Charmonium production from nonequilibrium charm & anticharm quarks in QGP

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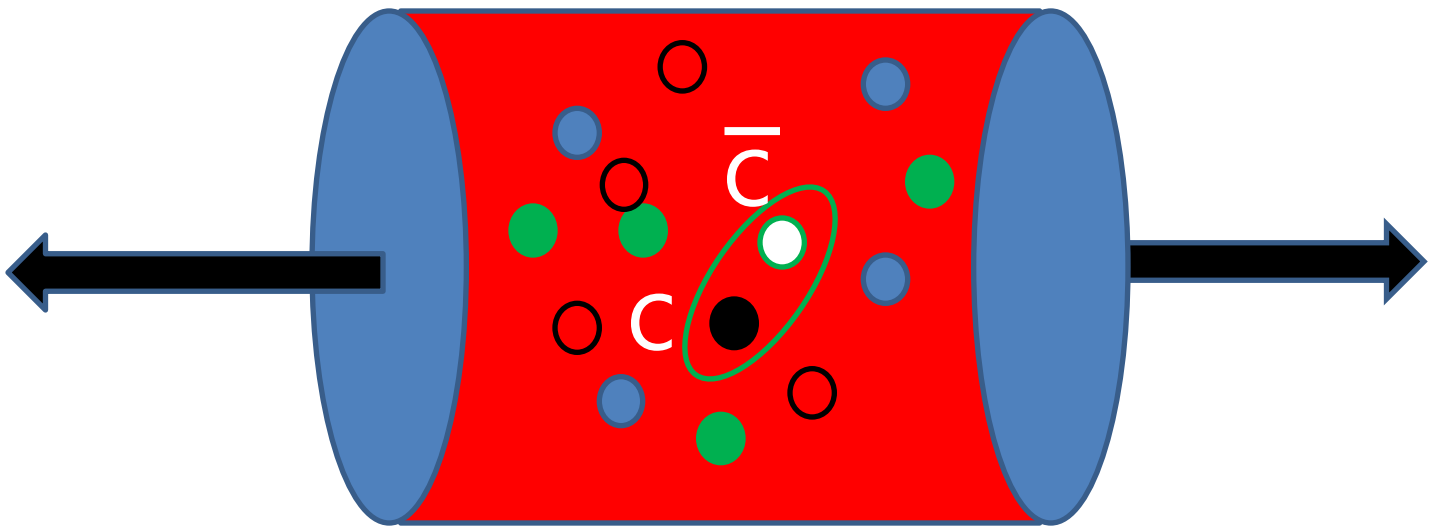
J/ψ suppression as a signature of QGP formation was suggested by Matsui & Satz:

1) QGP formation
2) Color Debye screening between charm & anticharm quark
3) J/ψ production is suppressed



Nuclear modification of J/ψ

Cold nuclear matter effect

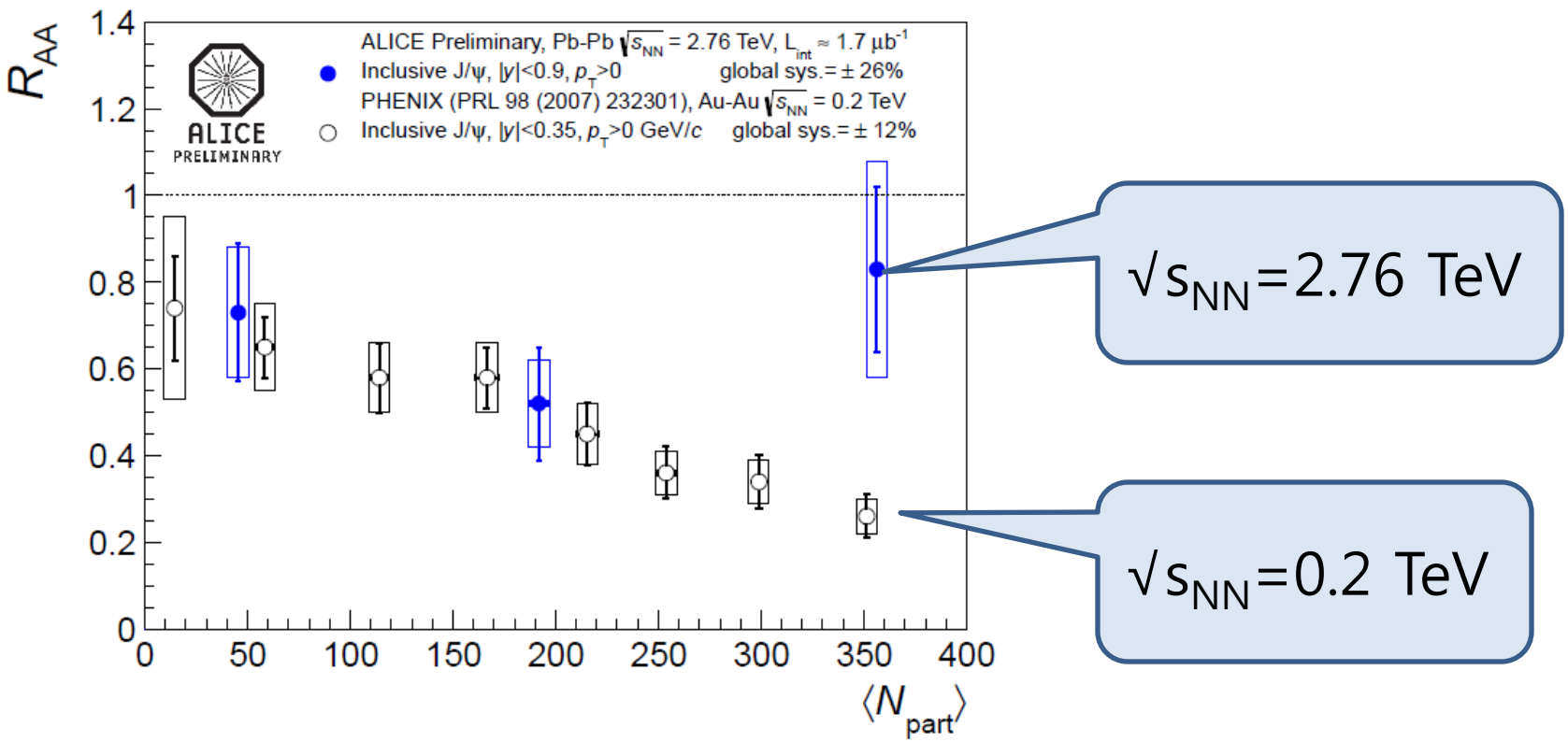
- (anti-)shadowing effect
- Cronin effect
- …

Hot nuclear matter effect

- Color Debye screening
- Collisional thermal decay
- Regeneration
- …

Regeneration is especially important
at high-energy and central heavy-ion collisions
(large number of charm quarks)

$N_{primordial\ J/\psi} \sim N_{charm}$, $N_{regenerated\ J/\psi} \sim N_{charm}^2$



Regeneration of J/ψ from thermalized charm and anticharm quarks

if $T_{dis} \leq T_c$, Statistical model

(A. Andronic, P. B. Munzinger, K.Redlich, J. Stachel, NPA 789, 34)

if $T_{dis} > T_c$, simultaneous production and dissociation of J/ψ between T_{dis} and T_c

(L. Yan, P. Zhuang, N. Xu, PRL 97, 232301)

$$\frac{dN_{J/\psi}}{dt} = -\Gamma\left(N_{J/\psi} - N_{J/\psi}^{equilibrium}\right)$$

Regeneration of J/ψ from nonthermalized charm and anticharm quarks

if $T_{dis} > T_c$, simultaneous production and dissociation of J/ψ between T_{dis} and T_c

(L. Grandchamp, R. Rapp, NPA 709, 415)

$$\frac{dN_{J/\psi}}{dt} = -\Gamma\left(N_{J/\psi} - \gamma N_{J/\psi}^{equilibrium}\right)$$

$$\gamma \equiv 1 - exp(-t/t_{charm\ relaxation})$$

: relaxation factor

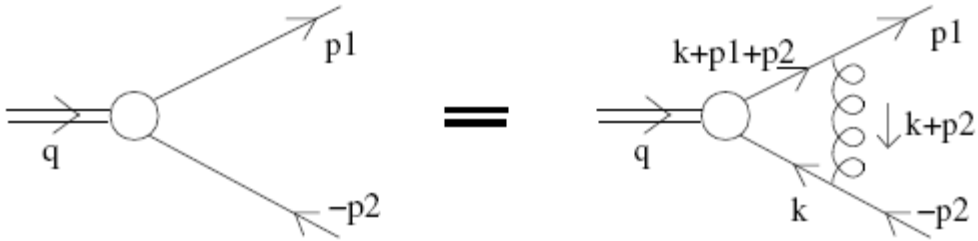
J/ψ formation in pQCD

- Leading order (LO)
- $c + \bar{c} \rightarrow J/\psi + g$

- Next-to-leading order (NLO)
- $c + \bar{c} + q(\bar{q}, g) \rightarrow J/\psi + q(\bar{q}, g)$
- $c + \bar{c} \rightarrow J/\psi + q + \bar{q}(g + g)$

Bethe-Salpeter amplitude for J/ψ

Definition ;



$$\Gamma_\mu(p_1,-p_2) = -g^2 C_F \int \frac{d^4K}{(2\pi)^4}\gamma^\alpha i\Delta(K+p_1+p_2)$$

$$\times\, \Gamma_\mu\,(K+p_1+p_2,K)i\Delta(K)\gamma_\alpha V(K+p_2)$$

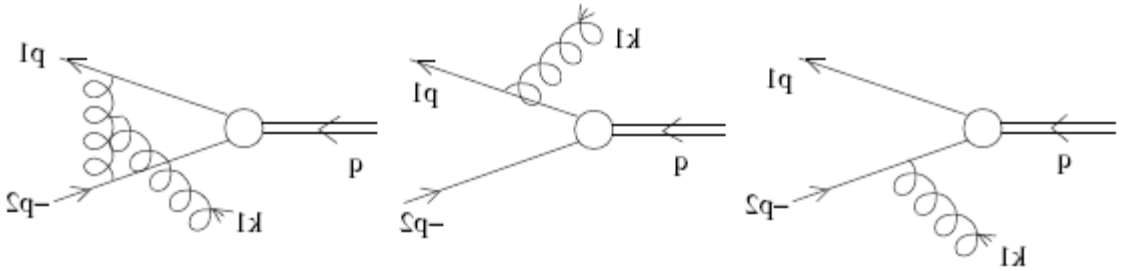
In nonrelativistic limit ;

Substituting,
Schrodinger Eq.

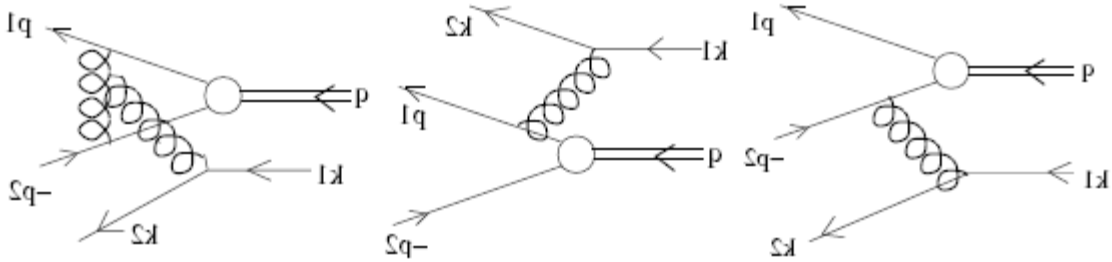
$$\Gamma_\mu\left(\frac{q}{2}+p,-\frac{q}{2}+p\right) = \left(\epsilon_o + \frac{\vec{p}^2}{m}\right)\psi(|\vec{p}|)$$

$$\times\sqrt{\frac{m_\Phi}{N_c}}\frac{1+\gamma^0}{2}\gamma_i g^i_\mu \frac{1-\gamma^0}{2}.$$

Leading Order (LO) $c + \bar{c} \rightarrow J/\psi + g$

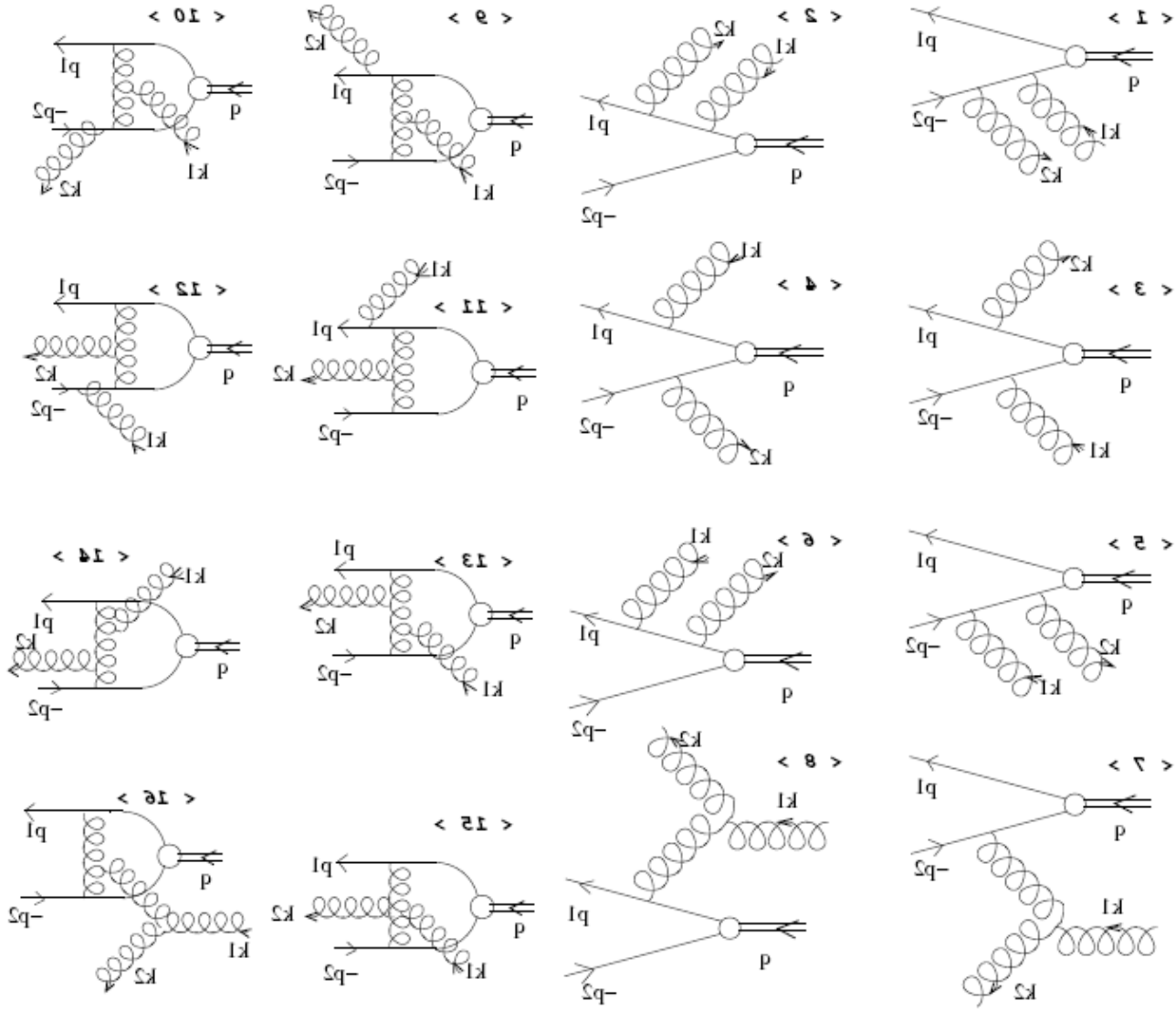


quark-induced Next to Leading Order (qNLO)
$c + \bar{c} + q(\bar{q}) \rightarrow J/\psi + q(\bar{q})$



gluon-induced Next to Leading Order (gNLO)

$$c + \bar{c} + g \rightarrow J/\psi + g$$



More …

quark-induced Next to Leading Order (qNLO)

$$c + \bar{c} \to J/\psi + q + \bar{q}$$

gluon-induced Next to Leading Order (gNLO)

$$c + \bar{c} \to J/\psi + g + g$$

Leading Order (LO)

$$\overline{|\mathcal{M}|}^2 = \frac{2g^2 m_c^2 m_\Phi (2k_0^2 + m_{k_1}^2)}{3N_c} \left| \frac{\partial \psi(\mathbf{p})}{\partial \mathbf{p}} \right|^2,$$

J/ψ wavefunction
Schrodinger Eq. with the screened Cornell potential is solved

$$p \equiv p_1 - p_2$$

quark-induced Next to Leading Order (qNLO)

$$\overline{|\mathcal{M}|}^2 = \frac{4}{3} g^4 m_c^2 m_\Phi \left| \frac{\partial \psi(\mathbf{p})}{\partial \mathbf{p}} \right|^2 \left(-\frac{1}{2} + \frac{k_{10}^2 + k_{20}^2}{2k_1 \cdot k_2} \right).$$

gluon-induced Next to Leading Order (gNLO)

$$\begin{aligned}\overline{|\mathcal{M}|}^2 = \frac{4}{3} g^4 m_c^2 m_\Phi \left| \frac{\partial \psi(\mathbf{p})}{\partial \mathbf{p}} \right|^2 \Bigg\{ & -4 + \frac{k_1 \cdot k_2}{k_{10} k_{20}} \\ & + \frac{2k_{10}}{k_{20}} + \frac{2k_{20}}{k_{10}} - \frac{k_{20}^2}{k_{10}^2} - \frac{k_{10}^2}{k_{20}^2} + \frac{2}{k_1 \cdot k_2} \\ & \times \left[\frac{(k_{10}^2 + k_{20}^2)^2}{k_{10} k_{20}} - 2k_{10}^2 - 2k_{20}^2 + k_{10} k_{20} \right] \Bigg\}.\end{aligned}$$

Production rate of J/ψ

$c + \bar{c} \to J/\psi + g$

$$(2\pi)^3 \frac{dN_{J/\psi}}{V d^3 q} = \frac{1}{2E_{j/\psi}} \int \frac{d^3k}{(2\pi)^3 2E_k} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^4(p_1 + p_2 - q - k)\, f_c(p_1) f_{\bar{c}}(p_2) |M|^2$$

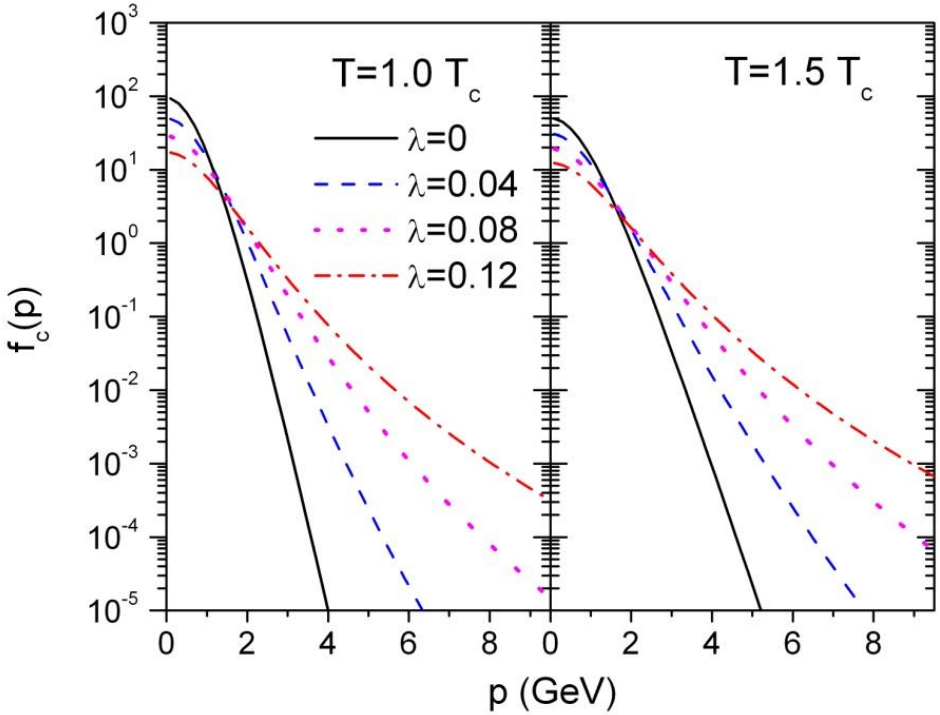
$c + \bar{c} \to J/\psi + q + \bar{q}(g + g)$

$$(2\pi)^3 \frac{dN_{J/\psi}}{V d^3 q} = \frac{1}{2E_{J/\psi}} \int \frac{d^3k_1}{(2\pi)^3 2E_{k1}} \int \frac{d^3k_2}{(2\pi)^3 2E_{k2}} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^4(p_1 + p_2 - q - k_1 - k_2)$$
$$\times f_c(p_1) f_{\bar{c}}(p_2) |M|^2$$

$c + \bar{c} + q(\bar{q}, g) \to J/\psi + q(\bar{q}, g)$

$$(2\pi)^3 \frac{dN_{J/\psi}}{V d^3 q} = \frac{1}{2E_{J/\psi}} \int \frac{d^3k_1}{(2\pi)^3 2E_{k1}} \int \frac{d^3k_2}{(2\pi)^3 2E_{k2}} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^4(p_1 + p_2 + k_1 - q - k_2)$$
$$\times f_c(p_1) f_{\bar{c}}(p_2) f_{q(\bar{q},g)}(k_1) |M|^2$$

Tsallis distribution for "f_c (p)"



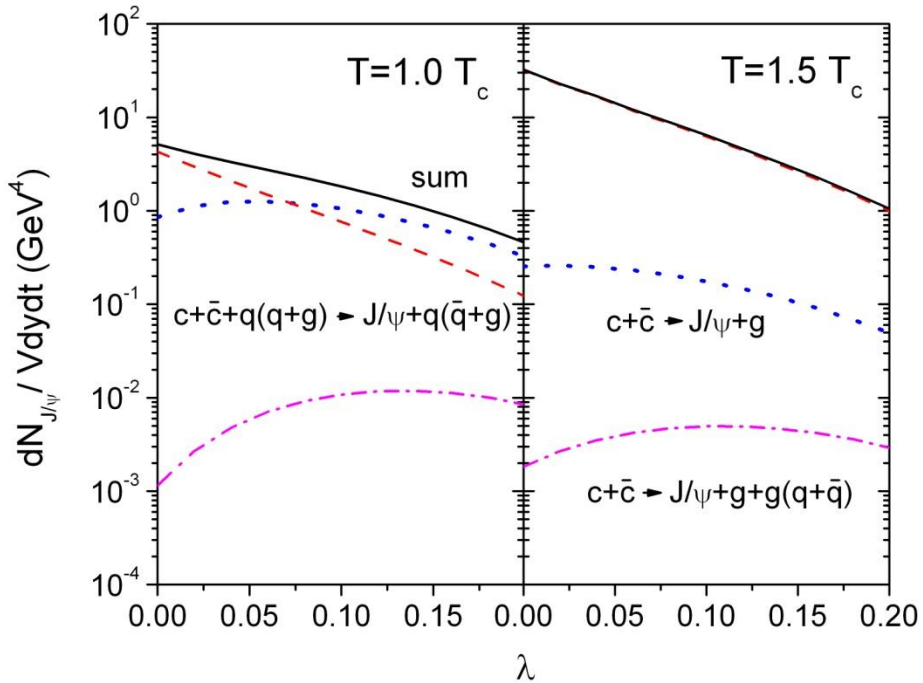
$[1+\lambda E/T]^{-1/\lambda}$

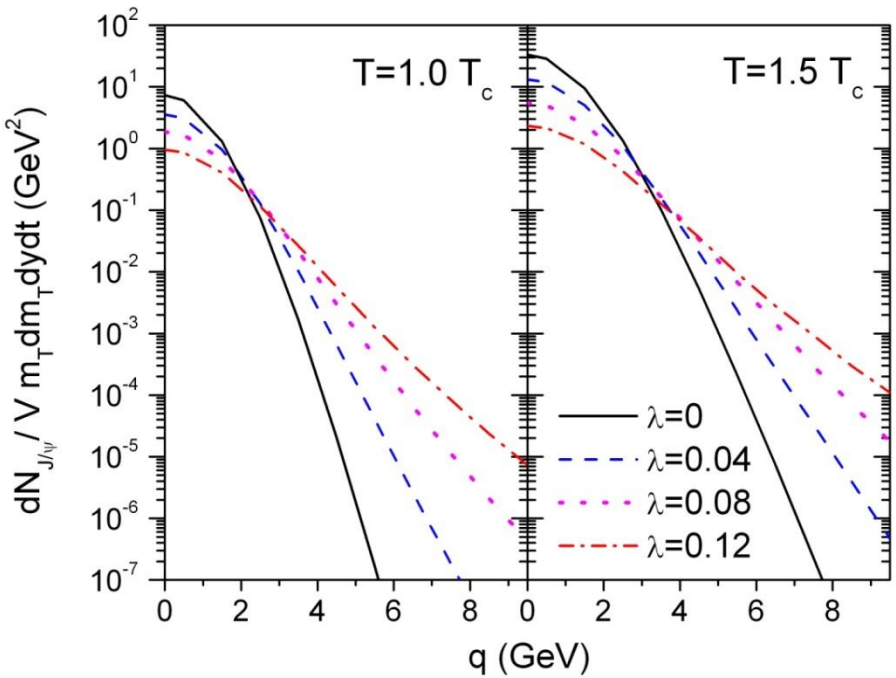
$\downarrow \lambda=0$

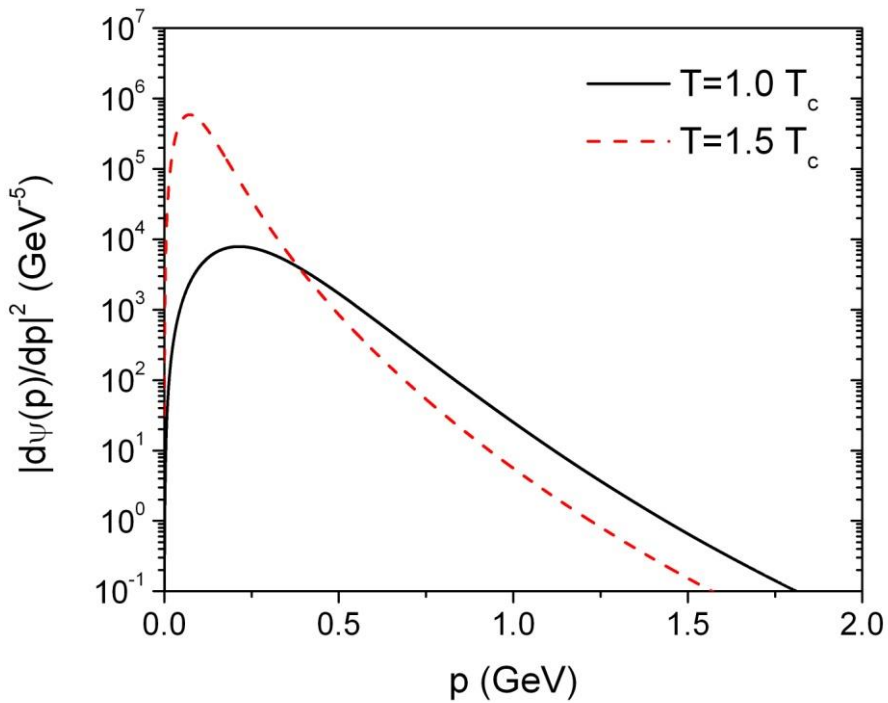
$e^{-E/T}$: Boltzman distribution

J/ψ production rate & spectra

Charm quark number density is determined from grandcanonical ensemble
Charm distribution is changed by various λ in Tsallis distribution function







- Small p is favored in all reactions

- Large p is favored in $c + \bar{c} \rightarrow J/\psi + g$,

  $c + \bar{c} \rightarrow J/\psi + q + \bar{q}(g + g)$

,

not in

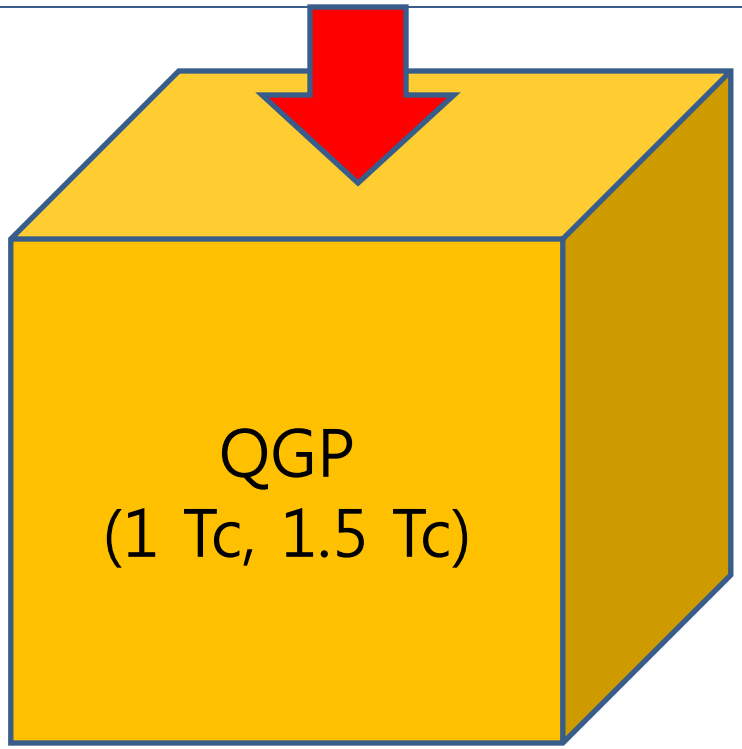
$c + \bar{c} + q(\bar{q}, g)$

$\rightarrow J/\psi + q(\bar{q}, g)$

Application to RHIC & LHC

Cascade method

Initial charm spectra at RHIC & LHC from PHYTIA



charm-parton cross section

σ_{cq}=1 mb

σ_{cg}=2 mb

Relaxation time of charm quarks

$$t_{\mathrm{rel}}^{-1} = \left\langle \sum_{i=q,\bar{q},g} \int \frac{d^3k}{(2\pi)^3} n_i(k,T) v_{\mathrm{rel}} \sigma_i \left(1 - \frac{\mathbf{p}\cdot\mathbf{p}'}{\mathbf{p}^2}\right)\right\rangle,$$

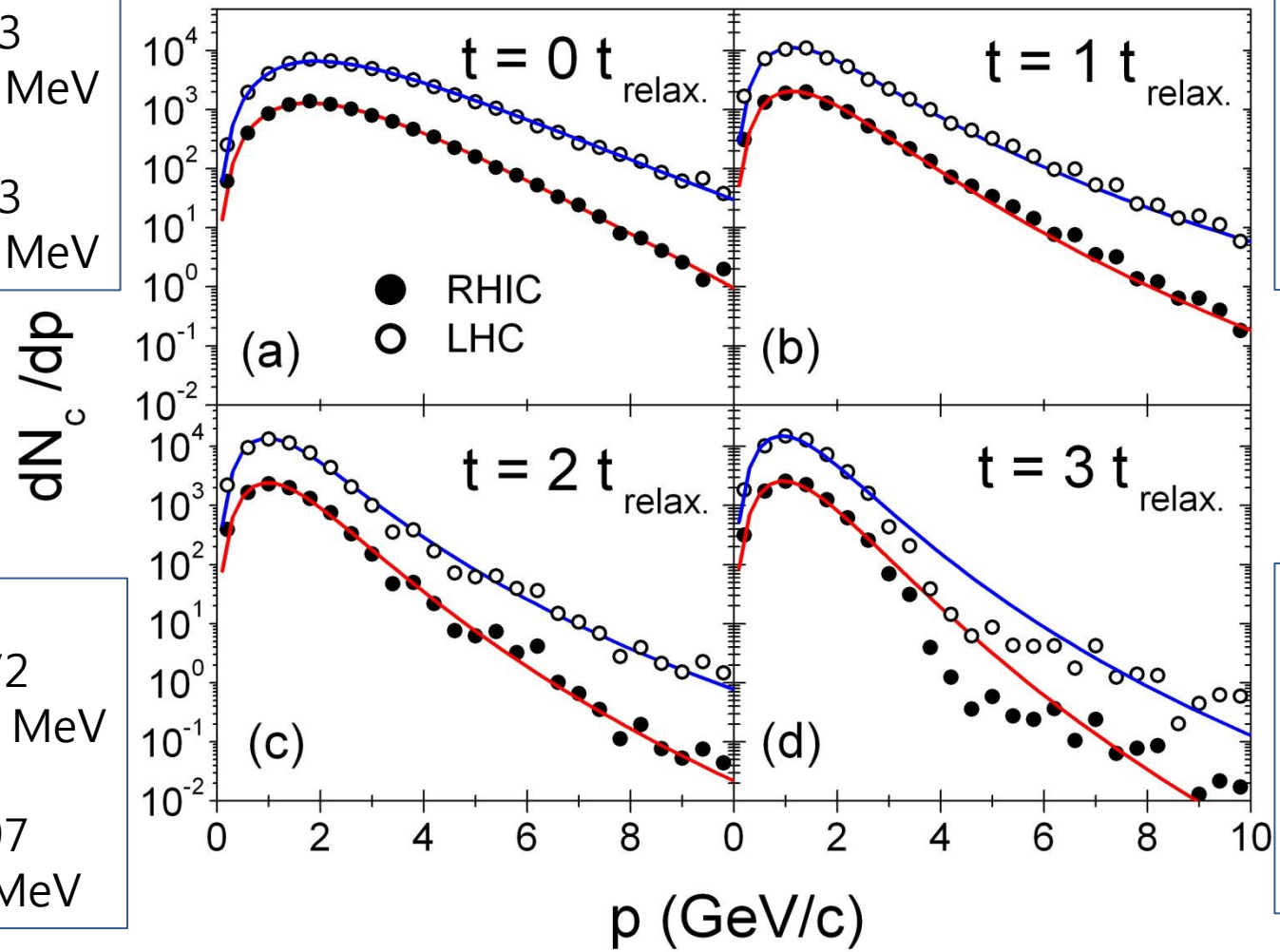
- n_i : the density of parton species i
- σ_i : the elastic cross section of charm with parton i
- p(p′) : incoming (outgoing) momentum of charm quark
- ⟨…⟩ : average over charm quark momentum distribution

- For T=1.5 T_c, t_{rel}=3.2 fm/c

The change of charm spectra with time

RHIC
λ=0.013
T=650 MeV
LHC
λ=0.033
T=680 MeV

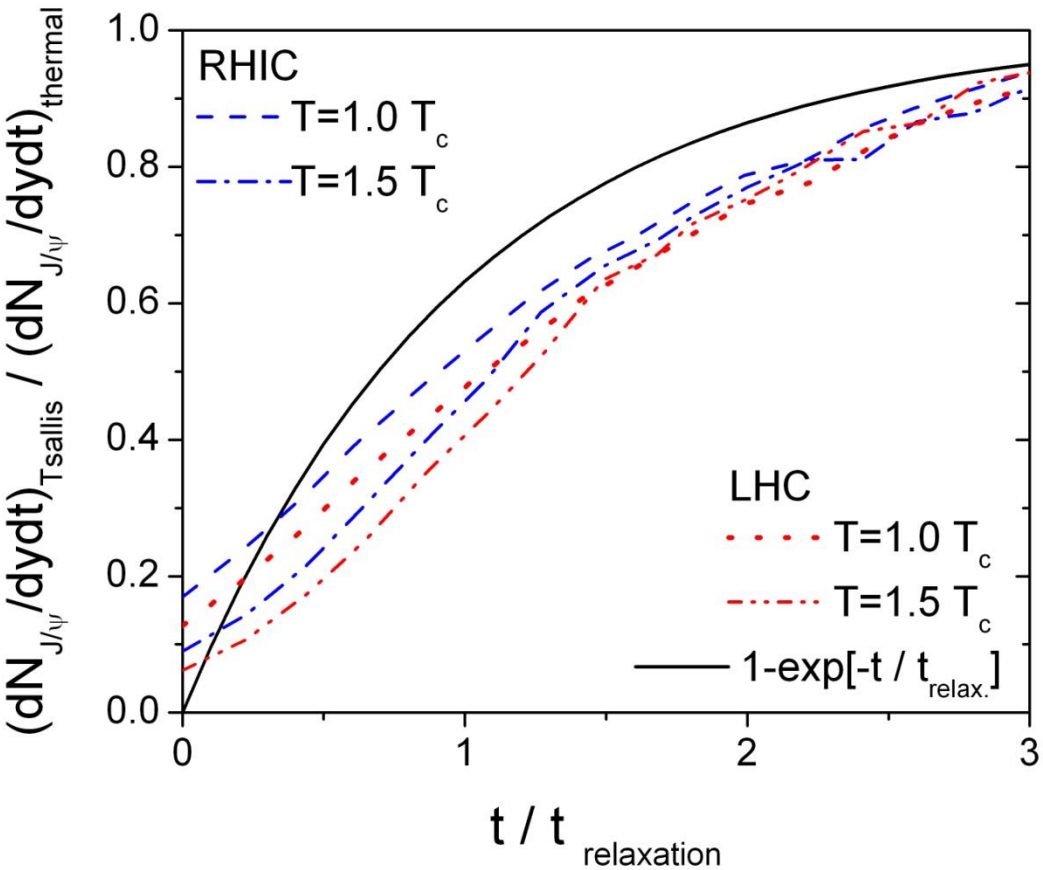
RHIC
λ=0.078
T=190 MeV
LHC
λ=0.107
T=140 MeV



RHIC
λ=0.072
T=140 MeV
LHC
λ=0.097
T=90 MeV

RHIC
λ=0.058
T=150 MeV
LHC
λ=0.081
T=100 MeV

Reduced J/ψ production rate due to the nonequilibrium of charm & anticharm quarks at RHIC & LHC



Conclusion

- Nonequilibrium charm and anticharm quarks suppresses J/ψ regeneration, compared to that from equilibrium ones.
- The thermal relaxation time correction introduced by R. Rapp is consistent with our microscopic results.