Charm quarks in heavy-ion collisions

Taesoo Song

PHSD (Parton-Hadron-String Dynamics) for heavy quark & quarknoium

- Initial heavy flavor from the PYTHIA 6.4.
- Partonic cross sections from Hamza Berrehrah
- Dynamical hadronization
- Hadronic cross sections from Laura Tolos, Daniel Cabrera, Juan Torres-Rincon

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In progress !!!

Charmonia formation in QGP

PRC 89, 044903 (2014)

Taesoo Song

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Outline

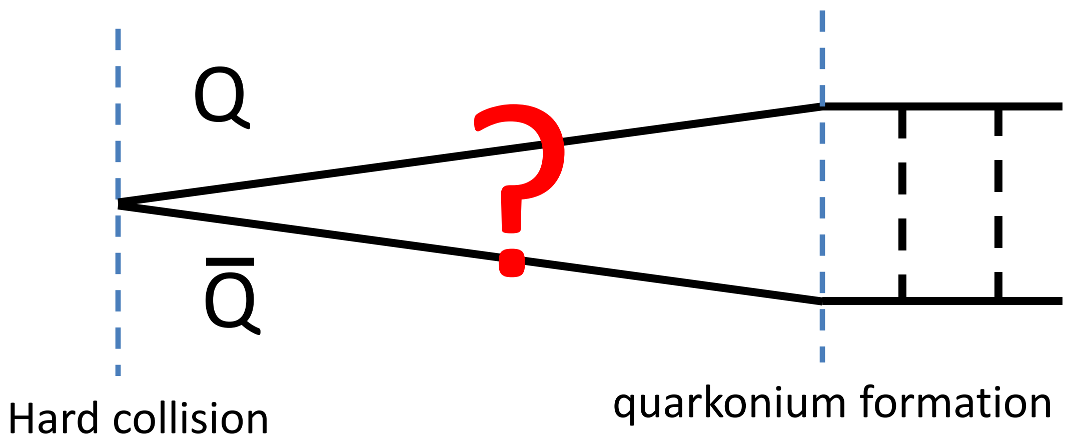
1. Motivation
2. Method
   2.1. color evaporation model
   2.2. Langevin equation
3. Results
4. Summary

Motivation

- It takes much longer time for quarkonium to be formed in QGP compared to in vacuum.

T. Song, S. H. Lee, and C. M. Ko, PRC 87, 034910 (2013)

- Nuclear medium effect after QQ production and before quarkonium formation is not well known.

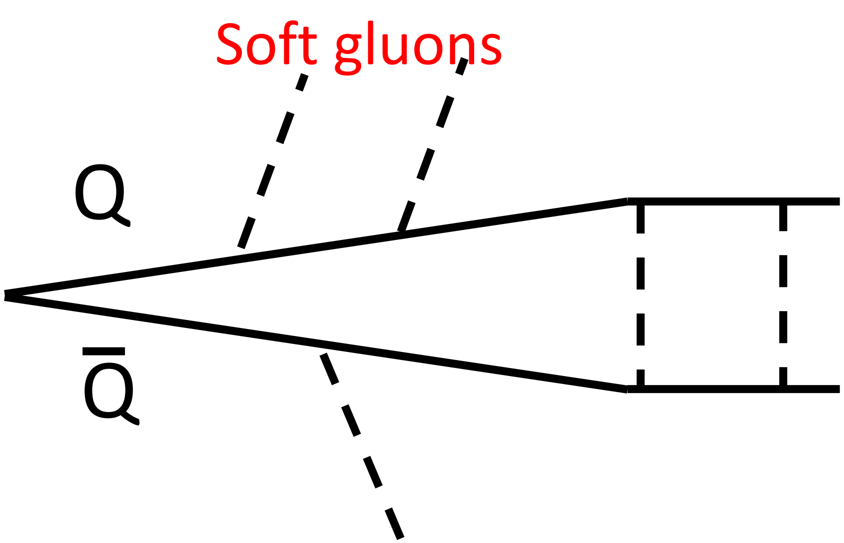


2.1. Color evaporation model

$$\sigma_{\text{hidden}} = \frac{1}{9}\int_{2m_c}^{2m_D} dM \frac{d\sigma_{c\bar{c}}}{dM},$$

$$\sigma_{\text{open}} = \frac{8}{9}\int_{2m_c}^{2m_D} dM \frac{d\sigma_{c\bar{c}}}{dM} + \int_{2m_D} dM \frac{d\sigma_{c\bar{c}}}{dM},$$

M : invariant mass of $c\bar{c}$



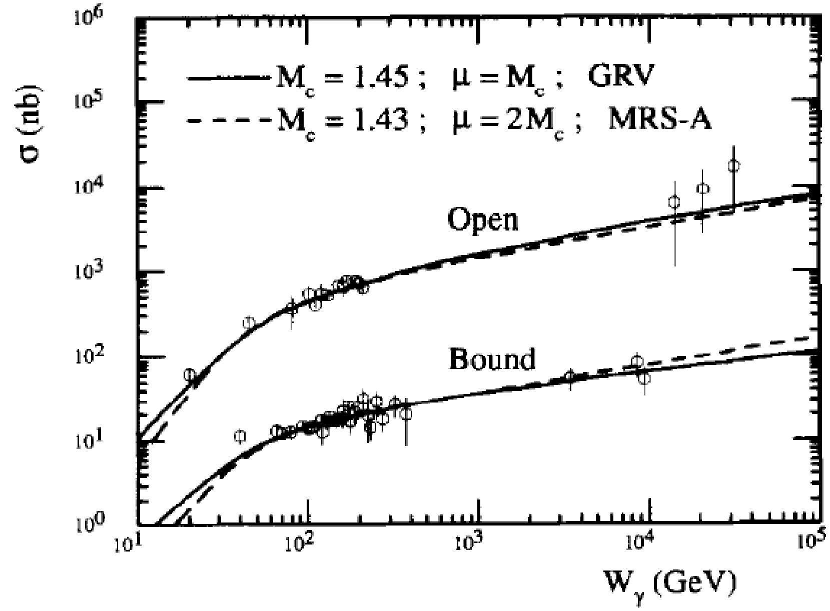
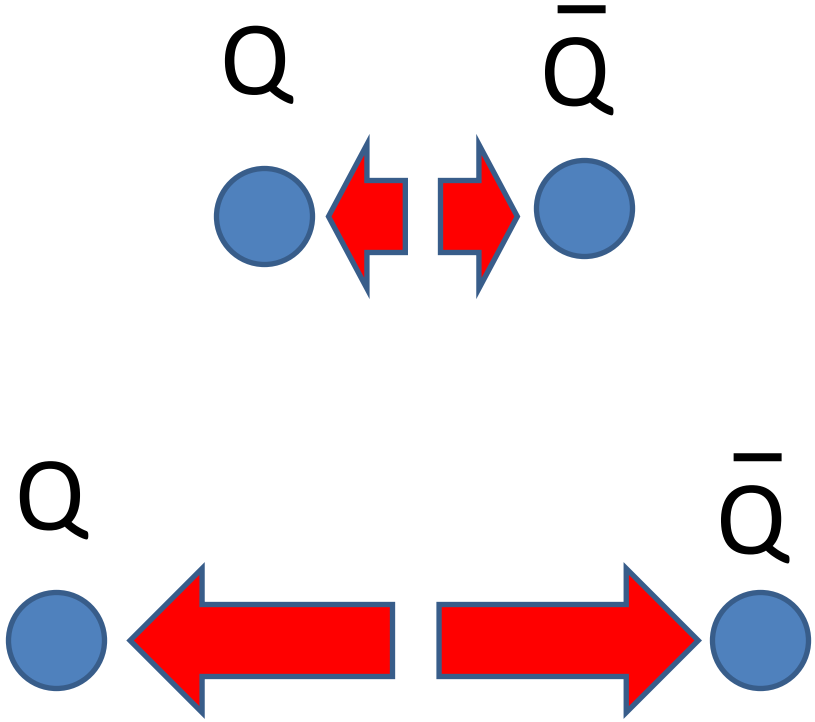


Fig. 4. Photoproduction data [18,19] and the predictions of the color evaporation model at next-to-leading order as a function of the photon energy in the hadron rest frame, W_γ. The normalizations in this figure are absolute.



Small M,
Large probability for quarkonium formation
(nonzero constant probability in CEM)

large M,
small probability for quarkonium formation
(zero probability in CEM)

Color evaporation model in QGP

In vauum

- $\sigma_{NN \to charmonium} = \int_{2m_c}^{2m_D} dM\, f_{c\bar{c}}(M)$

$$m_D = \tilde{m}_c + \frac{1}{2}\mathrm{V}(\mathrm{r} = \infty, T = 0)$$

$f_{c\bar{c}}(M)$: M distribution of $c\bar{c}$

In QGP

- $\sigma_{NN \to charmonium} = \int_{2m_c}^{2m_c^*(T)} dM\, f_{c\bar{c}}^*(M)$

$$m_c^* = \tilde{m}_c + \frac{1}{2}\mathrm{V}(\mathrm{r} = \infty, T)$$

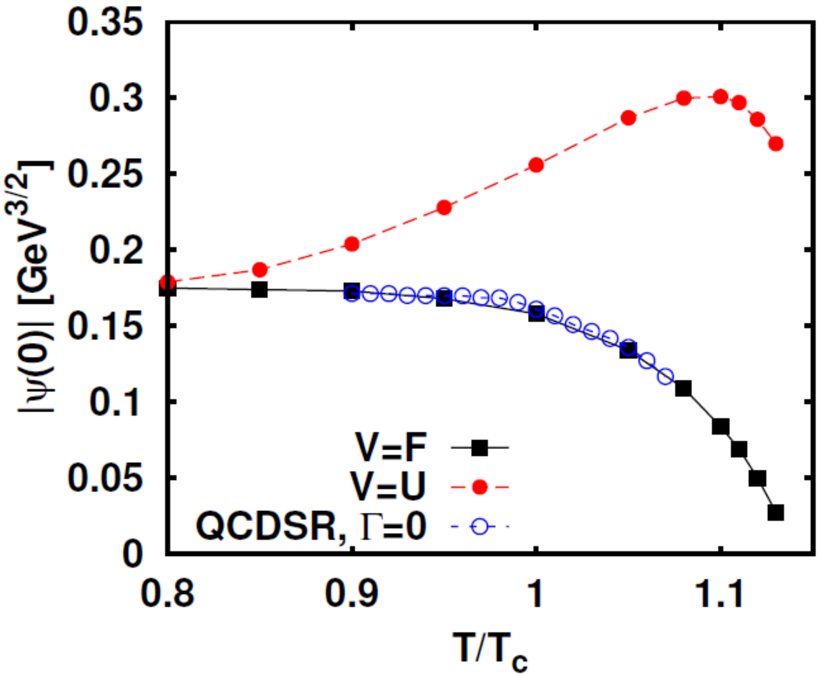
m_c : charm quark mass in pQCD (PDG)

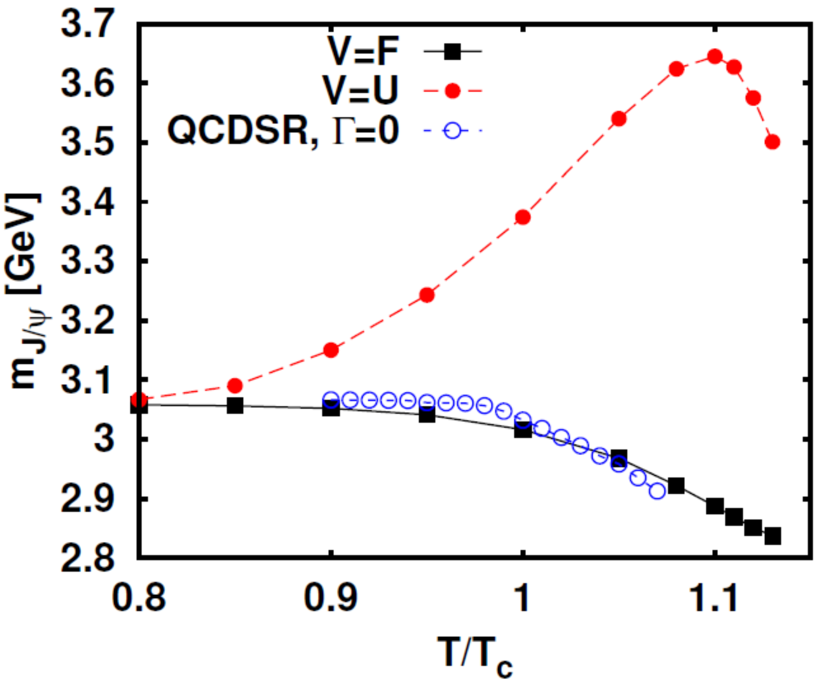
$\tilde{m}_c$: charm quark mass from charmonium spectroscopy in potential model ($\tilde{m}_Q \geq m_Q$)

$f_{c\bar{c}}^*(M)$: M distribution of $c\bar{c}$ at charmonium formation time in QGP

Comparison of ψ(0,T) and $m_{J/\psi}$ from QCD sum rule & Schrödinger equation

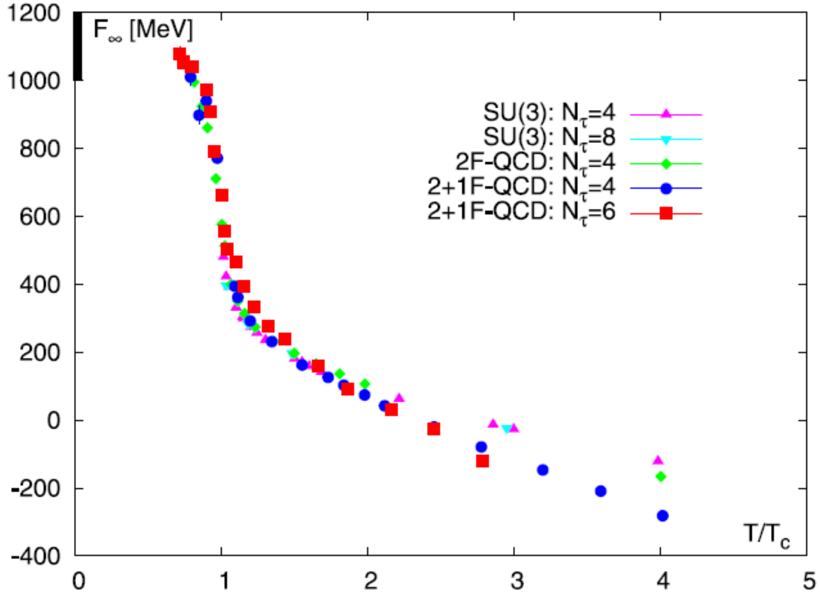
S. H. Lee, K. Morita, T. Song, and C. M. Ko, PRD 89, 094015 (2014)





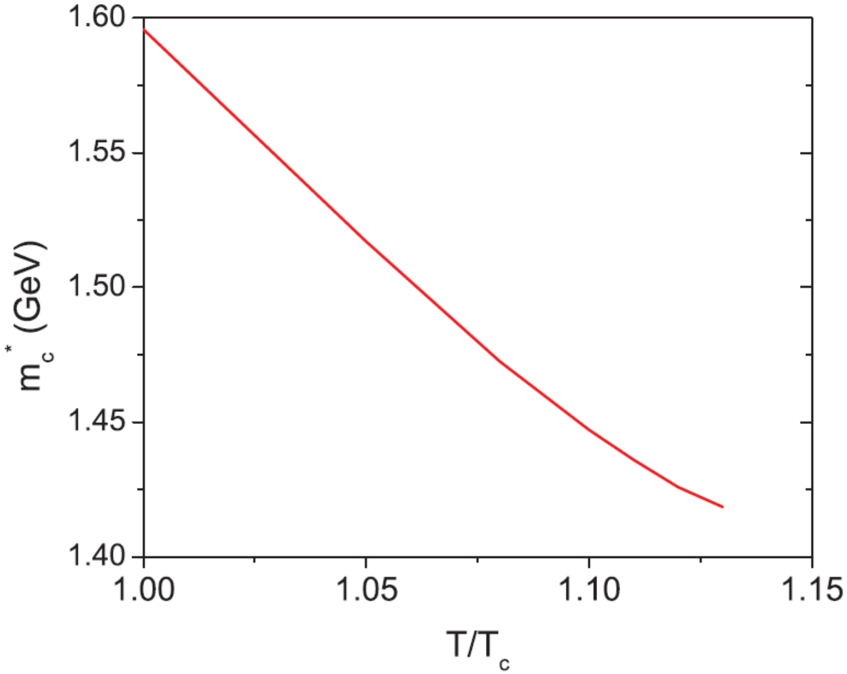
m_c^* from lattice free energy

F(r=∞,T)

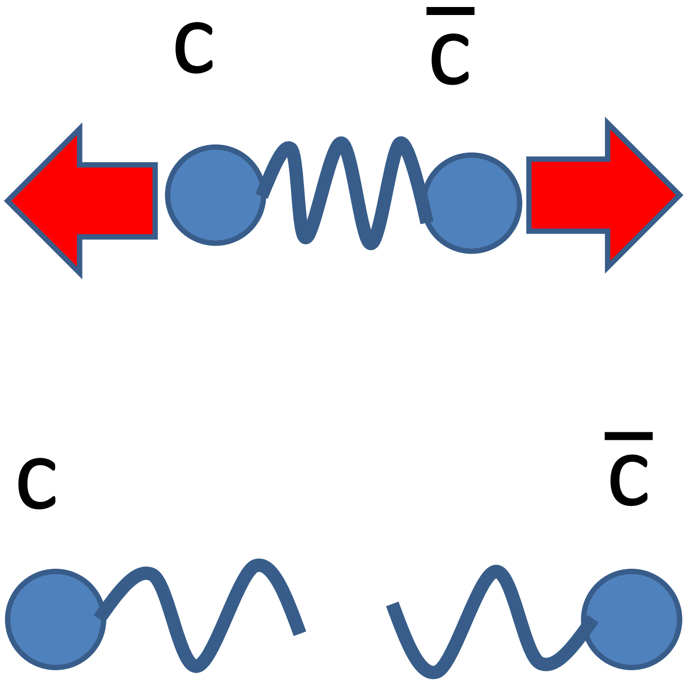


Eur. Phys. J. C61:811 (2009)

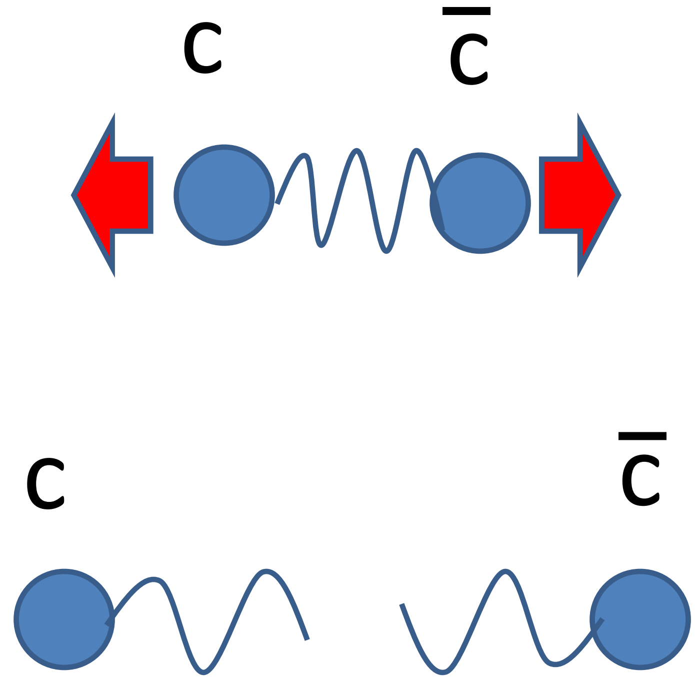
decreasing m_c^* with T



Strongly bound



Weakly bound



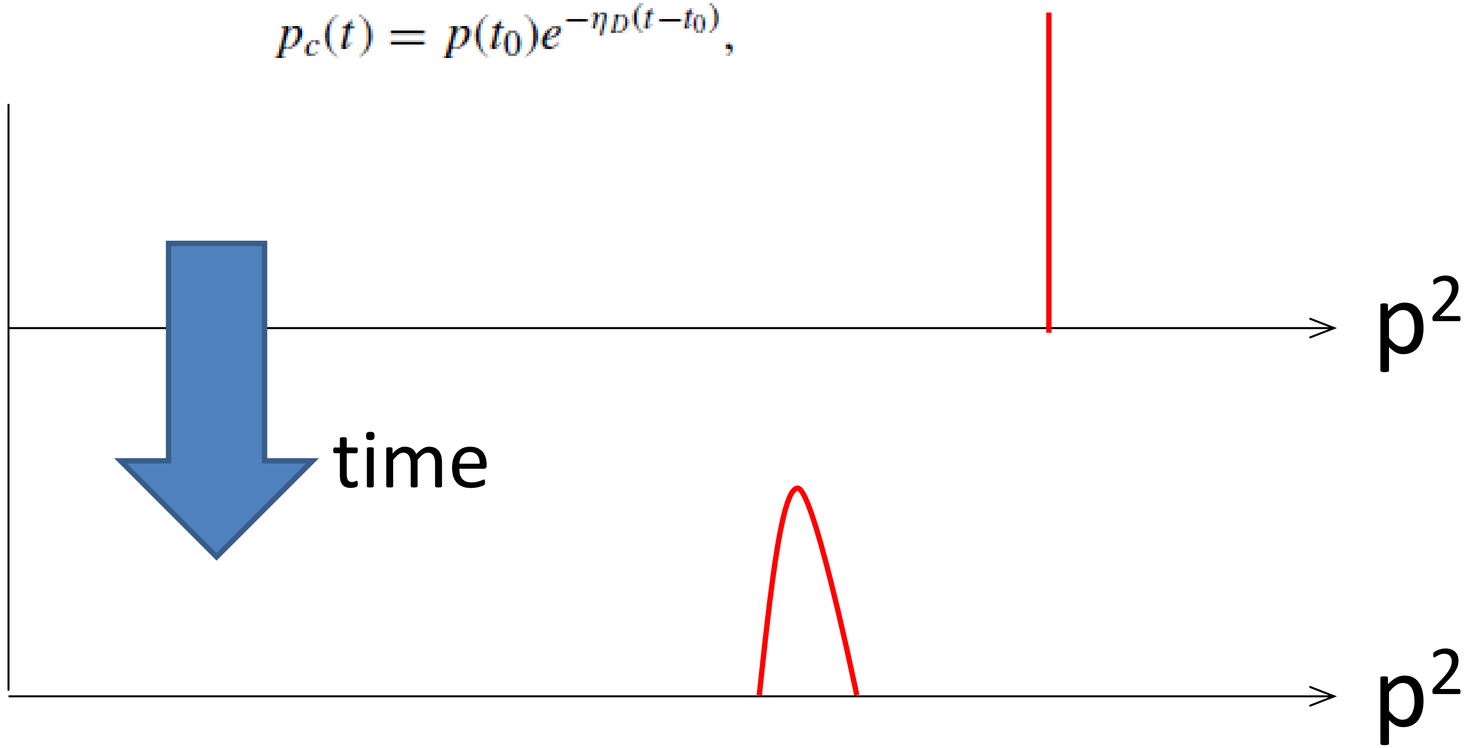
$$2m_c^{s*} > 2m_c^{w*}$$

2.2. $f^*_{c\bar{c}}(M)$ from Langevin equation

$$f_c(\vec{p}) = \frac{1}{(2\pi)^{3/2}\sigma_L\sigma_T^2} \exp\left[-\frac{\{p_L - p_c(t)\}^2}{2\sigma_L^2} - \frac{p_T^2}{2\sigma_T^2}\right],$$

which is centered at

$$p_c(t) = p(t_0)e^{-\eta_D(t-t_0)},$$



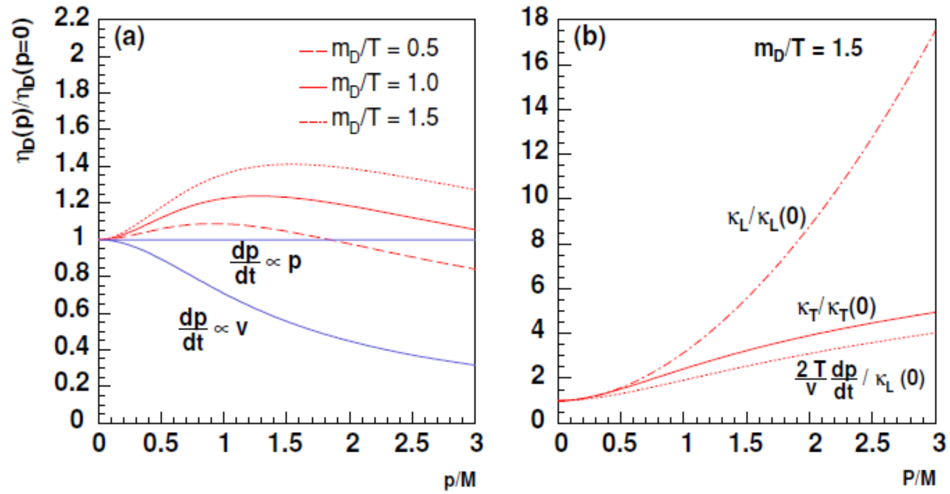
$$\sigma_L^2 = \int_{t_0}^{t} dt' \kappa_L(t') e^{-2\eta_D(t-t')},$$

$$\sigma_T^2 = 2\int_{t_0}^{t} dt' \kappa_T(t') e^{-2\eta_D(t-t')}.$$

$$\eta_D(p)$$

p dependence of K_L and K_T from pQCD

G. Moore, D. Teaney, PRC71, 064904 (2005)

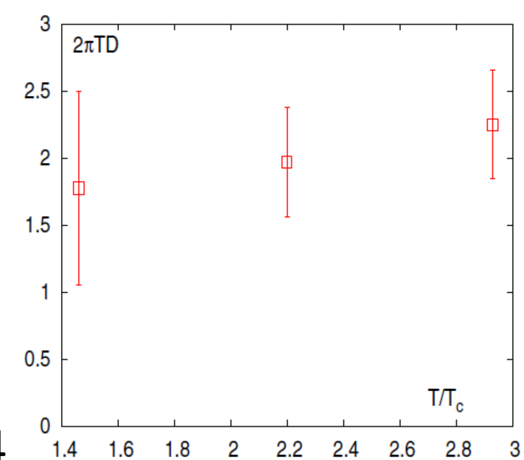


$$p = 0$$

$$\eta_D = \frac{T}{m_c D}, \quad \kappa_L = \kappa_T = \frac{2T^2}{D}.$$

diffusion constant D from lQCD

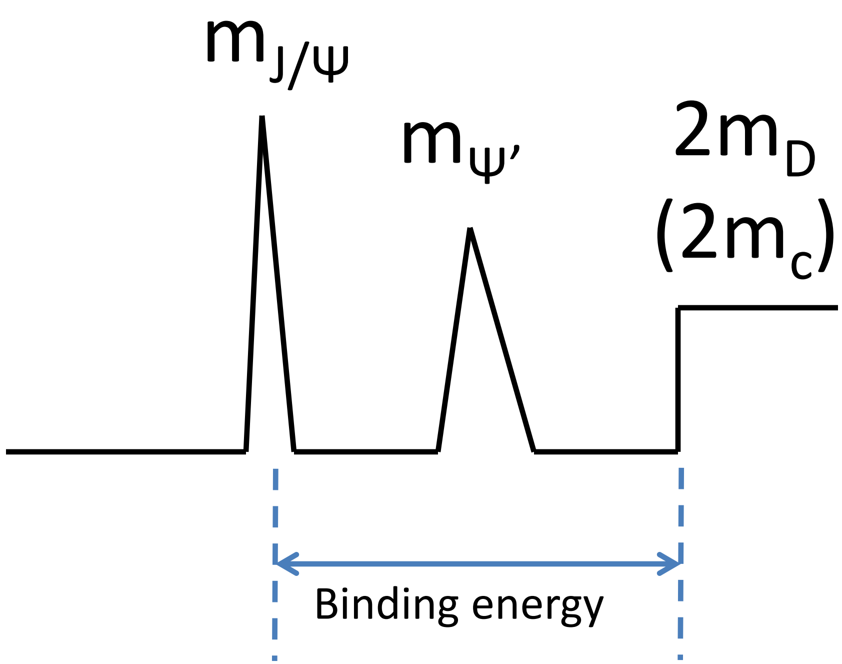
H. T. Ding, et al. PRD86, 014509 (2012)

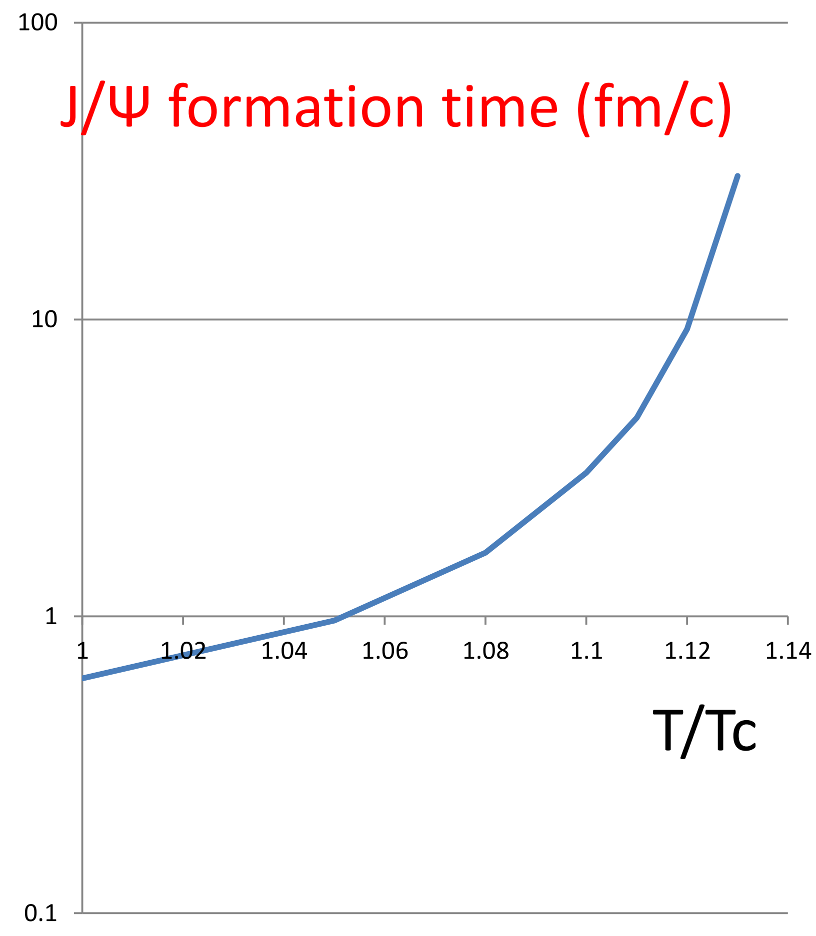


Quarkonium formation time

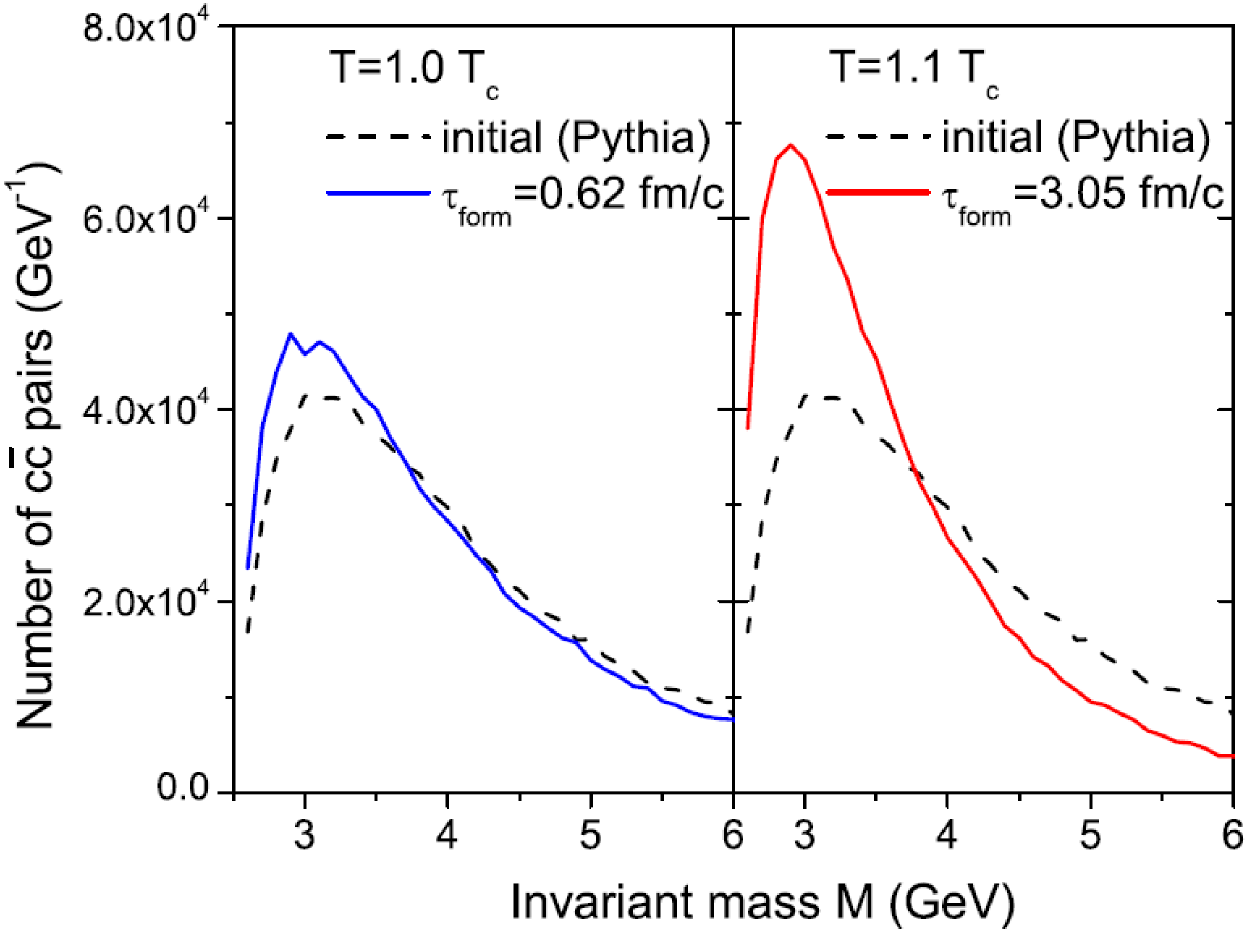
T. Song, S. H. Lee, and C. M. Ko, PRC 87, 034910 (2013)

Spectral function



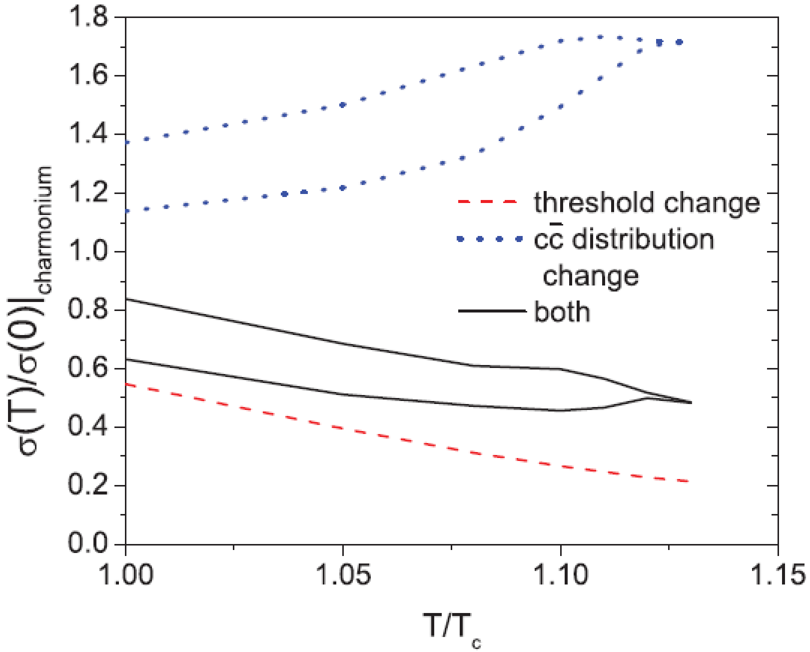


$f^*_{c\bar{c}}(M)$ at formation time in QGP



for
$2\pi TD = 3$

Results



Lower lines for $2\pi TD = 3$
Upper lines for $2\pi TD = 1$

- Decreasing m_c^* with T suppresses charomina formation
- Softened $c\bar{c}$ spectrum, $f_{c\bar{c}}^*(M)$, enhances charmonia formation
- As a result, charmonia production is suppressed about by a half.

about J/Ψ

- 50 % of charmonia produced at 200 GeV in p+p collisions are J/Ψ in vacuum.
- J/Ψ is the only charmonium that survives in QGP.
- J/Ψ yield in p+p collisions in QGP is similar to that in vacuum
- About 40 % of J/Ψ come from the decay of ψ', χ_c.
- Taking it into account, J/Ψ yield in p+p collisions in QGP is larger than that excluding the feed-down contribution.

Summary

- Using the color evaporation model, charmonia production at 200 GeV in p+p collisions is calculated in QGP.
- Charm quark mass decreasing with temperature suppresses the charmonium production.
- The invariant mass of $c\bar{c}$ pair which decreases in QGP due to scattering enhances the charmonium production.
- As a result, charmonium production is suppressed by a half in QGP.
- However, J/Ψ production is not suppressed, because it is the only survived charmonium in QGP, and some of them are produced by the decay of excited states.