J/ψ production in the Statistical Hadronization Model - limitations and implications

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Outline

- thermal and chemical equilibrium
- hadron production governed by parameters T (chemical freeze-out temperature), μ_B (baryochemical potential)
- production is instantaneous, same for all species

Partition function

$$\ln Z_i^{\mathrm{GC}} = \pm \frac{V g_i}{2\pi^2} \int_0^\infty \mathrm{d}p\, p^2 \ln\left(1 \pm \exp\left(-\frac{E_i - \mu_i}{T}\right)\right)$$

Particle density

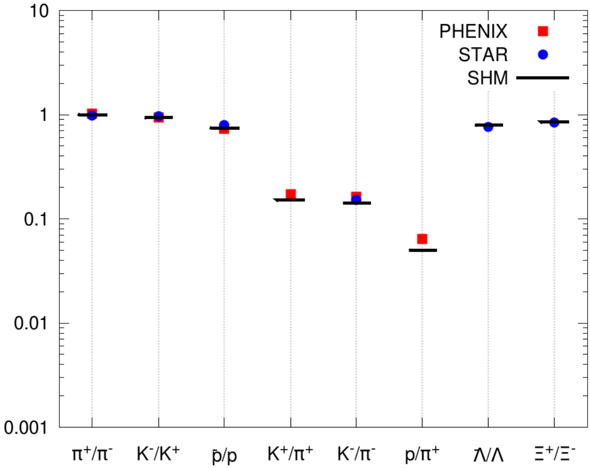
$$n_i^{\mathrm{th}} = \frac{g_i}{2\pi^2} \int_0^\infty \mathrm{d}p\, \frac{p^2}{\exp\left(\frac{E_i - \mu_i}{T}\right) \pm 1}$$

Partition function

$$\ln Z_i^{\mathrm{GC}} = \frac{VTg_i}{2\pi^2} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n+1}}{n^2} \lambda_i^n m_i^2 K_2 \left(\frac{nm_i}{T} \right)$$

Particle density

$$n_i^{\mathrm{th}} = \frac{Tg_i}{2\pi^2} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n+1}}{n} \lambda_i^n m_i^2 K_2 \left(\frac{nm_i}{T} \right)$$



- 200 GeV, Au+Au
- $T = 162\,\mathrm{MeV}$, $\mu_b = 24\,\mathrm{MeV}$

Andronic et al., Nucl. Phys. A904-905, 535c (2013)

- particle densities $\rightarrow$ multiplicities
- calibrated via measured number of charged hadrons
- corrected for finite hadron volumes

Volume

$$V^{\text{SHM}} = \frac{N_{\text{ch}}}{n_{\text{ch}}^{\text{th}}\left(T, \mu_B\right)}$$

- charm quarks are heavy: $m_c \gg T$
- charm far away from chemical equilibrium
- number of $c\bar{c}$ pairs $N_{c\bar{c}}^{\mathrm{dir}}$ fixed after initial production
  $\Rightarrow$ new model parameter

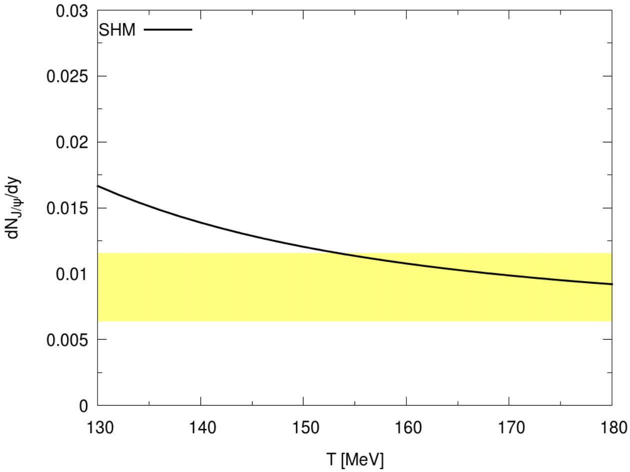
Charm budget

$$N_{c\bar{c}}^{\mathrm{dir}} = \underbrace{\frac{1}{2}\left(N_{D^+} + N_{D^-} + \cdots + N_{\Lambda_c} + \cdots\right)}_{\text{open charm } N_{\mathrm{oc}}} + \underbrace{N_{J/\psi} + N_{\psi'} + \cdots}_{\text{charmonia } N_{c\bar{c}}}$$

Balance equation

$$N_{c\bar{c}}^{\mathrm{dir}} = \frac{1}{2} g_c N_{\mathrm{oc}}^{\mathrm{th}} \frac{I_1\left(g_c N_{\mathrm{oc}}^{\mathrm{th}}\right)}{I_0\left(g_c N_{\mathrm{oc}}^{\mathrm{th}}\right)} + g_c^2 N_{c\bar{c}}^{\mathrm{th}}$$

Andronic et al., Phys.Lett. B571, 36 (2003)

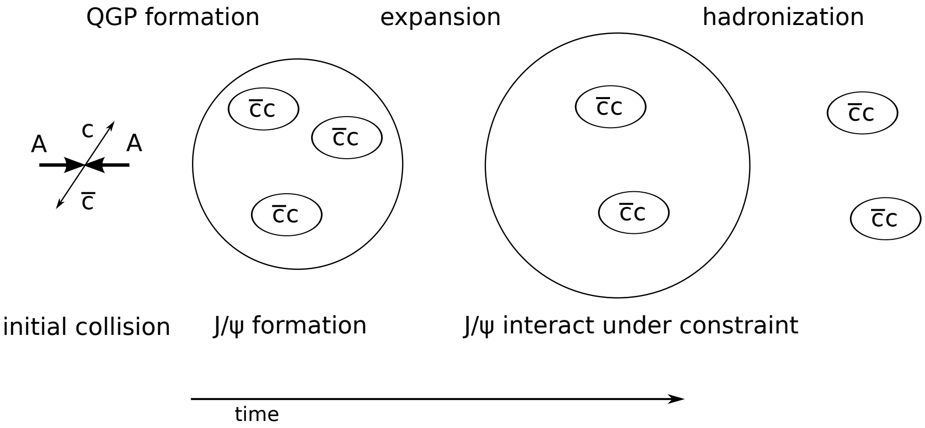


- 200 GeV, Au+Au
- $\mu_b = 24\,\mathrm{MeV}$
- $N_{\mathrm{ch}} = 730$, $N_{c\bar{c}}^{\mathrm{dir}} = 1.92$
- yellow band: PHENIX

$\Rightarrow$ J/ψ yield only weakly dependent on T

Adare et al., PRL 98, 232301 (2007)

- lattice results: J/ψ dissociate at 1.5-1.9 $T_c \rightarrow$ earlier production?
- production in the QGP describable in extended SHM?
- sensitive quantities of description?

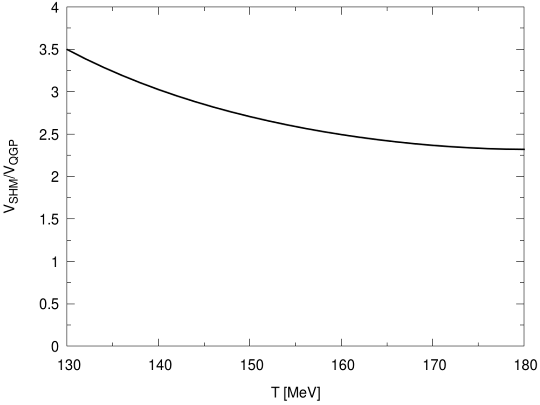

QGP formation
expansion
hadronization
A
c
A
c̄
c̄c
c̄c
c̄c
c̄c
c̄c
c̄c
c̄c
initial collision
J/ψ formation
J/ψ interact under constraint
time

- exact charm conservation
- J/ψ are in constrained equilibrium
- no J/ψ formed or destroyed during hadronization
- equal entropy in QGP and hadronic fireball at hadronization

Modified strategy to Grandchamp et al., PRL 92, 212301 (2004)

Analogous Quantities
J/ψ in the QGP

- $V^{\mathrm{SHM}} \rightarrow V^{\mathrm{QGP}}$ by entropy conservation
- $g_c \rightarrow \lambda_c$ by exact charm conservation



Volume calculation

$$S^{\mathrm{SHM}} = S^{\mathrm{QGP}} \Rightarrow V^{\mathrm{QGP}} = \frac{S^{SHM}}{s^{\mathrm{QGP}}}$$

Again, all charm quarks need to be accounted for:

Partonic charm balance

$$N_{c\bar{c}}^{\text{dir}} = \lambda_c \frac{2V^{\text{QGP}}}{2\pi^2} (m_c T)^{\frac{3}{2}} e^{-\frac{m_c}{T}}$$

Hadronic charm balance

$$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} g_c N_{\text{oc}}^{\text{th}} \frac{I_1\left(g_c N_{\text{oc}}^{\text{th}}\right)}{I_0\left(g_c N_{\text{oc}}^{\text{th}}\right)} + g_c^2 N_{c\bar{c}}^{\text{th}}$$

$\Rightarrow$ λ_c depends strongly on m_c!

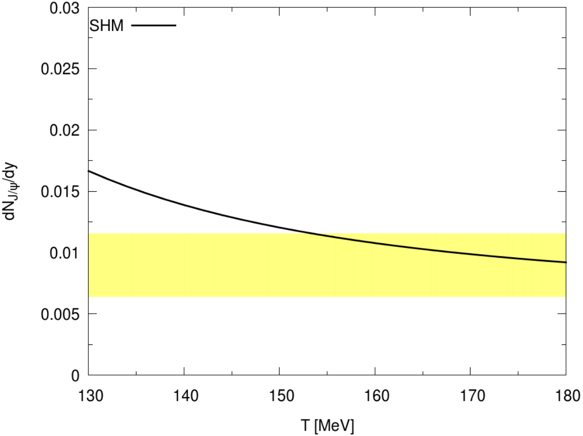
Partonic picture

$$N_{J/\psi}^{\mathrm{QGP}} = \frac{3\,V^{\mathrm{QGP}}}{2\pi^2}\,\lambda_c^2 \int_0^\infty \mathrm{d}p \frac{p^2}{\exp\left(\frac{E_{J/\psi}-\mu_{J/\psi}}{T}\right) - 1}$$

Hadronic picture

$$N_{J/\psi}^{\mathrm{SHM}} = \frac{3\,V^{\mathrm{SHM}}}{2\pi^2}\,g_c^2 \int_0^\infty \mathrm{d}p \frac{p^2}{\exp\left(\frac{E_{J/\psi}-\mu_{J/\psi}}{T}\right) - 1}$$

No J/ψ formed or destroyed during medium hadronization $\Rightarrow N_{J/\psi}^{SHM} = N_{J/\psi}^{QGP}$



- $\mu_b = 24\,\mathrm{MeV}$
- $N_{\mathrm{ch}} = 730$
- $N_{c\bar{c}}^{\mathrm{dir}} = 1.92$

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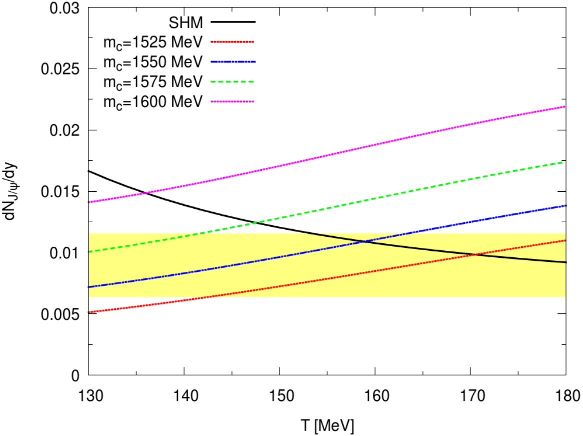
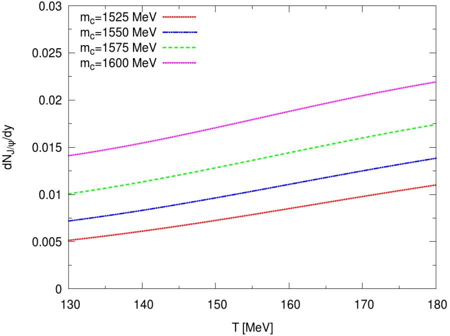


- intersections for (T, m_c) pairs
- $T \simeq 160\,\mathrm{MeV}$
  $\Rightarrow m_c \simeq 1550\,\mathrm{MeV}$

$N_{J/\psi}^{QGP}$ scales counterintuitively with m_c:



- higher $m_c \rightarrow N_c^{th}$ goes down
- for constant $N_{c\bar{c}}^{\mathrm{dir}}$, λ_c goes up to compensate
- λ_c contributes quadratically to $N_{J/\psi}^{QGP}$

$\Rightarrow$ $N_{J/\psi}^{QGP}$ rises with higher values for m_c!

Conclusions

- functional Statistical Hadronization Model
- possible to produce J/ψ in the QGP and stay consistent with SHM
- strong constraint on charm quark mass
- $m_c \simeq 1550\,\mathrm{MeV}$, cf. Grandchamp et al.: 1600-1700 MeV

? dynamical models reproduce J/ψ data, but use $m_c = 1870\,\mathrm{MeV}$

? investigate mass dependence of J/ψ dissociation and regeneration in parton cascade BAMPS

Zhou et al., arXiv:1401.5845

Back-up

- Include finite hadron volumes
- $V^{\mathrm{excl}} = 4\frac{4}{3}\pi R^3$, $R = 0.3\,\mathrm{fm}$
- Includes $\sim$ 500 particle species

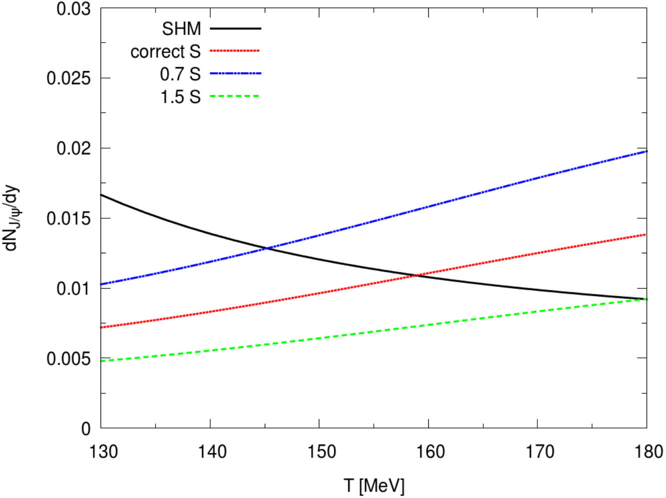
Iteration

$$\hat{p}\,(T,\mu) = p^{\mathrm{id}}\,(T,\hat{\mu}_1,\ldots,\hat{\mu}_k)$$
$$\hat{\mu}_i = \mu_i - v_i \cdot \hat{p}\,(T,\mu_1,\ldots,\mu_k)$$

Volume

$$V^{\mathrm{SHM}} = \frac{N_{\mathrm{ch}}}{n_{\mathrm{ch}}^{\mathrm{th}}\,(T,\hat{\mu}_B)}$$

Rischke et al., Z. Phys. C51, 485 (1991)


SHM
correct S
0.7 S
1.5 S
0.03
0.025
0.02
0.015
0.01
0.005
0
130
140
150
160
170
180
T [MeV]
$dN_{J/\psi}/dy$

Fireball entropy

$$S_i^{\mathrm{SHM}} = \frac{g_i V^{\mathrm{SHM}}}{2\pi^2} m_i^2 \sum_{n=1}^{\infty} (\pm 1)^{n+1} \frac{\lambda_i^n}{n^2} (2T - \mu n) K_2\left(\frac{nm_i}{T}\right) + \frac{nm_i}{2}\left[K_1\left(\frac{nm_i}{T}\right) + K_3\left(\frac{nm_i}{T}\right)\right]$$

QGP entropy density

$$s^{\mathrm{QGP}} = 4\left(16 + \frac{21}{2} N_f\right) \frac{\pi^2}{90} T^3$$