R_{AA} of J/ψ near mid-rapidity in RHIC at $\sqrt{s_{NN}}$=200 GeV and in LHC

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and Su Houng Lee
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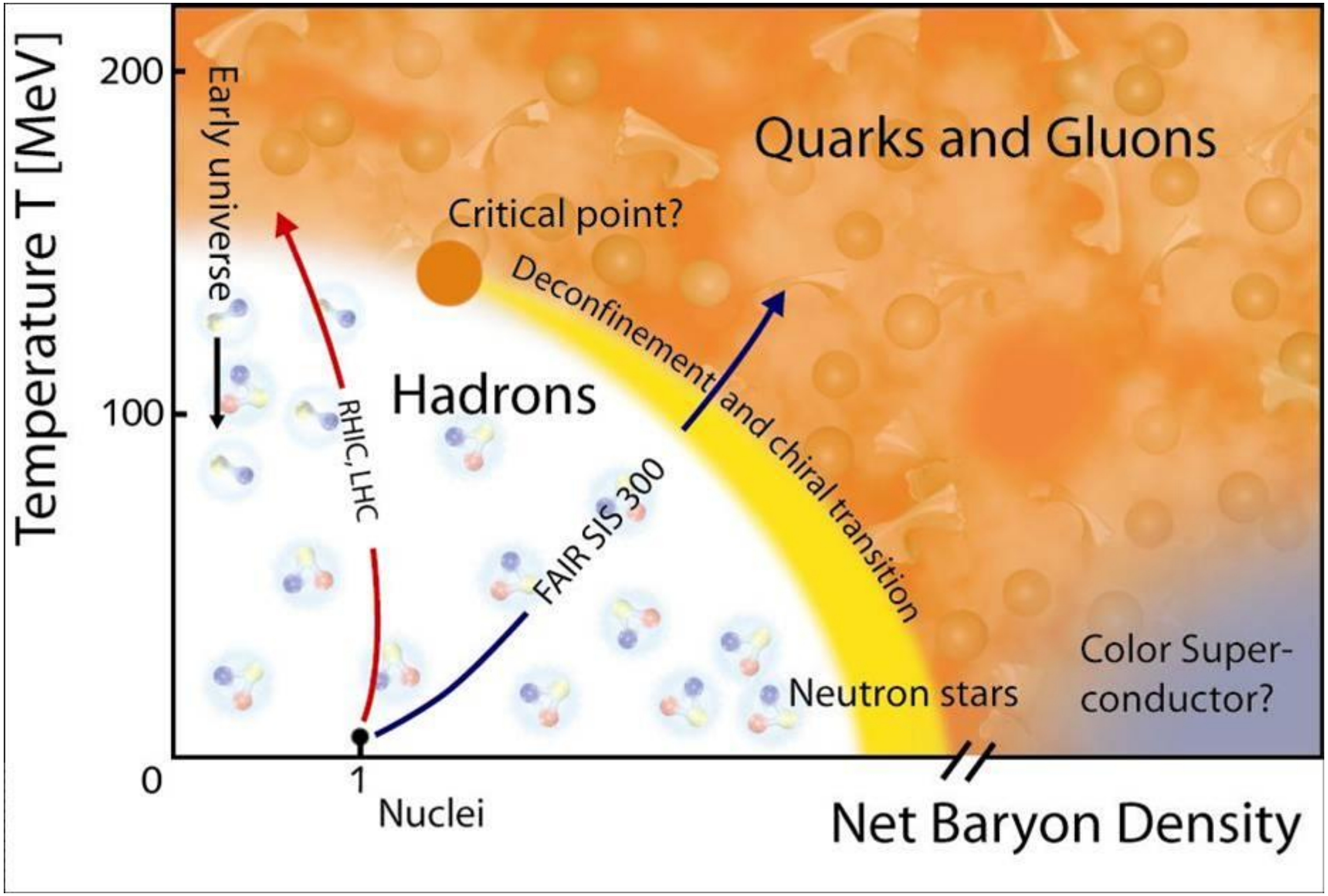
QCD phase diagram



There are many probes to investigate the properties of hot nuclear matter.
One of them is J/ψ

Brief history of J/ψ in ultrarelativistic heavy ion collision

- J/ψ suppression due to the Debye screening of color charge between c and anti-c pair was first suggested as a signature of quark-gluon plasma (QGP) formation in relativistic heavy ion collision by T. Matsui, H. Satz in 1986.

T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986)

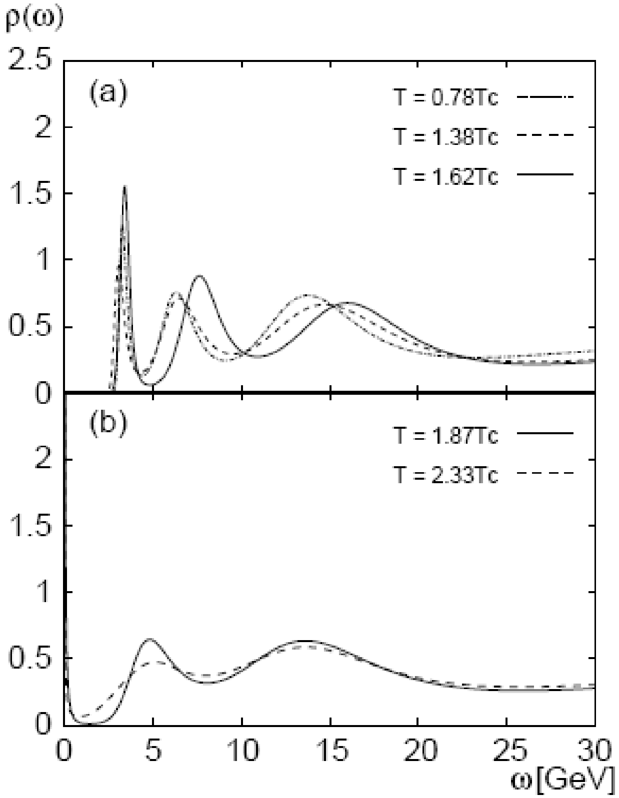


FIG. 1: Spectral functions for J/ψ (a) for $T/T_c = 0.78, 1.38$, and 1.62 (b) for $T/T_c = 1.87$ and 2.33.

- Recently, lattice calculations support that J/ψ survives above Tc

  M. Asakawa, T. Hatsuda, PRL 92, 012001 (2004), …

- However, J/ψ is still a good probe to investigate the property of hot nuclear matter created from ultrarelativistic heavy ion collision, because its melting point is believed to exist between Tc and the initial temperature of hot nuclear matter created through the relativistic heavy ion collisions in RHIC.

Phenomenological models to describe J/ψ production in relativistic heavy ion collision

1. Thermal model (P. Braun-Munzinger et al.)

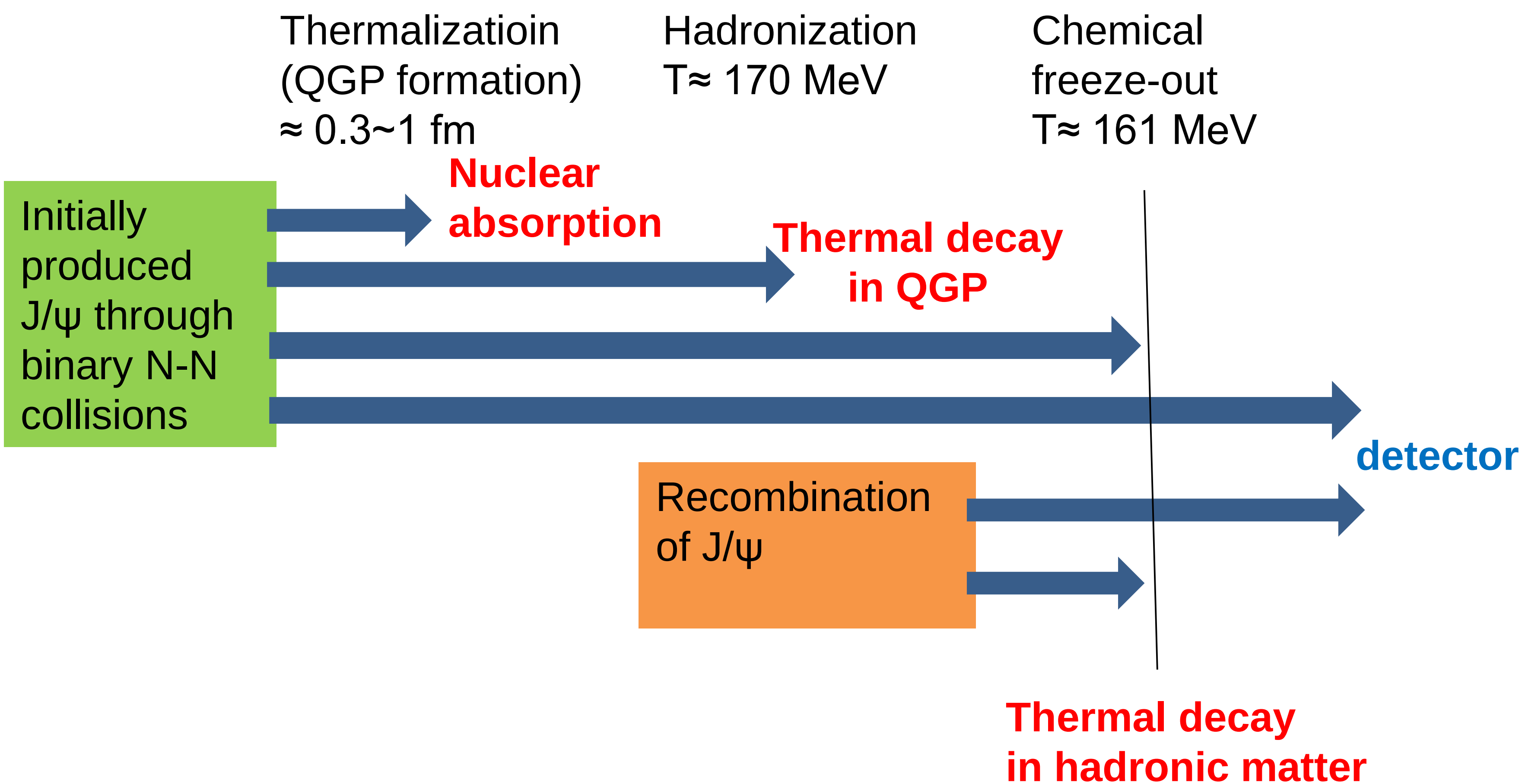
   Initially produced J/Ψ does not survive. All J/Ψs are formed at hadronization stage by recombination of charm and anti-charm.

2. Two component model (R. Rapp et al.)

   Observed J/Ψ comes from at initial collisions or at hadronization stage.

3. Simultaneous dissociation and recombination of J/Ψ during the fireball expansion (P. Zhuang et al.)

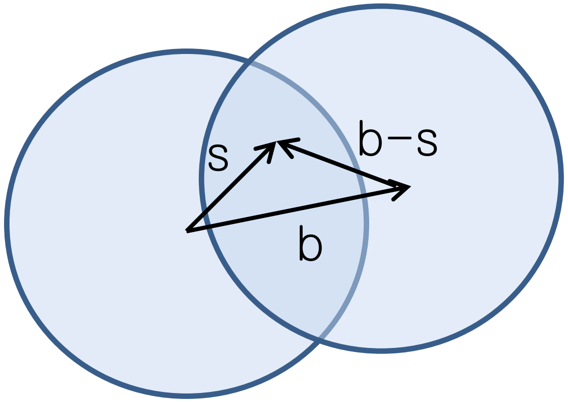
Two-component model



Glauber model

1. Woods-Saxon distribution

$$\rho(\mathrm{r}) = \frac{\rho_0}{1+\mathrm{e}^{(\mathrm{r}-\mathrm{r}_0)/C}}$$



2. Number of participants (wounded nucleons)

$$N_{part}(\vec{b}) = A\int T_A(\vec{s})\left\{1-\left[1-T_B(\vec{b}-\vec{s})\sigma_{in}\right]^B\right\}d^2s$$
$$+B\int T_B(\vec{b}-\vec{s})\left\{1-\left[1-T_A(\vec{s})\sigma_{in}\right]^A\right\}d^2s$$

, where $T_{A,B}(\vec{b}) \equiv \int^{\infty} \rho_{A,B}(\vec{b},x)dx$; thickness function.

The quantity of bulk matter is proportional to # of participants

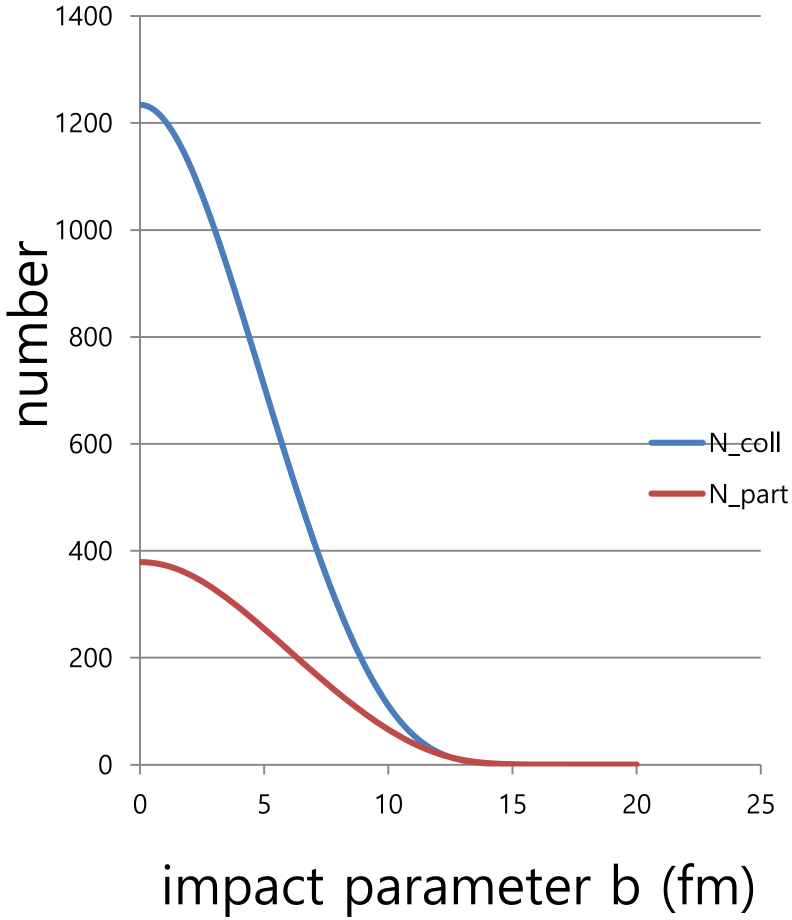
3. Nuclear overlap function of two colliding nuclei

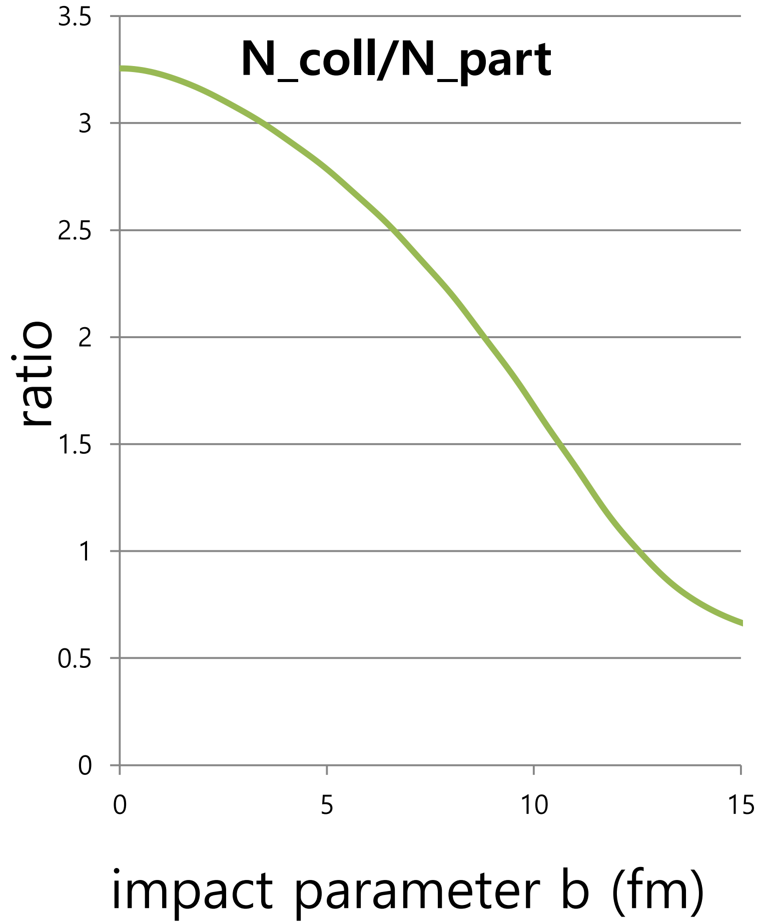
$$T_{AB}(\vec{b}) = \int d^2s dz dz' \, \rho_A(\vec{s},z)\, \rho_B(\vec{b}-\vec{s},z')$$

As an example, the number of J/ψ produced in two nuclei collision with impact parameter b is $\sigma_{J/\psi}T_{AB}(\vec{b})$.

The quantity of hard particles such as J/ψ is proportional to # of binary collisions

of participants vs. # of binary collisions with σ_{in}=42 mb



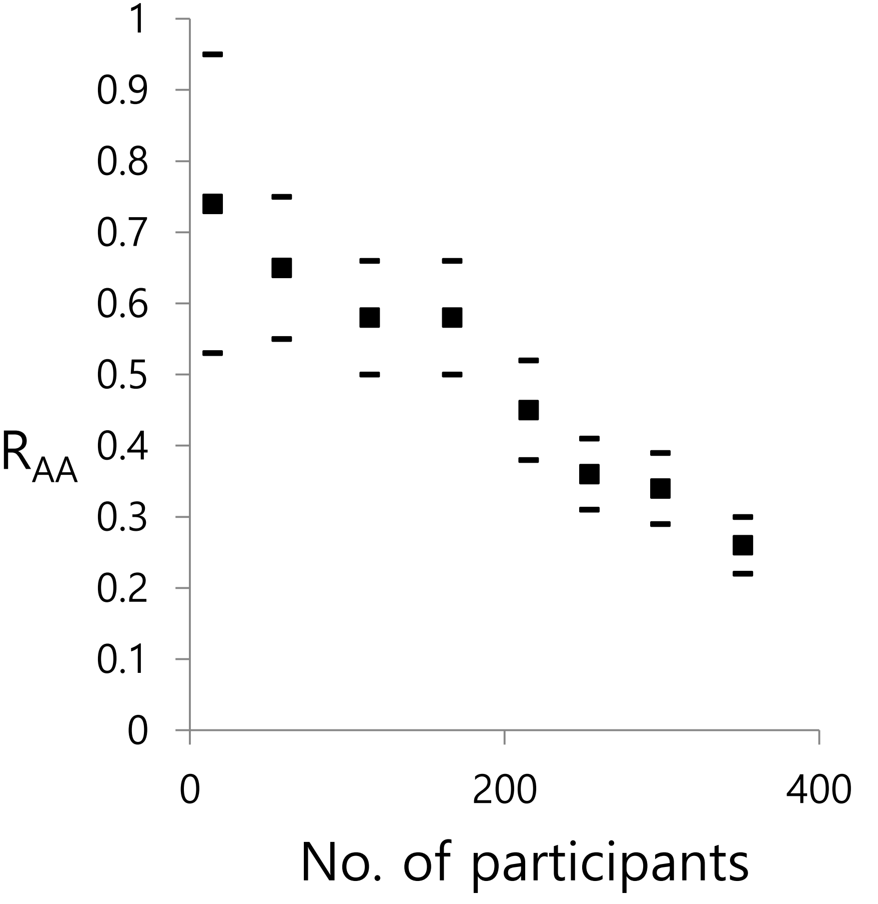


What is R_{AA}?

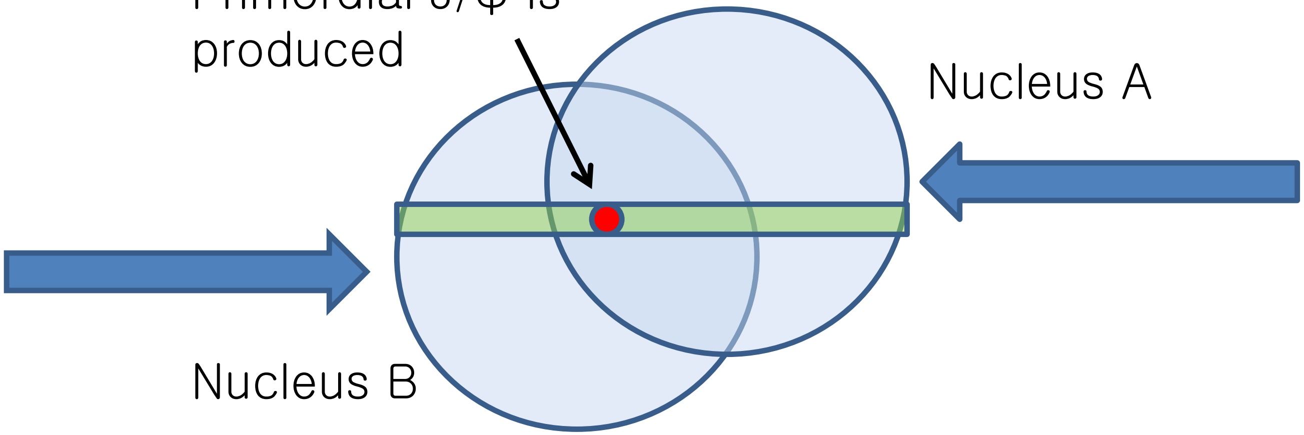
$$R_{AA}^{J/\Psi} = \frac{1}{N_{coll}} \times \frac{N_{A+A}^{J/\Psi}}{N_{n+n}^{J/\Psi}}$$

If R_{AA} is below 1, it is called that J/Ψ is suppressed.
If R_{AA} is above 1, it is called that J/Ψ is enhenced.

From RHIC with $\sqrt{s} = 200\,GeV$ at mid-rapidity,



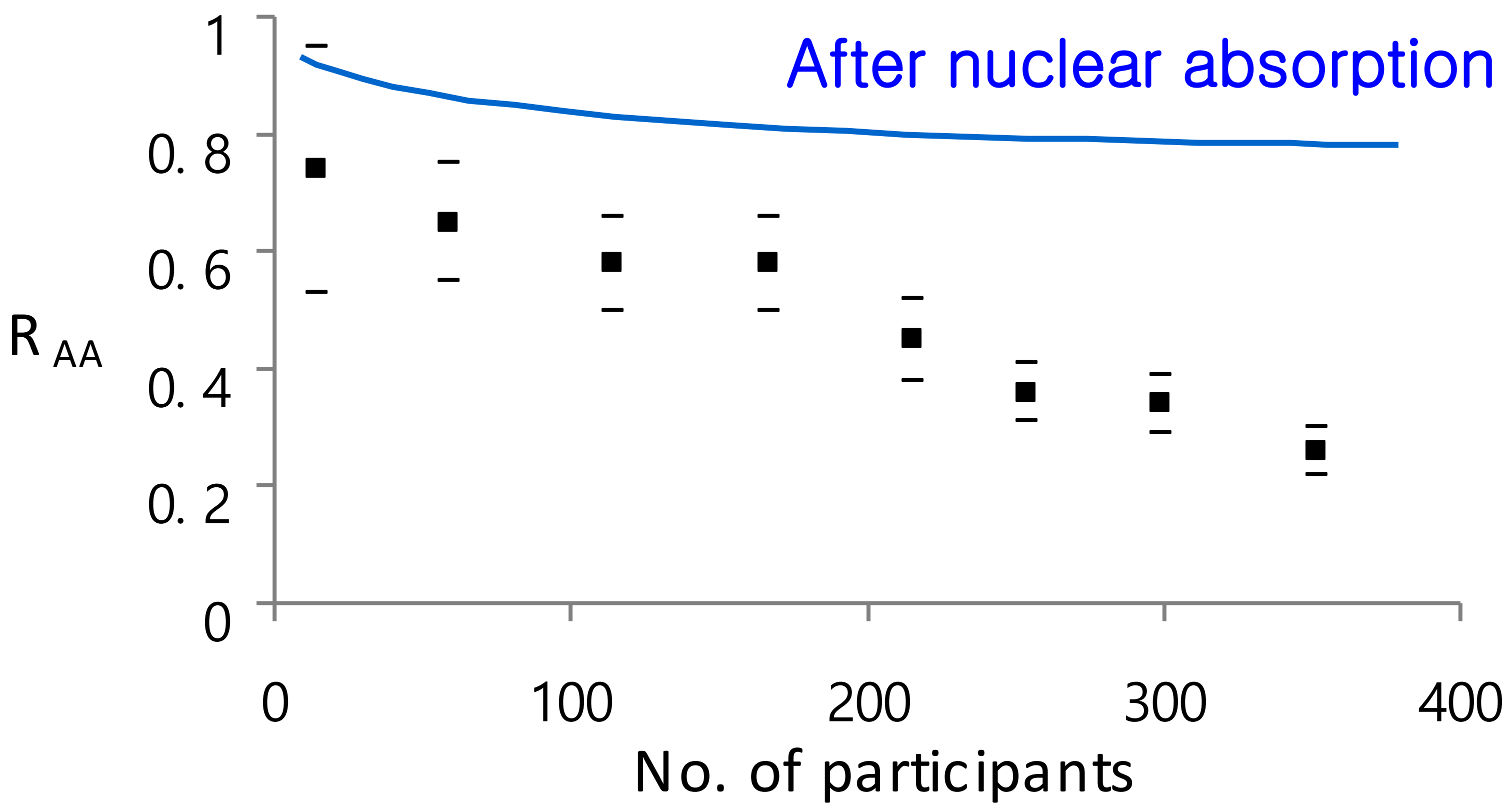
1. Nuclear absorption



$$S_{nuc}(b,\sigma_{nuc}) = \frac{1}{T_{AB}(b)} \int d^2 s dz dz' \rho_A(\vec{s},z)\rho_B(\vec{b}-\vec{s},z')$$
$$\times \exp\left\{-(A-1)\int_z^\infty dz_A \rho_A(\vec{s},z_A)\sigma_{nuc}\right\}$$
$$\times \exp\left\{-(B-1)\int_{z'}^\infty dz_B \rho_B(\vec{b}-\vec{s},z_B)\sigma_{nuc}\right\}$$

Nuclear absorption cross section is obtained from pA collision
σ_{diss}=1.5mb

Comparison with experimental data of RHIC ($\sqrt{s}$=200 GeV at midrapidity)

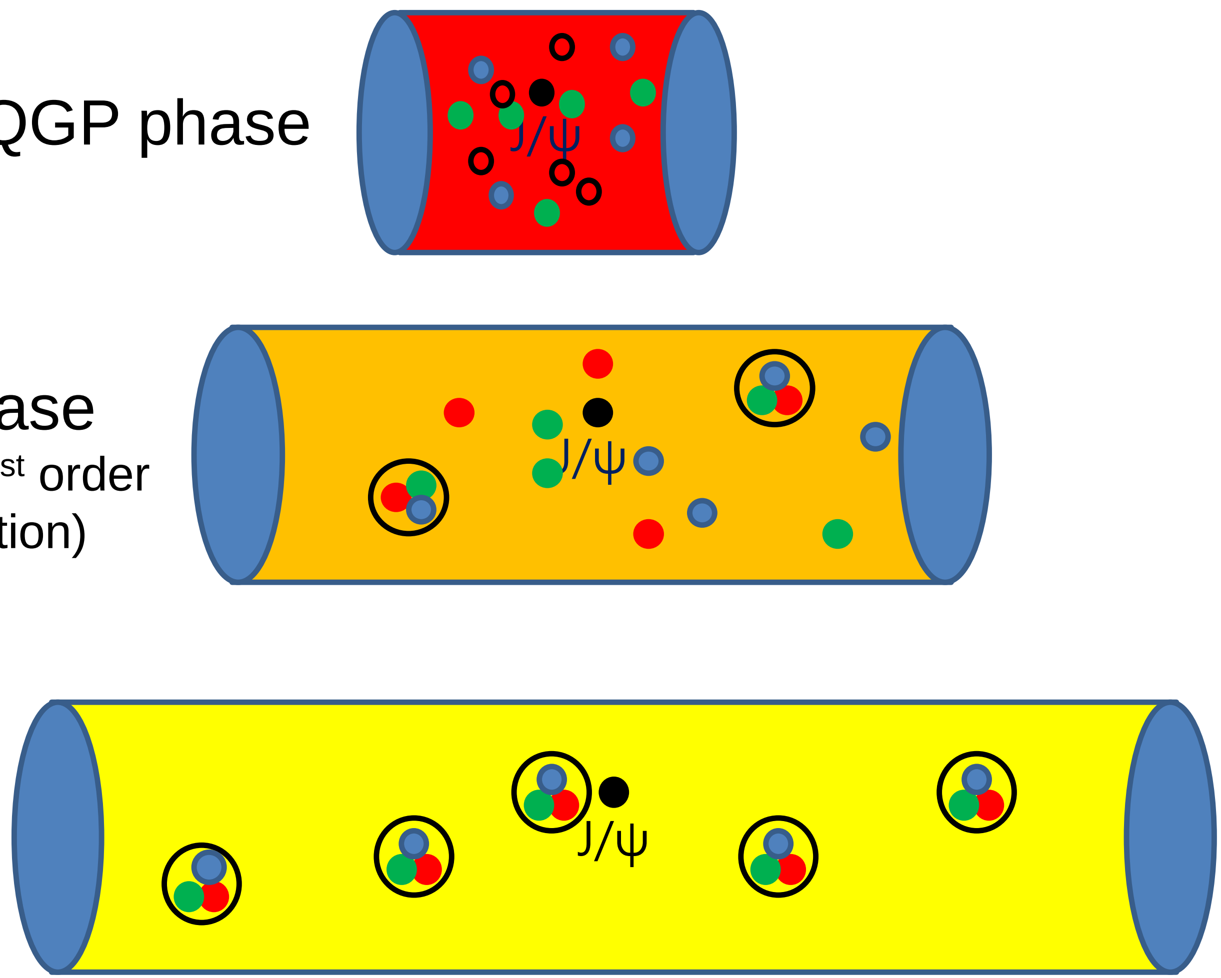


2. Thermal decay in fireball

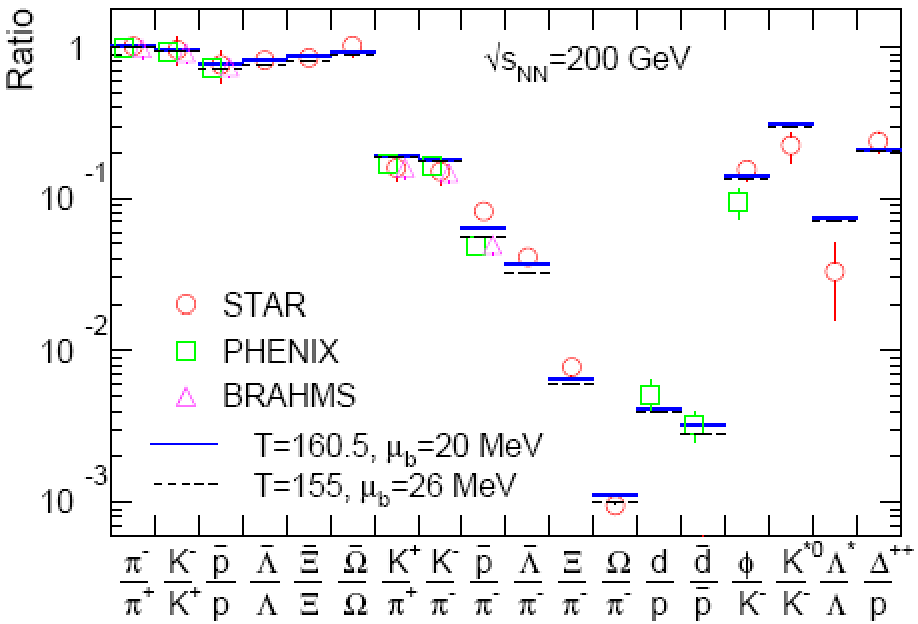
QGP phase

Mixed phase
(Assuming 1st order phase transition)

HG phase



2.1. Thermal model



A.Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel
NPA 772, 167 (2006)

Thermal model successfully describes particle ratios n_i/n_j at chemical freeze-out stage

,where $n_j\,(\mu_b\,,\ \mu_{I3}\,,\ \mu_S\,,\ \mu_C\,,\ T_{cfo}\,)$ is particle number density in grand canonical ensemble

$$n_j = \frac{d_j}{2\pi^2}\int dp\,p^2\left[\exp\left(\frac{E_j-\mu_j}{T_{cfo}}\right)\pm 1\right]^{-1}$$

$$\mu_j = \mu_B B_j + \mu_{I3} I_3 + \mu_s S_j + \mu_C C_j$$

The latest result for RHIC data at mid-rapidity ($\sqrt{s}$=200 GeV) :

T_{cfo}=161 MeV, μ_b=22.4 MeV

A.Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel
NPA 789, 334 (2007)

Z, N and other quantities μ_{I3} , μ_S , μ_C, at chemical freeze-out are obtained from below constraints.

Baryon number conservation $$V\sum_j n_j B_j = Z + N$$

Isospin conservation $$V\sum_j n_j I_{3j} = \frac{Z - N}{2}$$

Strangeness conservation $$V\sum_j n_j S_j = 0$$

Charm conservation $$V\sum_j n_j C_j = 0$$

,where Z is the net number of wounded protons and N is that of wounded neutrons in the fireball at mid-rapidity

Absolute hadron yields can also be reproduced in thermal model

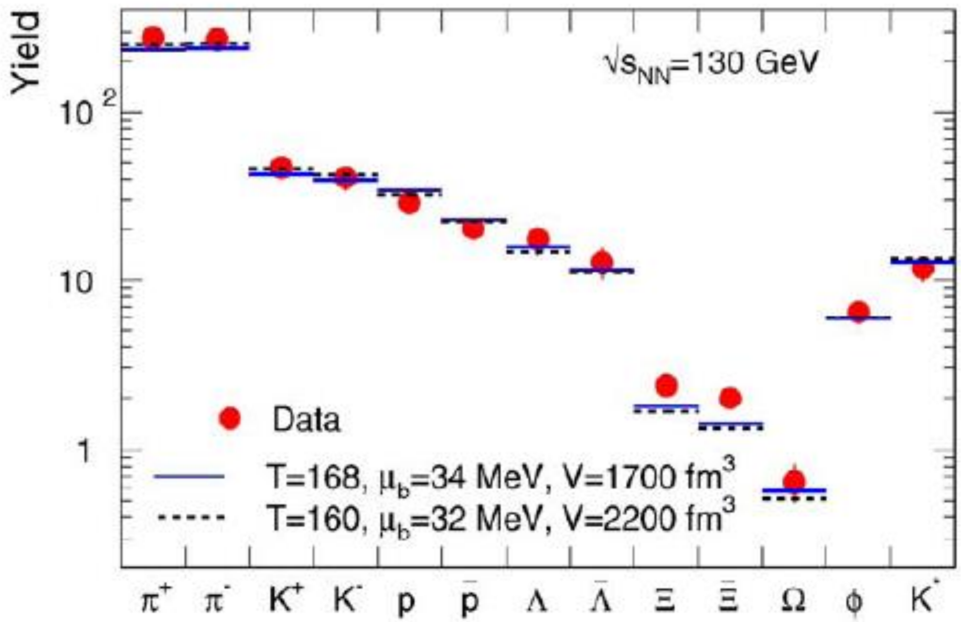


Fig. 23. Hadron yields with best fit at $\sqrt{s_{NN}} = 130$ GeV. The dashed lines are for the best fit excluding the Ξ hyperons. The Ω yield includes both Ω and $\bar{\Omega}$.

At midrapidity (|y|<1) with √s=200 GeV & N_{part}=350, V_{cf}≈2400 fm^3

Here we parameterize total entropy as the combination of N_{part} and N_{coll}

$$S = 21.5\left\{(1-x)\frac{N_{part}}{2} + xN_{coll}\right\},$$

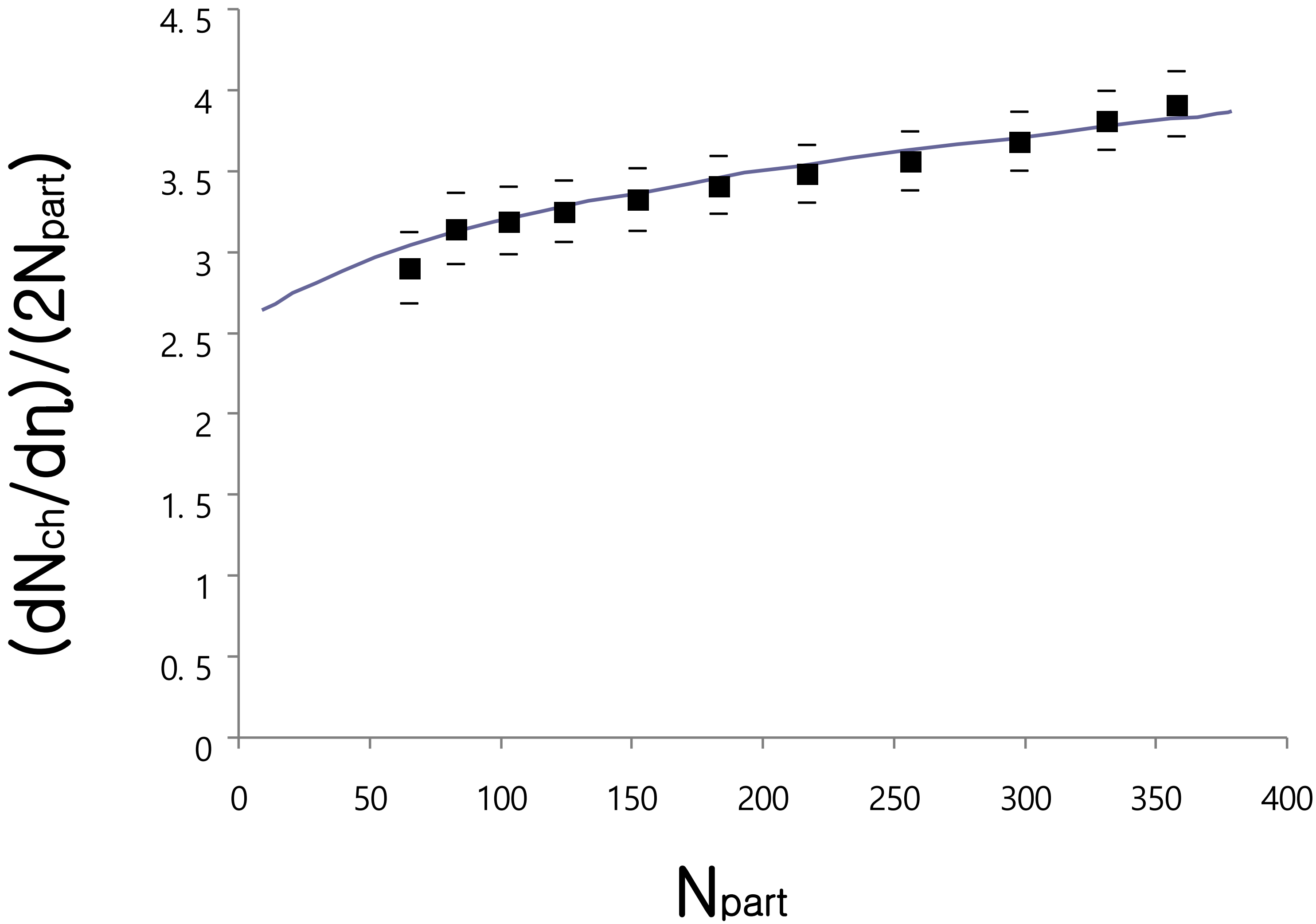
where $\mathrm{x} = 0.11$ at $\sqrt{\mathrm{s_{NN}}} = 200\,\mathrm{GeV}$, and 0.09 at $\sqrt{\mathrm{s_{NN}}} = 130\,\mathrm{GeV}$

Local entropy density at initial stage is assumed to be

$$s = \frac{S}{V} = 21.5\left\{(1-x)\frac{n_{part}}{2} + xn_{coll}\right\},$$

where $n_{part} = N_{part}/V, \quad n_{coll} = N_{coll}/V$

Multiplicities of charged particles vs. # of participants



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NPA 789, 334 (2007)

Z, N and other quantities μ_{I3} , μ_S , μ_C, at chemical freeze-out are obtained from below constraints.

Baryon number conservation $V\sum_j n_j B_j = Z + N$ set at about $N_{part}/20$ in $|y|<0.35$

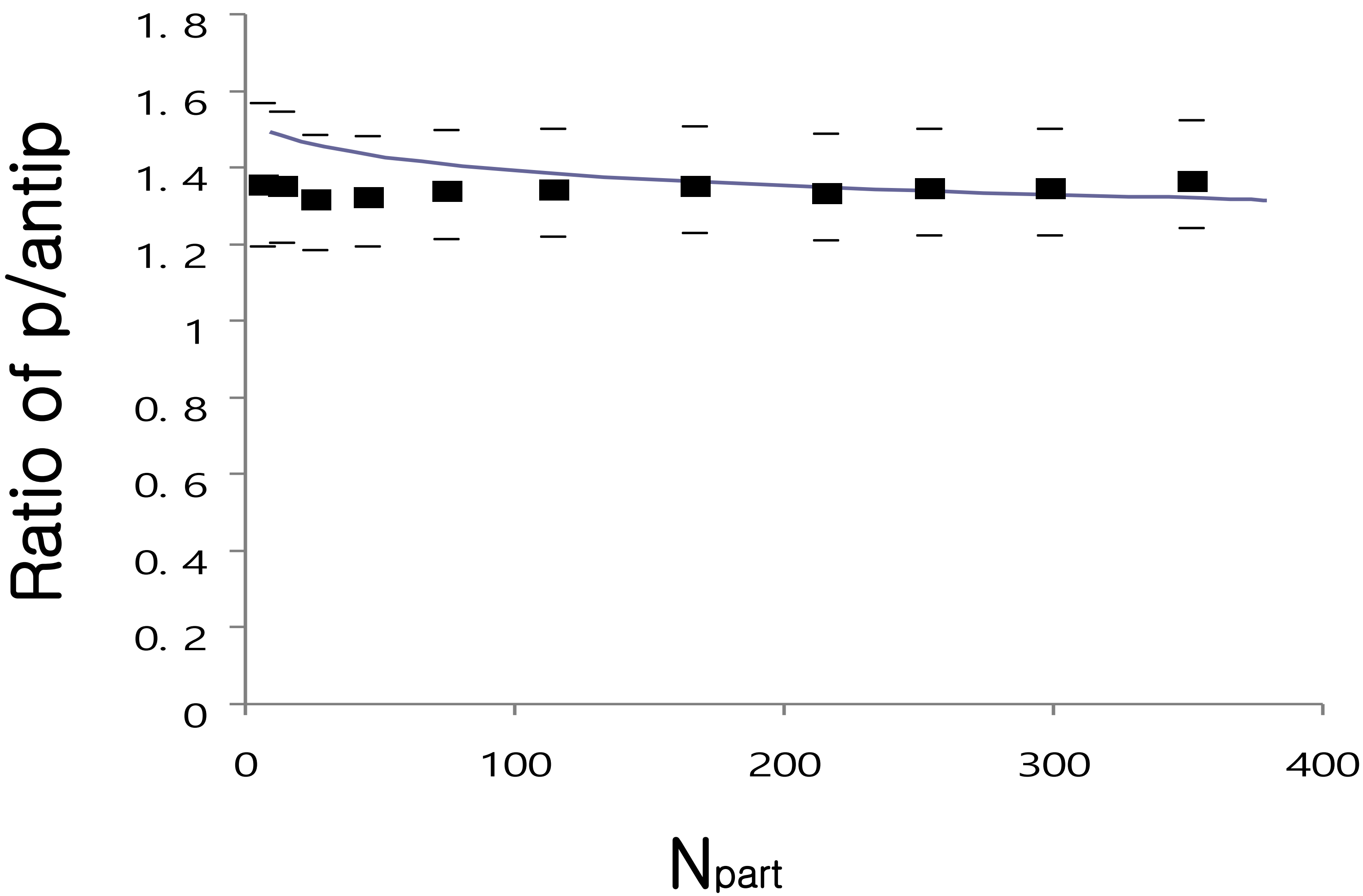
Isospin conservation $V\sum_j n_j I_{3j} = \frac{Z-N}{2}$

Strangeness conservation $V\sum_j n_j S_j = 0$

Charm conservation $V\sum_j n_j C_j = 0$

,where Z is the net number of wounded protons and N is that of wounded neutrons in the fireball at mid-rapidity

Ratios of proton and anti-proton vs. # of participants



Thermal mass of partons in QGP

Peter Levai & Ulrich Heinz PRC 57, 1879 (1998)

Strongly interacting massless partons
→ Noninteracting massive partons, reproducing well thermal quantities obtained from LQCD

$$m_g^2 = \frac{g^2(T)\,T^2}{2}\left(\frac{N_c}{3}+\frac{N_f}{6}\right), \qquad m_q^2 = \frac{g^2(T)\,T^2}{3}$$

$$\text{, where } g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln F^2(T,T_c,\Lambda)}$$

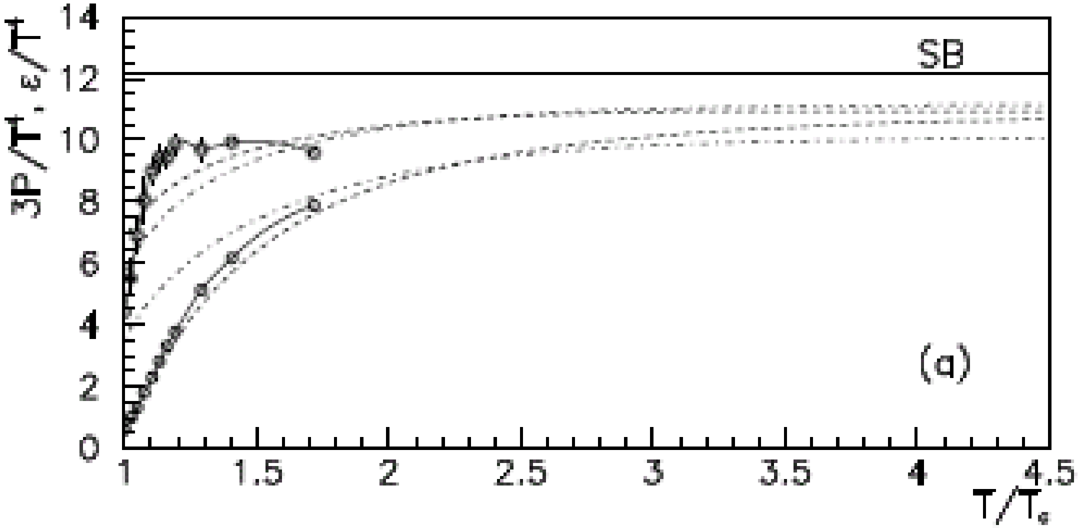
$$F(T,T_c,\Lambda) = \frac{18}{18.4e^{-0.5(T/T_C)^2}+1}\frac{T}{T_c}\frac{T_c}{\Lambda}$$

$$N_f = 0,\quad T_c = 260MeV,\quad T_c/\Lambda = 1.03$$

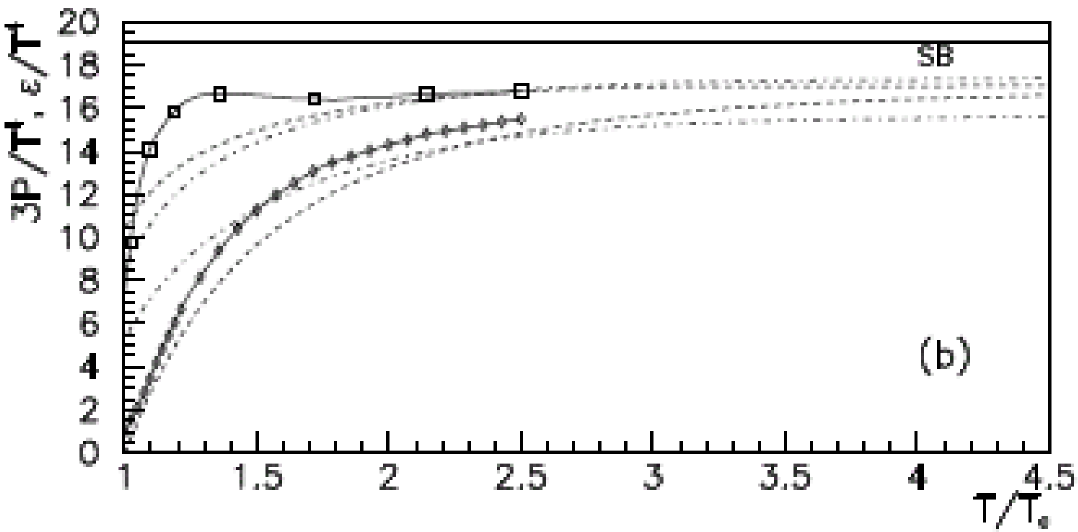
$$N_f = 2,\quad T_c = 140MeV,\quad T_c/\Lambda = 1.03$$

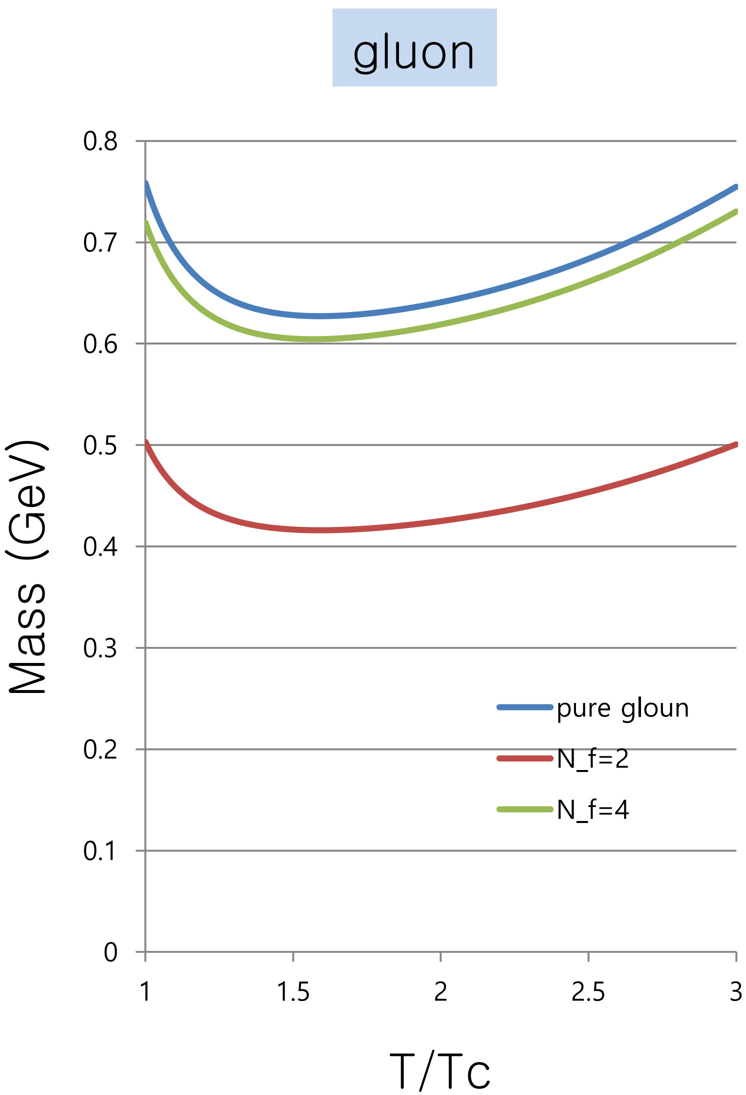
$$N_f = 4,\quad T_c = 170MeV,\quad T_c/\Lambda = 1.05$$

$N_f=2$

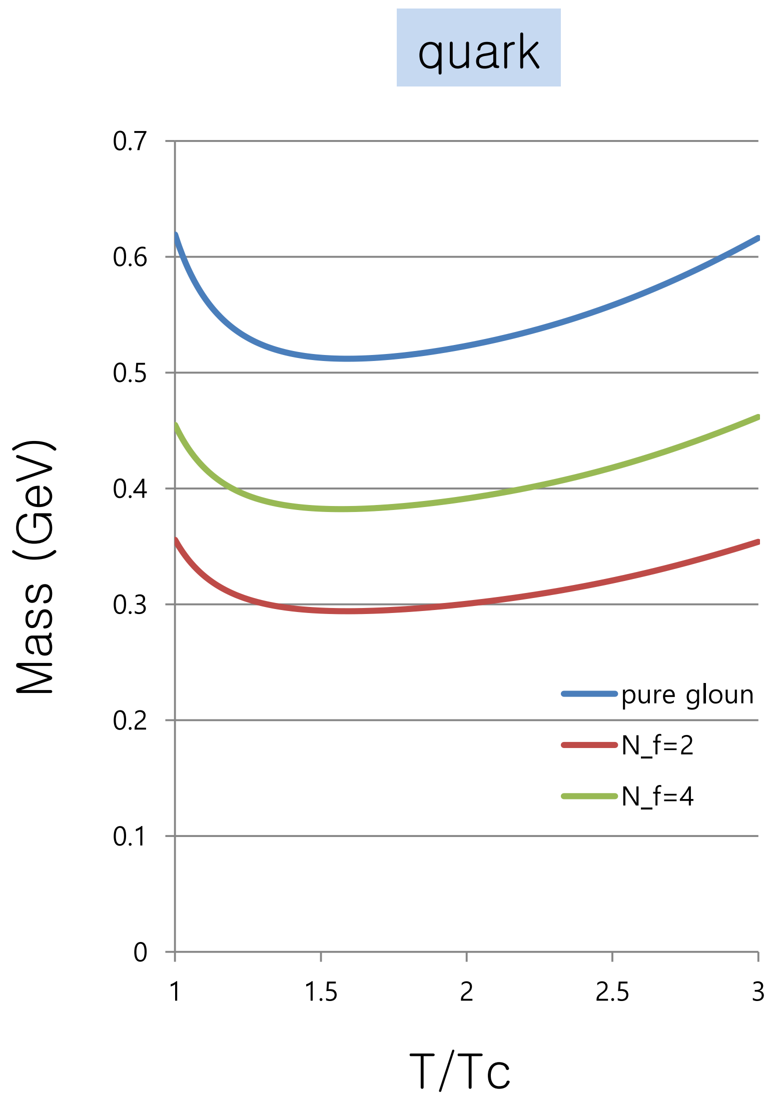


$N_f=4$





gluon
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass (GeV)
1
1.5
2
2.5
3
T/Tc
pure gloun
N_f=2
N_f=4



quark
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass (GeV)
1
1.5
2
2.5
3
T/Tc
pure gloun
N_f=2
N_f=4

Entropy density in QGP & in HG

in HG,

$$s=-\frac{1}{V}\frac{\partial\Phi}{\partial T}\bigg|_{V,\mu}=\frac{1}{6\pi^2}\sum_i\int_0^\infty dk\,\frac{k^4(E_i-\mu_i)}{E_iT^2}\frac{e^{(E_i-\mu_i)/T}}{\left(e^{(E_i-\mu_i)/T}\pm1\right)^2}$$

All mesons below 1.5 GeV, &
All baryons below 2.0 GeV

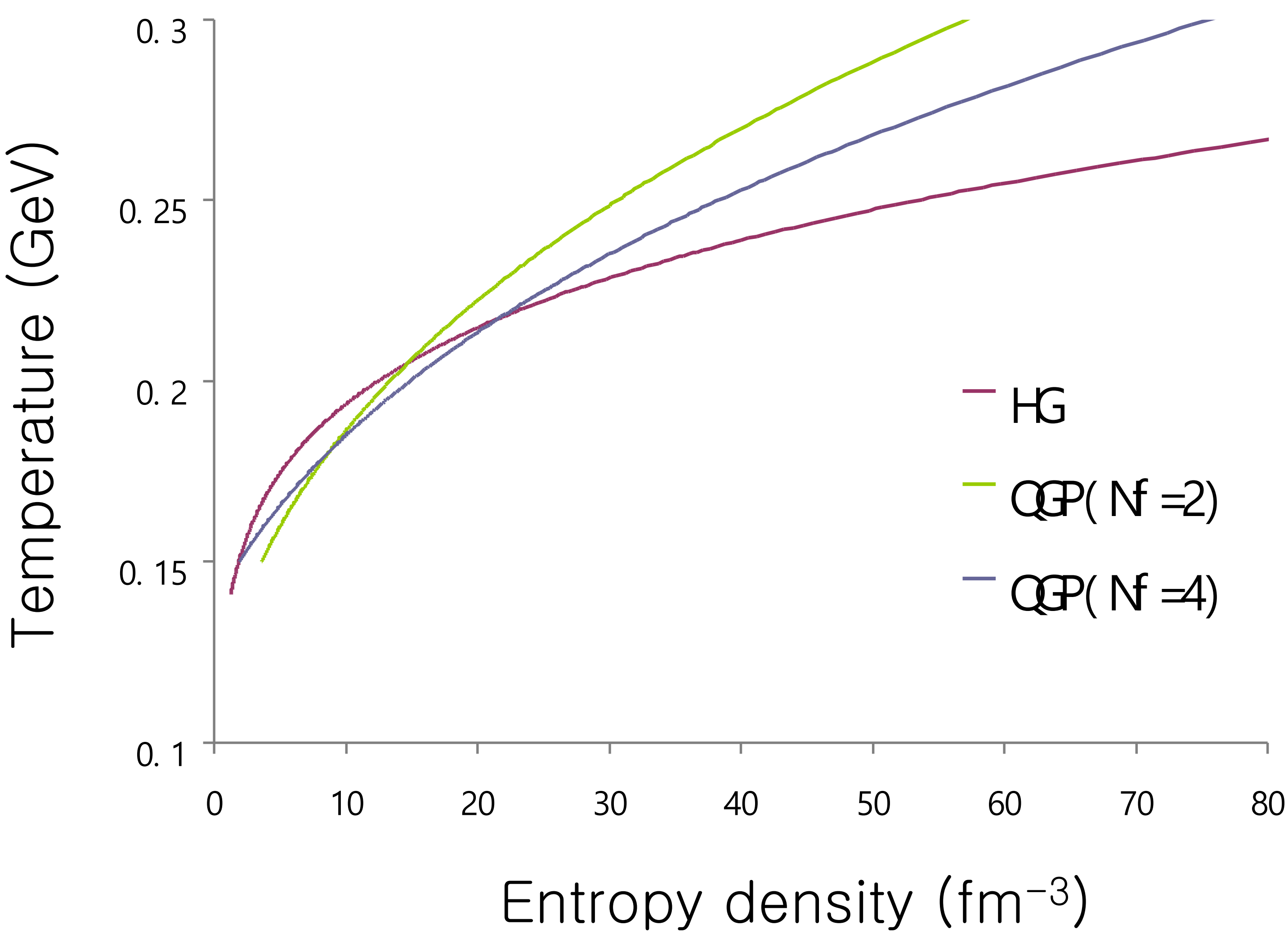
in QGP,

$$s=-\frac{1}{V}\frac{\partial\Phi}{\partial T}\bigg|_{V,\mu}=\frac{1}{6\pi^2}\sum_i\int_0^\infty dk\left[\frac{k^4(E_i-\mu_i)}{E_iT^2}\frac{e^{(E_i-\mu_i)/T}}{\left(e^{(E_i-\mu_i)/T}\pm1\right)^2}\right.$$

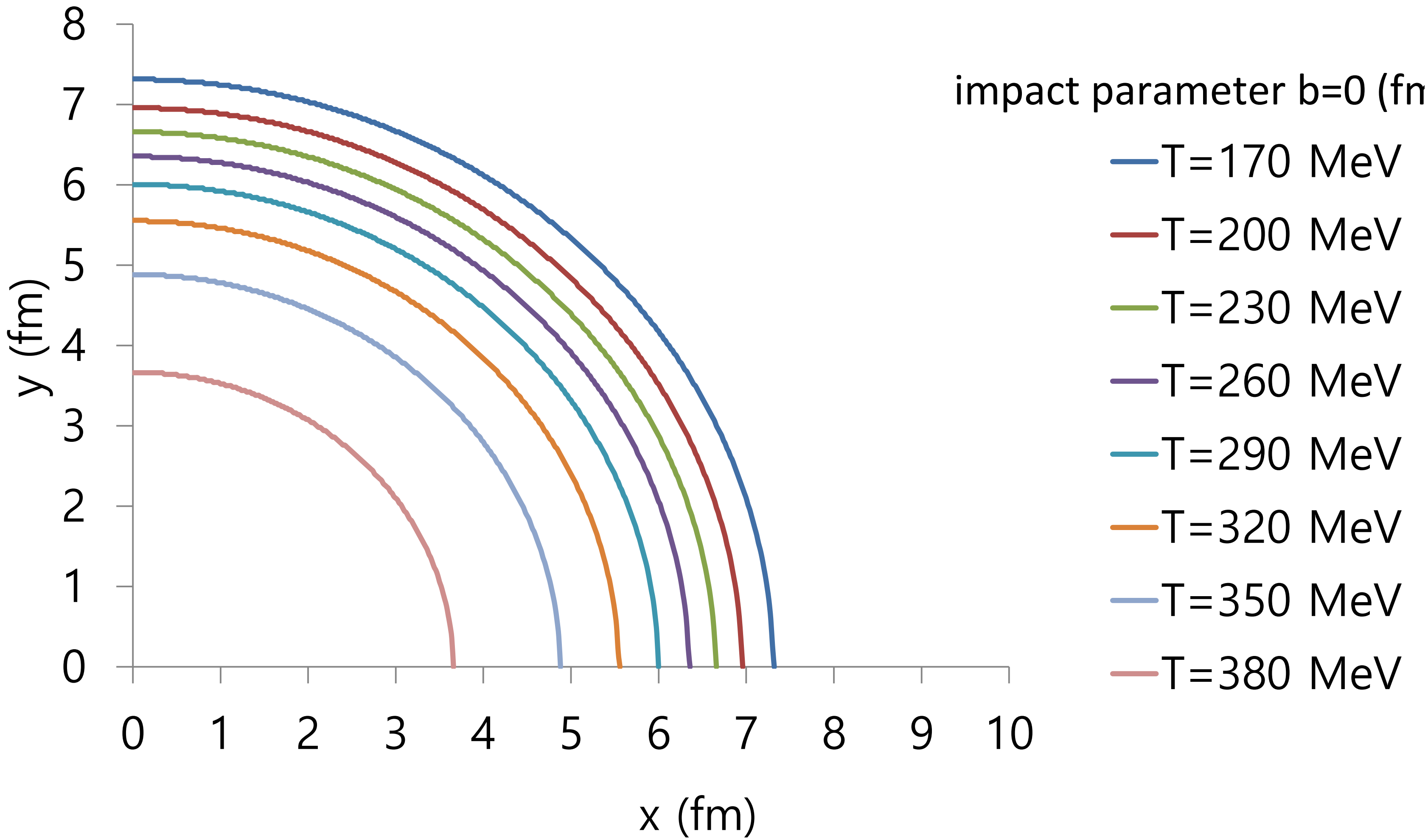
$$\left.-\left(\frac{\partial m_i^2}{\partial T}\right)\left(\frac{1}{2E_i^3}\frac{1}{e^{(E_i-\mu_i)/T}\pm1}+\frac{1}{2E_i^2T}\frac{e^{(E_i-\mu_i)/T}}{\left(e^{(E_i-\mu_i)/T}\pm1\right)^2}\right)\right]$$

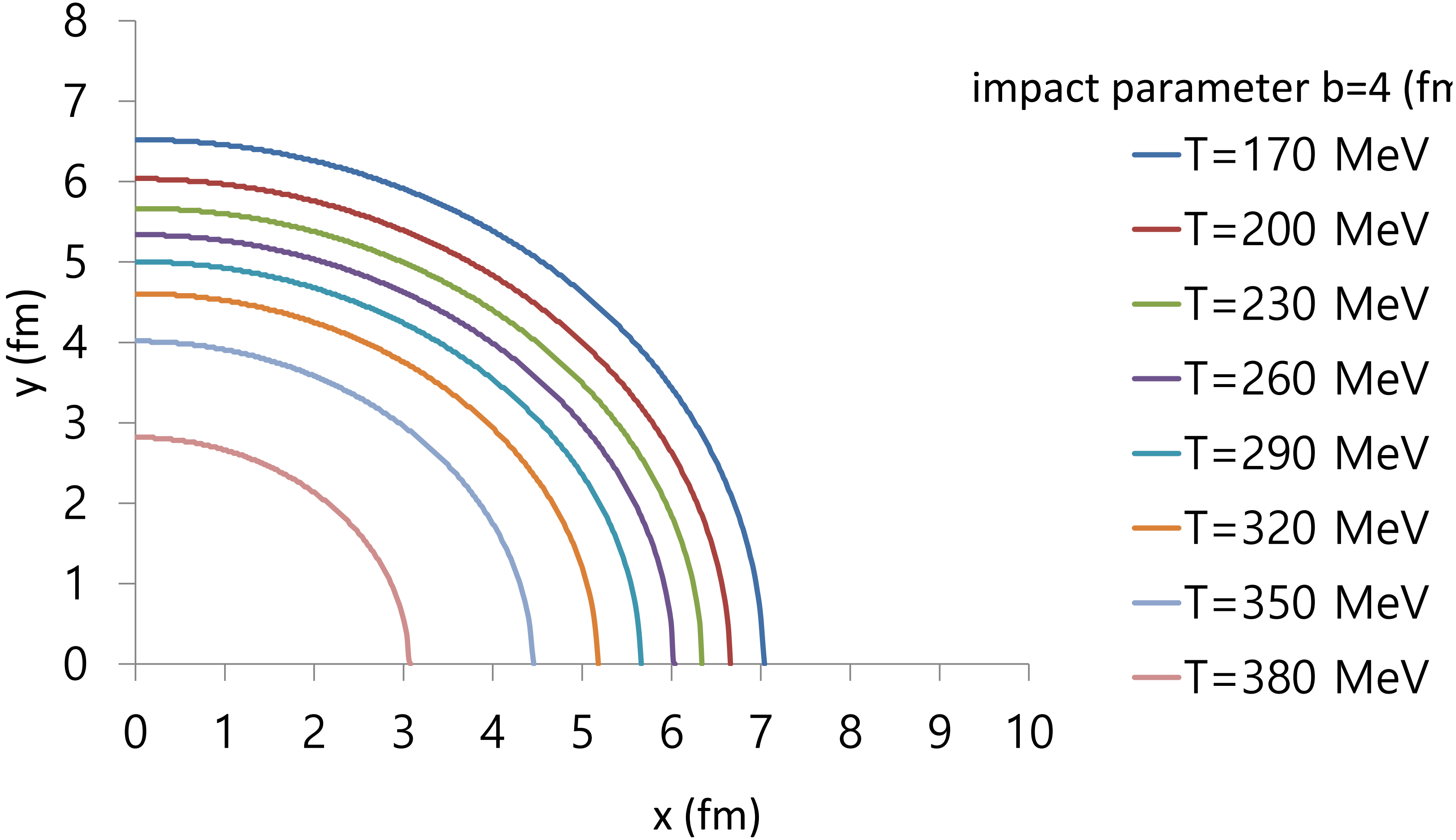
Thermal quark/anti-quark & gluon

Entropy density vs. temperature

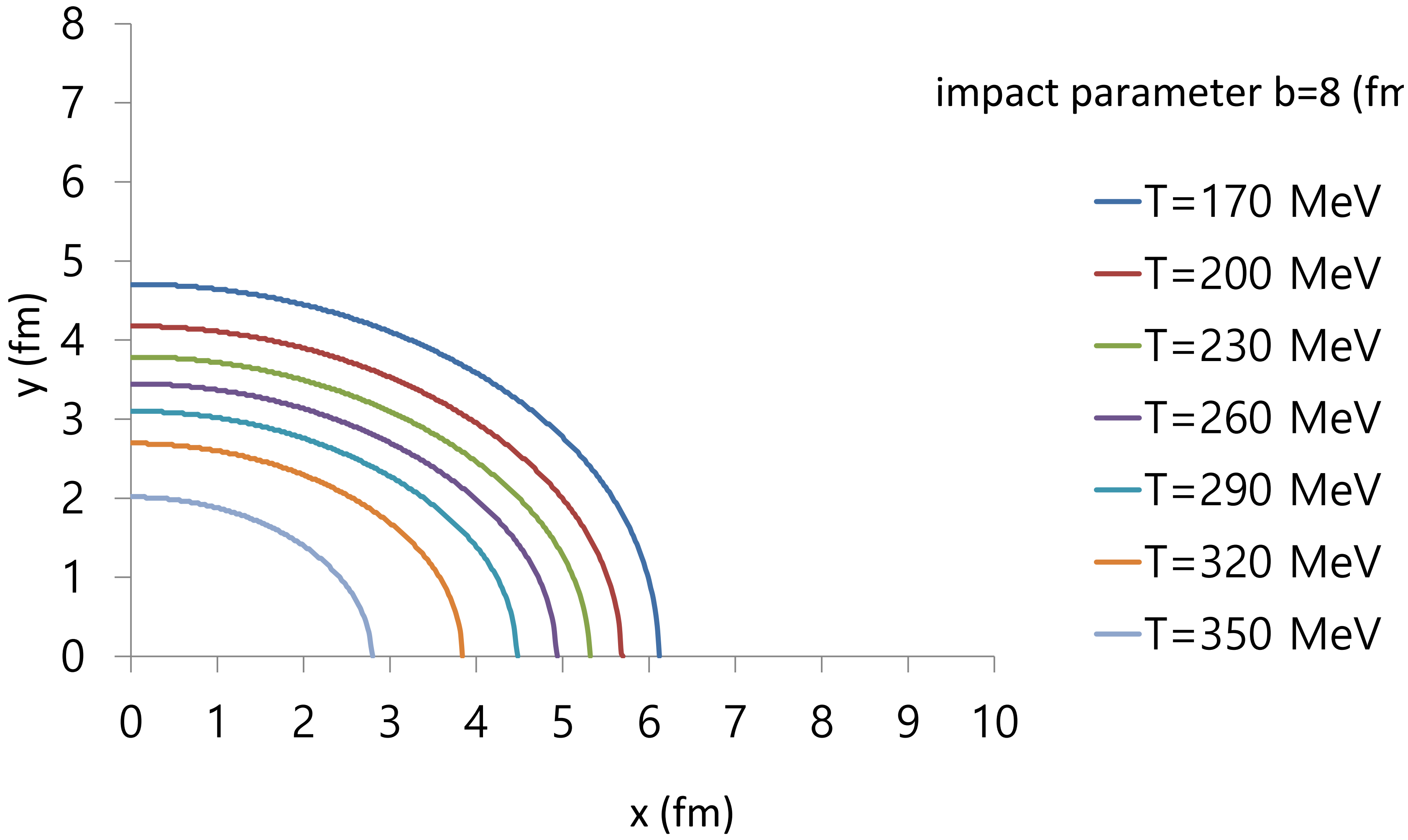


Temperature distribution on transverse plane at formation time

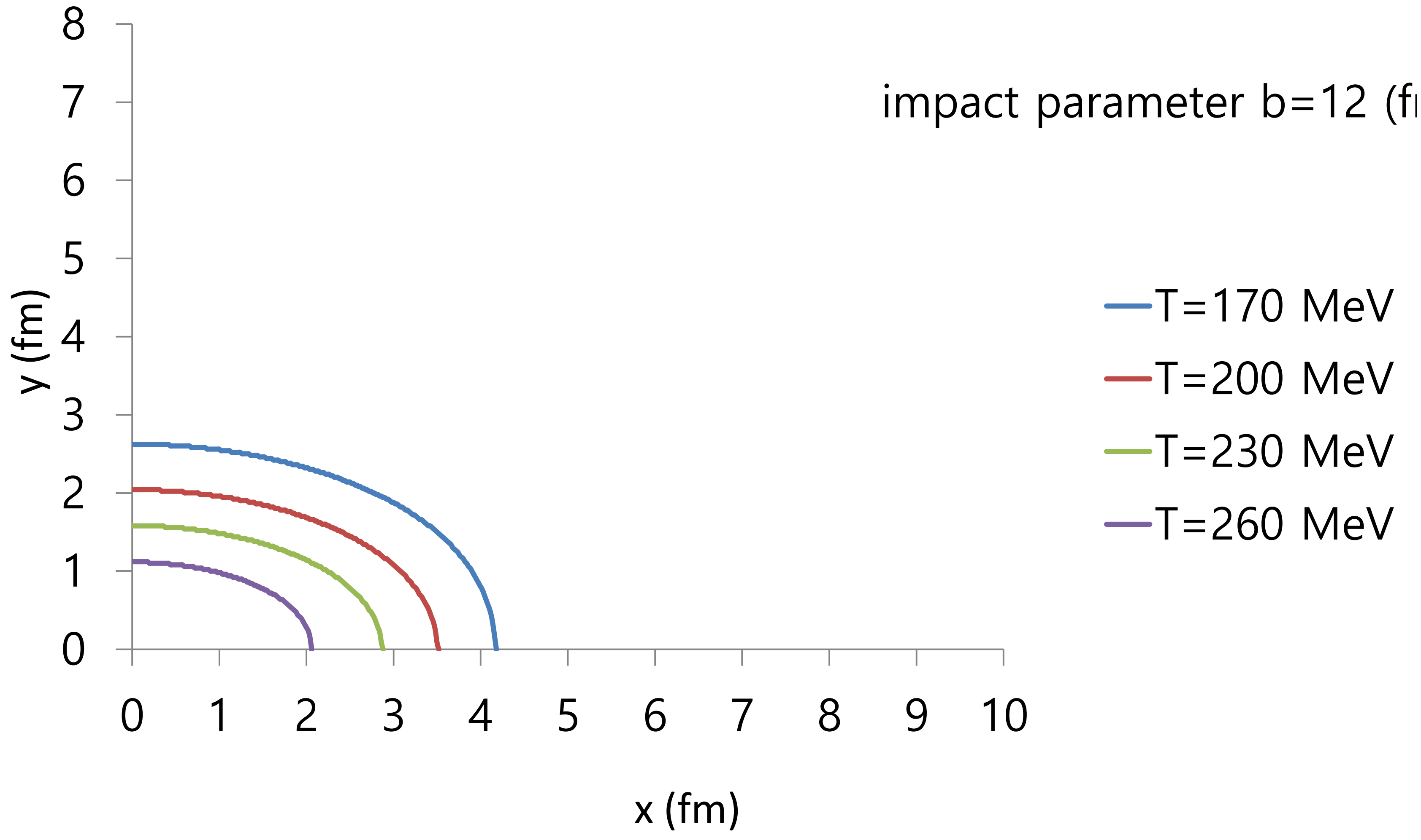




impact parameter b=4 (fm
T=170 MeV
T=200 MeV
T=230 MeV
T=260 MeV
T=290 MeV
T=320 MeV
T=350 MeV
T=380 MeV
y (fm)
x (fm)
0
1
2
3
4
5
6
7
8
9
10

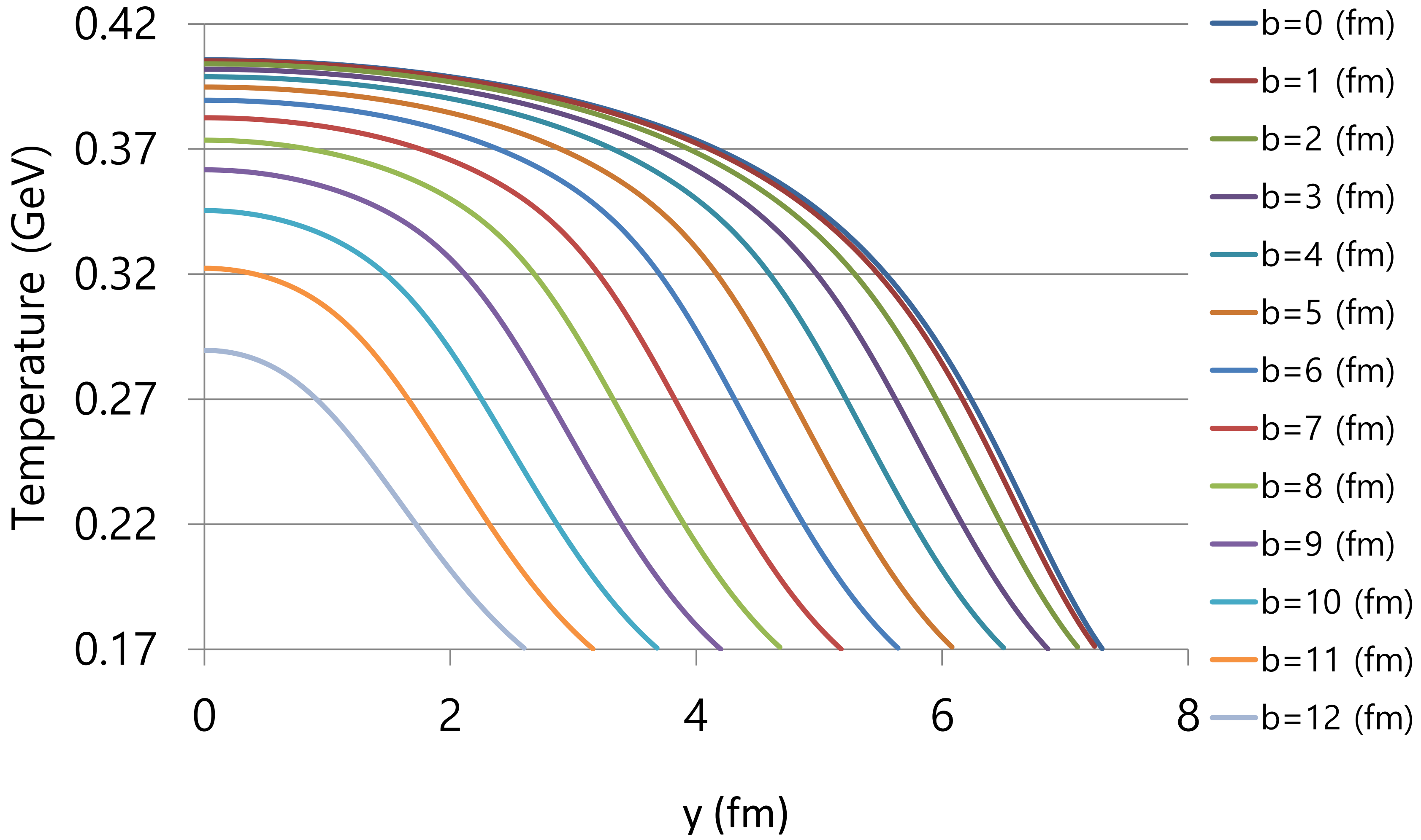


8
7
6
5
4
3
2
1
0
y (fm)
0
1
2
3
4
5
6
7
8
9
10
x (fm)
impact parameter b=8 (fm
T=170 MeV
T=200 MeV
T=230 MeV
T=260 MeV
T=290 MeV
T=320 MeV
T=350 MeV



impact parameter b=12 (fı
T=170 MeV
T=200 MeV
T=230 MeV
T=260 MeV
y (fm)
x (fm)
0
1
2
3
4
5
6
7
8
9
10

Temperature profiles with various impact parameters



Assuming isentropic expansion of fireball, with the below time-dependent volume

$$V_{FB}(\tau) = 2 \times y(\tau_0 + \tau) \times \pi \left(r_0 + \frac{1}{2} a_{\perp} \tau^2 \right)^2,$$

"we can deduce temperatures and chemical potentials at midrapidity before reaching chemical freeze-out stage."

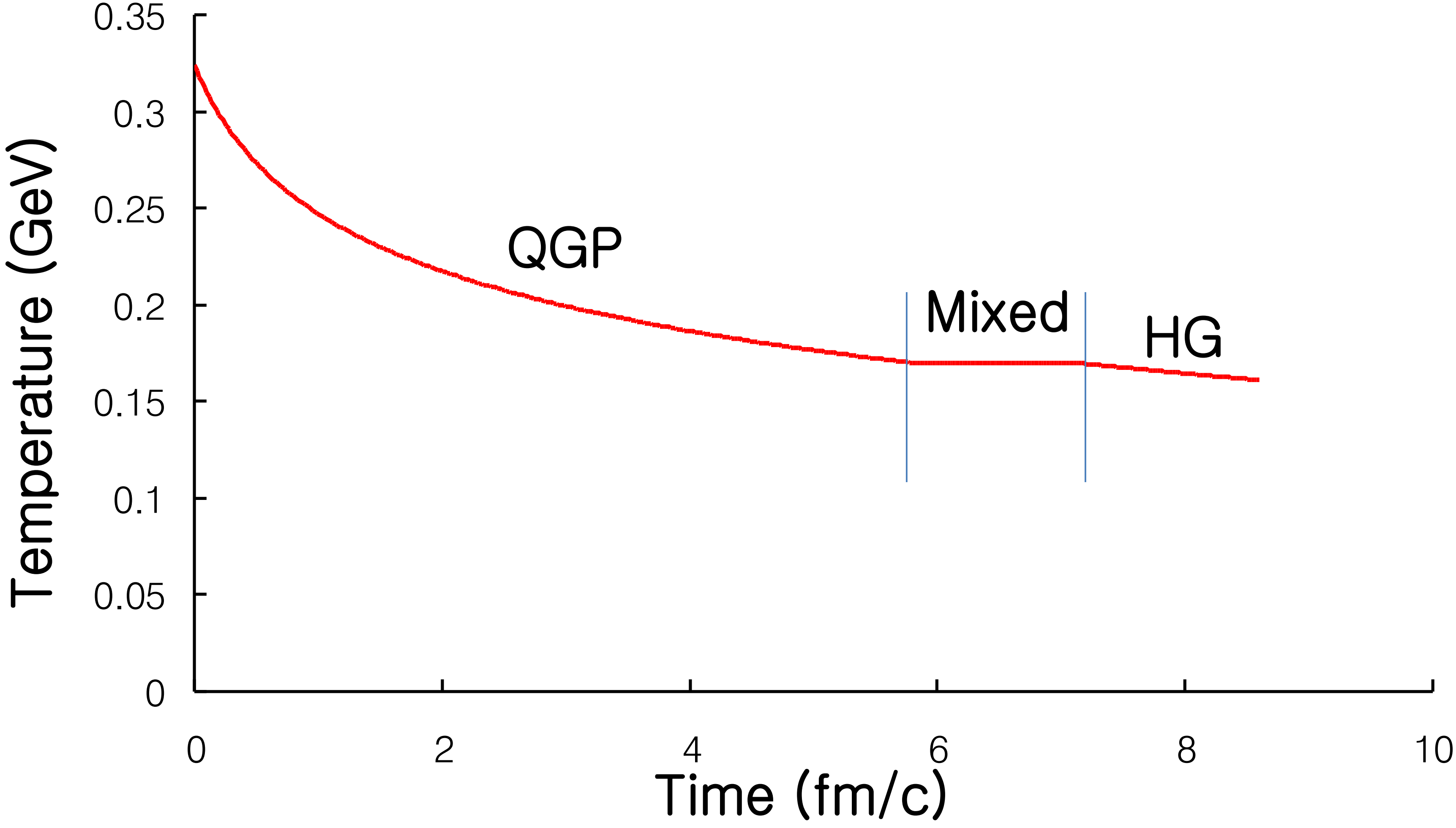
From hydrodynamics simulation,

1. τ_0 is the thermalization time of fireball ≈ 0.6 fm/c

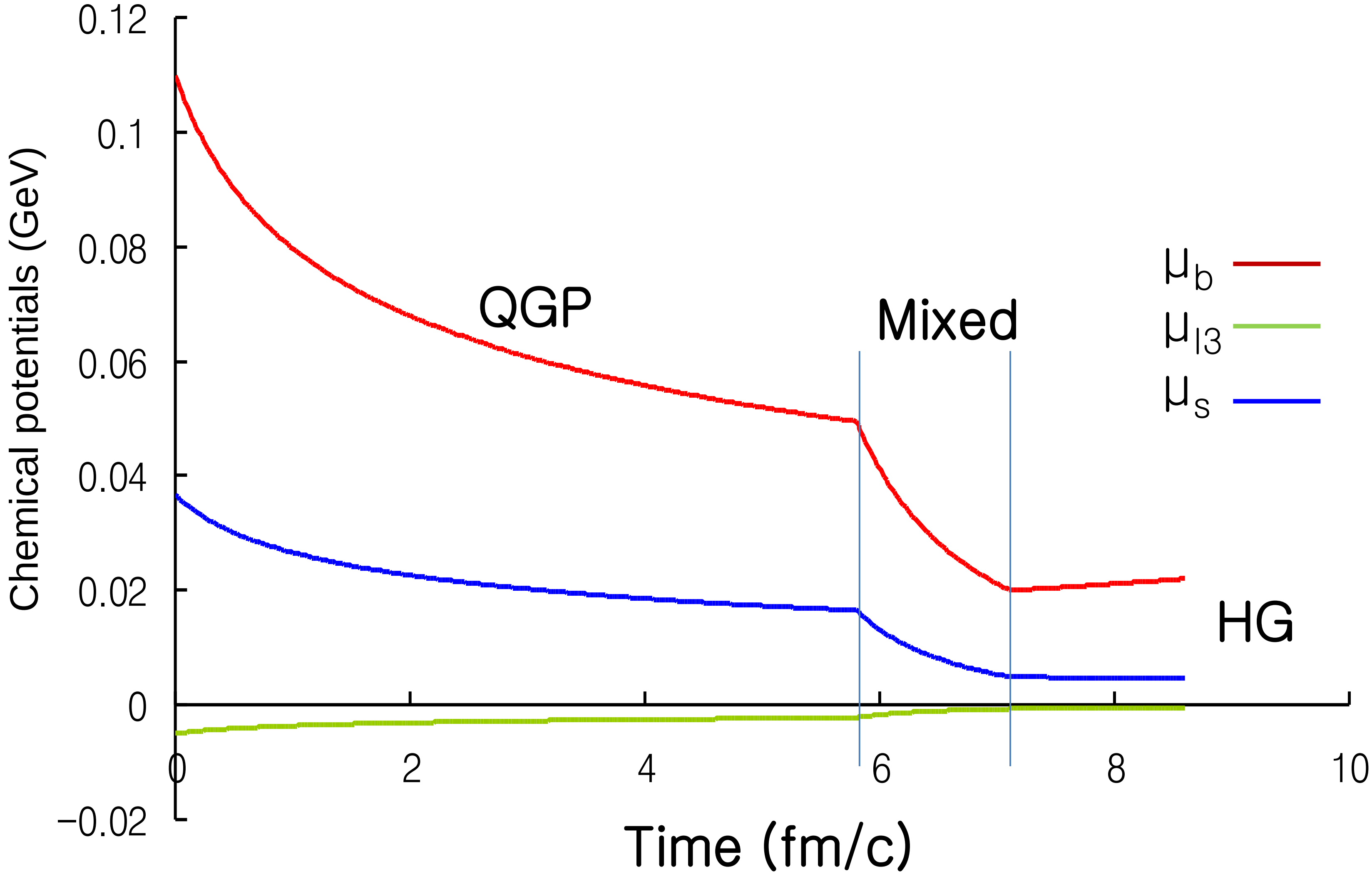
2. $a_{\perp}$ is transverse acceleration , which was set at 0.1 c^2/fm
   X. Zhao, R. Rapp, PLB664, 253 (2008)
   terminal transverse velocity was set at 0.6 c

3. r_0 is initial transverse radius of QGP

Fireball expansion (b=0 fm)



Fireball expansion (b=0 fm)



2.2. survival rate from the thermal decay

Considering feed-down from χ_c , Ψ' to J/ψ,
survival rate of J/ψ from the thermal decay is

$$S_{QGP+HG} = 0.67\, S_{QGP+HG}^{J/\Psi} + 0.25\, S_{QGP+HG}^{\chi_c} + 0.08\, S_{QGP+HG}^{\Psi'}$$

,where

$$S_{QGP+HG}^{j} = \exp\left\{ -\int_0^{\tau} \Gamma^{j}(\tau')d\tau' \right\}$$

and $\Gamma^j(\tau)$ is thermal width of charmonia j

$\Gamma^j(\tau) = \Gamma_{QGP}^j(\tau)$ (T>Tc) in QGP phase
$\Gamma^j(\tau) = f\,\Gamma_{QGP}^j(\tau) + (1-f)\,\Gamma_{HG}^j(\tau)$ (T=Tc) in mixed phase
$\Gamma^j(\tau) = \Gamma_{HG}^j(\tau)$ (T<Tc) in HG phase

Thermal decay widths in QGP & HG

Thermal width

$$\Gamma = \sum_j g_j \int \frac{d^3k}{(2\pi)^3} n_j(T,\mu) v_{rel}(T) \sigma_{diss}(T)$$

n_j : density of parton or hardon dissociating J/ψ

v_{rel} : relative velocity between j and J/ψ

σ_{diss} : dissociation cross section of J/ψ

(in QGP, j=quark, antiquark, gluon
in hadronic matter, j=pion, kaon, …)

In order to calculate thermal width Γ, we must know

1) Thermodynamic quantities such as T, μ
2) Dissociation cross section σ_{diss}

Dissociation cross section σ_{diss}

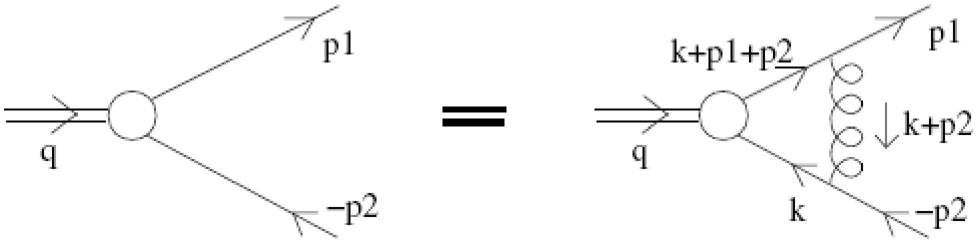
Dissociation cross section σ_{diss} is a crucial quantity to calculate thermal width.

Most studies use two different models for QGP dissociation and hadronic dissociation.
(As an example,
for the decay in QGP, quasi-free particle approximation,
and for that in HG, meson exchange model,…)

Here we use the same approach, pQCD, in QGP and in HG.

Bethe-Salpeter amplitude to describe the bound state of heavy quarkonia

Definition ;

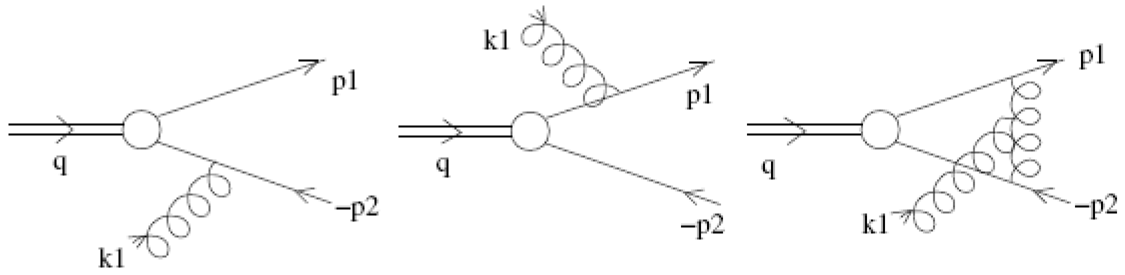


$$\Gamma_\mu(p_1,-p_2) = -ig^2 C_F \int \frac{d^4K}{(2\pi)^4} \gamma^\alpha i\Delta(K+p_1+p_2)\Gamma_\mu \times (K+p_1+p_2,K) i\Delta(K)\gamma_\alpha V(K+p_2),$$

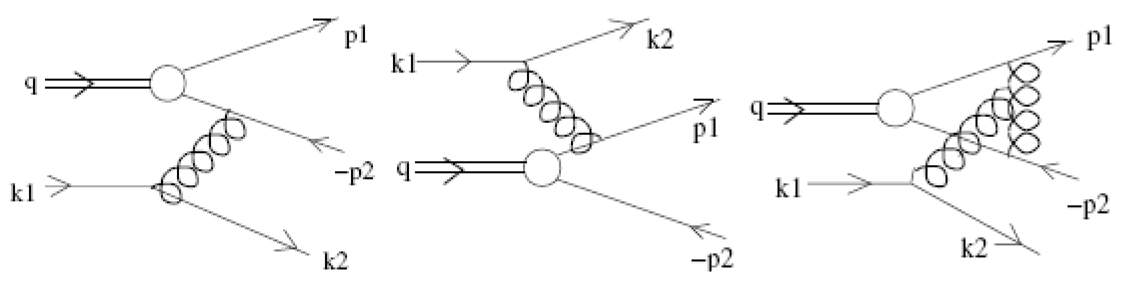
Solution is NR limit ;

$$\Gamma_\mu\left(\frac{q}{2}+p,-\frac{q}{2}+p\right) = \left(\epsilon_o + \frac{\vec{p}^2}{m}\right)\psi(|\vec{p}|) \times \sqrt{\frac{m_\Phi}{N_c}} \frac{1+\gamma^0}{2}\gamma_i g^i_\mu \frac{1-\gamma^0}{2}.$$

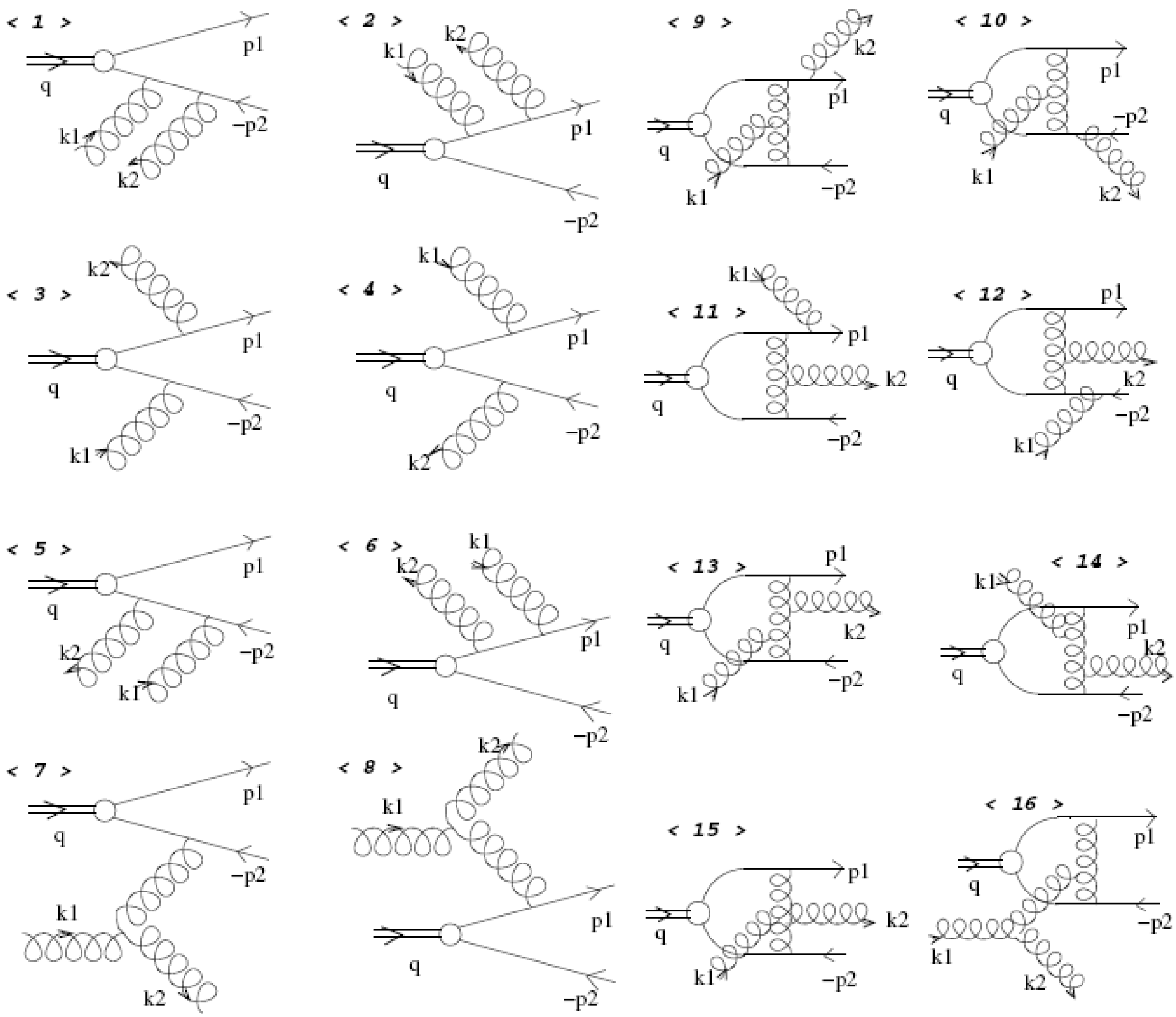
Leading Order (LO)



quark-induced
Next to Leading Order (qNLO)



gluon-induced
Next to Leading Order (gNLO)



Leading Order (LO)

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

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)

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

Wavefunctions of charmonia at finite T

Modified Cornell potential

F. Karsch, M.T. Mehr, H. Satz, Z phys. C. 37, 617 (1988)

$$V(r,T) = \frac{\sigma}{\mu(T)}\left(1 - e^{-\mu(T)r}\right) - \frac{\alpha}{r} e^{-\mu(T)r}$$

σ=0.192 GeV^2 : string tension

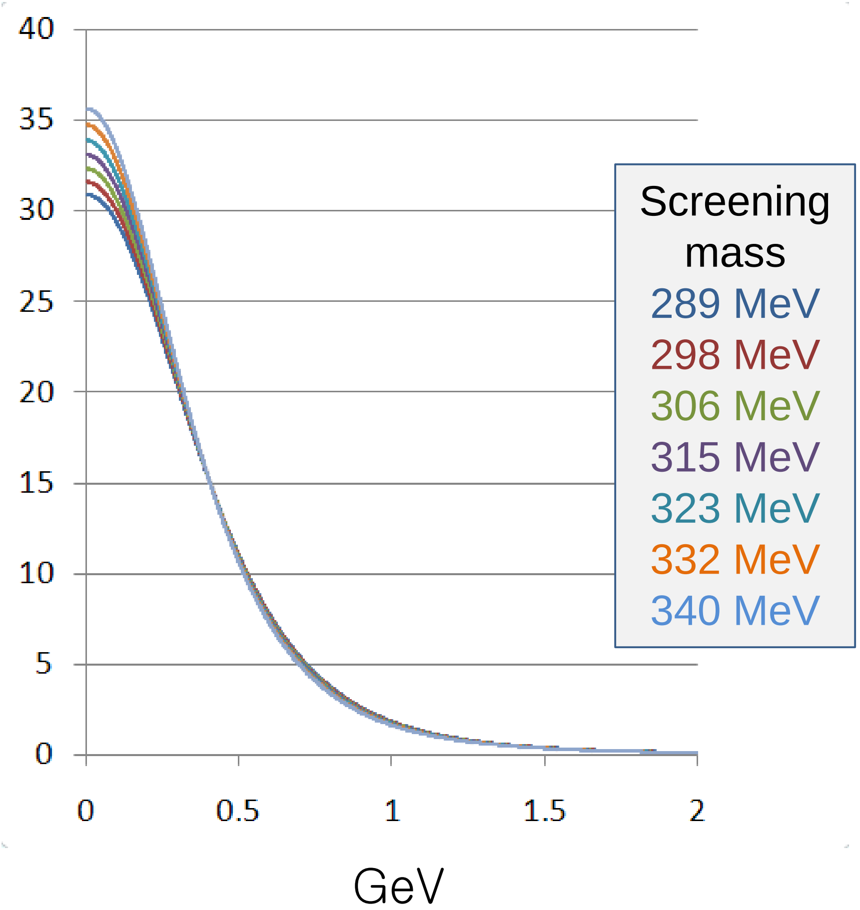
α=0.471 : Coulomb-like potential constant

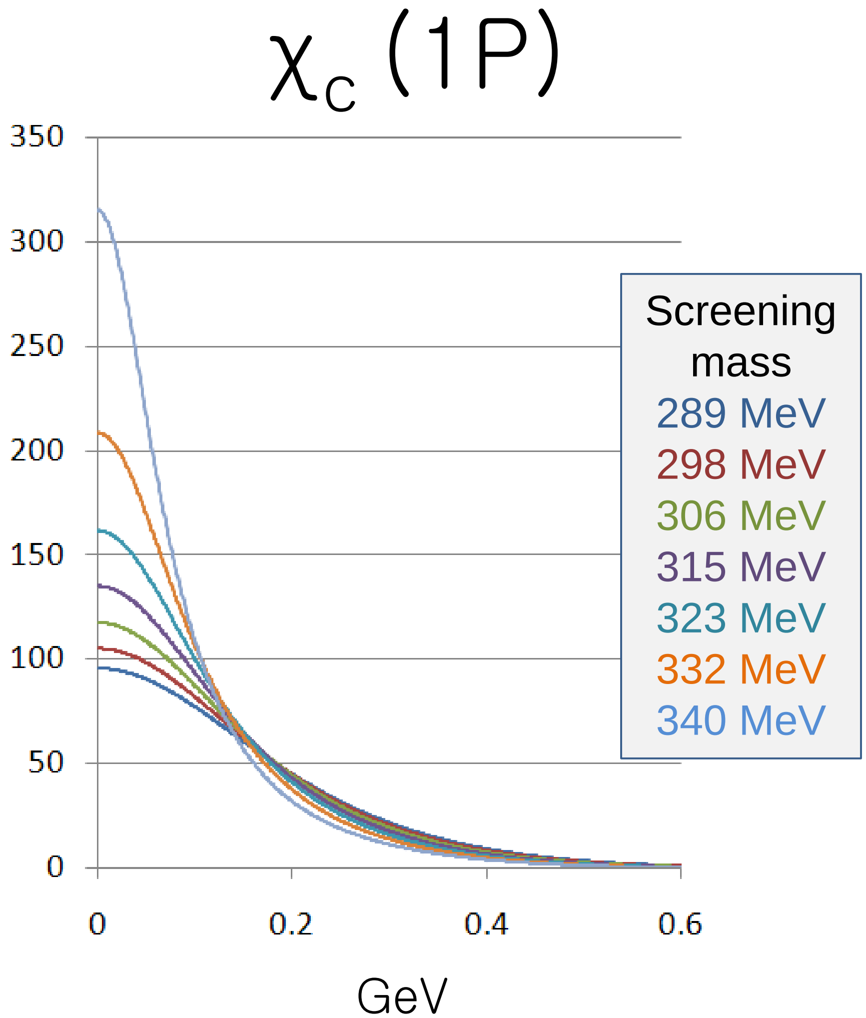
μ(T) ~gT is the screening mass

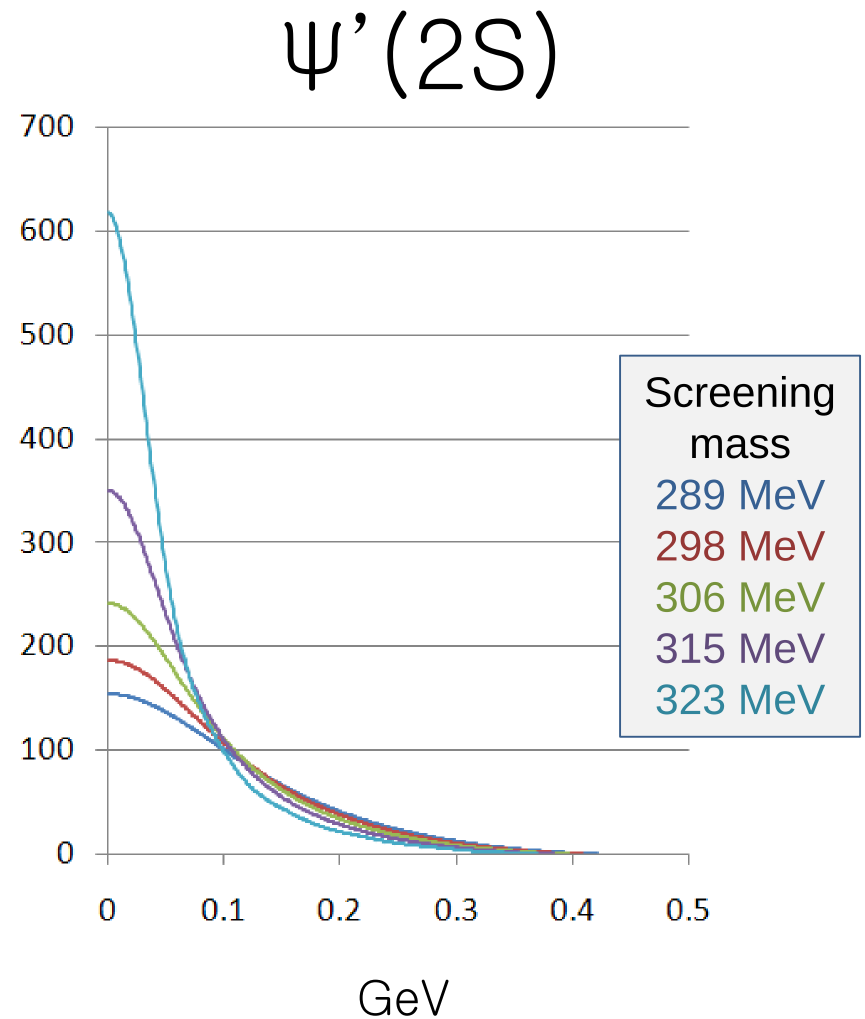
In the limit μ(T)→0,

$$V(r,T) \to \sigma\, r - \frac{\alpha}{r}$$

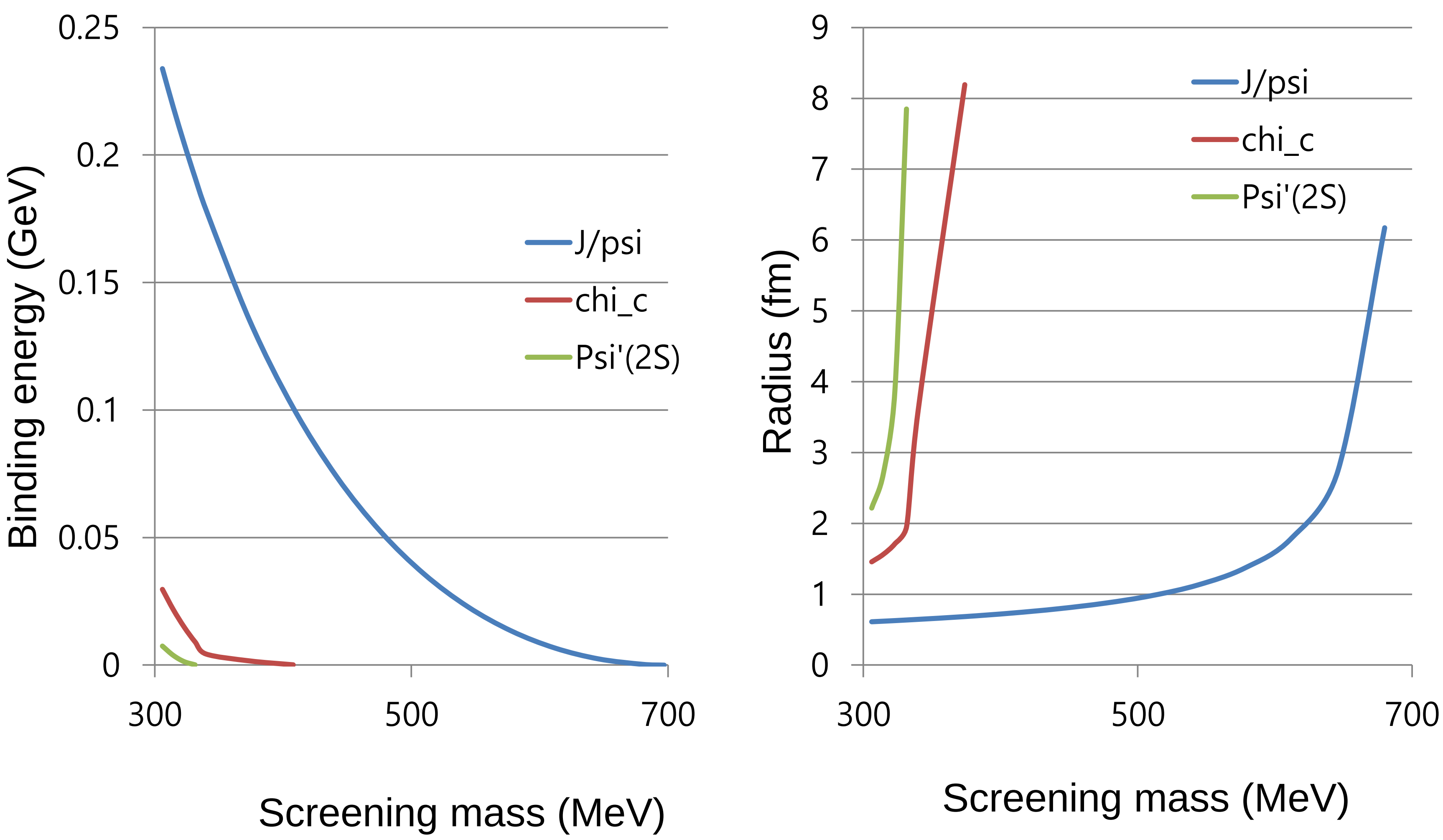
J/ψ (1S)




χ_c (1P)
350
300
250
200
150
100
50
0
0
0.2
0.4
0.6
GeV
Screening mass
289 MeV
298 MeV
306 MeV
315 MeV
323 MeV
332 MeV
340 MeV


ψ'(2S)
700
600
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
GeV
Screening mass
289 MeV
298 MeV
306 MeV
315 MeV
323 MeV

Binding energies & radii of charmonia



In QGP

$\sigma_{diss} = \sigma_{pQCD}$

1. partons with thermal mass ~gT,
2. temperature-dependent wavefunction is used.

In hadronic matter

$\sigma_{diss}(p) = \int dx\, \sigma_{pQCD}(xp) D(x)$

: factorization formula

D(x) is parton distribution Ft. of hadrons(pion, here) interacting with charmonia

1. Massless partons
2. (mass factorization, loop diagrams, and renormalization are required to remove collinear divergence, infrared divergence, and ultraviolet divergence)

2. Coulomb wavefunction is used.

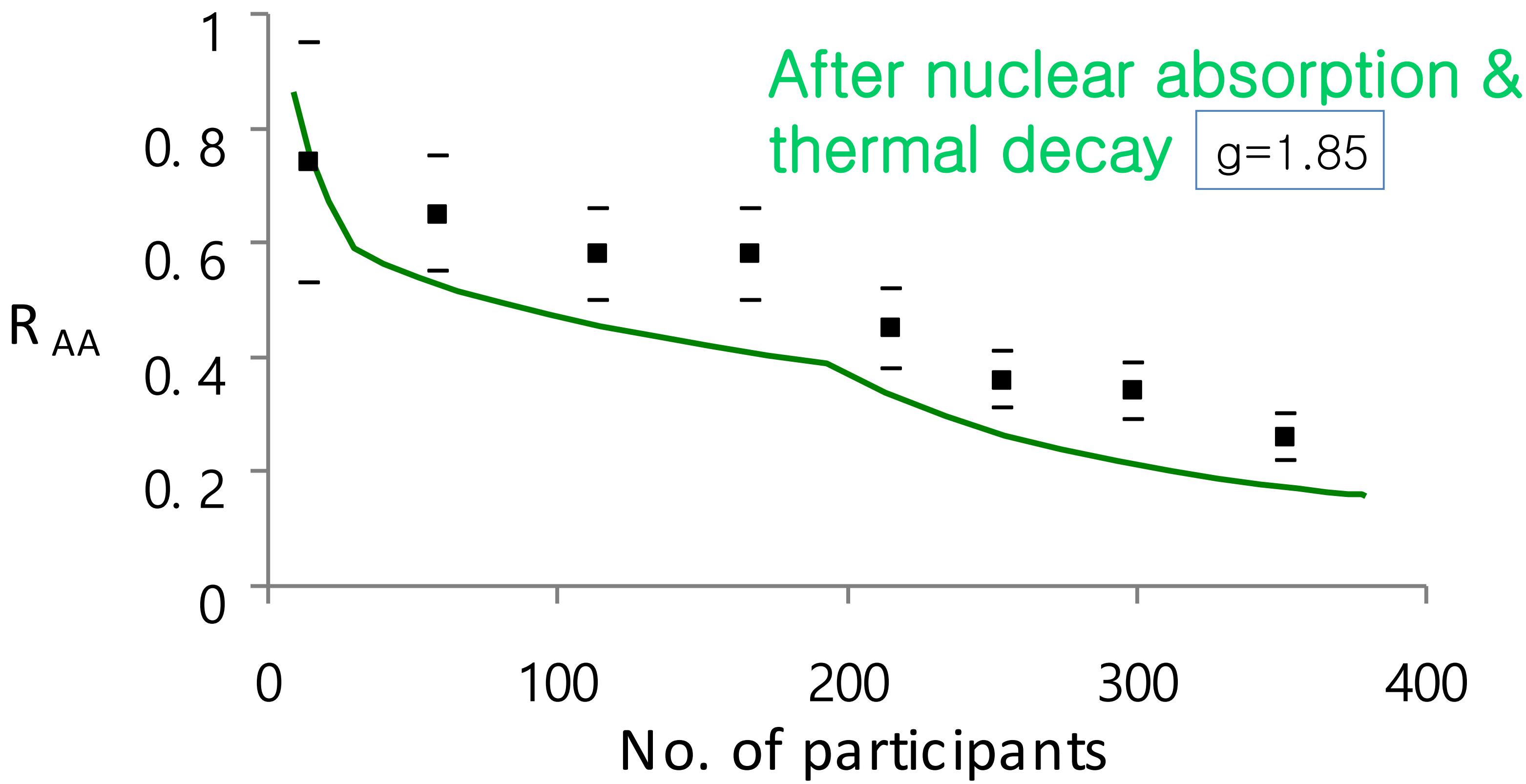
The role of coupling constant 'g'

1. 'g' determines the thermal width of J/ψ
   (in LO, $\Gamma \sim g^2$, and in NLO, $\Gamma \sim g^4$)

2. 'g' determines the screening mass, that is, the melting temperature of charmonia (screening mass $\mu = gT$)

$T_{J/\psi}$=377 MeV, $T_{\chi c}$ =221 MeV, $T_{\psi'}$=179 MeV

Comparison with experimental data of RHIC (√s=200 GeV at midrapidity)



3. Recombination of J/ψ at hadronization

If the number of cc pair is completely thermalized,

$$N_{c\bar{c}}^{AB} = \left(\frac{1}{2} n_{openC} + n_{hiddenC} \right) V$$

However, the cross section for 'cc pair → others' or 'others → cc pair' is very small.
The life time of fireball is insufficient for the thermalization of the number of cc pair.
→ corrected with fugacity γ

$$N_{c\bar{c}}^{AB} = \frac{1}{2} \gamma \, n_{openC} V + \gamma^2 n_{hiddenC} V$$

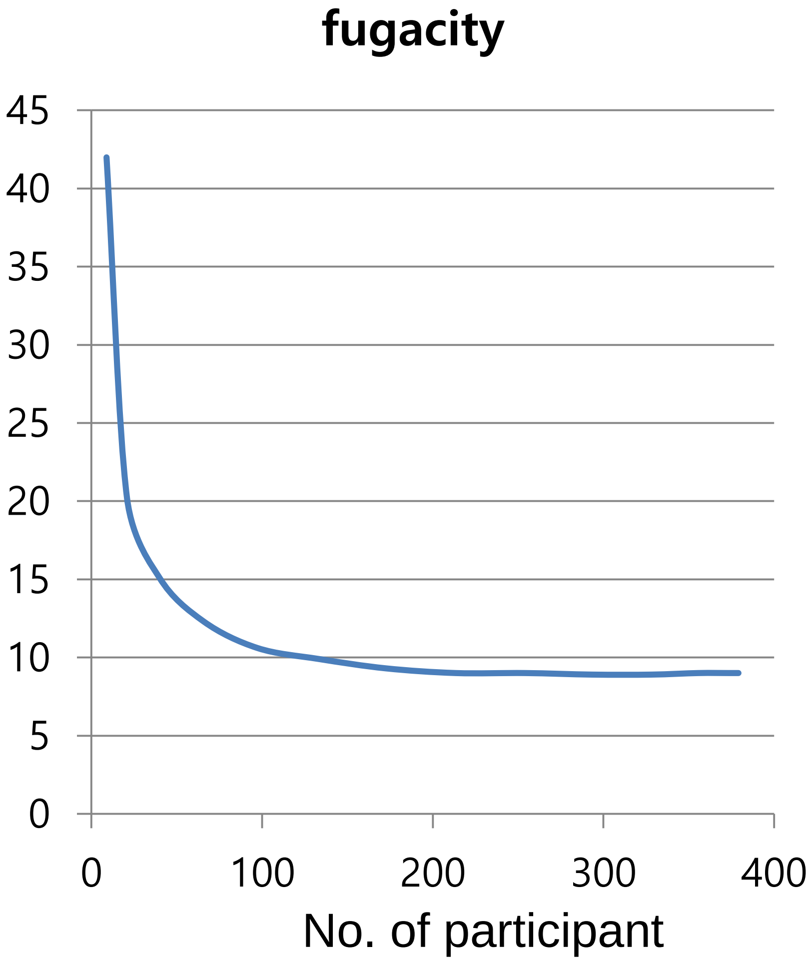
If produced cc pairs are very few, GCE must turn to CE
→ canonical ensemble suppression

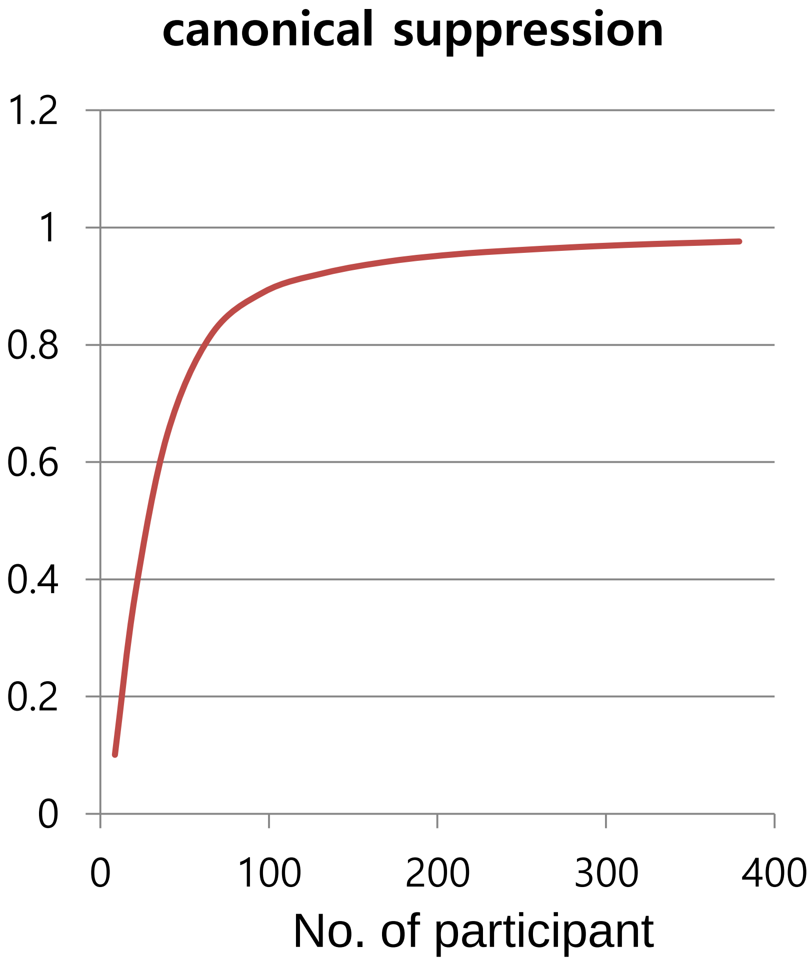
$$N_{c\bar{c}}^{AB} = \frac{1}{2} \gamma \, n_{openC} V \, \frac{I_1(\gamma \, n_{openC} V)}{I_0(\gamma \, n_{hiddenC} V)} + \gamma^2 n_{hiddenC} V$$

If the number of cc pair initially produced in AB collision is conserved, it scales with the number of binary collision between nucleons in colliding nuclei.

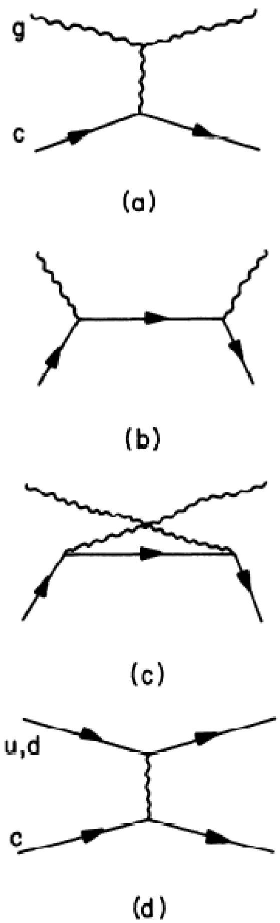
$$N_{c\bar{c}}^{AB}(\vec{b}) = \sigma_{c\bar{c}}^{NN} AB \int d^2 s \int dz_A \rho_A(\vec{s}, z_A) \int dz_B \rho_B(\vec{b} - \vec{s}, z_B)$$

, where $d\sigma_{cc}^{NN}/dy = 63.7(\mu b)$ from pQCD.


fugacity
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
No. of participant


canonical suppression
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
No. of participant

Relaxation factor for kinematical equilibrium



$$R = 1 - \exp\left(- \int_{\tau_0}^{\tau_H} \frac{d\tau}{\tau_{eq}} \right)$$

, where a thermalization time $\tau_{eq} = 1/(n\sigma)$

n : the total density of quark/gluon in the system

σ : the elastic scattering cross section of charm/anti-charm

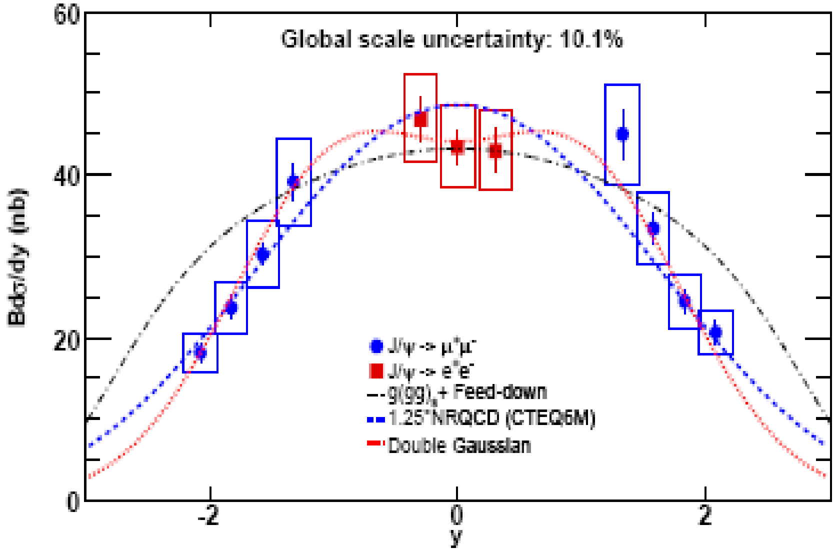
τ_H : the time at hadronization

- Finally, the number of recombined J/ψ is

$V R \gamma^2 \{n_{J/\psi} + Br(\chi_c) * n_{\chi c} + Br(\psi') * n_{\psi'}\}$

< Reference for R_{AA}>

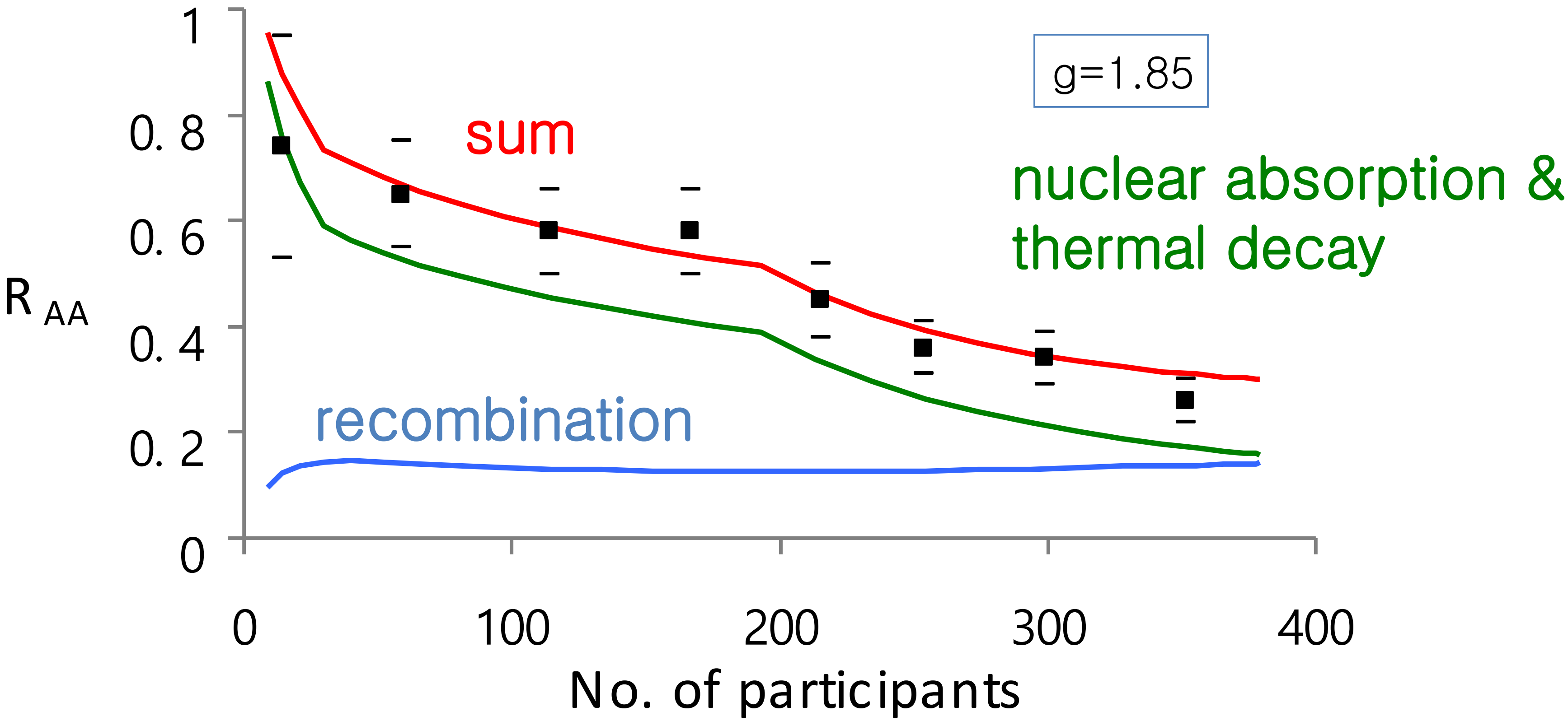
- J/ψ production in pp collisions at √s=200 GeV PHENIX Collaboration, PRL 98, 232002 (2007)



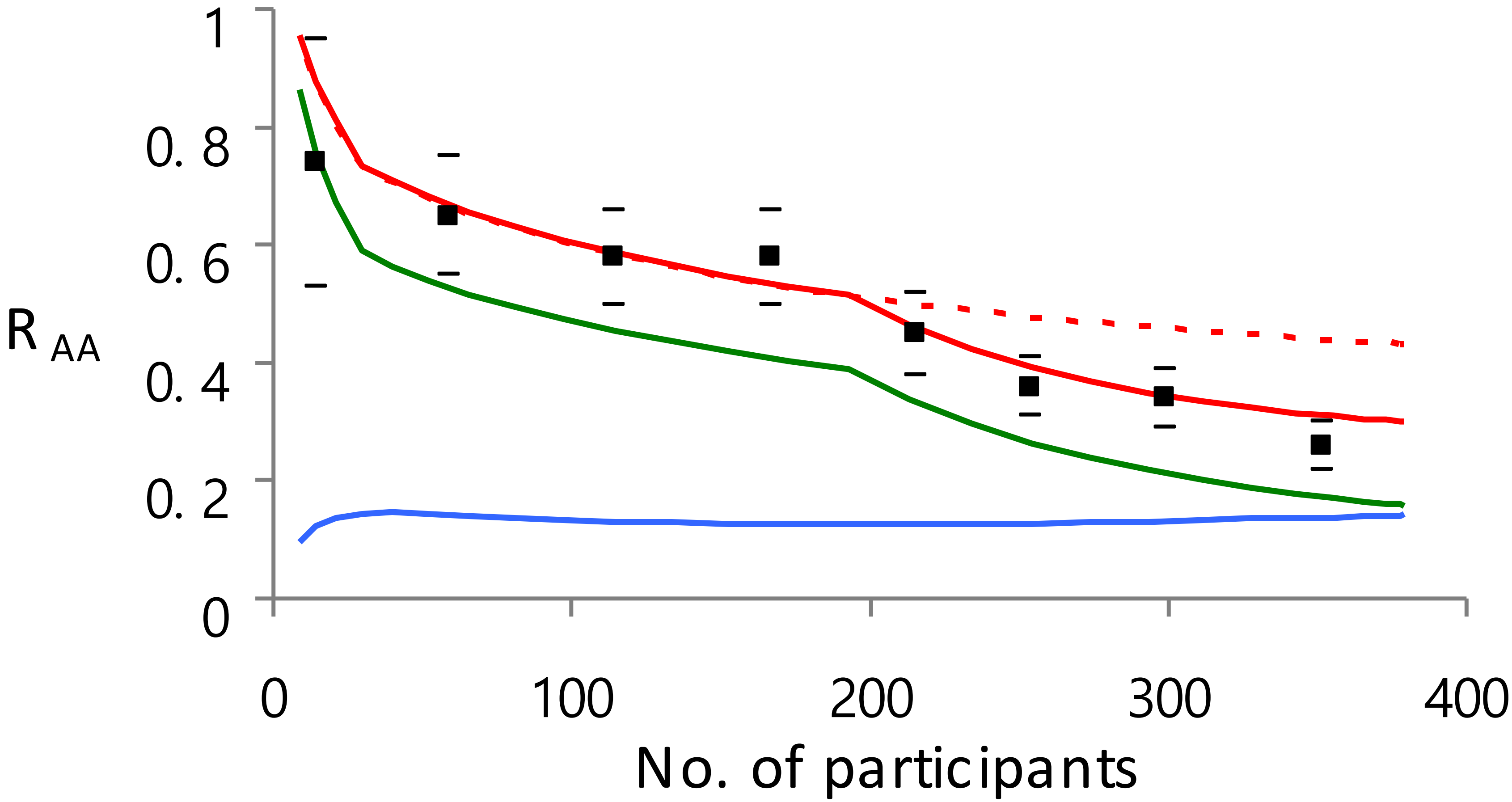
The role of coupling constant ‘g’

3. ‘g’ determines relaxation factor of charm/anti-charm quarks (relaxation time$\sim g^2$)

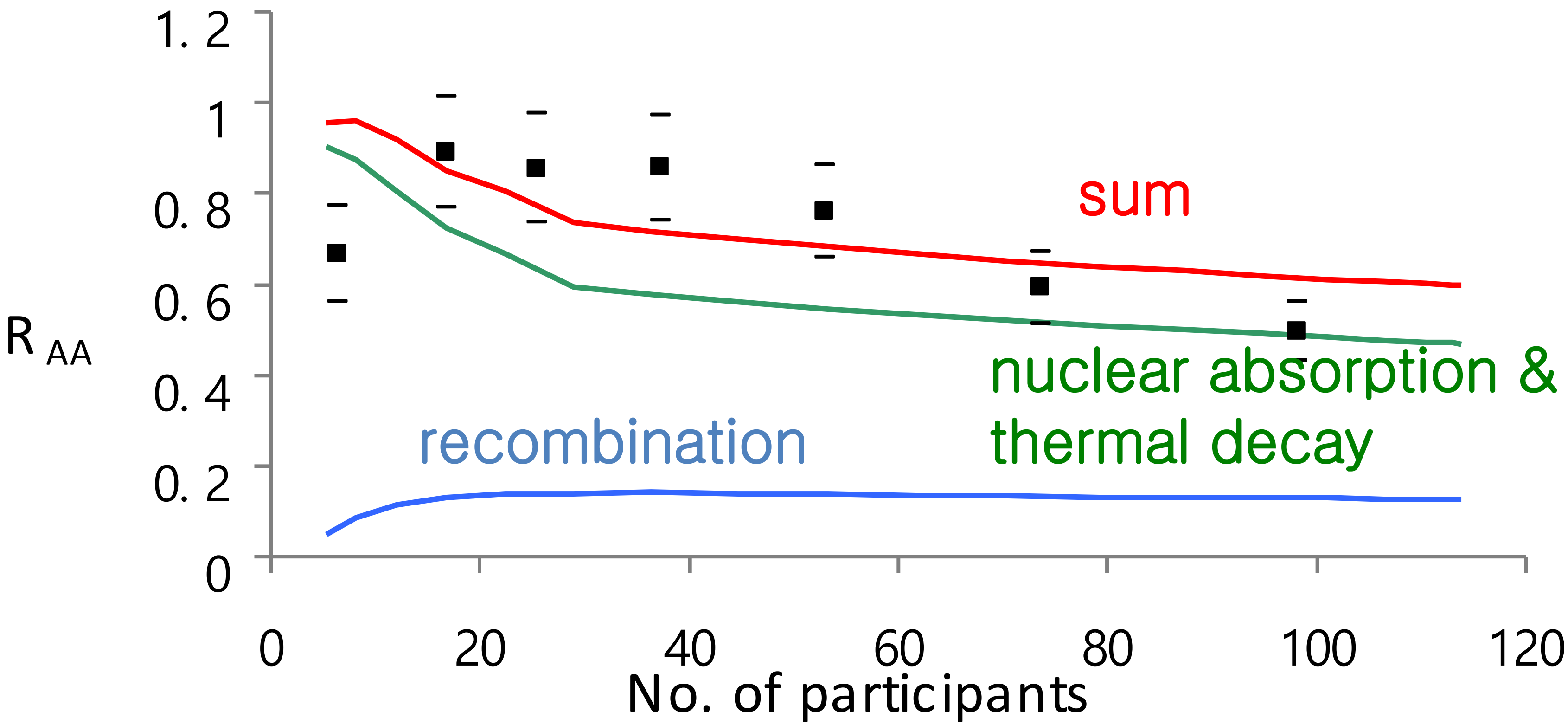
Comparison with experimental data of RHIC ($\sqrt{s}$=200 GeV at midrapidity)



If there is no initial melting of J/ψ



Cu+Cu in RHIC at $\sqrt{s_{NN}}$=200 GeV



For LHC prediction

- By extrapolation,

Entropy S= 21.5{(1-x)N_{part}/2+xN_{coll}}

to 55.7{(1-x)N_{part}/2+xN_{coll}}, where x=0.11

J/ψ production cross section in p+p collision per rapidity

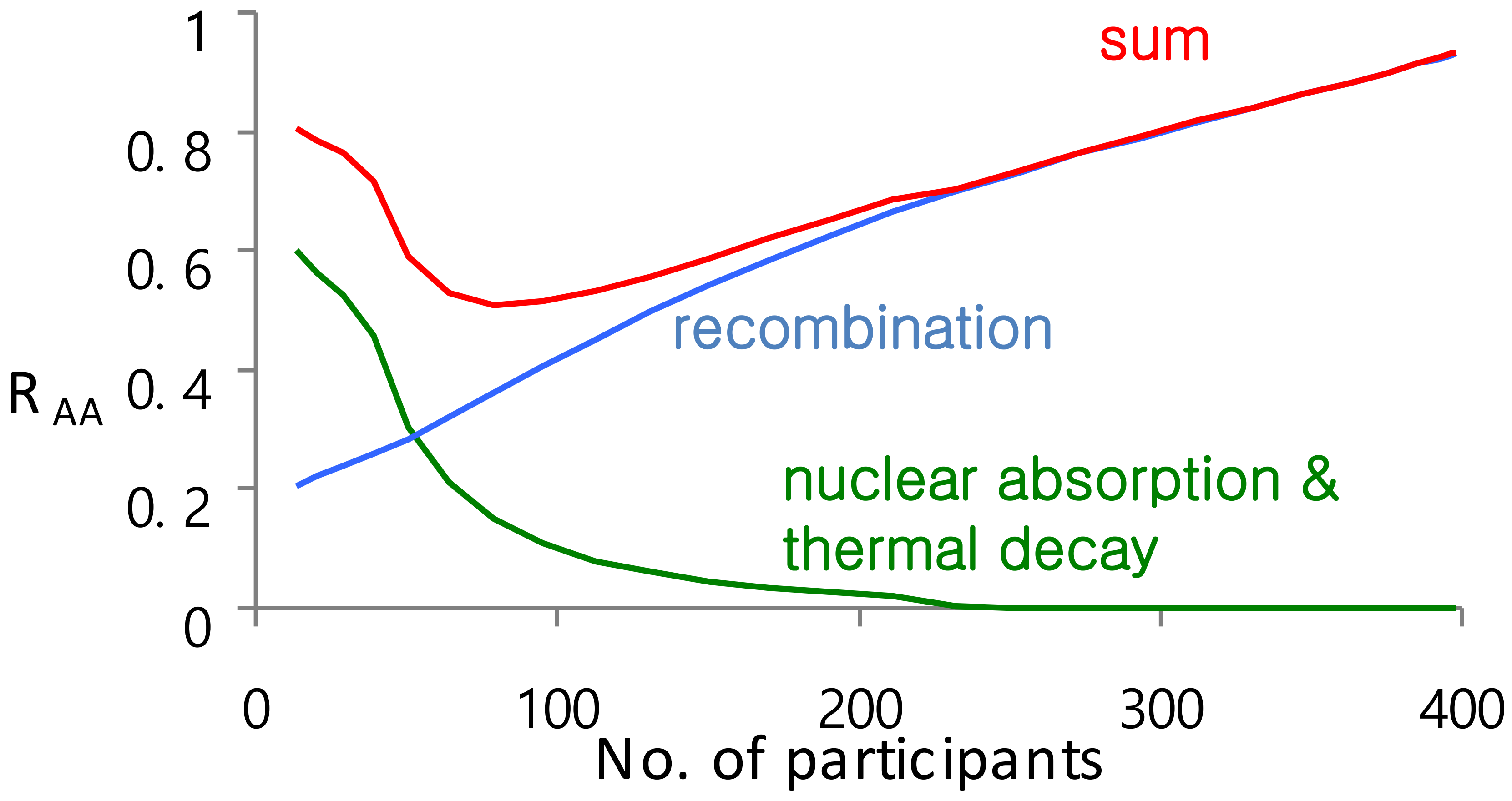
$d\sigma_{J/\psi}^{pp}/dy$= 0.774 μb to 6.4 μb

- By pQCD,

cc production cross section in p+p collision per rapidity

$d\sigma_{cc}^{pp}/dy$= 63.7 μb to 639 μb

Pb+Pb in LHC at $\sqrt{s_{NN}}$=5.5 TeV



Summary

- R_{AA} of J/ψ near midrapidity in Au+Au collision at $\sqrt{s_{NN}}$=200 GeV is well reproduced with almost no free parameter.
- Something new different from other models are followings:

1. It is assumed that the sudden drop of R_{AA} around N_{part}=190 is caused by that the maximum temperature of the fireball begins to be over the melting temperature of J/ψ there.
2. Thermal masses of partons extracted from LQCD are used to obtain thermal quantities of expanding fireball and to calculate dissociation cross sections of charmonia
3. From this, g is determined, because the screening mass is assumed to be gT.

- The same method was applied to Cu+Cu collision at the same energy, and the result is not bad.
- With some modified parameters, R_{AA} of J/ψ in LHC was calculated. Different from RHIC, recombination effect is dominant, because most charmonia produced at initial stage are melt and much larger number of charm quark are produced in LHC.

- The future plan is to reproduce or predict

1. R_{AA} at forward rapidity
2. The dependence of R_{AA} on transverse momentum of J/ψ
3. R_{AA} of heavier system such as Upsilon
4. …