What have we learnt from quarkonia production in relativsitic heavy ion collisions?

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- Introduction
- In-medium properties of quarkonia
- Quarkonia production in HIC
- Nuclear modification factor for charmonia
- Nuclear modification factor for bottomonia
- Comparison of theoretical approaches
- Hot medium effects in p+Pb
- Summary

Support by Department of Energy and The Welch Foundation

J/ψ suppression by quark-gluon plasma formation

Matui & Satz, PLB 178, 416 (1986), most cited paper in RHIC (2774 citations in inSpire)

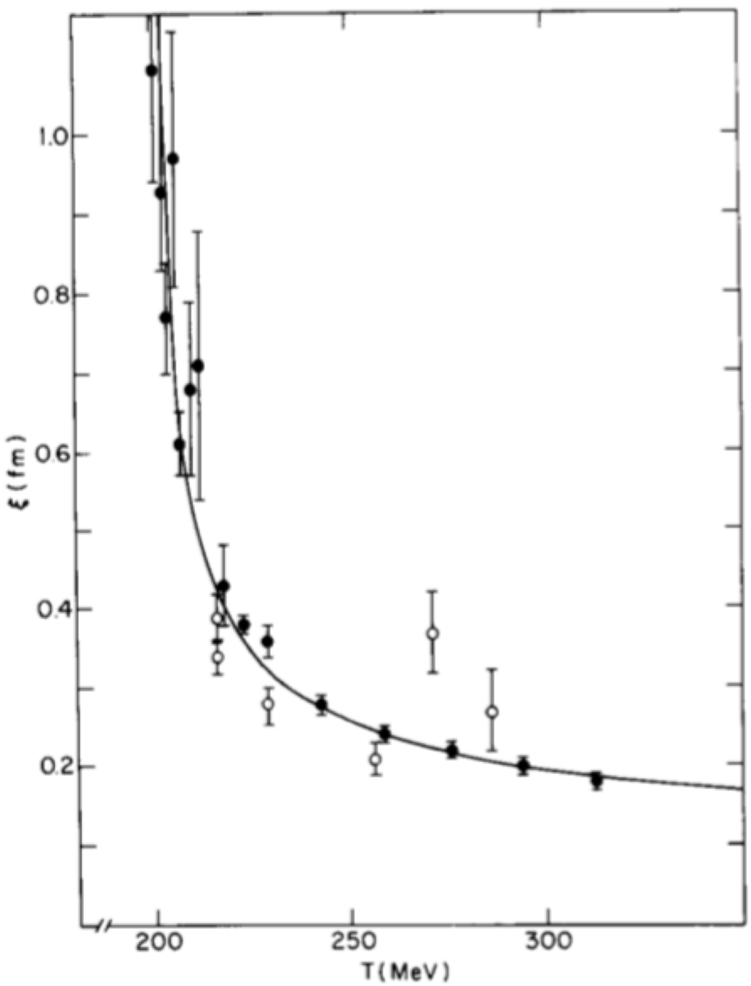


Fig. 1. Temperature dependence of the correlation length, as obtained in SU(2) gauge theory (solid dots, from ref. [5]) and in SU(3) gauge theory (open circles, from ref. [6]); here $T_c = 200$ MeV was used to fix the scale.

- Correlation of Polyakov loops in lattice gauge theory at finite temperature

$$\Gamma(r,T) \sim \exp\left[-\frac{r}{\xi(T)}\right]$$

- Expect to lead to Debye screening of gluonic interaction

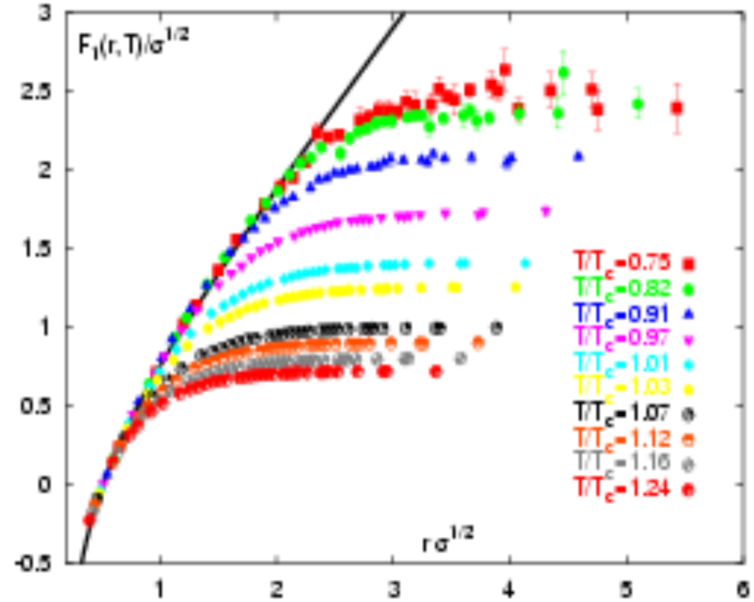
$$V(r,T) \sim -\left(\frac{\alpha_s}{r}\right)\exp\left[-\frac{r}{r_D(T)}\right]$$

- Dissociation of charmonia takes place if $r_D(T)$ or $\xi(T)$is sufficiently small.

- Melting of charmonia in QGP and thus their suppressed production in HIC.

Quarkonia in QGP

Free energy F for a pair of $Q\bar{Q}$ from LQCD
[Kacmareck, EJP 61, 811 (2009)]



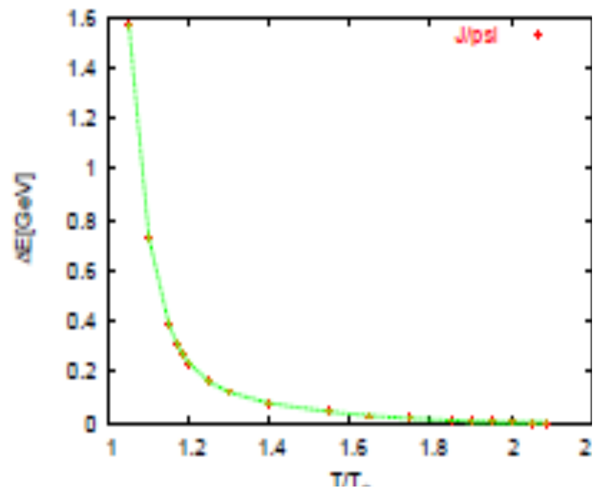
Two limits of the potential:

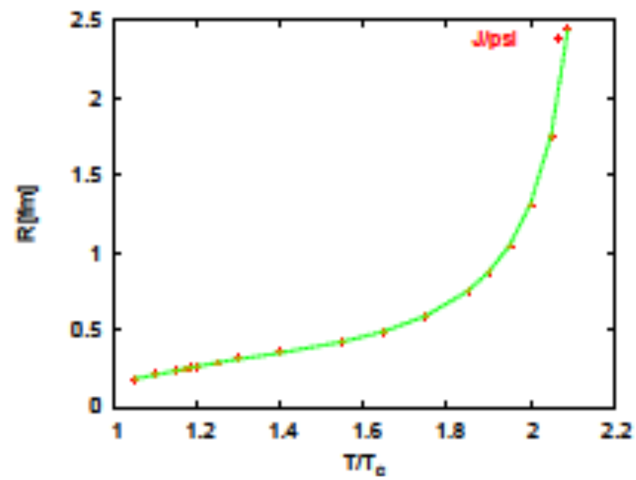
$$V(r,T) = F$$

$$\text{or } V(r,T) = U = F + TS$$

Schroedinger equation at finite T:

binding energy ε(T)
radius R(T)





Dissociation temperature:

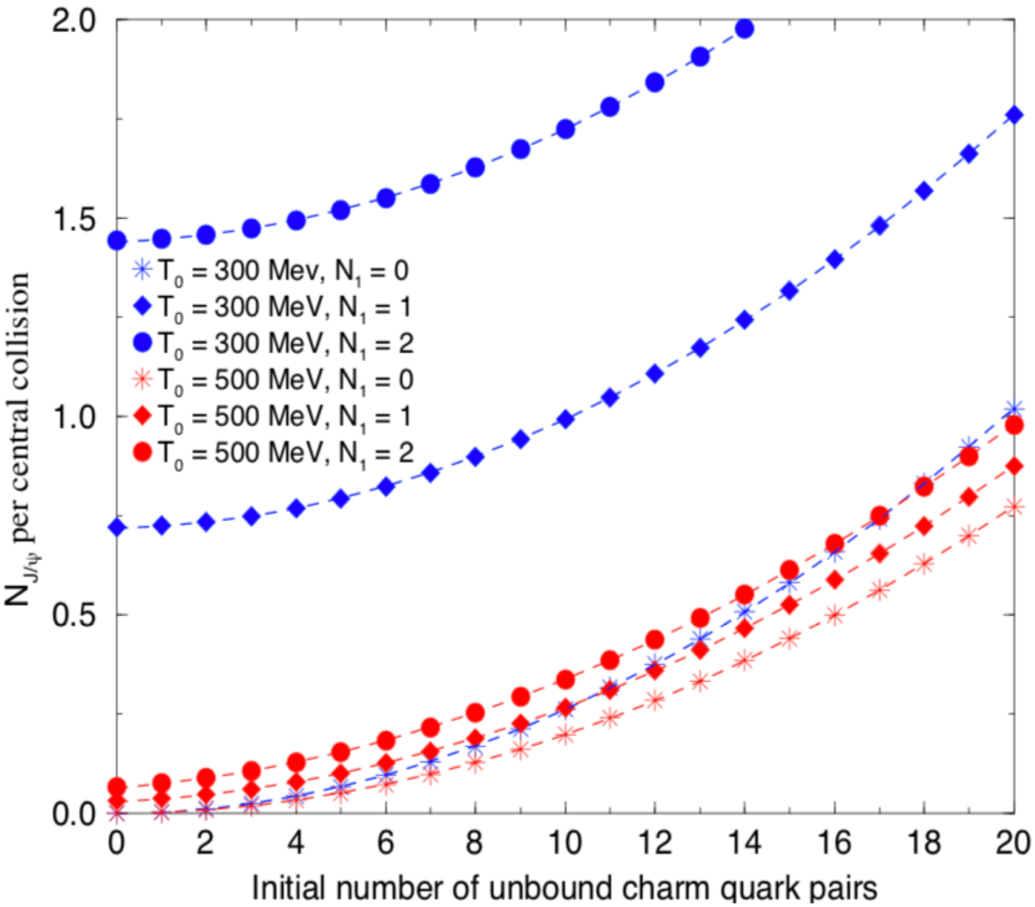
$\varepsilon(T_D) \rightarrow 0$, $R(T_D) \rightarrow \infty$

For V=U (Satz et al.)

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Charmonium regeneration from QGP

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_{\mathrm{F}} N_c \, \rho_{\bar{c}} - \lambda_{\mathrm{D}} N_{J/\psi} \, \rho_g$$



Thews, Shroedter & Rafelski,
PRC 63, 054905 (2001)

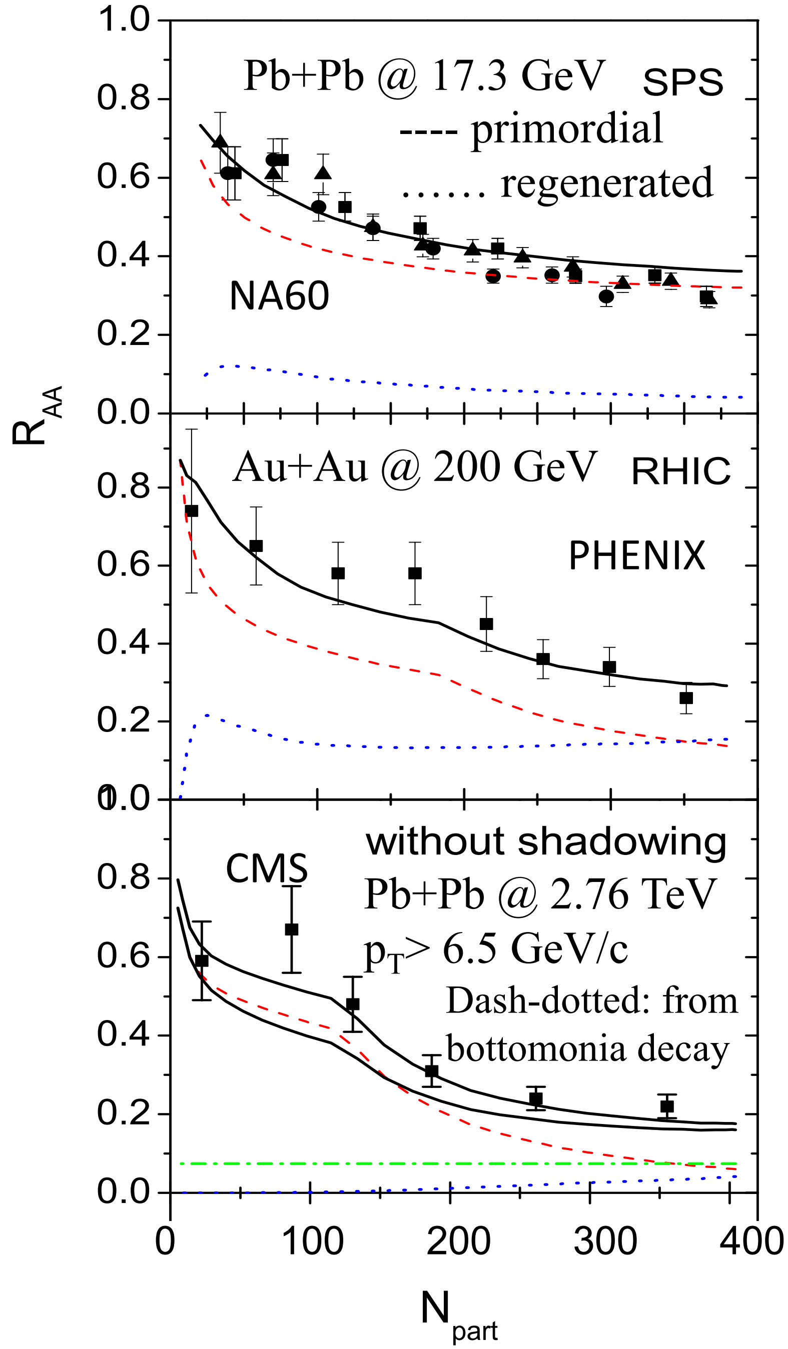
Central collisions at RHIC
T_0: Initial temperature
N_1: Initial J/ψ number

Formation rate: $\lambda_F = \langle \sigma_{cc \to J/\psi g} v \rangle$
Destruction rate: $\lambda_F = \langle \sigma_{J/\psi g \to cc} v \rangle$

- Charmonia enhancement when initial charm pairs are large.
- Sufficiently large cross section can lead to chemical equilibration and thus the statistical model description of Andronic, Braun-Munzinger and Stachel [NPA 789, 334 (2007)].

Nuclear modification factor for J/ψ

Song, Han & Ko, PRC 84, 034907 (2011)



	SPS	RHIC	LHC	LHC p_T >6.5 GeV
production (μb)				
$d\sigma^{pp}_{J/\psi}/dy$	0.05	0.774	4.0	
$d\sigma^{pp}_{c\bar{c}}/dy$	5.7	119	615	
feed-down (%)				
f_{χ_c}	25	32	26.4	23.5
$f_{\psi'(2S)}$	8	9.6	5.6	5
f_b			11	21
nuclear absorp.				
$\sigma_{\rm abs}$ (mb)	4.18	2.8	0 or 2.8	

- Most J/ψ are survivors from initially produced
- Kink in R_{AA} is due to the onset of initial temperature above the J/ψ dissociation temperature in QGP
- Inclusion of shadowing reduces slightly R_{AA}

Screened Cornell potential for heavy quark and antiquark in QGP

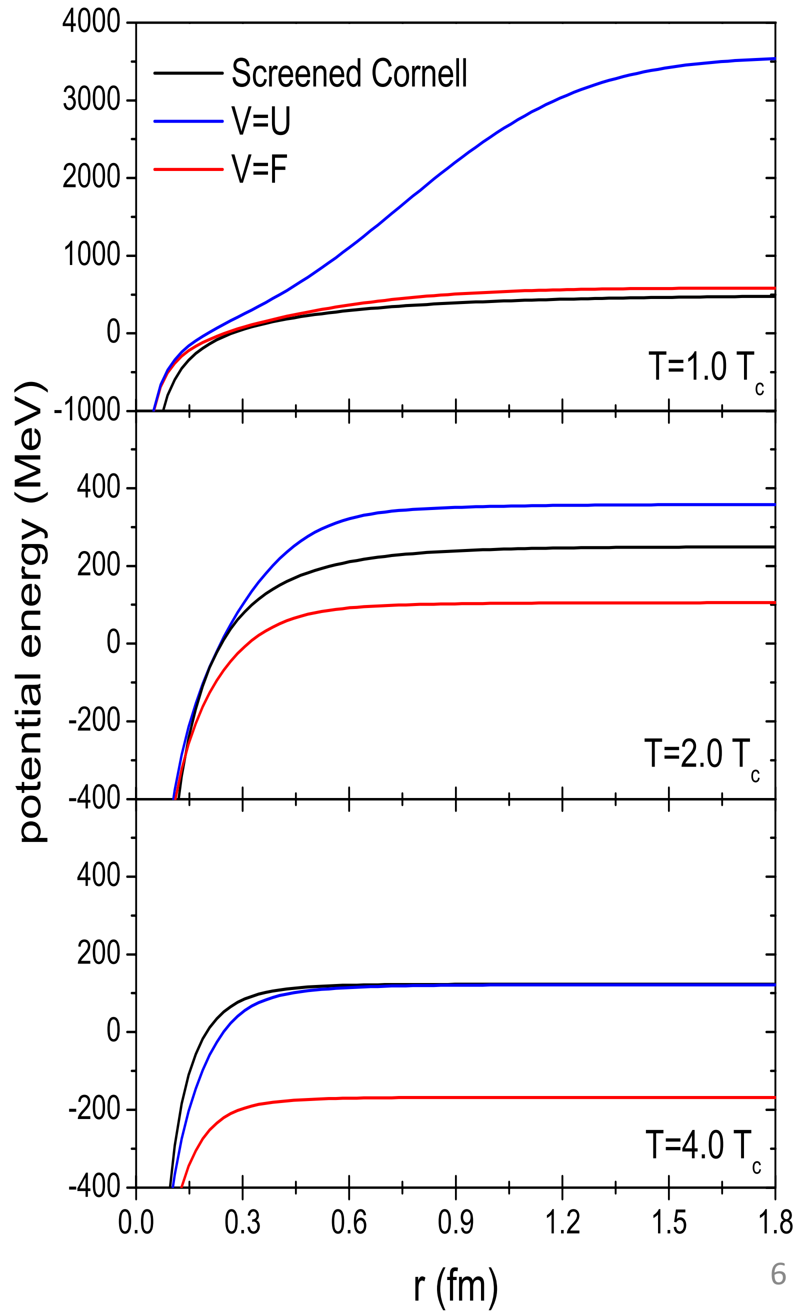
- Screened Cornell potential between charm and anticharm quarks

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

with string tension $\sigma = 0.192\ \mathrm{GeV}^2$ and screening mass

$$\mu(T) = \sqrt{\frac{N_c}{3} + \frac{N_f}{6}}\, gT$$

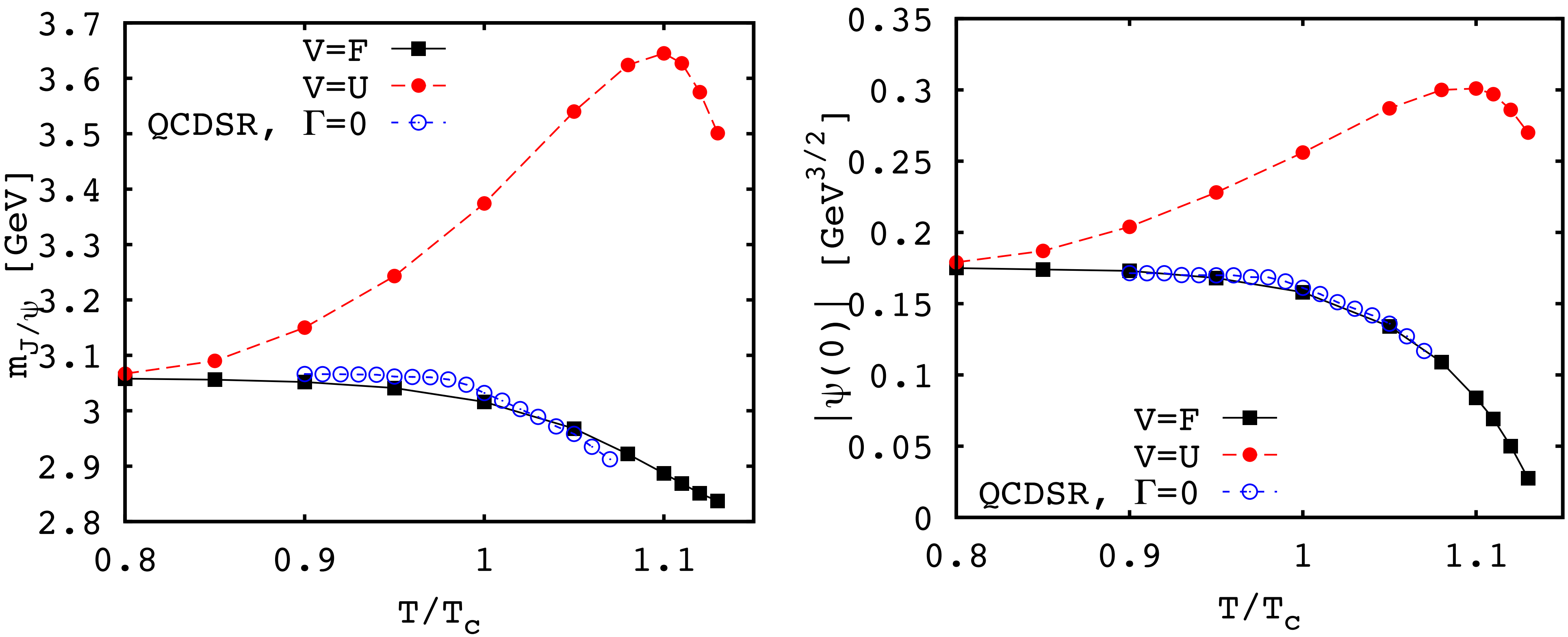
- Its strength is between the internal energy (U) and free energy (F) of heavy quark and antiquark from LQCD; similar to F at T_c and to U at $4T_c$ (T_c=170 MeV).



QCD sum rule study of J/ψ

Lee, Morita, Song & Ko, PRD 89, 094015 (2014)

$$\Pi_{\mu\nu}(q) = i \int d^4x \, e^{iqx} \langle T[\bar{c}(x)\gamma_\mu c(x)\bar{c}(0)\gamma_\nu c(0)]\rangle.$$



- Results favor free energy as the potential between charm and anticharm quarks near T_c.

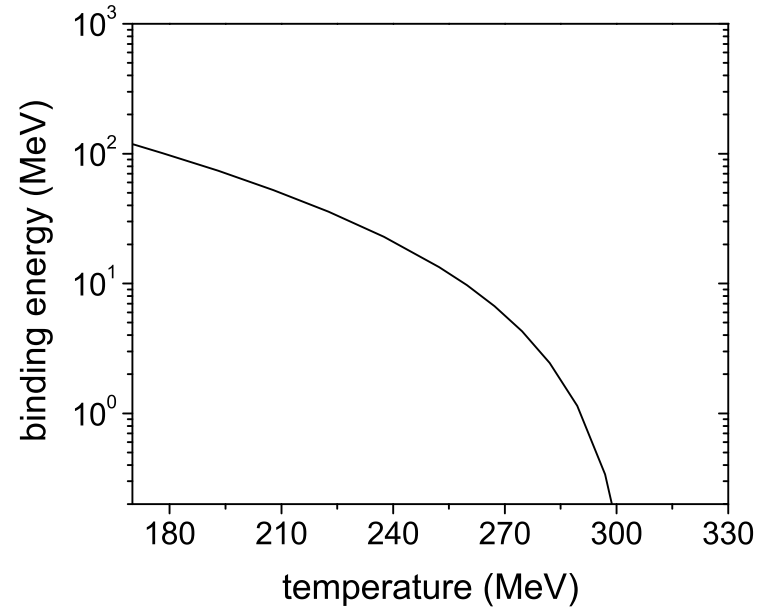
Thermal properties of charmonia

- Binding energy

$$\varepsilon_0 = 2m_c + \frac{\sigma}{\mu(T)} - E$$

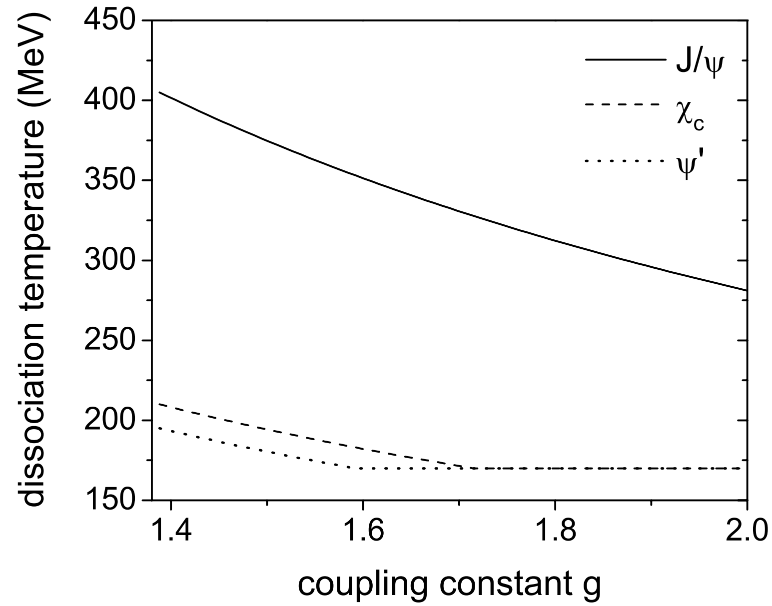
Charm quark mass m_c=1.32 GeV

E: eigenvalues of Cornell potential

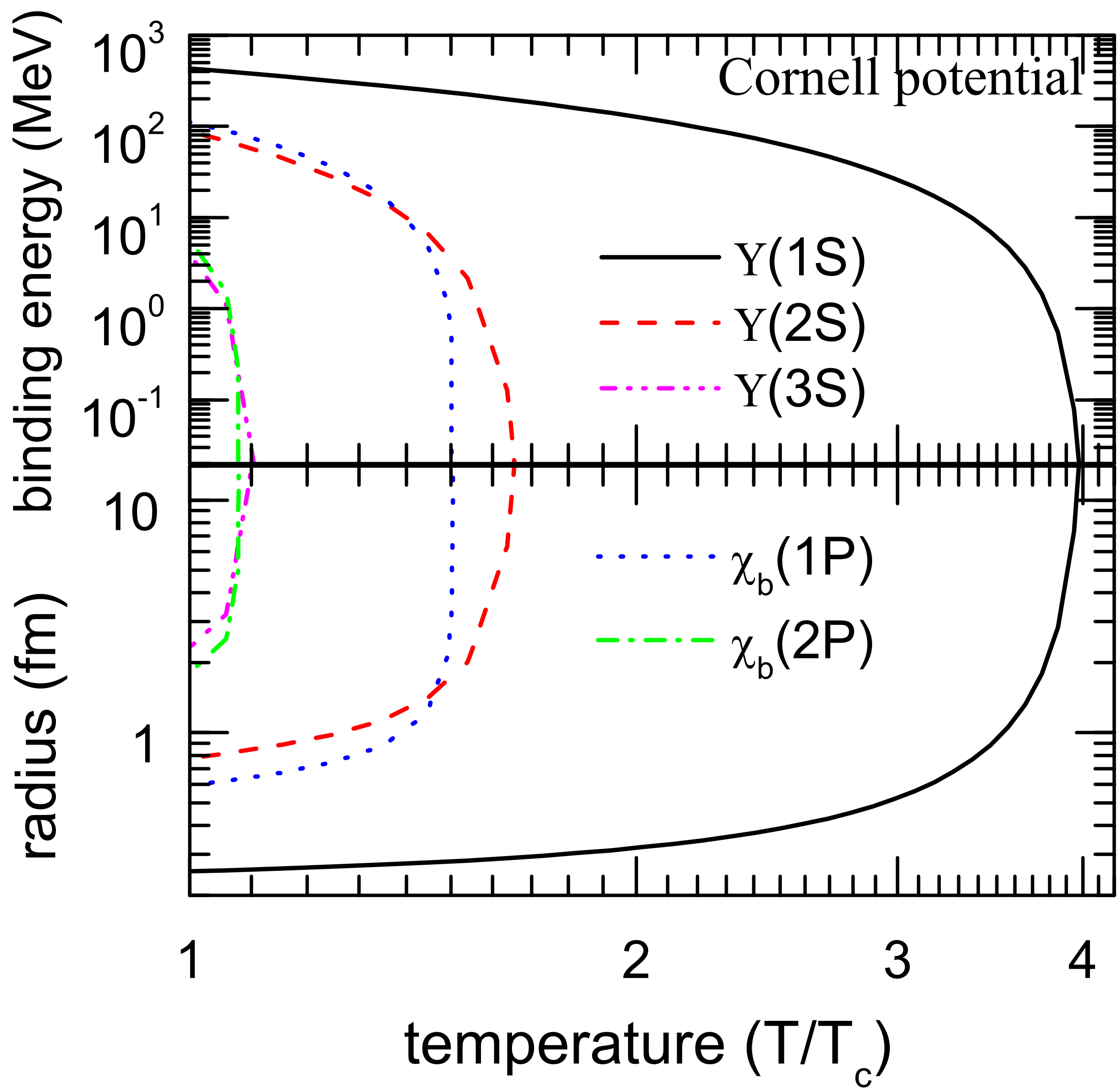


- Dissociation temperature T_D: corresponding to ε_0=0

For g=1.87, T_D~300 MeV for J/ψ and ~T_D=175 MeV for ψ' and χ_c



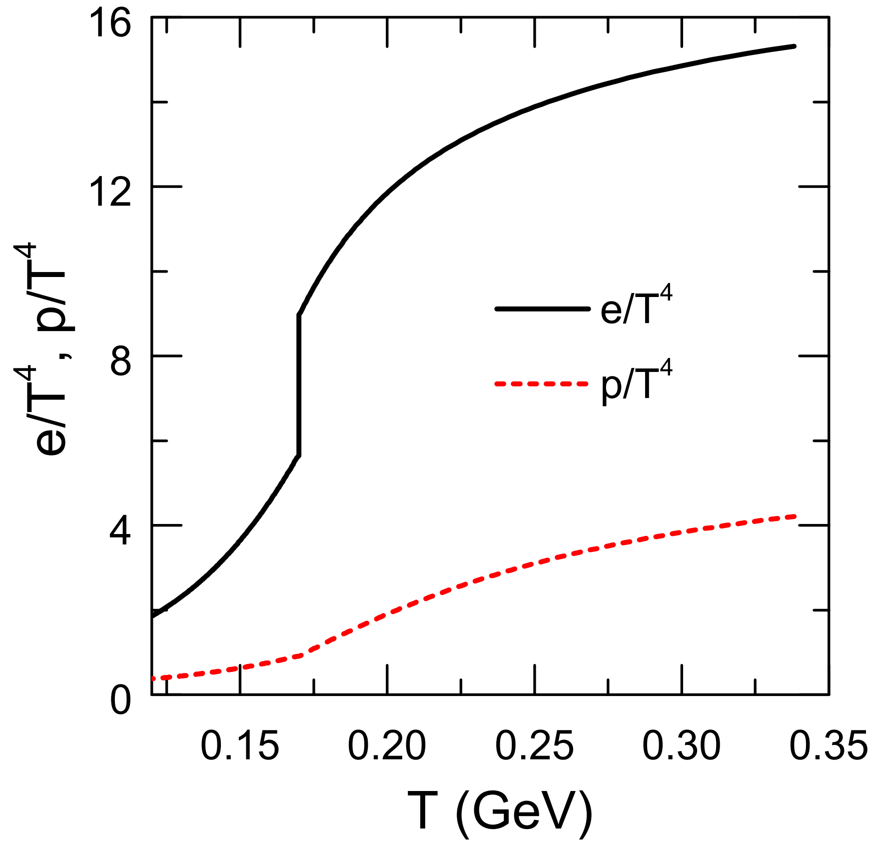
Thermal properties of bottomonia



State	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon'(2S)$	$\chi_b'(2P)$	$\Upsilon''(3S)$
Dissociation temp (T_c)	4	1.51	1.67	1.09	1.12

Quasiparticle model for QGP

P. Levai and U. Heinz, PRC , 1879 (1998)



$$p(T) = \sum_{i=g,q,\bar{q}} \frac{g_i}{6\pi^2} \int_0^\infty dk f_i(T) \frac{k^4}{E_i} - B(T)$$

$$e(T) = \sum_{i=g,q,\bar{q}} \frac{g_i}{2\pi^2} \int_0^\infty dk k^2 f_i(T) E_i + B(T)$$

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

$$m_q^2 = \frac{g^2(T)T^2}{3}$$

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

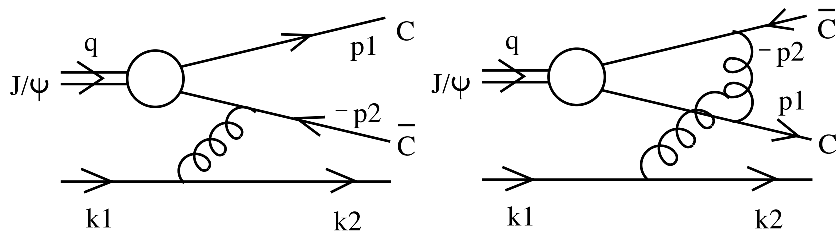
$$F(T,T_c,\Lambda) = \frac{18}{18.4e^{-(T/T_c)^2/2} + 1} \frac{T}{T_c} \frac{T_c}{\Lambda}$$

- Resulting EOS is similar to that from LQCD by the hot QCD collaboration, and the difference is smaller than that between the hot QCD and Wuppertal-Budapest Collaborations

Thermal decay widths of quarkonia

Song, Park & Lee, PRC 81, 034914 (10)

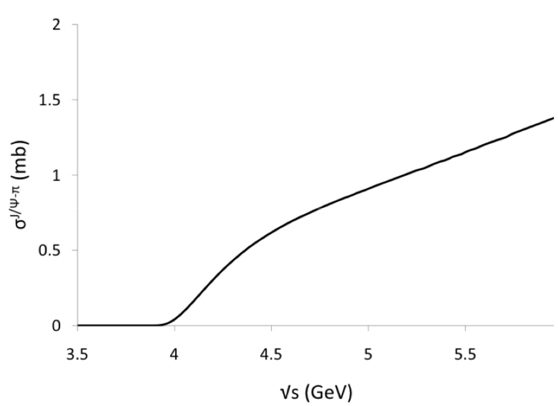
- Dissociation by partons (NLO pQCD)



$$\left|\overline{M}\right|^2 = \frac{4}{3} g^4 m_c^2 m_{J/\psi} \left|\frac{\partial \psi(p)}{\partial p}\right|^2 \left\{ -\frac{1}{2} + \frac{(k_1^0)^2 + (k_2^0)^2}{2k_1 \cdot k_2} \right\}$$

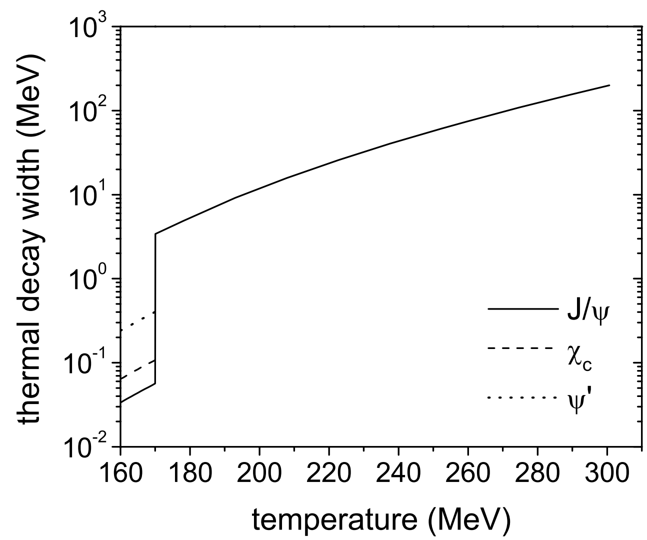
- Dissociation by hadrons

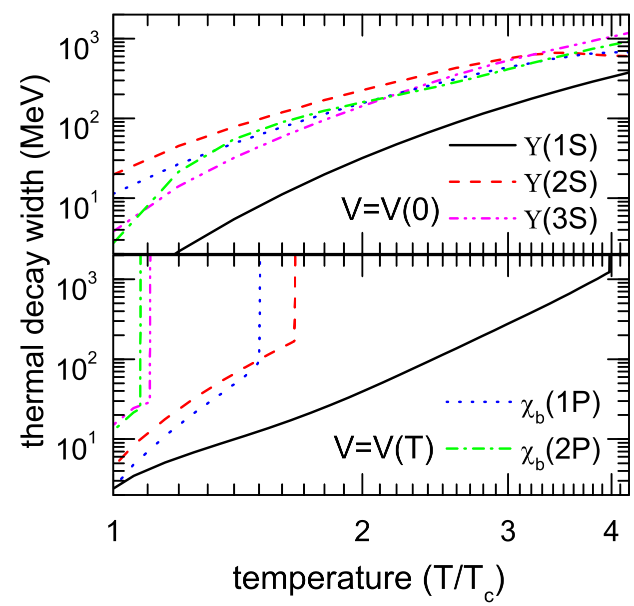
$$\sigma(s) = \sum_i \int dx n_i(x, Q^2) \sigma_i(xs, Q^2)$$



- Thermal dissociation width

$$\Gamma(T) = \sum_i \int \frac{d^3k}{(2\pi)^3} v_{rel}(k) n_i(k,T) \sigma_i^{diss}(k,T)$$





Directly produced J/ψ

Song, Park & Lee, PRC 81, 034914 (10)

- Number of initially produced

$$N^{AA}_{J/\psi} = \sigma^{NN}_{J/\psi} A^2 T_{AA}(\vec{b})$$

  - $\sigma^{NN}_{J/\psi}$: J/ψ production cross section in NN collision; ~ 0.774 μb at $s^{1/2}$= 200 GeV
  - Overlap function

$$T_{AA}(\vec{b}) = \int d^2\vec{s}\, T_A(\vec{s}) T_A(\vec{b}-\vec{s})$$

  - Thickness function

$$T_A(\vec{s}) = \int_{-\infty}^{\infty} dz \rho_A(\vec{s},z)$$

  - Normalized density distribution

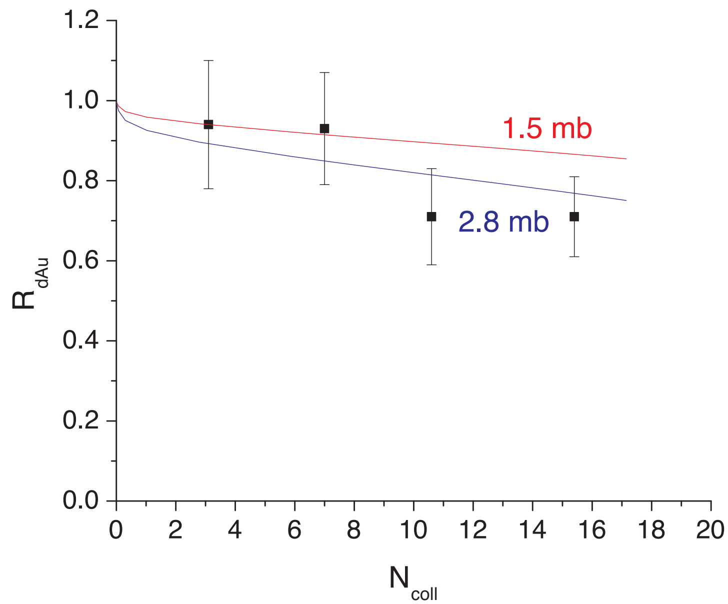
$$\rho(r) = \frac{\rho_0}{1+e^{(r-r_0)/c}}$$

r_0= 6.38 fm, c=0.535 fm for Au

- Nuclear absorption

  - Survival probability

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



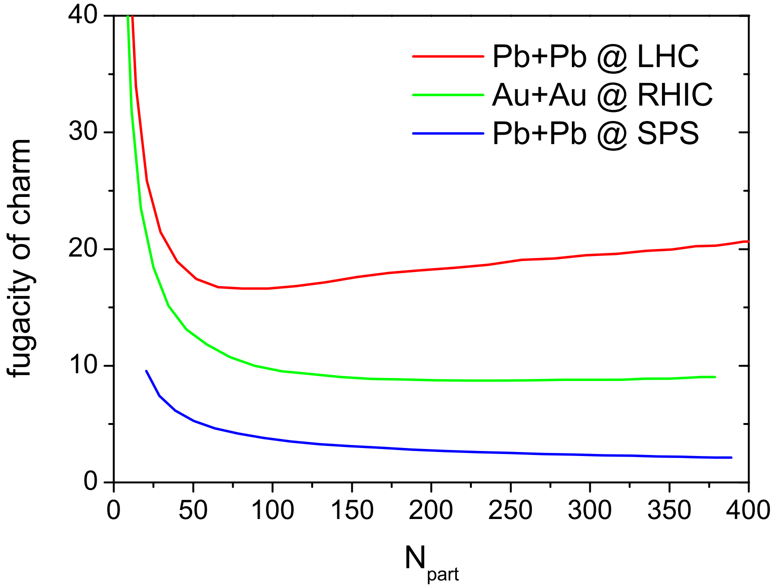
Regenerated J/ψ

Rate equation for J/ψ production $\frac{dN_i}{d\tau} = -\Gamma_i\left(N_i - N_i^{eq}\right), \quad N_i^{eq} = \gamma^2 R n_i^{GC} V$

- Charm fugacity is determined by

$$N_{c\bar{c}}^{AA} = \left[\frac{1}{2}\gamma n_o \frac{I_1(\gamma n_0 V)}{I_0(\gamma n_0 V)} + \gamma^2 n_h\right] V = \sigma_{c\bar{c}}^{NN} A^2 T_{AA}(\vec{b})$$

  - $\sigma_{c\bar{c}}^{NN}$: charm production cross section in NN collision; ~ 119 μb at $s^{1/2}$= 200 GeV

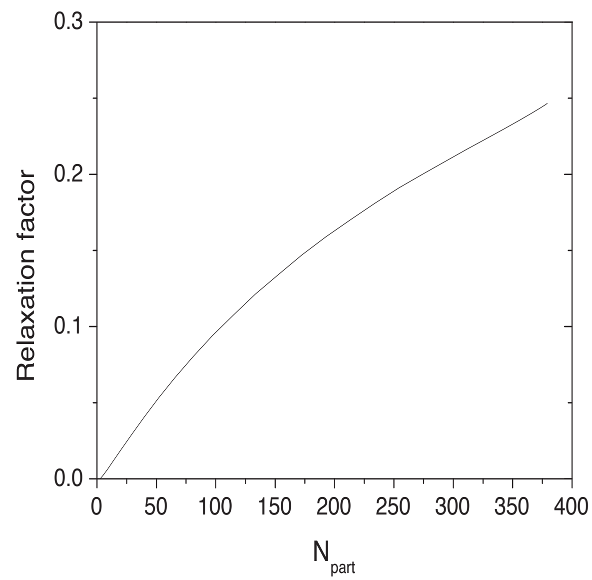


- Charm relaxation factor

$$R = 1 - \exp\left\{-\int_{\tau_0}^{\tau_{QGP}} d\tau \Gamma_c(T(\tau))\right\}$$

$$\Gamma(T) = \sum_i \int \frac{d^3k}{(2\pi)^3} v_{rel}(k) n_i(k,T) \times \sigma_i^{diss}(k,T)\left(1 - \vec{p}\cdot\vec{p}'/p^2\right)$$

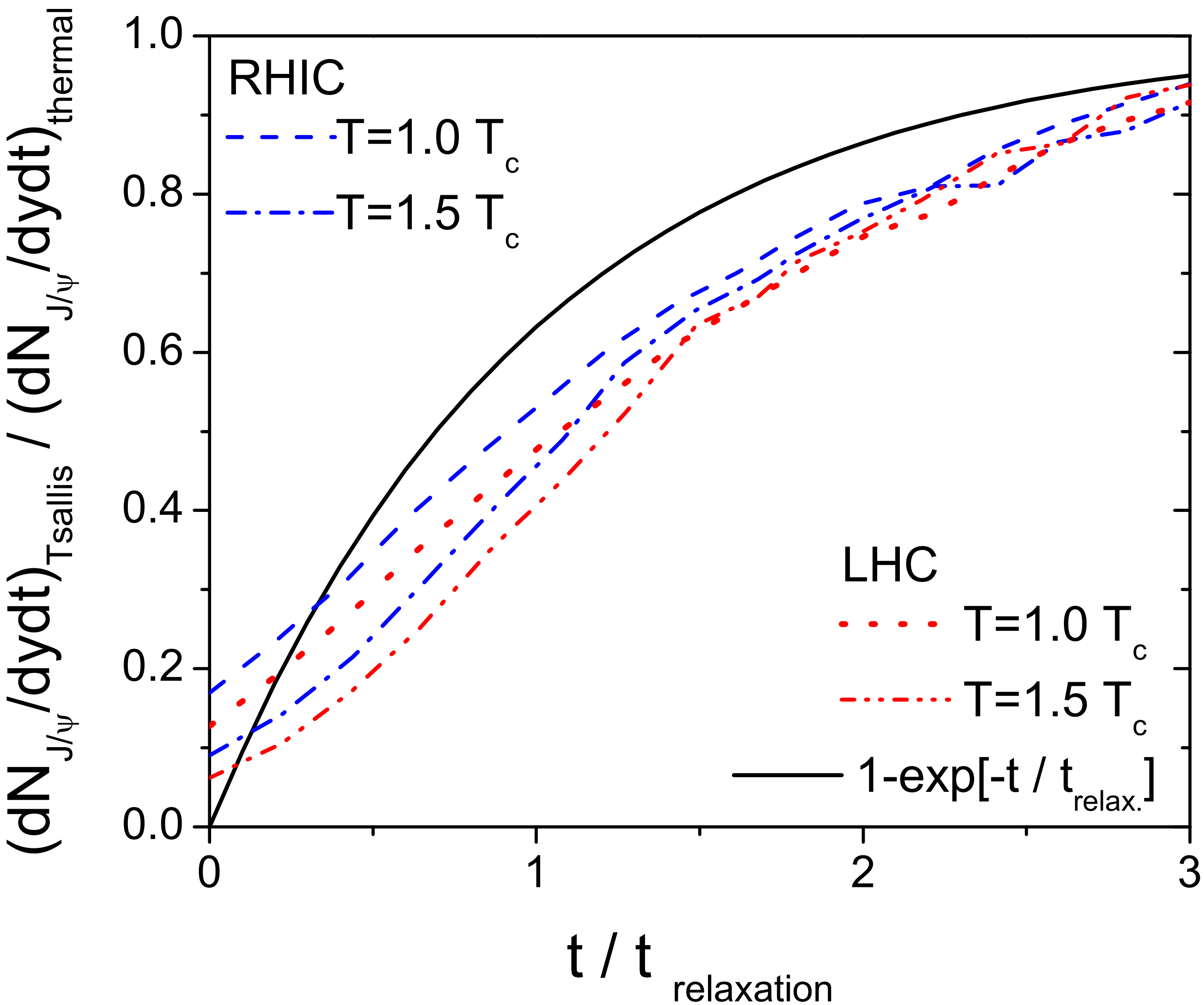
as J/ψ is more likely to be formed if charm quarks are in thermal equilibrium



Approximately reproduced by non-equilibrium charm quarks from parton cascade [PRC 85, 954905 (12)]

Nonequilibrium effects on J/Ψ production

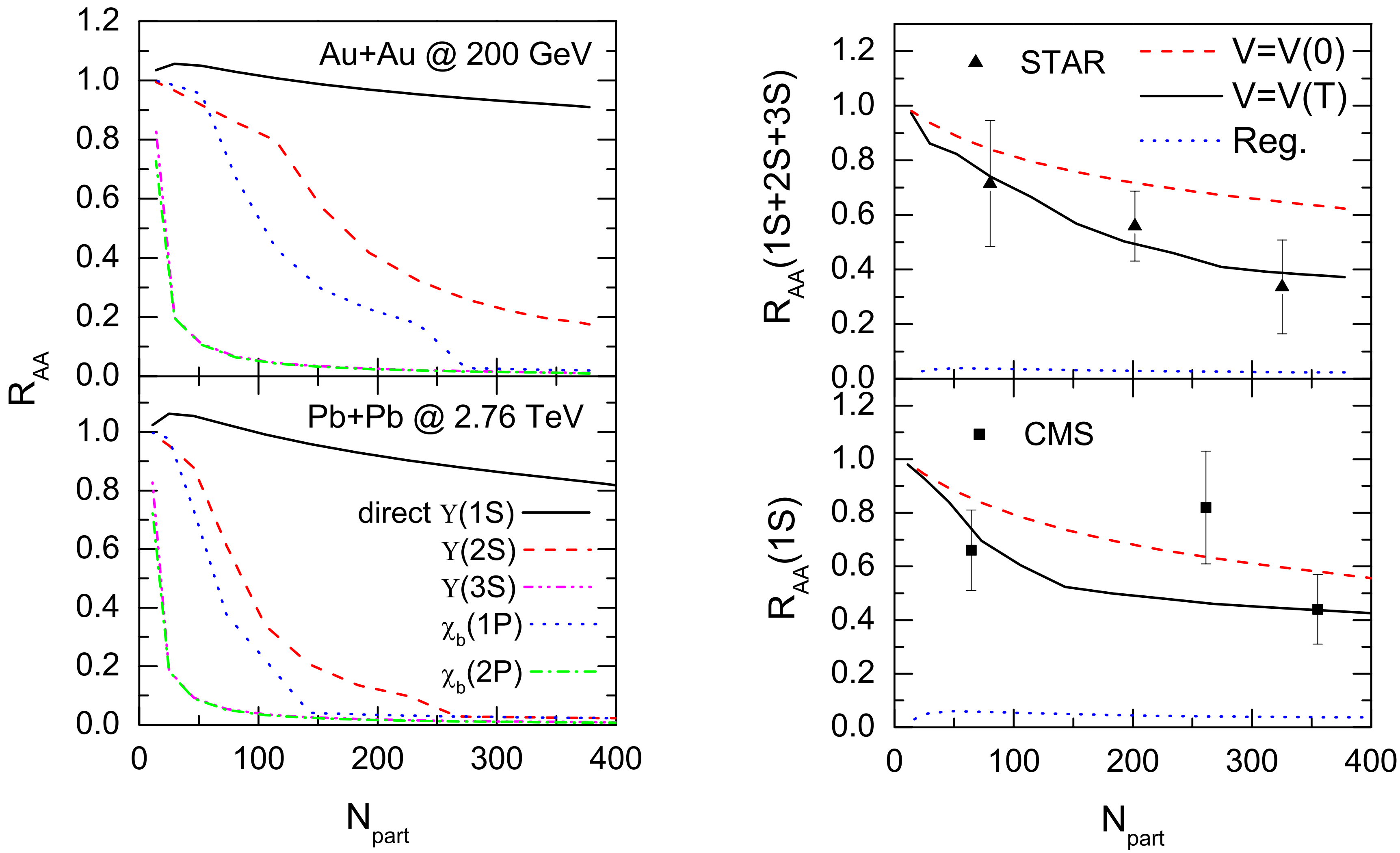
Song, Han & Ko, PRC 85, 054905 (2012)



- Nonequilibrium effects can be approximated by the relaxation factor

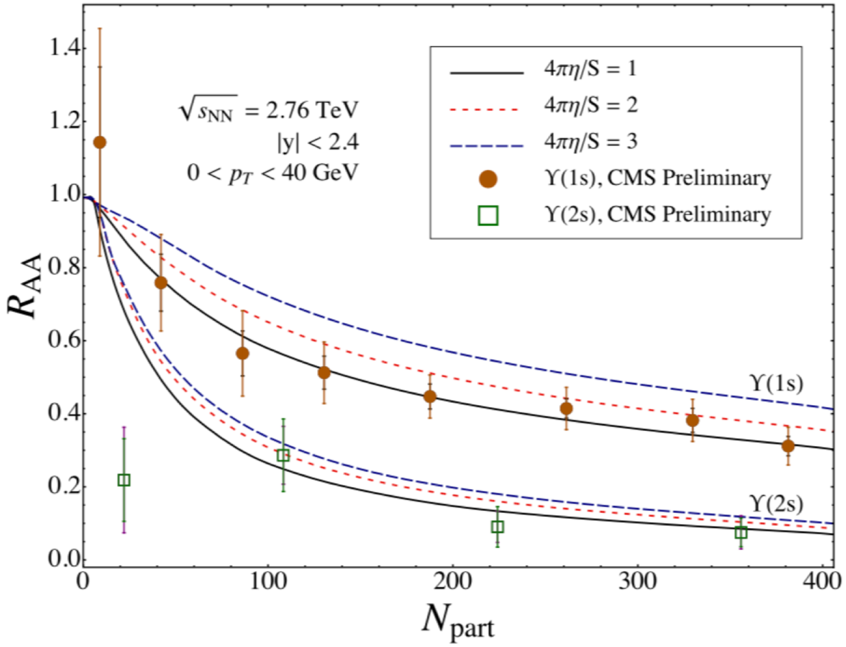
Nuclear modification factor for ϒ(1S)

Song, Han & Ko, PRC 85, 014902 (2012)



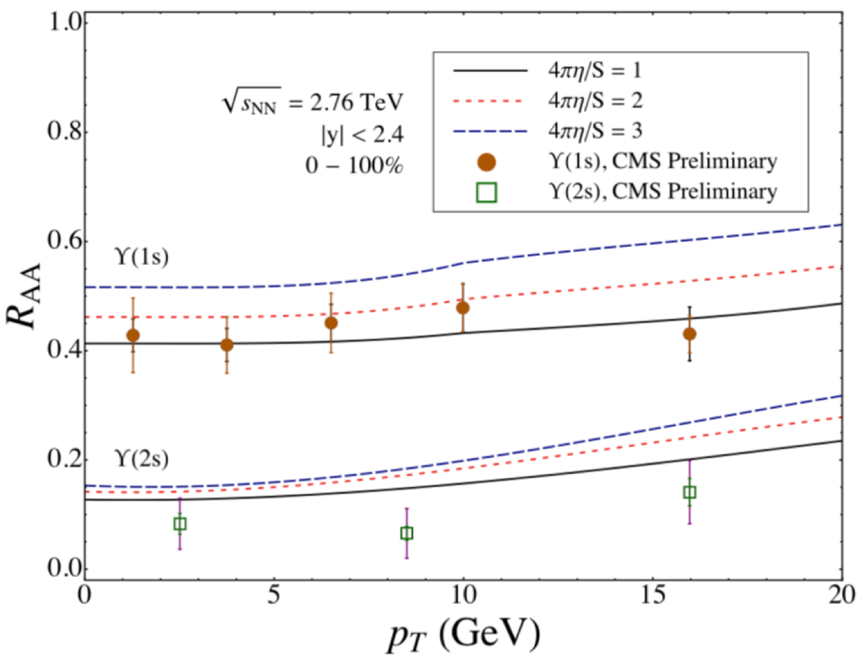
- Regeneration contribution is negligible
- Primordial excited bottomonia are largely dissociated
- Medium effects on bottomonia reduce R_{AA} of ϒ(1S)

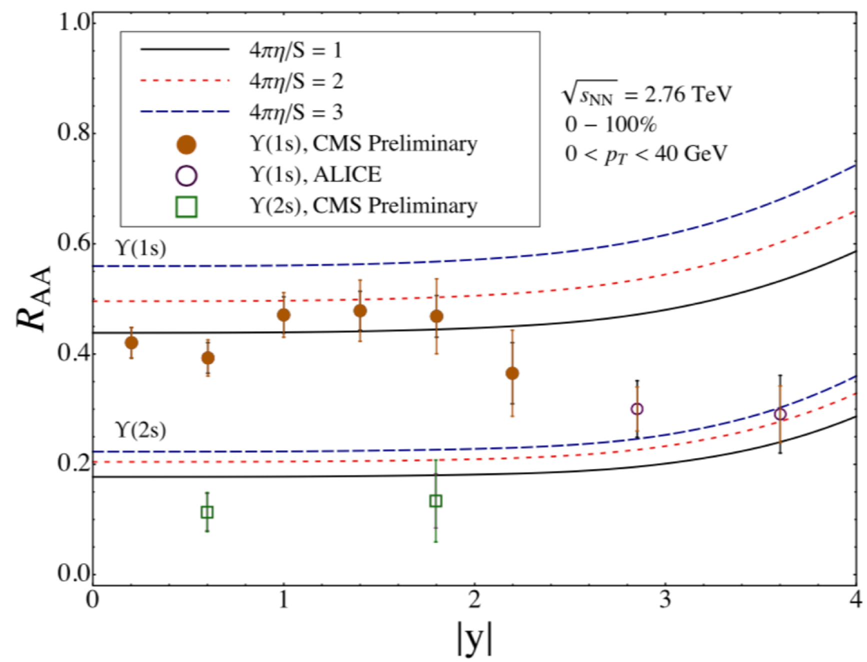
Bottomonia in anisotropic hydrodynamics



Strickland, PRC 92, 061901 (R) (2015)

- Potential: in-medium Cornell
- Dissociation: LO pQCD
- Dynamics: anisotropic hydro
- Sensitivity to η/s

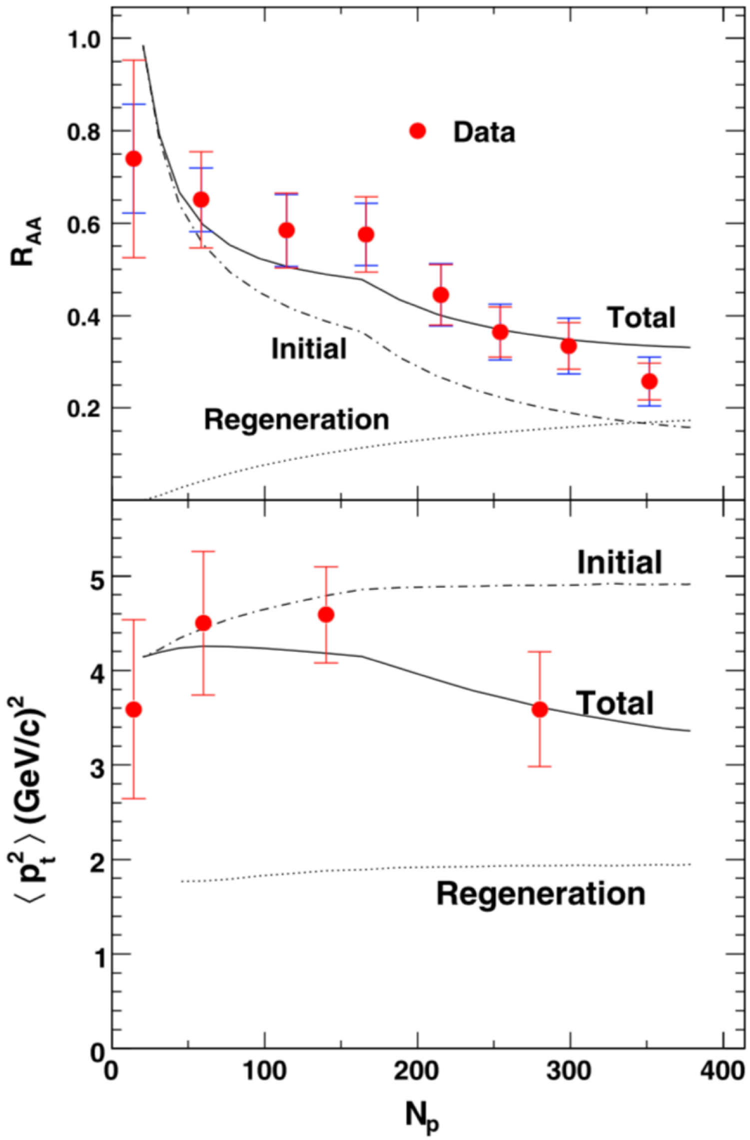


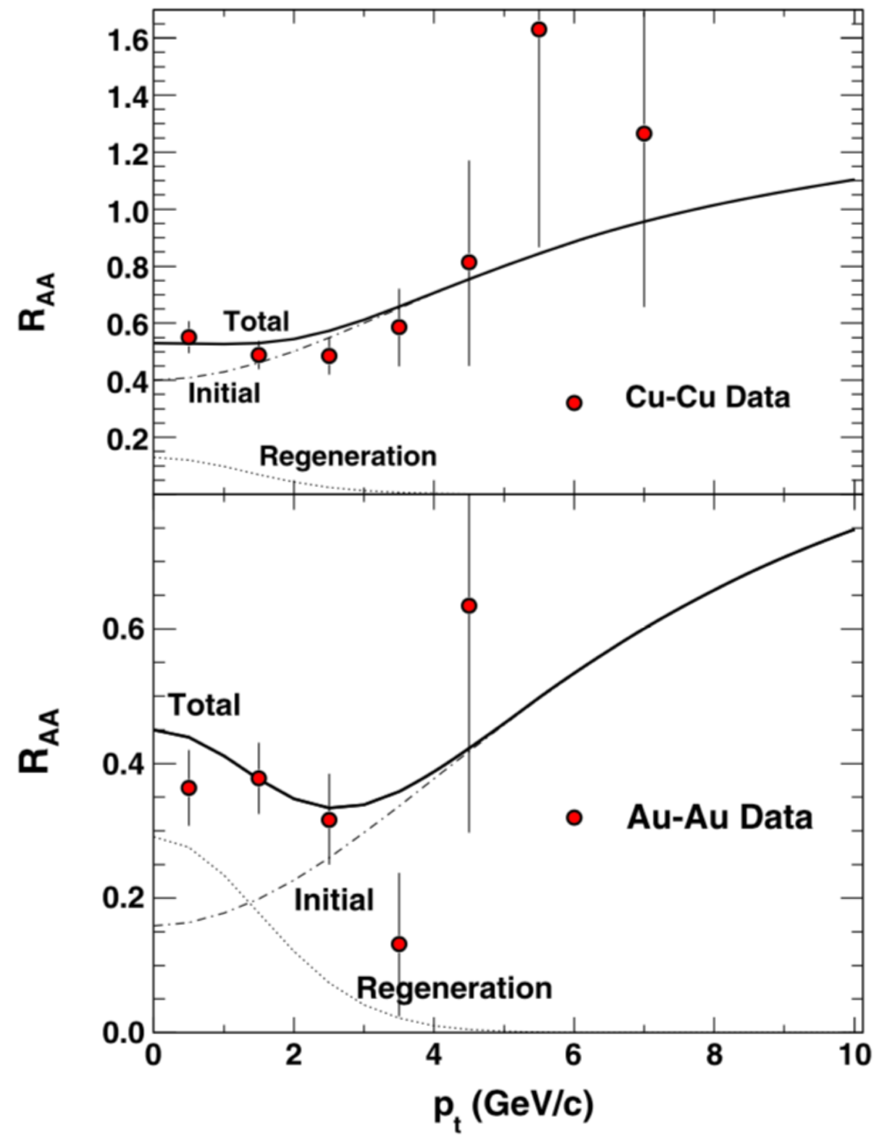


J/ψ production at RHIC by Tsinghua Group

- Dissociation temperature: $T_d = 1.92\ T_c$
- Dissociation cross section: vacuum gluo-dissociation
- Dynamics: ideal hydrodynamic

Liu, Qu, Xu & Zhuang,
PLB 678, 72 (2009)

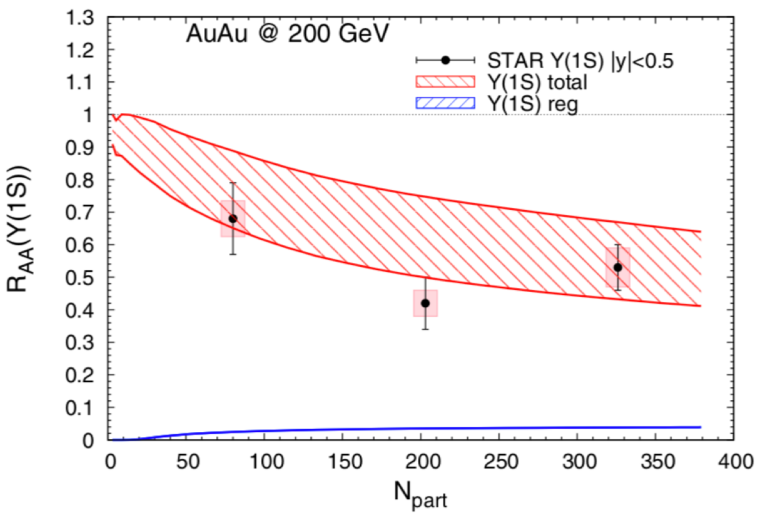


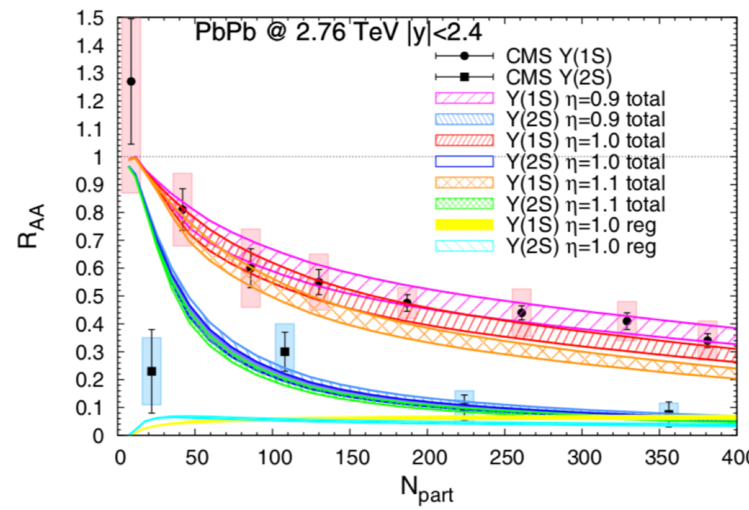


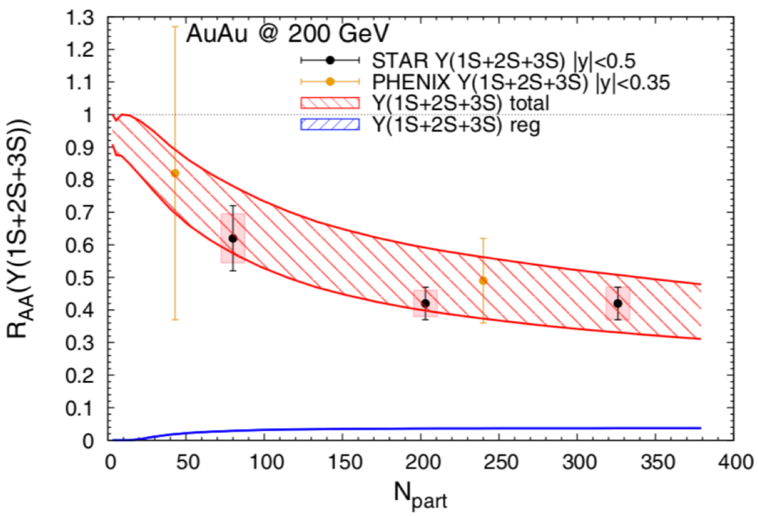
T-matrix approach to quarkonia and their production in HIC

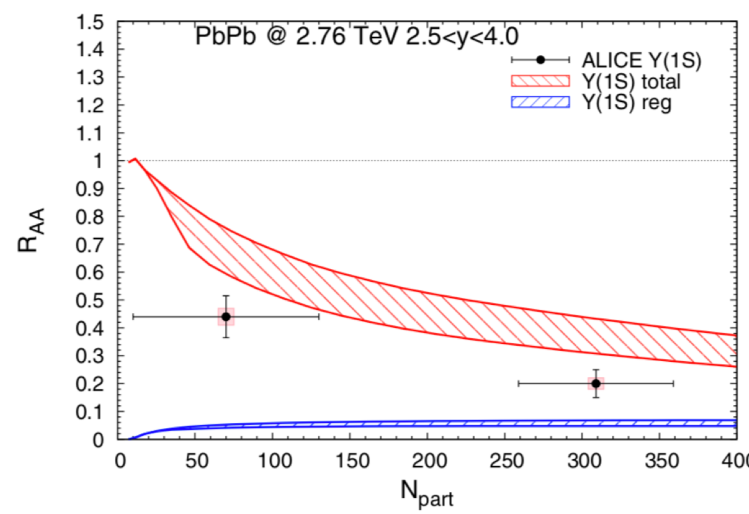
Du, He & Rapp, PRC 96, 054901 (2017)

- In-medium binding and dissociation rate using potential from T-matrix fit to lQCD spectral functions.
- Fireball dynamics with lQCD equation of state.

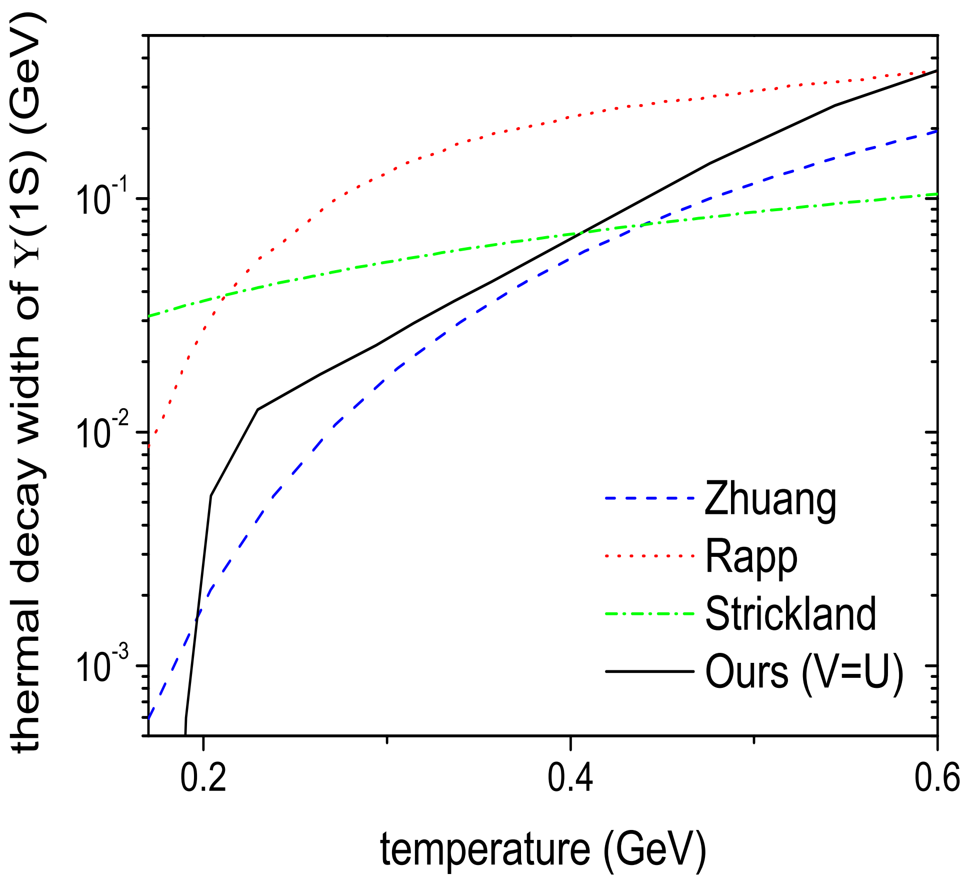








Thermal decay width of Υ(1S) in different models

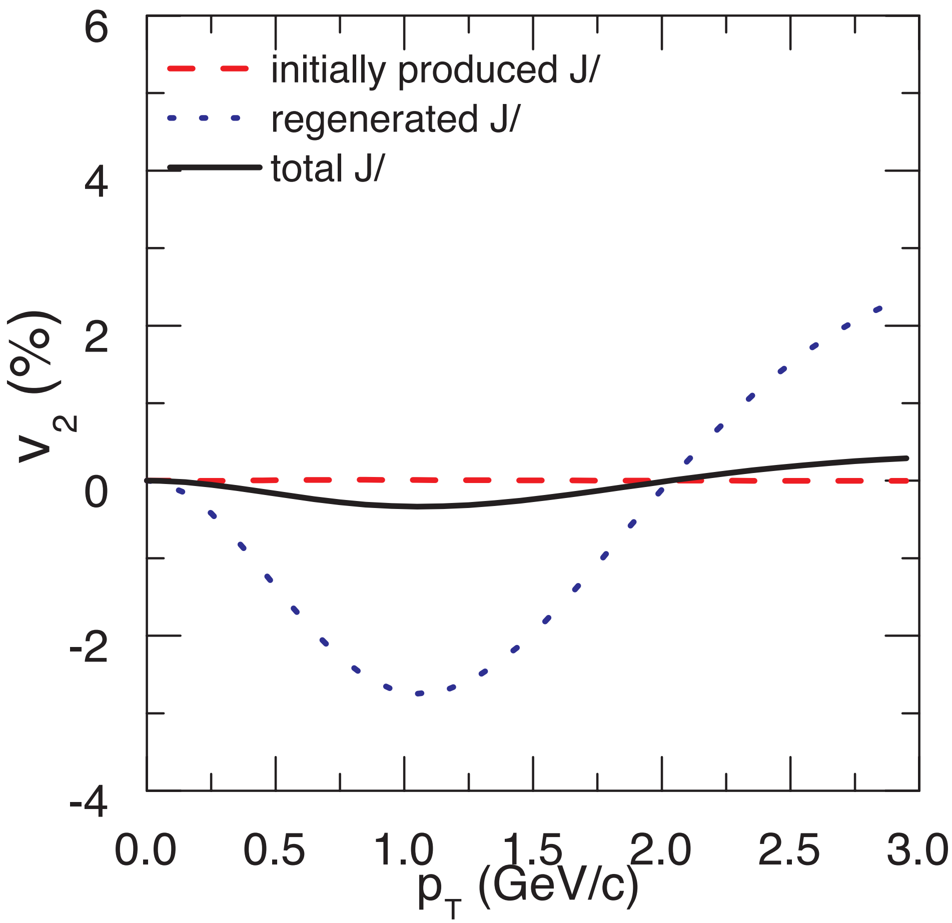


- Thermal decay width
  - Rapp: quasielastic scattering
  - Zhuang: OPE by Peskin
  - Strickland: LO pQCD
  - Song: NLO pQCD

- Very different thermal decay widths are used in different models

J/ψ elliptic flow

Song, Lee, Xu & Ko, PRC 83, 014914 (11)



$$v_2 = \frac{\int d\varphi \cos(2\varphi)(dN/dyd^2p_T)}{\int d\varphi (dN/dyd^2p_T)}$$

$$= \frac{\int dA_T \cos(2\varphi) I_2(p_T \sinh\rho/T) K_1(m_T \cosh\rho/T)}{\int dA_T I_0(p_T \sinh\rho/T) K_1(m_T \cosh\rho/T)}$$

$\rho=\tanh(v_T)$=transverse rapidity

Introducing viscous effect at freeze out T=125 MeV

$$\Delta v = (v_x - v_y)\exp[-Cp_T/n]$$

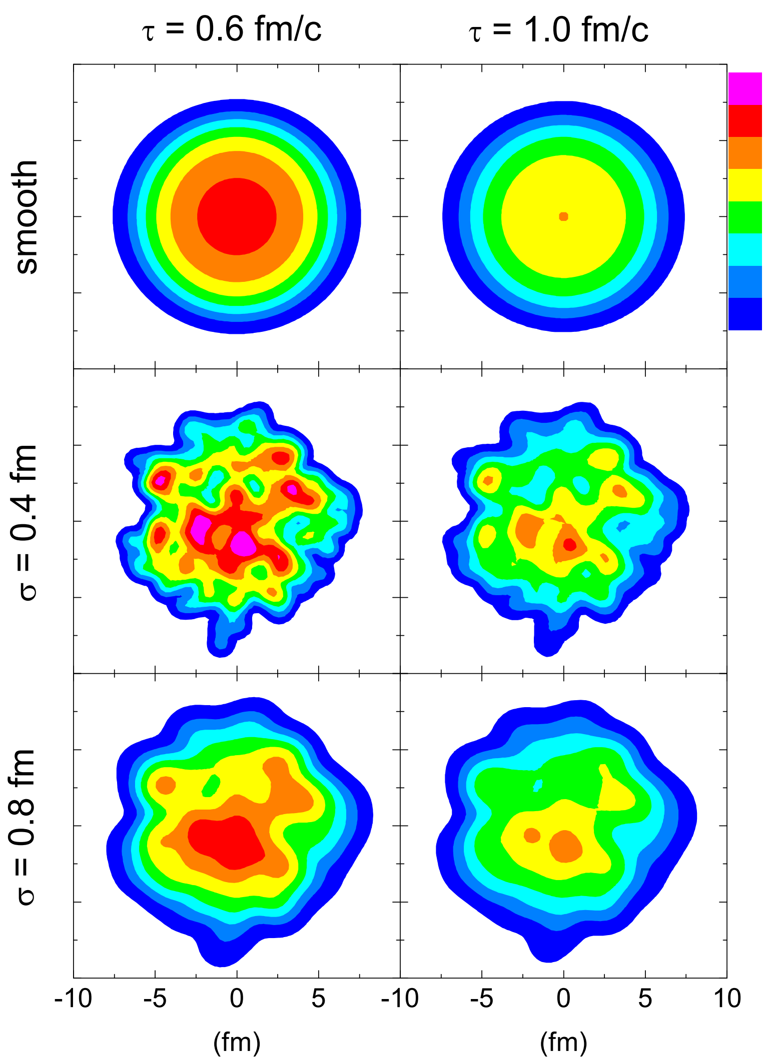
with C=1.14 GeV^{-1} and n= number of quarks in a hadron

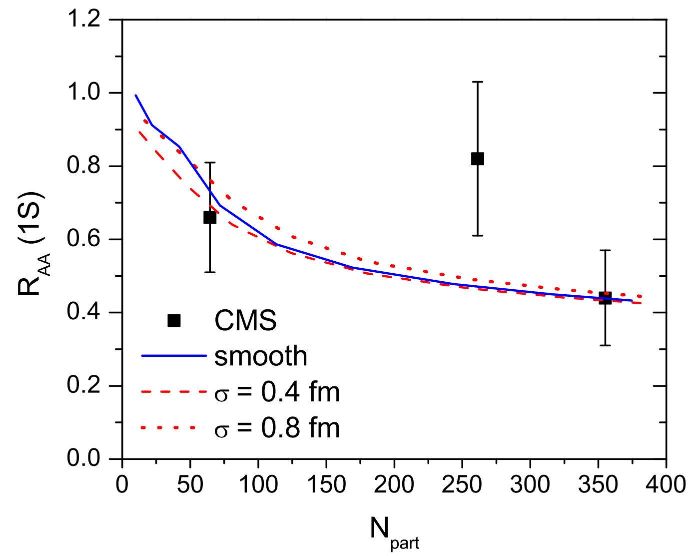
- Initially produced J/ψ have essentially vanishing v_2
- Regenerated J/ψ have large v_2
- Final J/ψ v_2 is small as most are initially produced

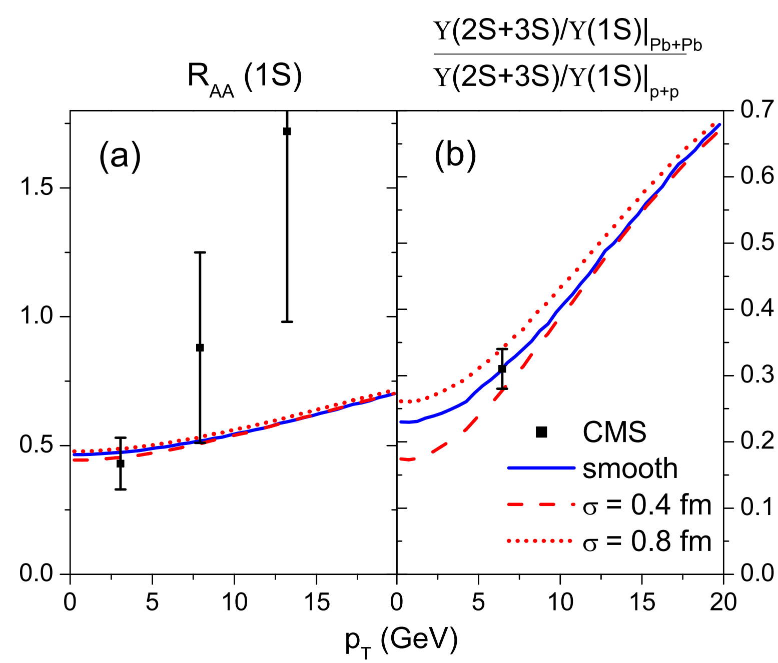
Effects of initial fluctuations on bottomonia production

Song, Han & Ko, NPA 897, 141 (2012)

2+1 ideal hydro

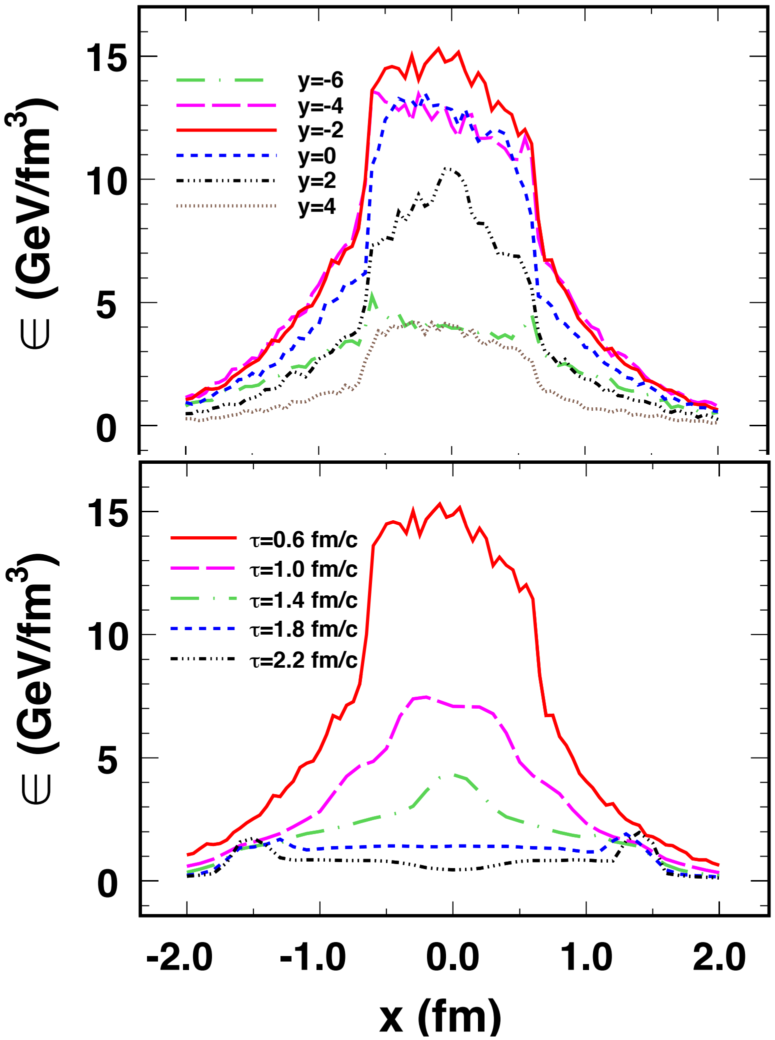






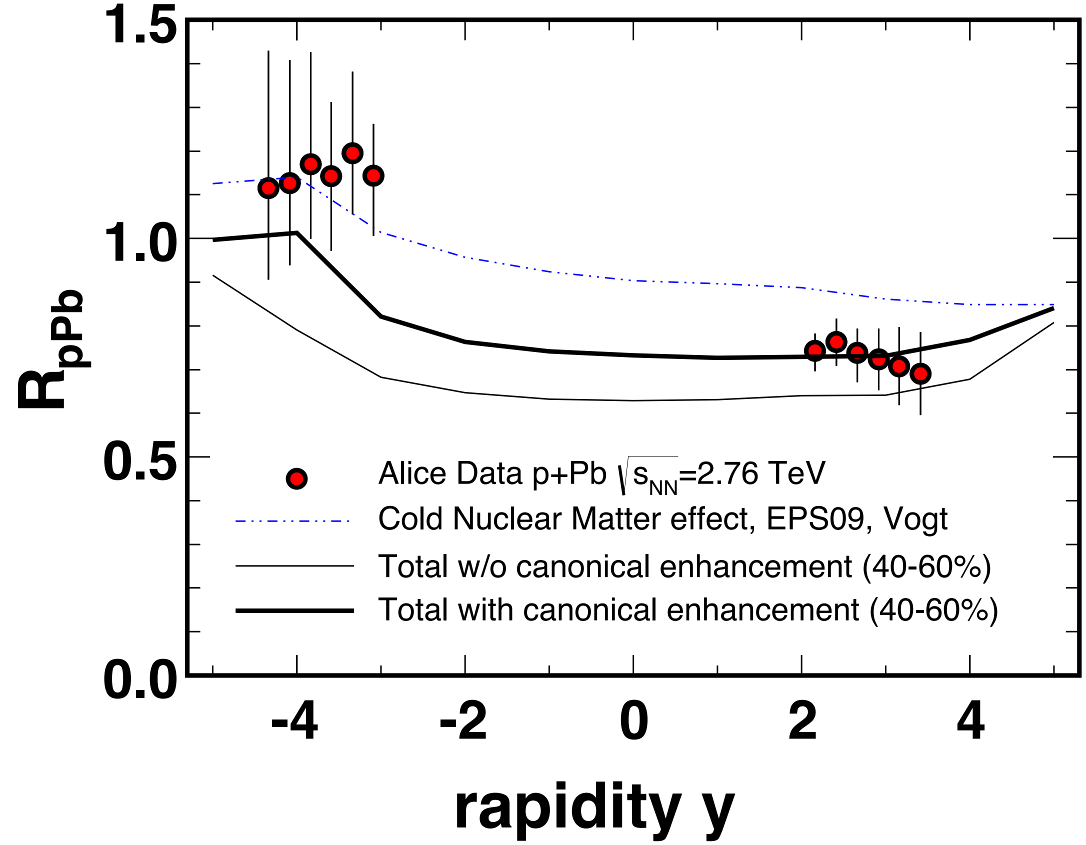
- Initial fluctuations obtained from AMPT affect R_{AA} of bottomonia in peripheral collisions and at low p_T.

J/ψ production in p+Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



- Most central 10% collisions from AMPT

Liu, Song & Ko, PLB 728, 437 (2013)



- Including hot medium effects better describes data

$$\frac{dN}{dt} = -\Gamma(N - N^{\rm eq}), \quad N^{\rm eq} = (1 + 1/N_c)\gamma^2 R n^{\rm GC} V$$

Summary

- J/ψ survives up to 1.7 T_c and Υ(1S) survives up to 4 T_c.
- Most observed J/ψ and Υ(1S) are from primordially produced; contribution from regeneration is small at present HIC.
- Various models with different assumptions can describe experimental data.
- Elliptic flow of regenerated J/ψ is large, while that of directly produced ones is essentially zero. Studying v_2 of J/ψ is useful for distinguishing the mechanism for J/ψ production in HIC.
- Initial fluctuations affect R_{AA} of bottomonia in peripheral collisions and at low p_T .
- Hot medium effects describe better J/ψ data from p+Pb collisions.
- Quarkonia production in HIC is consistent with formation of quark-gluon plasma but has not yet provided information on its properties.