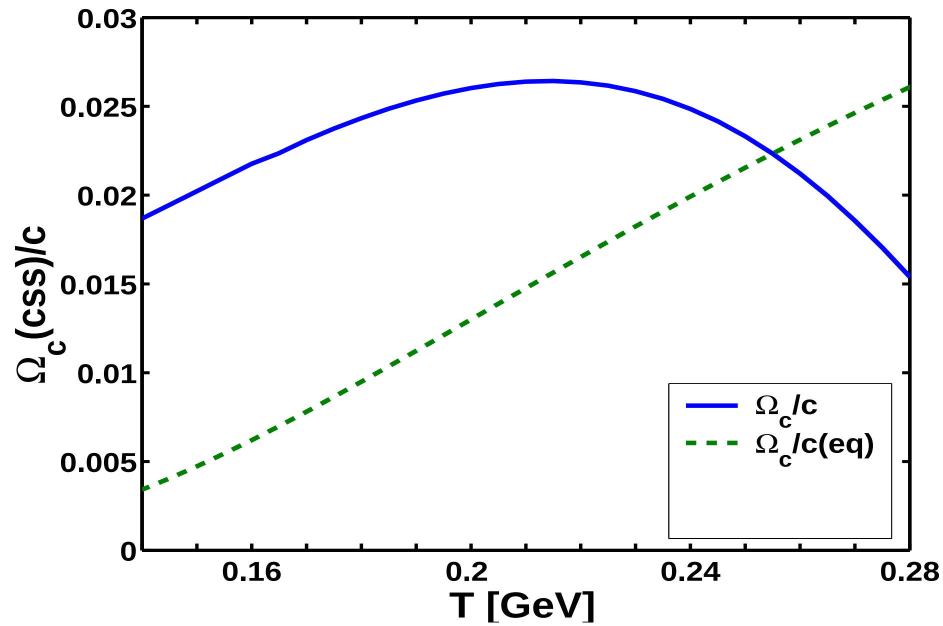


Yields of (strange) charmed BARYONS









Where things are: attempt at a summary

PHYSICS ISSUES WE CAN ADDRESS:

- **Magic ratios of particles test for hadronization T of charm compared to strangeness.**
- **Measurement of D_s/D will produce γ_s^h/γ_q^h.**
- **Important issue: is strangeness OVERSTAURATED in QGP? We have shown that the absolute and relative charm hadron yields are sensitive and will yield the answer. Effect is LARGE since the mass of strange-charm hadrons are not much bigger than regular charmed hadrons – unlike K/π where mass difference eats much of the effect.**
- **J/Ψ, Bc, ...to come. Probe hadronization mechanisms, deconfinement.**