Quarkonia Production in Heavy Ion Collisions

Che-Ming Ko,
Texas A&M University

- In-medium properties of quarkonia
- Quarkonia production mechanisms in HIC
- Nuclear modification factor for J/ψ
- Nuclear modification factor for Υ(1S)
- J/ψ elliptic flow
- Effects of initial fluctuation on J/ψ production

Based on work with Taesoo Song and Kyong chol Han: PRC 83, 014914 (2011); 84, 034907 (2011); 85, 014902 (2012); 85, 054905 (2012); arXiv:1109.6691 [nucl-th]

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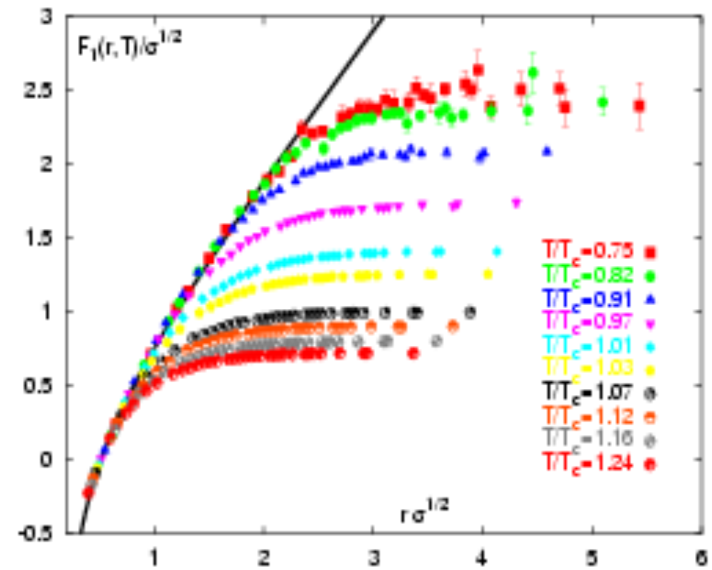
Quarkonia in QGP



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

Two limits of the potential:

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

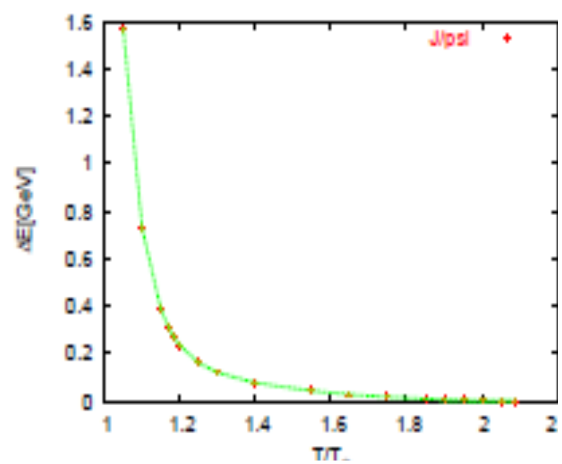
$$\text{or } V(r,T) = U = F + TS$$

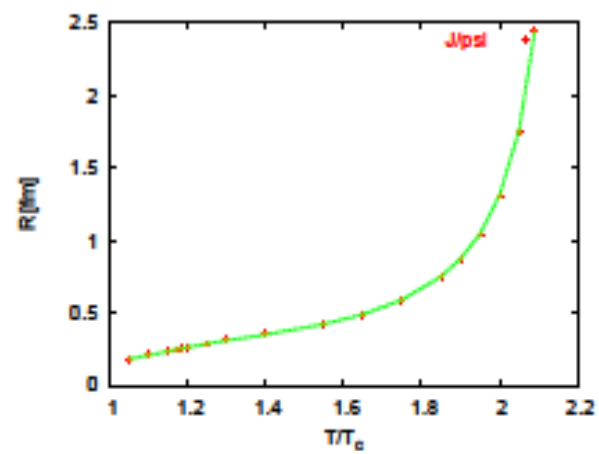
Schroedinger equation at finite T:

binding energy ε(T)
radius R(T)

Dissociation temperature:

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





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

Screened Cornell potential for heavy quark and antiquark in QGP

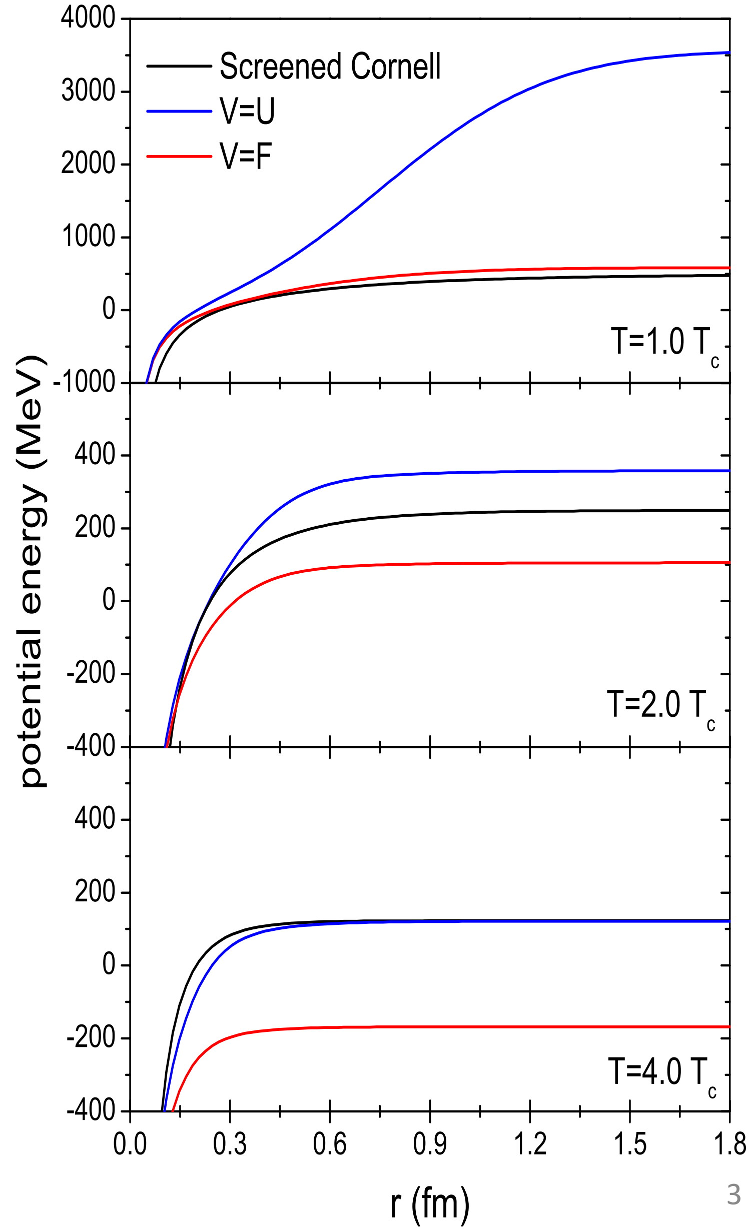
- Screened Cornell potential between charm and anticharm quarks

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

with string tension σ = 0.192 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 $4T_c$.



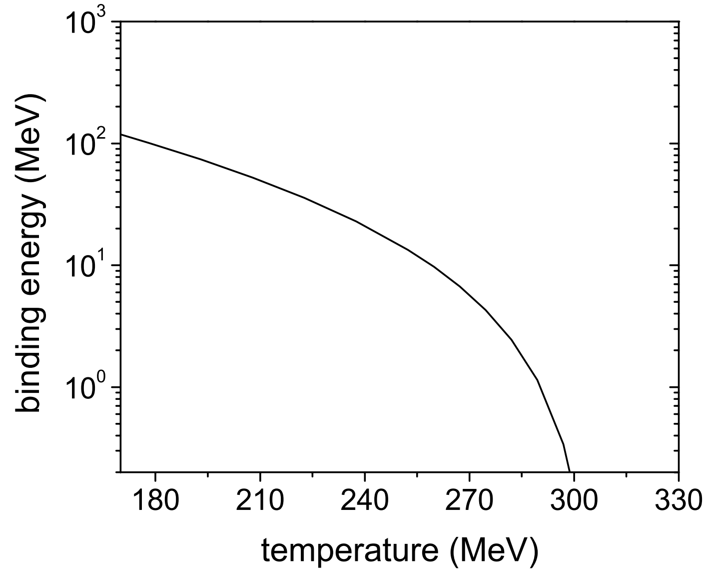
Thermal properties of charmonia

- Binding energy

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

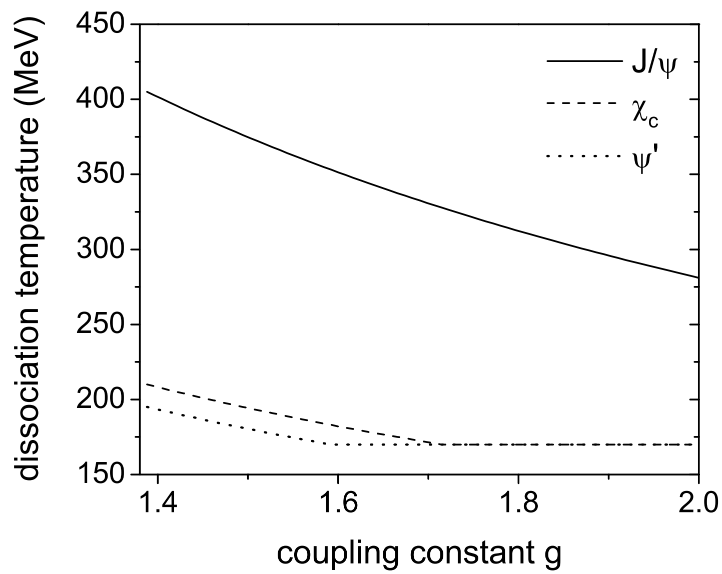
Charm quark mass m_c=1.32 GeV

E: eigenvalues of Cornell potential

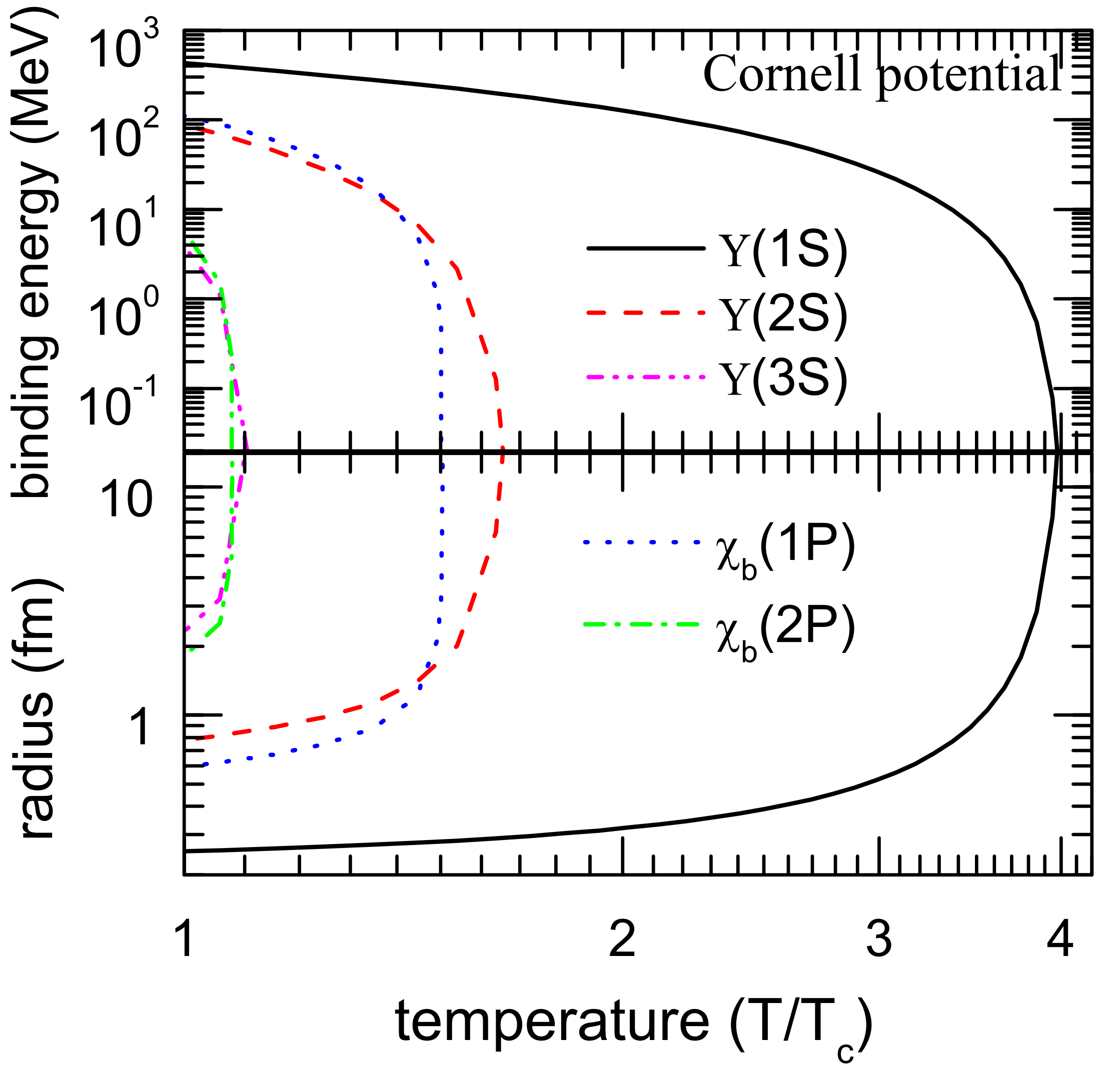


- Dissociation temperature T_D: corresponding to ε_0=0

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

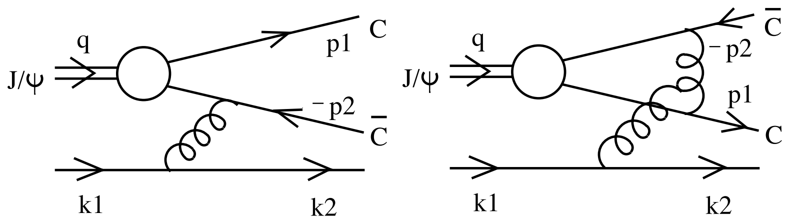


State	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon'(2S)$	$\chi_b'(2P)$	$\Upsilon''(3S)$
Dissociation temp (T_c)	4	1.51	1.67	1.09	1.12

Thermal decay widths of quarkonia

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

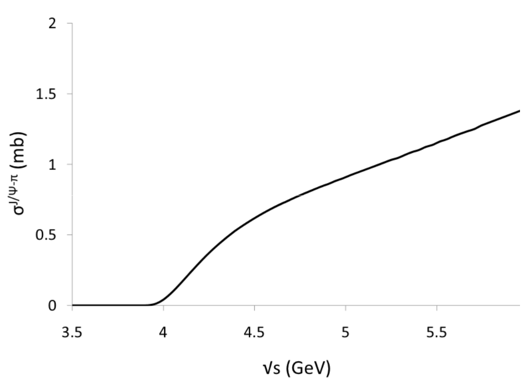
- Dissociation by partons (NLO pQCD)



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

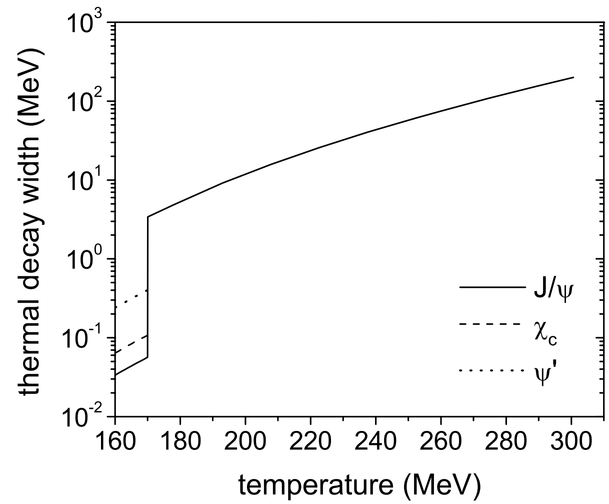
- Dissociation by hadrons

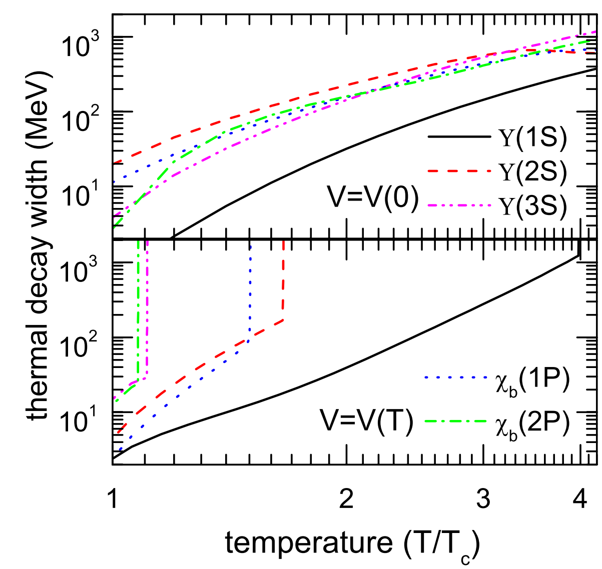
$$\sigma(s) = \sum_i \int dx n_i(x, Q^2) \sigma_i(xs, Q^2)$$



- 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

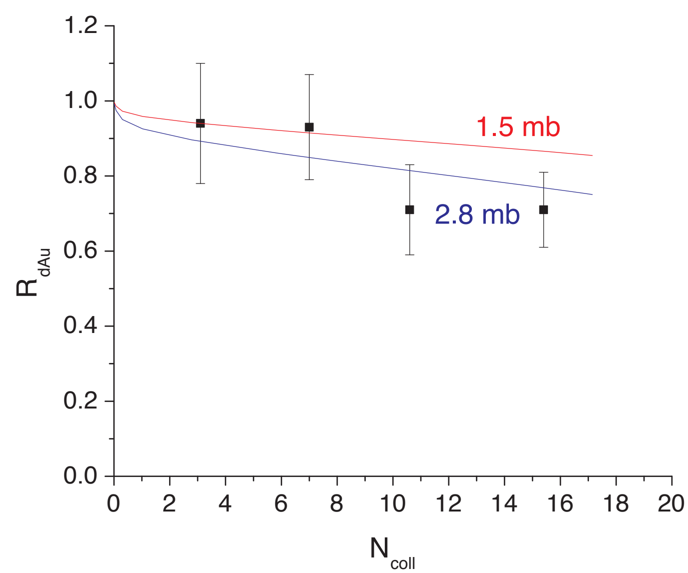
$$\rho(r) = \frac{\rho_0}{1+e^{(r-r_0)/c}}$$

r_0= 6.38 fm, c=0.535 fm for Au

- Nuclear absorption

  - Survival probability

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



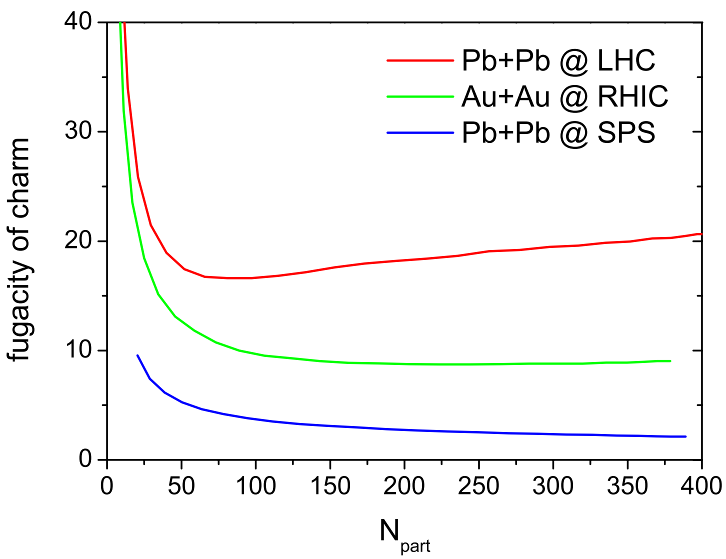
Regenerated J/ψ

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; ~ 63.7 μb at $s^{1/2}$= 200 GeV

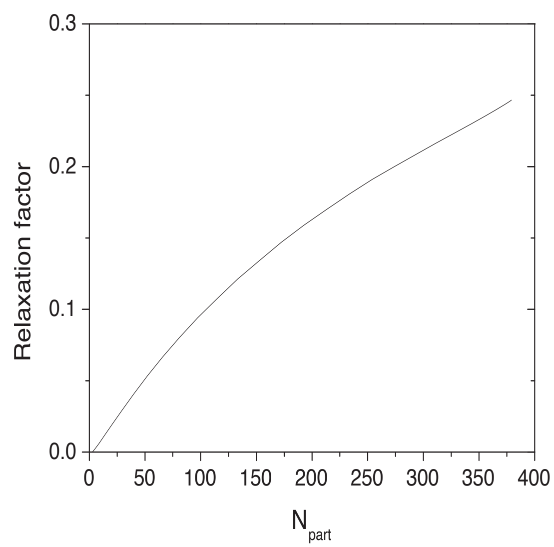


- Charm relaxation factor

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

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

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)]

Viscous hydrodynamics

Heinz, Song & Chaudhuri, PRC 73, 034904 (06)

Hydrodynamic Equations

$\partial_\mu T^{\mu\nu}(x) = 0$ Energy-momentum conservation

$\partial_\mu n_j u^\mu(x) = 0$ Charge conservations (baryon, strangeness,…)

$$\pi_{\mu\nu} = \eta\left(\partial_\mu u_\nu + \partial_\mu u_\nu - \frac{2}{3}\Delta_{\mu\nu}\partial_\alpha u^\alpha\right) - \tau_\pi\left(\frac{4}{3}\pi_{\mu\nu}\partial_\alpha u^\alpha + \Delta^\alpha_\mu \Delta^\beta_\nu u^\sigma \partial_\sigma \pi_{\alpha\beta}\right)$$ (Israel-Stewart)

with $T^{\mu\nu}(x) = \left[e(x) + p(x)\right]u^\mu(x)u^\nu(x) - p(x)g^{\mu\nu} + \pi_{\mu\upsilon}$

e: energy density, p(e): pressure, $\pi_{\mu\nu}$: shear stress tensor, u^μ: four velocity, τ_π: relaxation time

Cooper-Frye instantaneous freeze out

$$E\frac{dN_i}{d^3q} \approx \frac{g_i}{(2\pi)^3}\int q\cdot d\sigma \frac{1}{\exp(q\cdot u/T) \pm 1}\left[1 + \frac{q_\mu q_\nu \pi^{\mu\nu}}{2T^2(e+p)}\right]$$

Schematic viscous hydrodynamics

Song, Han & Ko, PRC 83, 014914 (11)

Assuming thermal quantities (energy density, temperature, entropy density, and pressures) and shear tensor are uniform along the transverse direction

$$\partial_\tau(A\tau\langle T^{\tau\tau}\rangle) = -\left(p+\pi_\eta^\eta\right)A,$$

$$\frac{T}{\tau}\partial_\tau(A\tau s\langle\gamma_r\rangle) = -A\left\langle\frac{\gamma_r v_r}{r}\right\rangle\pi_\phi^\phi - \frac{A\langle\gamma_r\rangle}{\tau}\pi_\eta^\eta + \left\{\partial_\tau(A\langle\gamma_r\rangle) - \frac{\gamma_R\dot{R}}{R}A\right\}\left(\pi_\phi^\phi+\pi_\eta^\eta\right),$$

$$\partial_\tau\left(A\langle\gamma_r\rangle\pi_\eta^\eta\right) - \left\{\partial_\tau(A\langle\gamma_r\rangle) + 2\frac{A\langle\gamma_r\rangle}{\tau}\right\}\pi_\eta^\eta = -\frac{A}{\tau_\pi}\left[\pi_\eta^\eta - 2\eta_s\left\{\frac{\langle\theta\rangle}{3} - \frac{\langle\gamma_r\rangle}{\tau}\right\}\right],$$

$$\partial_\tau\left(A\langle\gamma_r\rangle\pi_\phi^\phi\right) - \left\{\partial_\tau(A\langle\gamma_r\rangle) + 2A\left\langle\frac{\gamma_r v_r}{r}\right\rangle\right\}\pi_\phi^\phi = -\frac{A}{\tau_\pi}\left[\pi_\phi^\phi - 2\eta_s\left\{\frac{\langle\theta\rangle}{3} - \left\langle\frac{\gamma_r v_r}{r}\right\rangle\right\}\right],$$

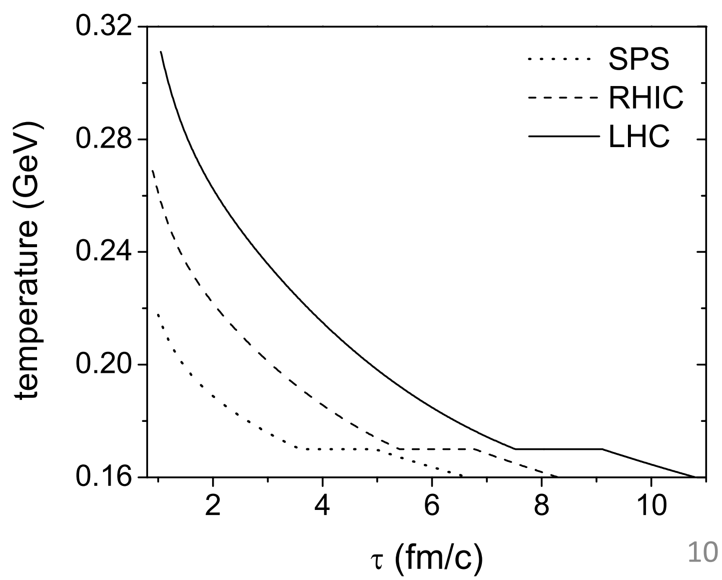
with

$$\langle\gamma_r\rangle = \frac{2}{3\gamma_R^2\dot{R}^2}\left(\gamma_R^3-1\right),\quad \left\langle\frac{\gamma_r v_r}{r}\right\rangle = \frac{\gamma_R\dot{R}^2}{R}$$

$$\langle\gamma_r^2\rangle = 1+\frac{\gamma_R^2\dot{R}^2}{2},\quad \langle\gamma_r^2 v_r^2\rangle = \frac{\gamma_R^2\dot{R}^2}{2},\quad \gamma_R = \frac{1}{\sqrt{1-\dot{R}^2}}$$

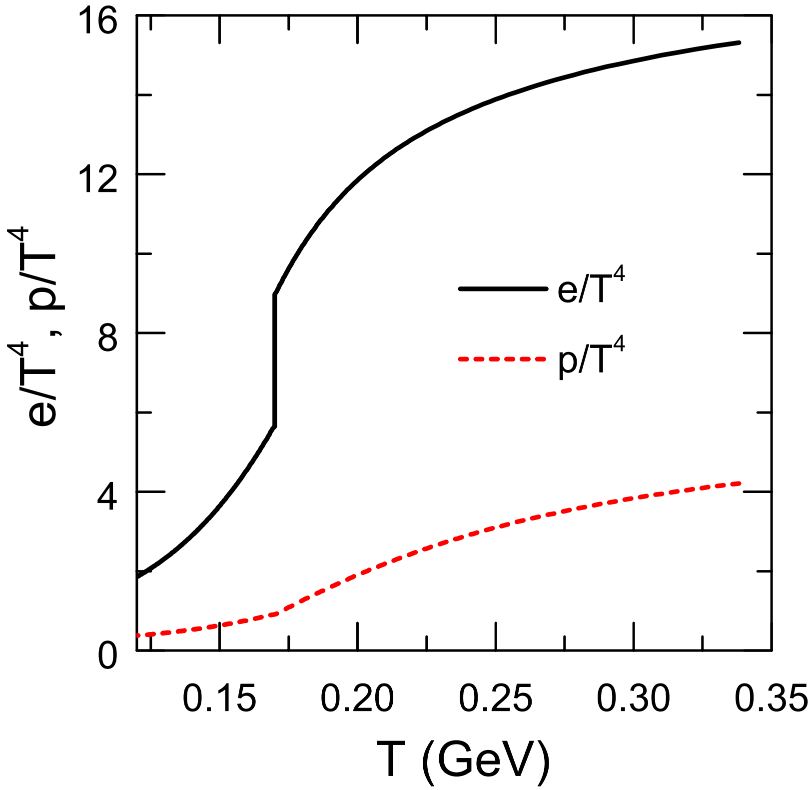
$$\theta = \frac{1}{\tau}\partial_\tau(\tau\gamma_r) + \frac{1}{r}\partial_r(r v_r\gamma_r),\quad A = \pi R^2$$

Taking initial thermalization time τ_0=1.0, 0.9 and 1.05 for SPS, RHIC and LHC; η/s=0.16 for QGP at SPS and RHIC and 0.2 at LHC, and 0.8 for HG; and $\tau_\pi=3/T(\eta/s)$



Quasiparticle model for QGP

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



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

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

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

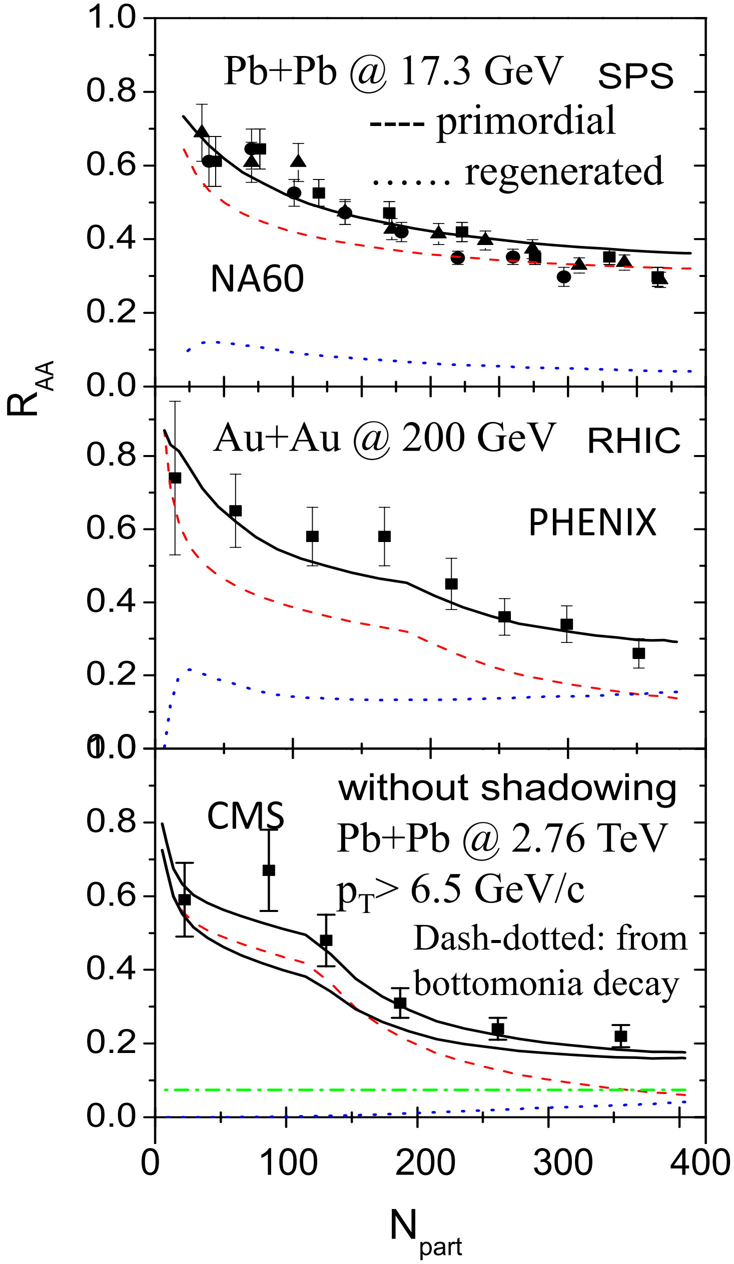
$$m_q^2 = \frac{g^2(T) T^2}{3}$$

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

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

- 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

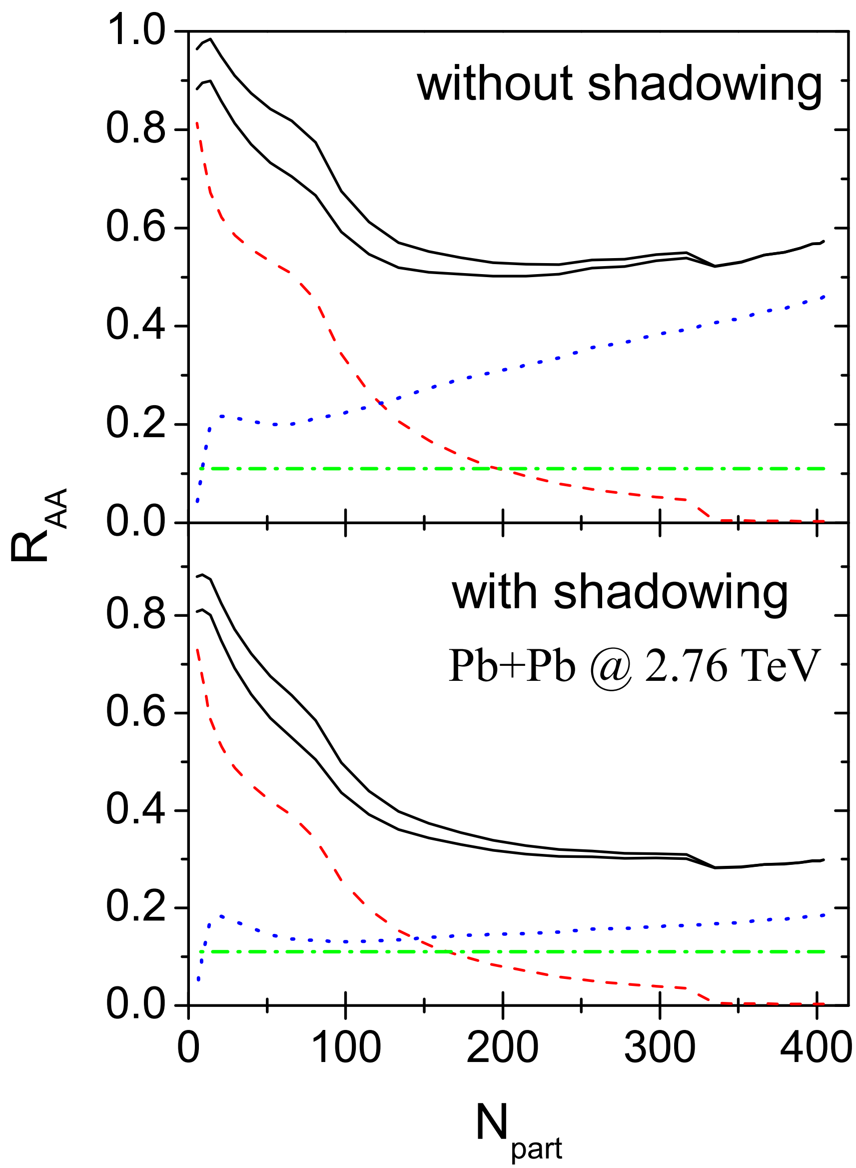
Nuclear modification factor for J/ψ



	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}

Nuclear modification factor for J/ψ at LHC

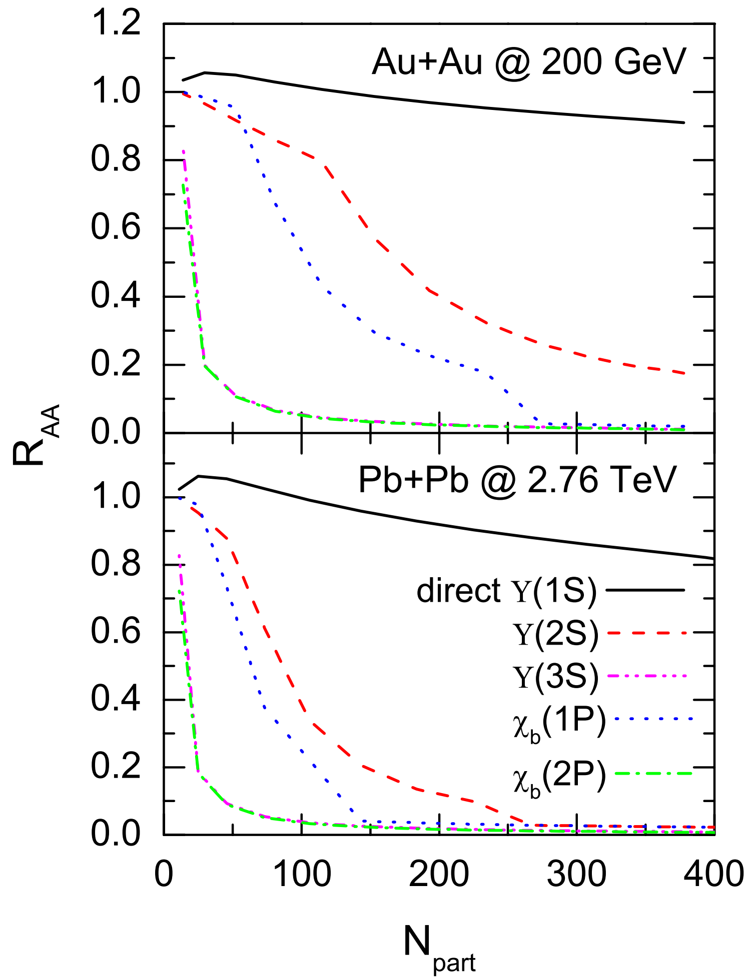


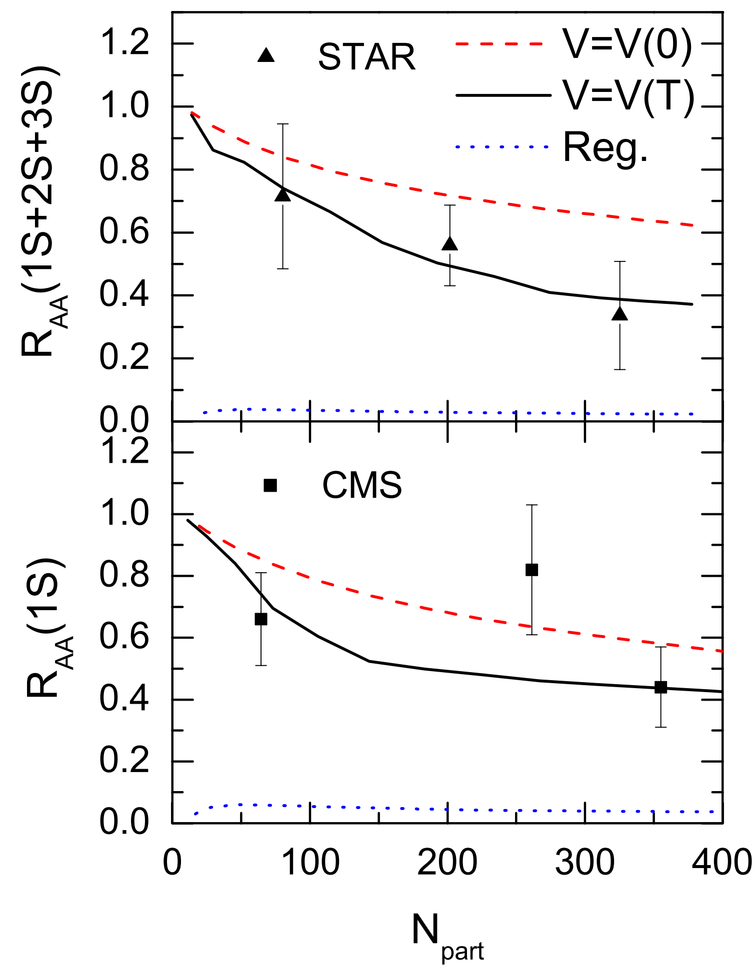
Upper solid: $\sigma_{abs}=0$
Lower solid: $\sigma_{abs}=2.8$ mb
Dashed: primordial
Dotted: regenerated
Dash-dotted: B decay

For J/ψ with $p_T > 0$

- Survival of primordial J/ψ dominates in peripheral collisions
- Regeneration contribution dominates in central collisions

Nuclear modification factor for Υ(1S)

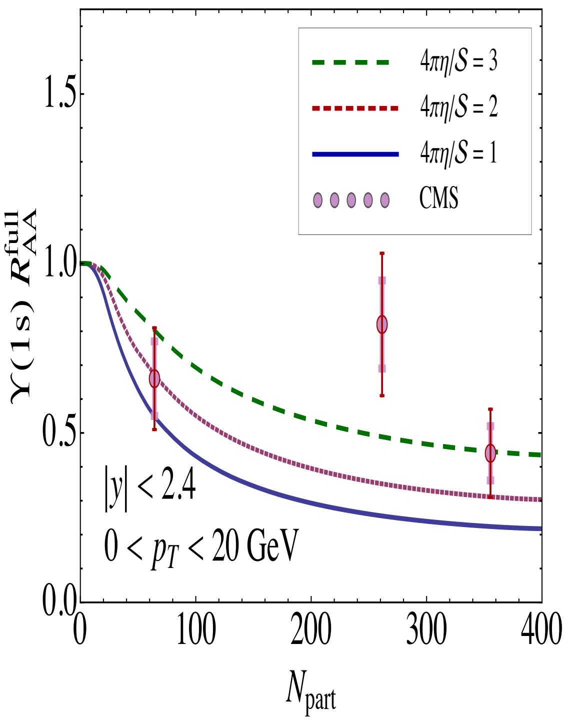




- Regeneration contribution is negligible
- Primordial excited bottomonia are largely dissociated
- Medium effects on bottomonia reduce R_{AA} of Υ(1S)

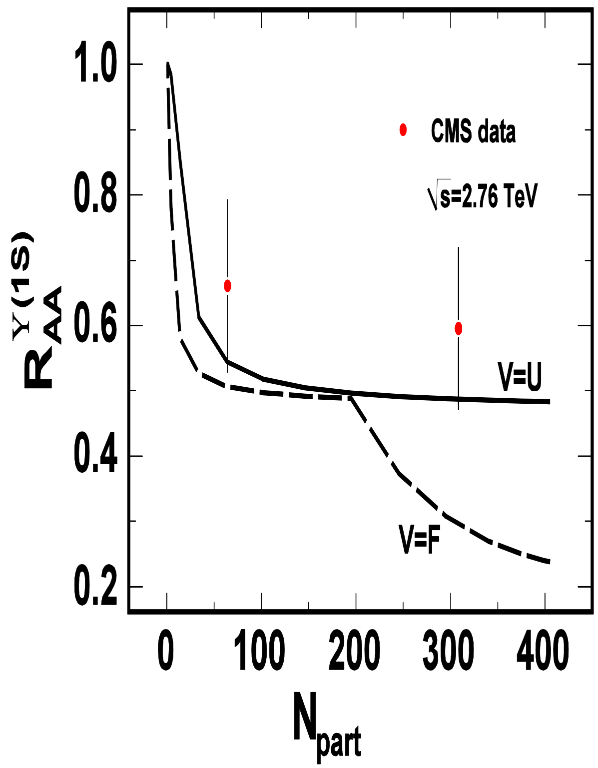
Υ(1S) nuclear modification factor at LHC from other models

1) Strickland, PRL 107, 132301 (2011)



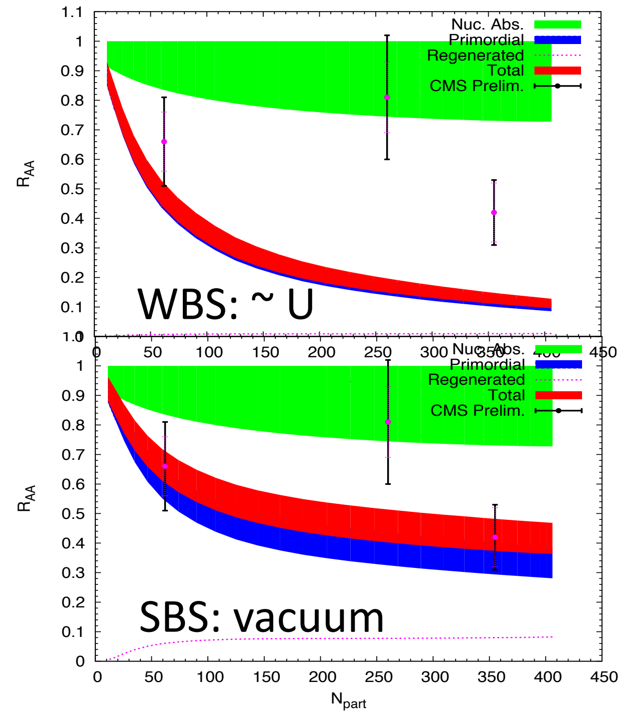
- Potential: in-medium Cornell
- Disso.: LO pQCD
- Dynamics: anisotropic hydro

2) Zhuang et al.,



- Potential: U or F
- Disso.: vacuum gluo-disso.
- Dynamics: ideal hydro

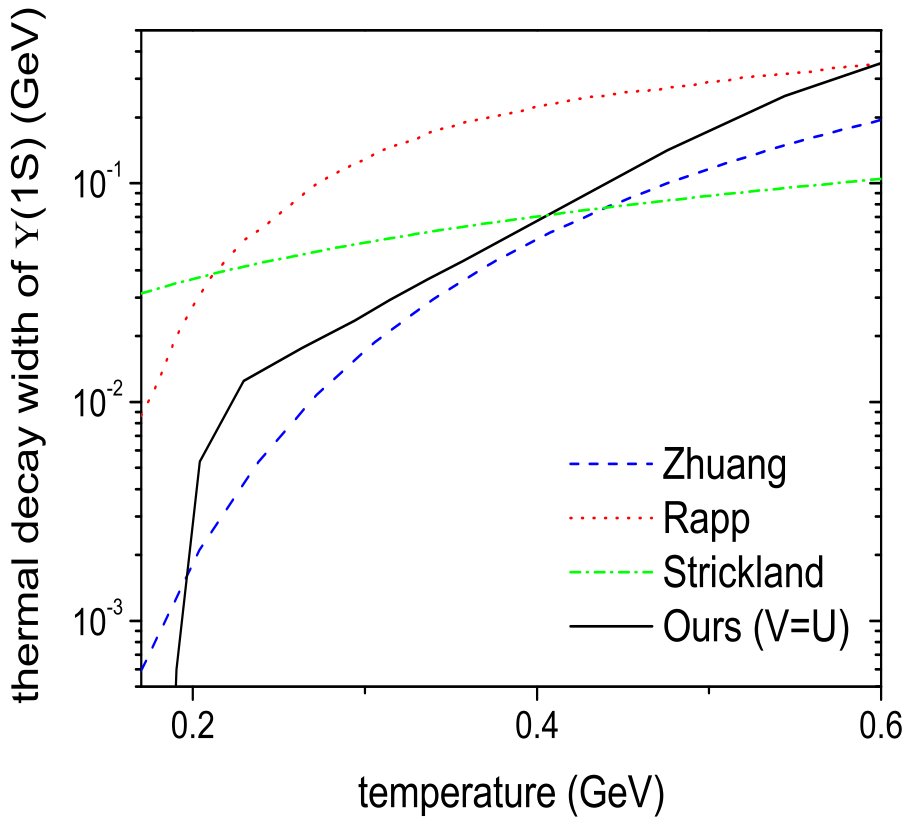
3) Emerick, Zhao & Rapp, arXiv: 1111.6537 [hep-ph]



- Potential: ~ U or vacuum
- Diss.: vacuum gluo-disso.
- Dynamics: fireball

4) Brezinzki & Wolschin, PLB 707, 534 (12): estimate using in-medium gluo-dissociation

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

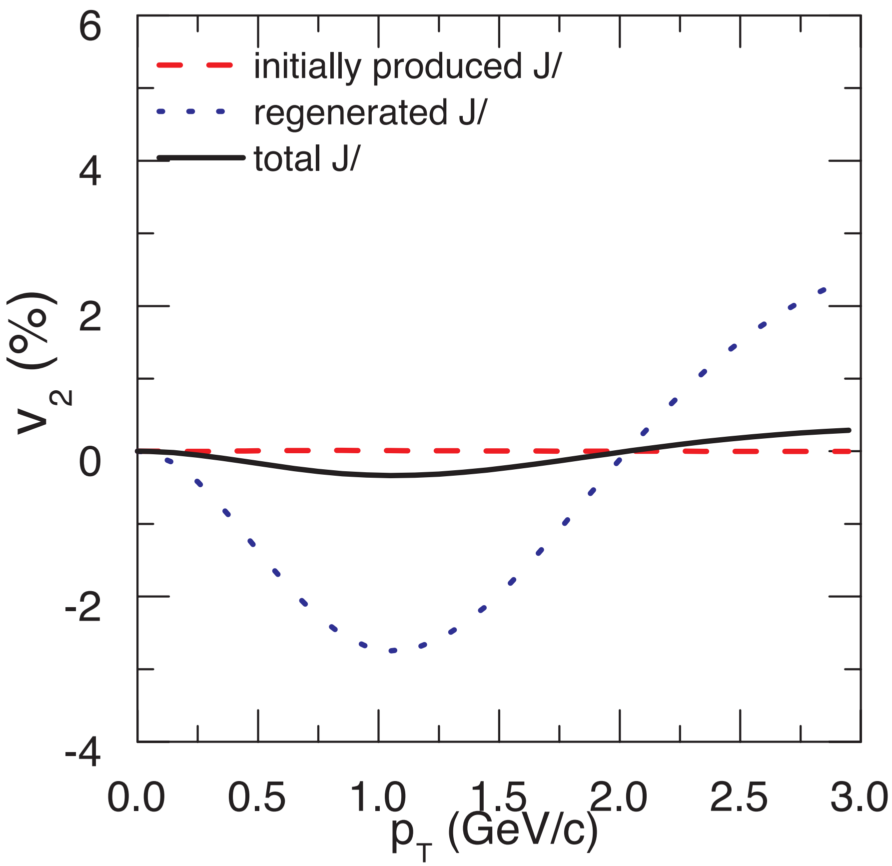


- Thermal decay width
  - Rapp: quasielastic scattering
  - Zhuang: OPE by Peskin
  - Stricland: LO pQCD
  - Song: NLO pQCD

- 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

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

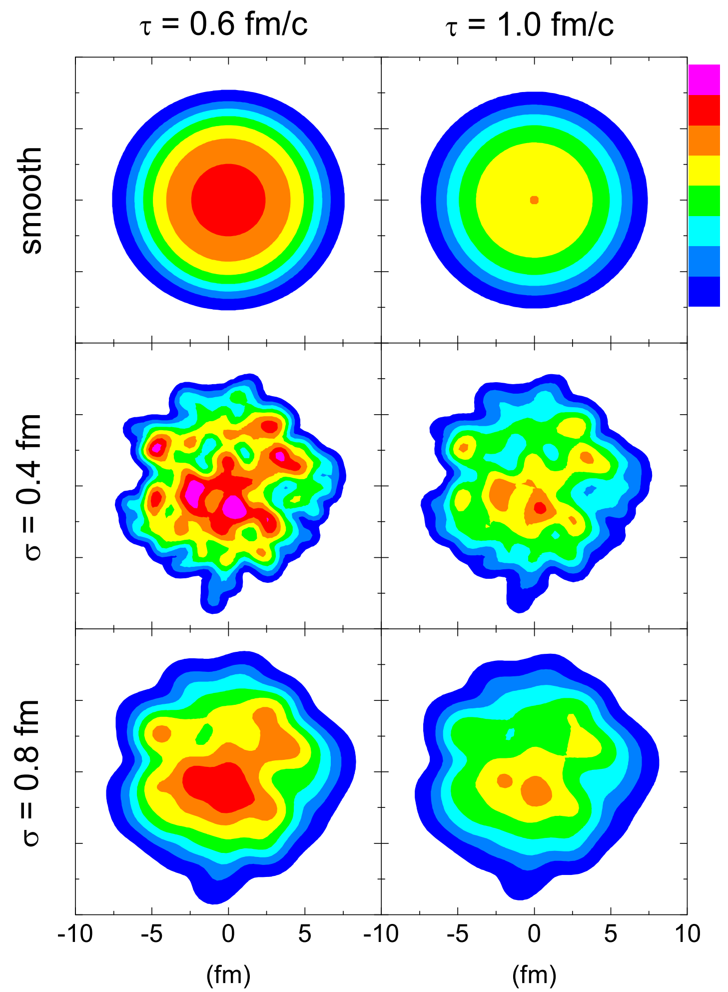
with $C=1.14\ \mathrm{GeV}^{-1}$ and n= number of quarks in a hadron

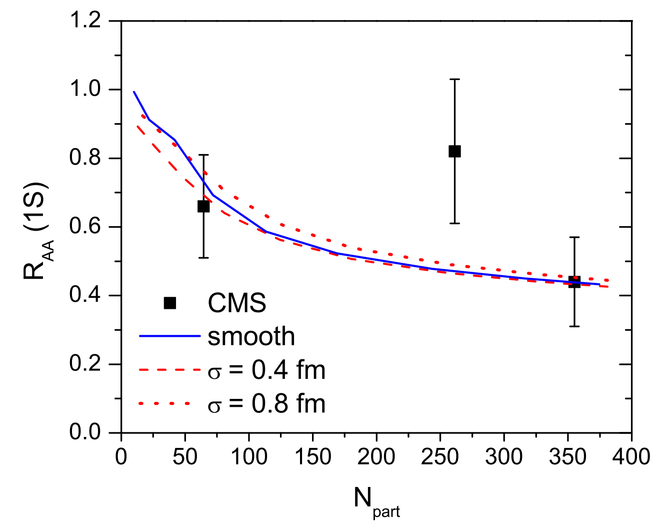
- Initially produced J/ψ have essentially vanishing v_2
- Regenerated J/ψ have large v_2
- Final J/ψ v_2 is small as most are initially produced

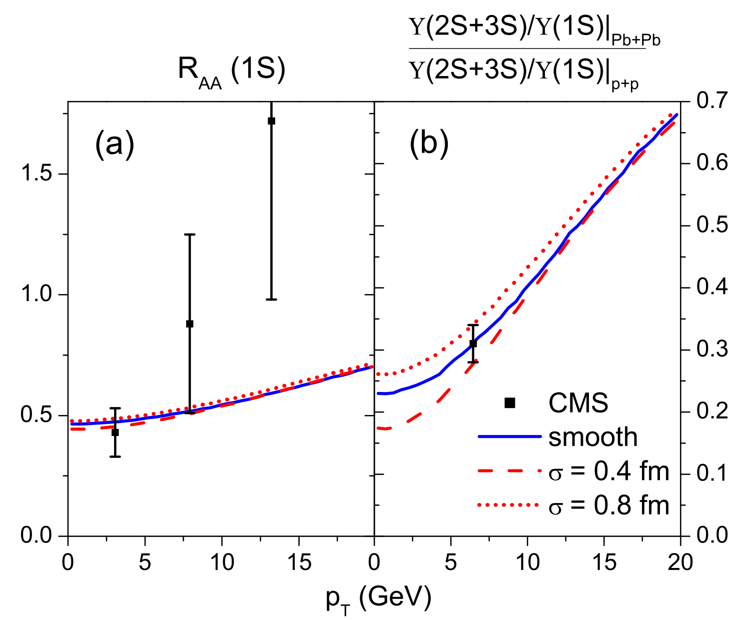
Effects of initial fluctuations on bottomonia production

Song, Han & Ko, arXiv:1109.6691 [nucl-th]

2+1 ideal hydro







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

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