Quarkonia Production in Heavy Ion Collisions

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

Quarkonia in vacuum

State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
m (GeV/c^2)	3.10	3.53	3.68
r (fm)	0.5	0.72	0.90
Contribution to J/ψ@RHIC (%)	60	30	10

State	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon'(2S)$	$\chi_b'(2P)$	$\Upsilon''(3S)$
m (GeV/c^2)	9.46	9.99	10.02	10.26	10.36
r (fm)	0.28	0.44	0.56	0.68	0.78
Contribution to $\Upsilon(1S)$@RHIC (%)	51	27	11	10	1

Quarkonia in QGP

Free energy F from a pair of $Q\bar{Q}$ from LQCD
[Kacmareck, EJP 61, 811 (200)]

Two limits of the potential:

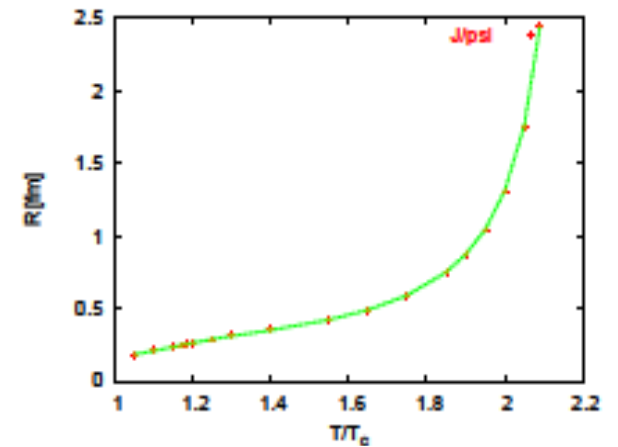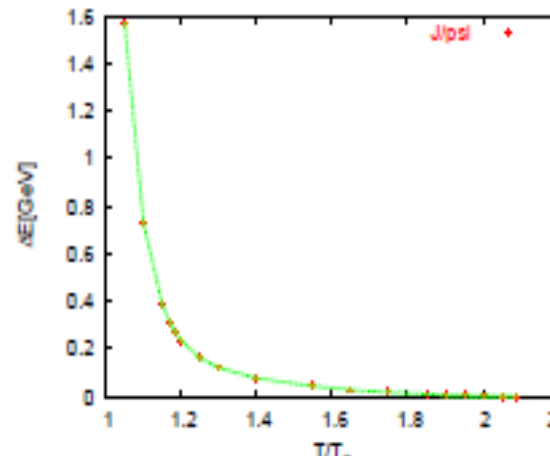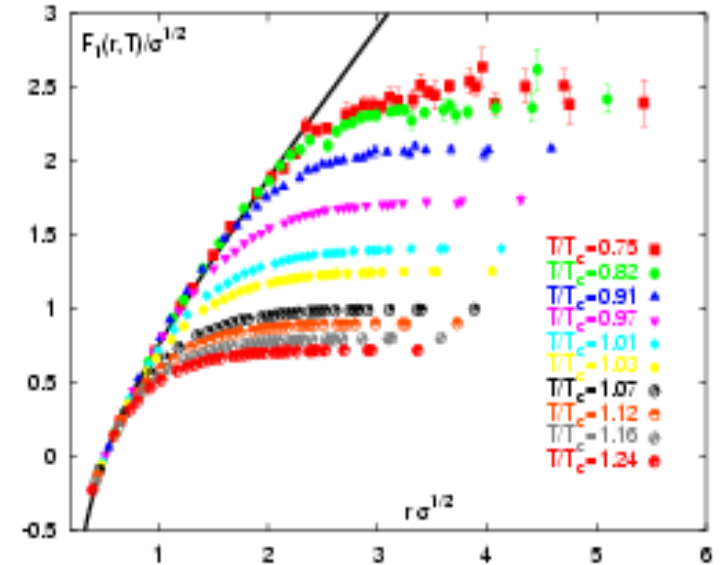$$V(r,T) = \begin{cases} F, & \text{slow dissociation} \\ U = F + TS, & \text{rapid dissociation} \end{cases}$$

Schroedinger equation at finite T:

binding energy $\varepsilon(T)$
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

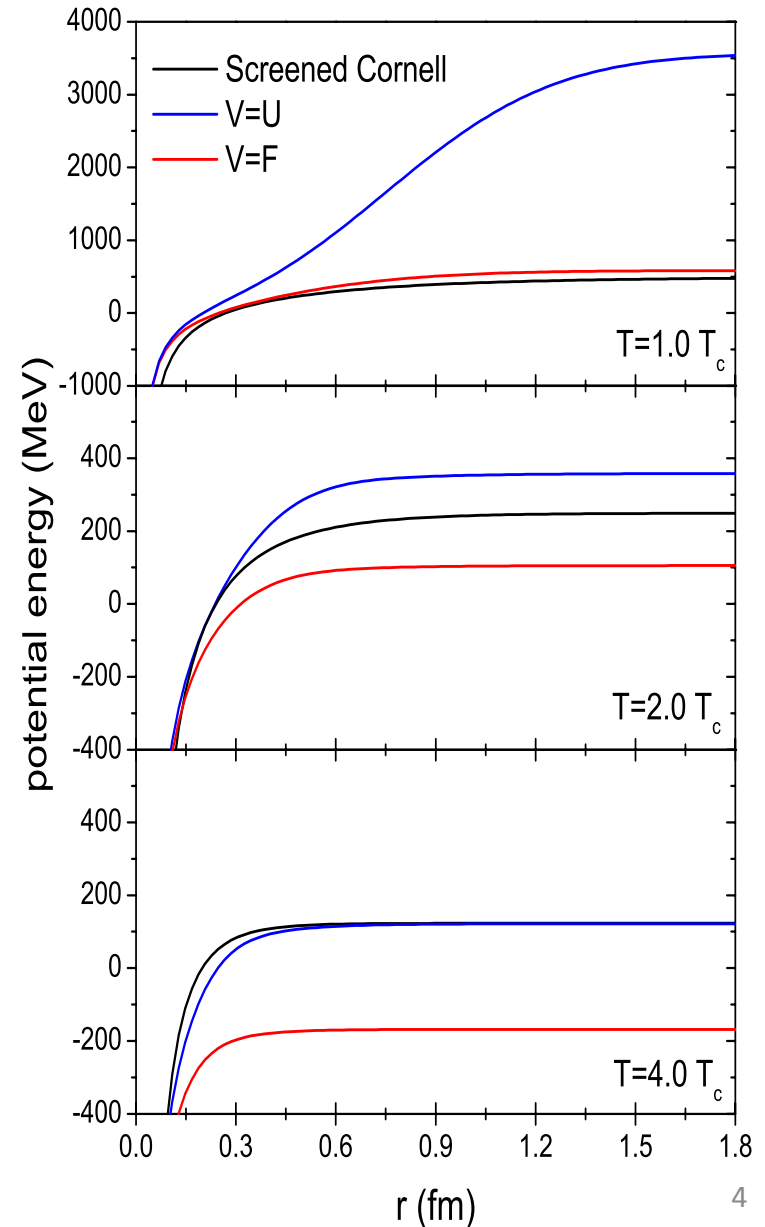# Screened Cornell potential for heavy quark and antiquark in QGP

- 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 $\sigma = 0.192$ 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
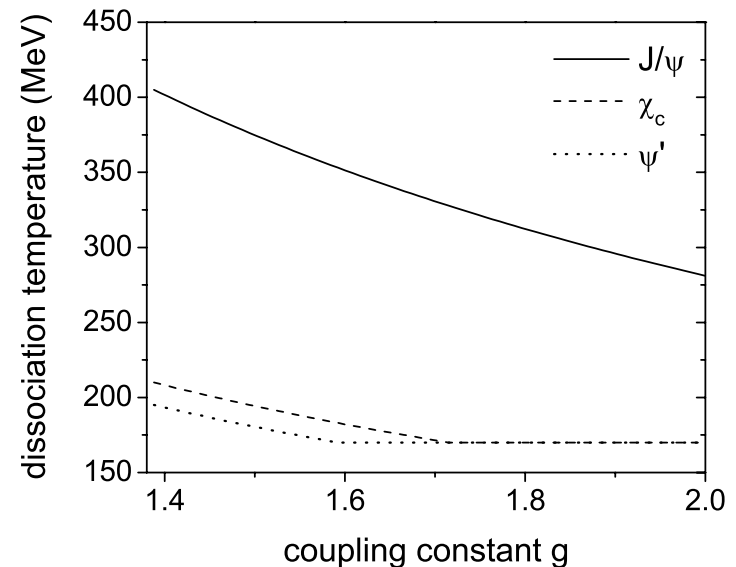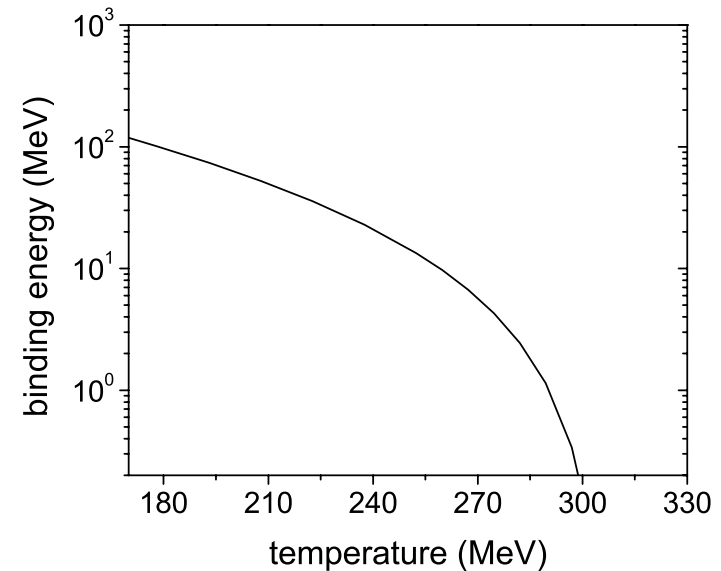
- Binding energy

$$\varepsilon_0 = 2m_c + \frac{\sigma}{\mu(T)} - E$$
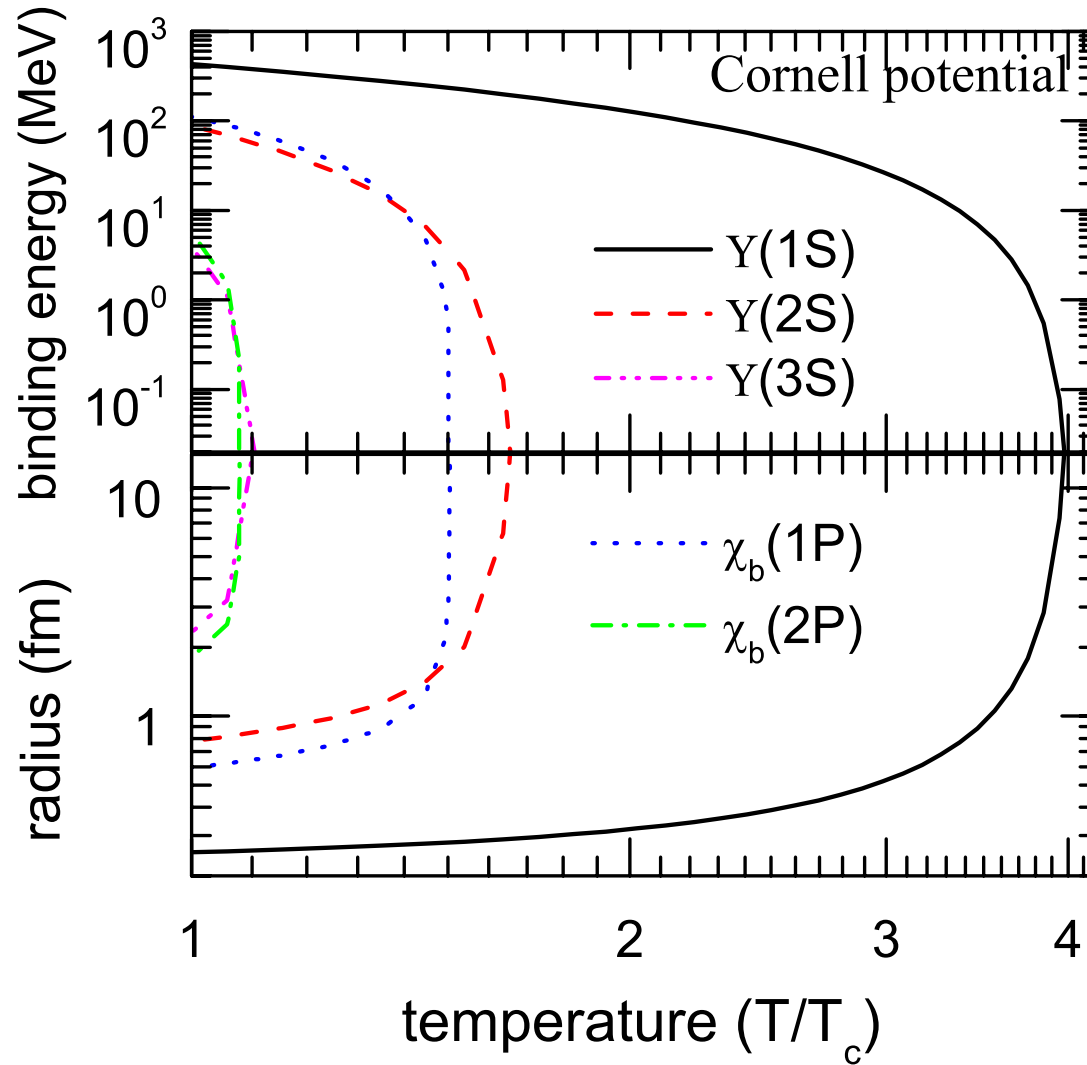
Charm quark mass m_c=1.32 GeV

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_c=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

- Dissociation by partons (NLO pQCD)

- Thermal dissociation width

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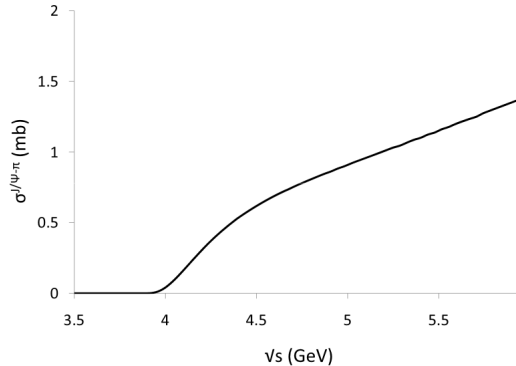

$$|\overline{M}|^2 = \frac{4}{3} g^4 m_c^2 m_{J/\psi} \left| \frac{\partial \psi(p)}{\partial p} \right|^2 \left\{ -\frac{1}{2} + \frac{(k_1^0)^2 + (k_2^0)^2}{2k_1 \cdot k_2} \right\}$$
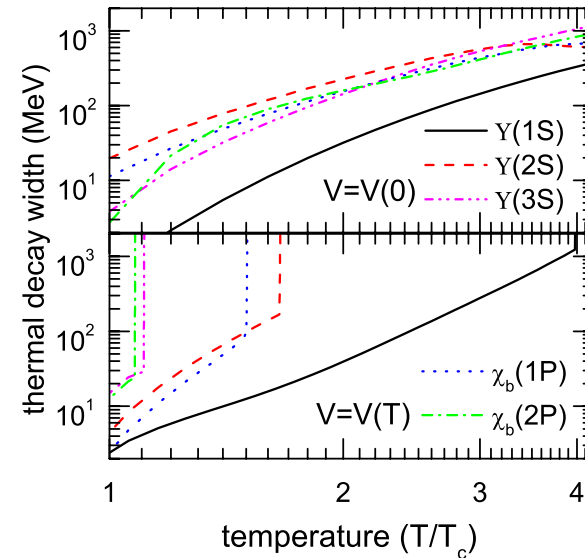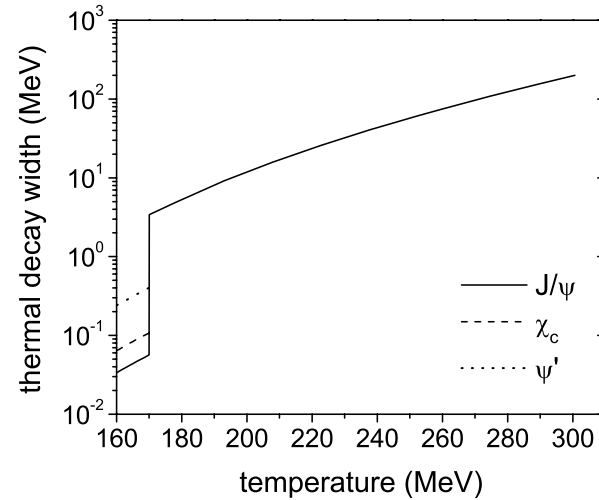
- Dissociation by hadrons

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

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Directly produced J/ψ

▪ Number of initially produced

$$N_{J/\psi}^{AA} = \sigma_{J/\psi}^{NN} A^2 T_{AA}(\vec{b})$$

- $\sigma_{J/\psi}^{NN}$: 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

$$S_{nucl}(\vec{b},\vec{s}) = \frac{1}{T_{AB}(\vec{b})} \int dz dz' \rho_A(\vec{s},z) \rho_B(\vec{b}-\vec{s},z')$$

$$\times \exp\left\{ -(A-1)\int_z^{\infty} dz_A \rho_A(\vec{s},z_A)\sigma_{nuc} \right\}$$

$$\times \exp\left\{ -(B-1)\int_{z'}^{\infty} dz_B \rho_B(\vec{s},z_B)\sigma_{nuc} \right\}$$

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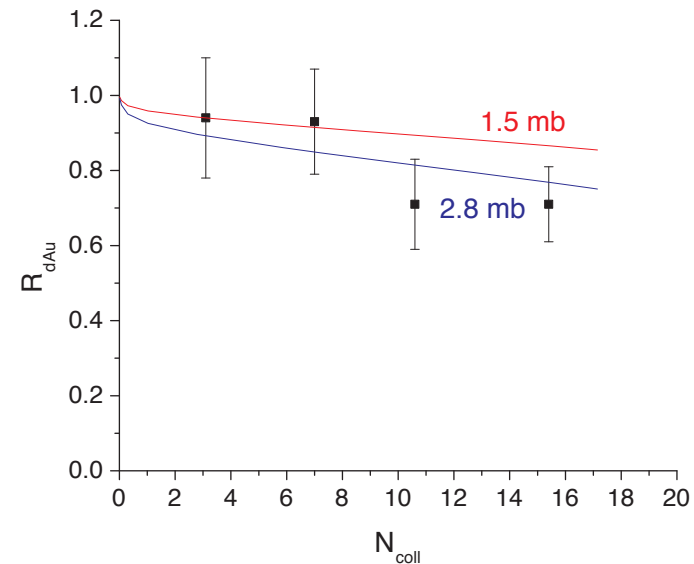
Regenerated J/ψ

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

$$N_{c\bar{c}}^{AA} = \left[\frac{1}{2}\gamma n_o \frac{I_1(\gamma n_0 V)}{I_0(\gamma n_0 V)} + \gamma^2 n_h\right] V = \sigma_{c\bar{c}}^{NN} A^2 T_{AA}(\vec{b})$$
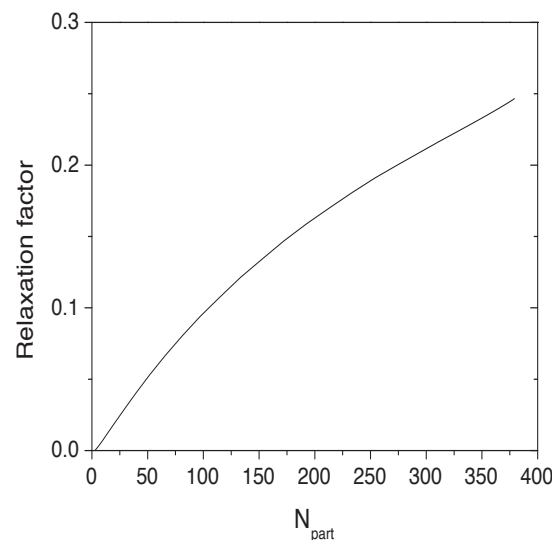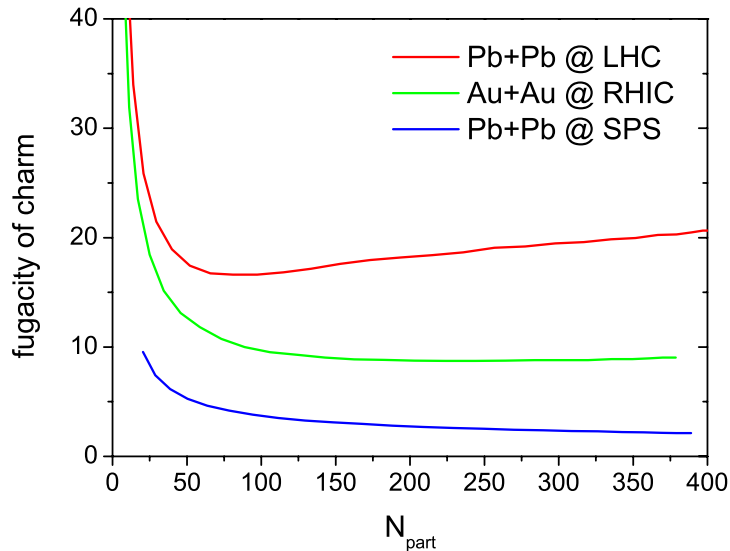
- $\sigma_{c\bar{c}}^{NN}$: charm production cross section in NN collision; ~ 63.7 μb at $s^{1/2}= 200$ GeV

- 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 off-equilibrium charm quarks from parton cascade [PRC 85, 954905 (12)]

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

Hydrodynamic Equations

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

$$\partial_\mu n_j u^\mu(x) = 0 \qquad \text{Charge conservations (baryon, strangeness,...)}$$

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

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

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

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

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

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

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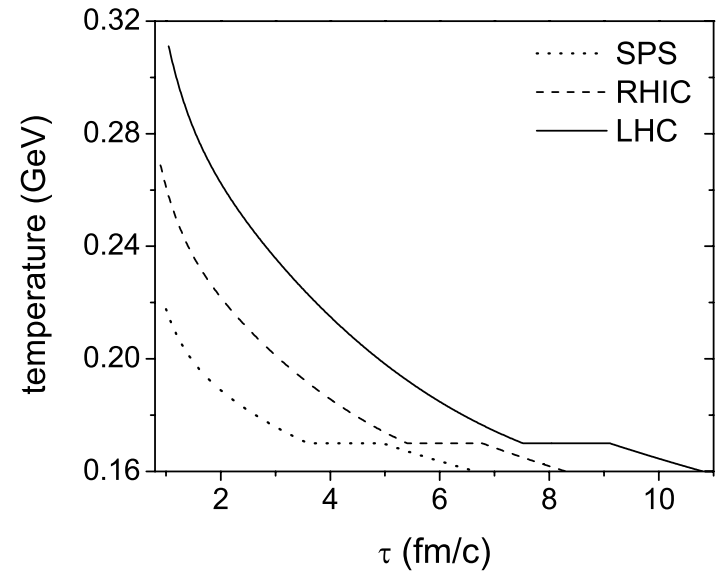
with

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

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

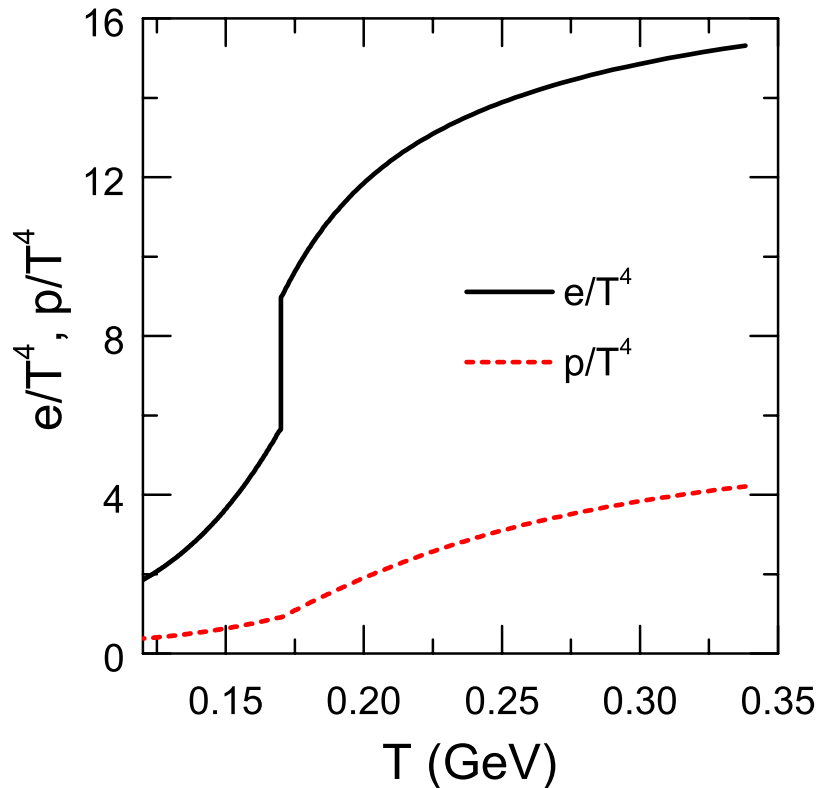$$\theta = \frac{1}{\tau}\partial_\tau(\tau \gamma_r) + \frac{1}{r}\partial_r(r v_r \gamma_r), \quad A = \pi R^2$$

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

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Quasiparticle model for QGP

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

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

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

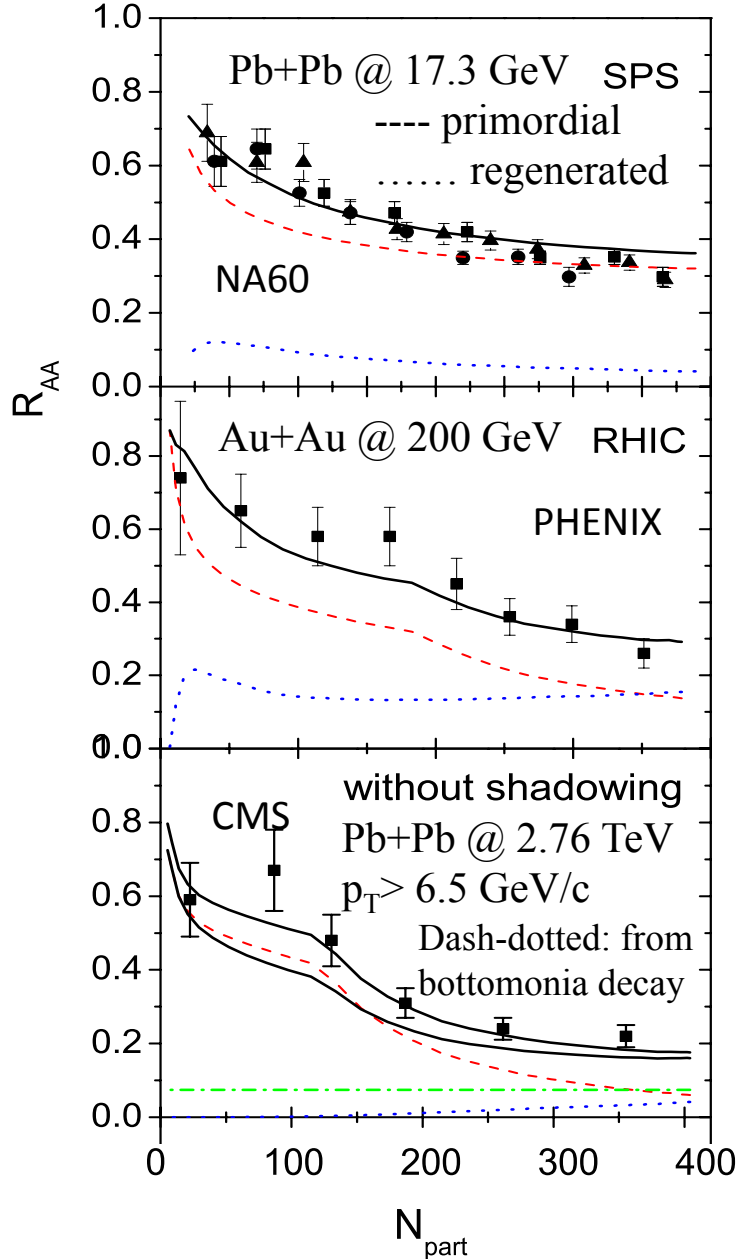$$m_g^2 = \left(\frac{N_c}{3} + \frac{N_f}{6} \right) \frac{g^2(T)T^2}{2}$$

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

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

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

- Resulting EOS is similar to that from LQCD by the hot QCD collaboration, and the difference is smaller than between the hot QCD and Wuppertal-Budapest Collaborations
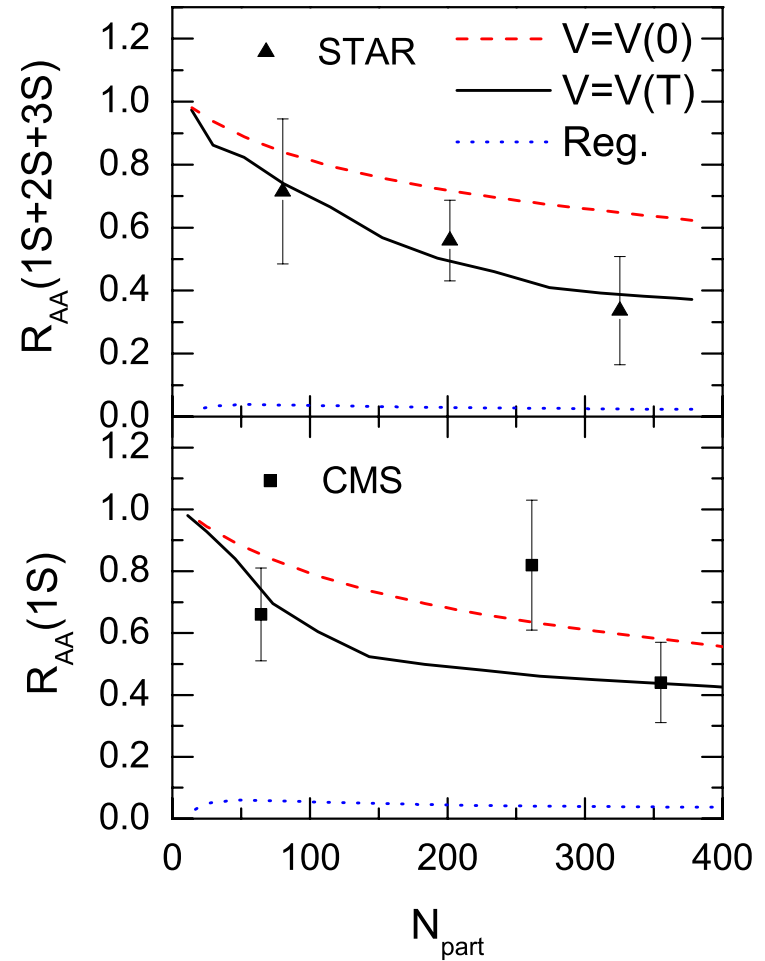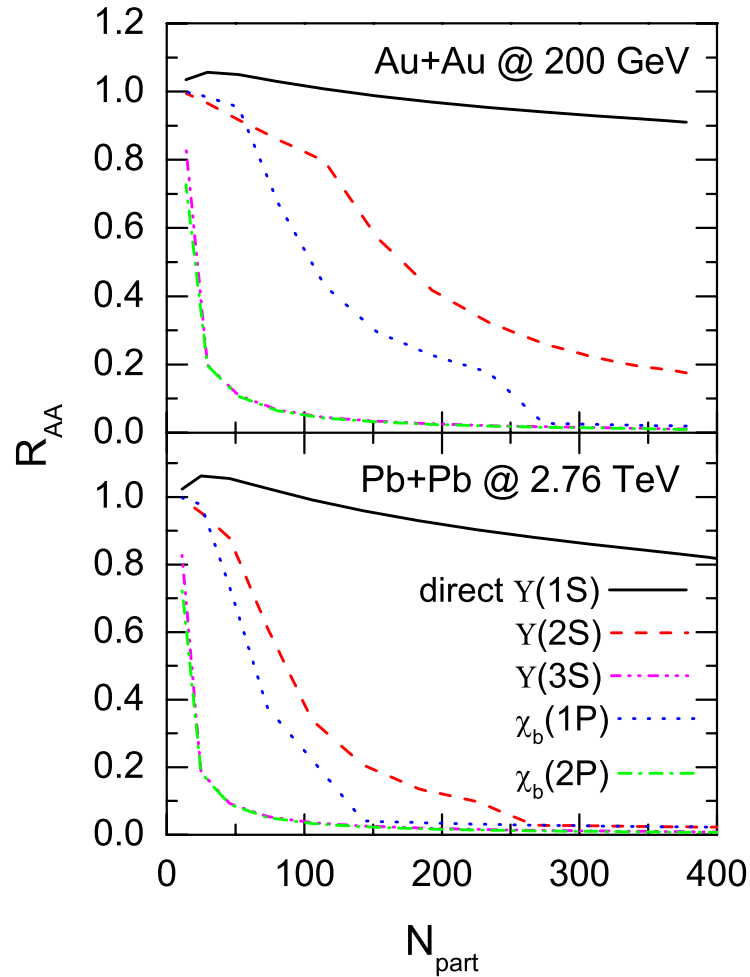
Nuclear modification factor for J/ψ

	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.				
σ_{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}
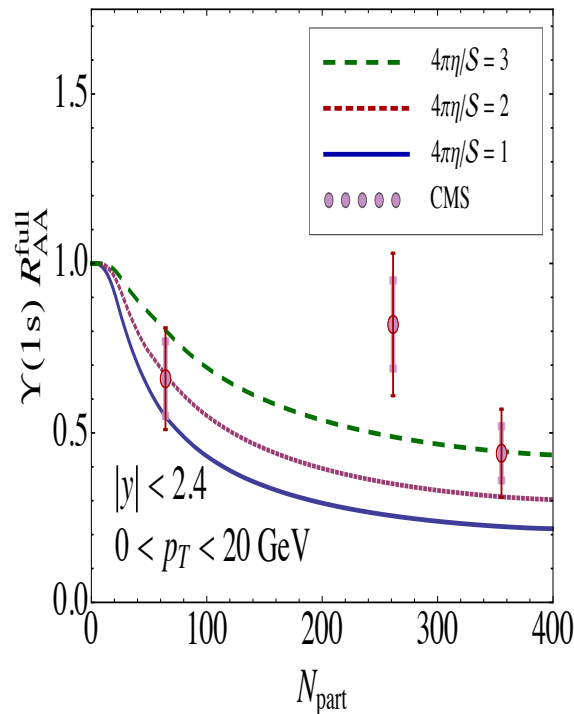
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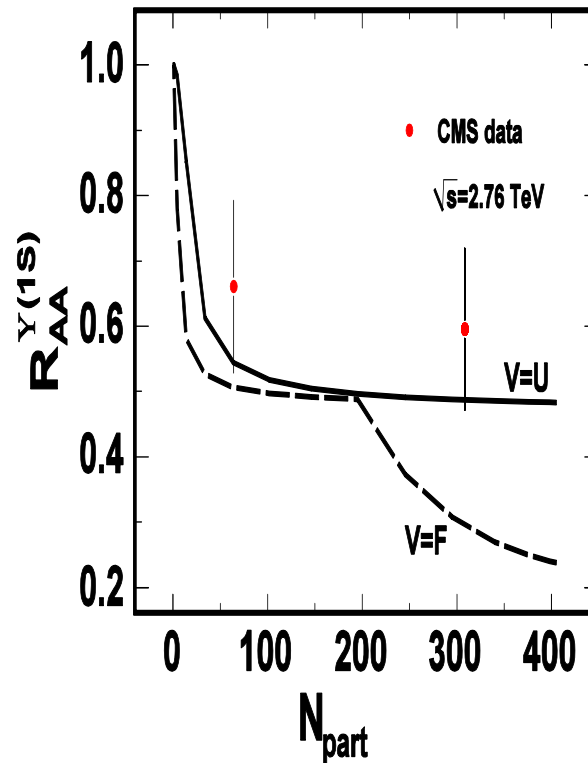# Nuclear modification factor for $\Upsilon(1S)$

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

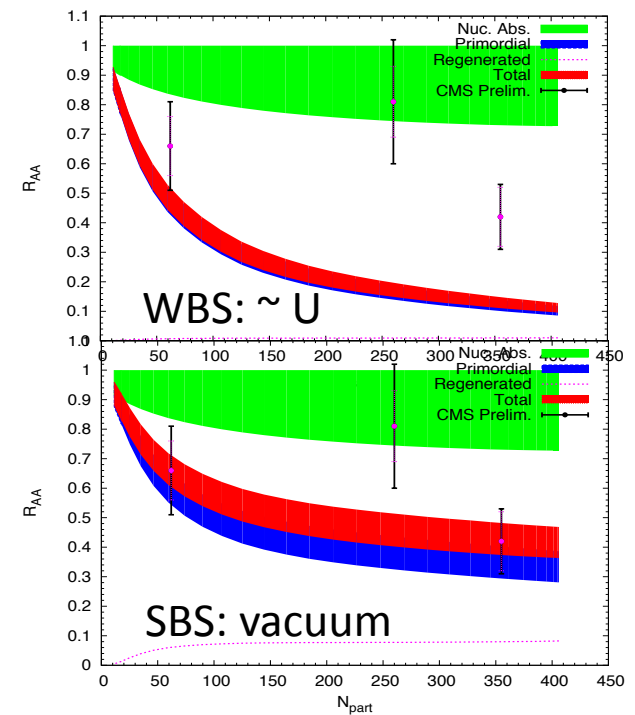# Y(1S) nuclear modification factor at LHC from other models

1) Strickland, PRL 107, 132301 (2011)

2) Zhuang et al.,
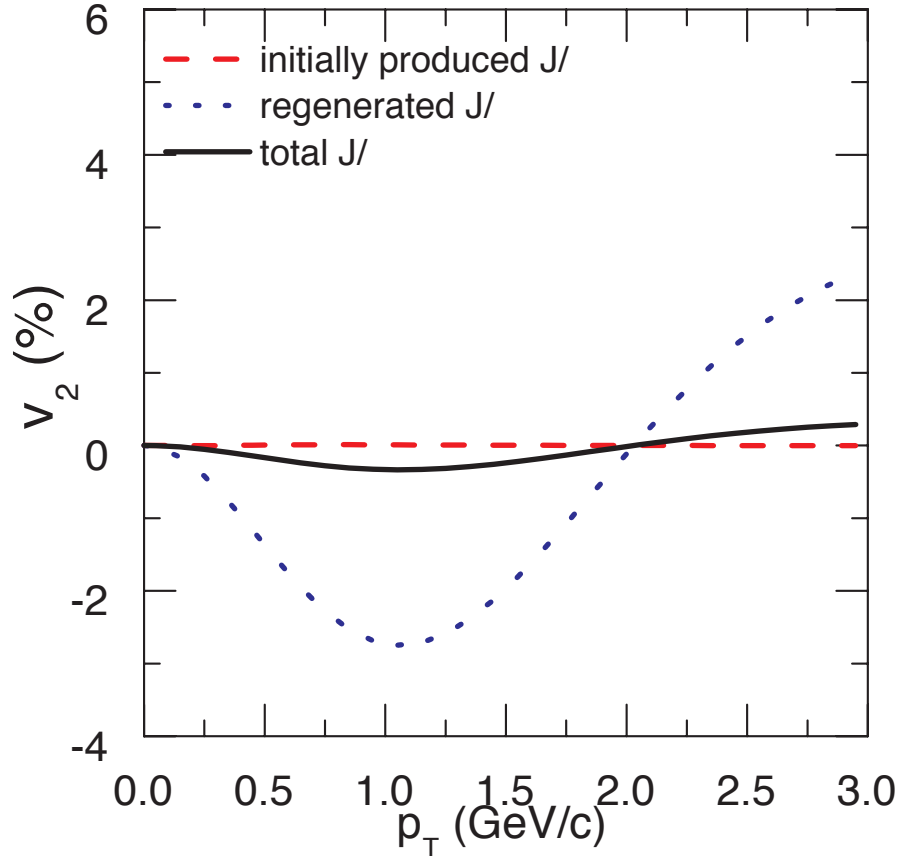
3) Emerick, Zhao & Rapp, arXiv: 1111.6537 [hep-ph]

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

- Potential:
- Disso.: vacuum gluo-disso.
- Dynamics: ideal hydro

- Potential: ~ U or vacuum
- Disso.:
- Dynamics: fireball

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

J/ψ elliptic flow

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

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

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

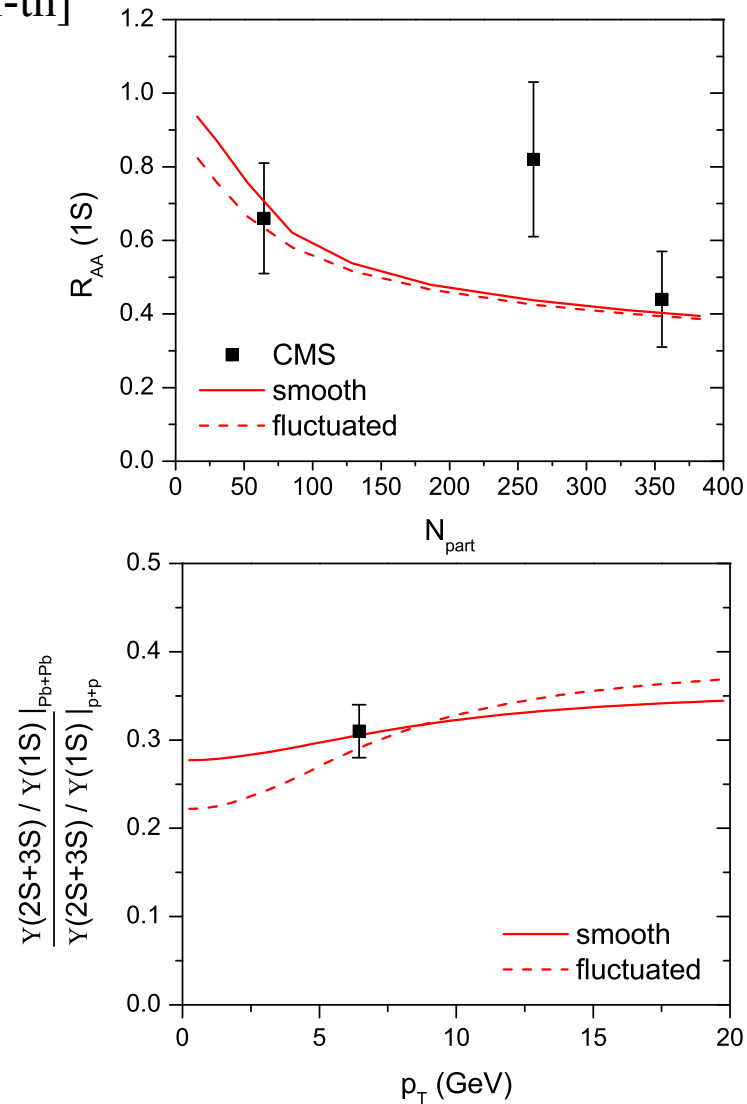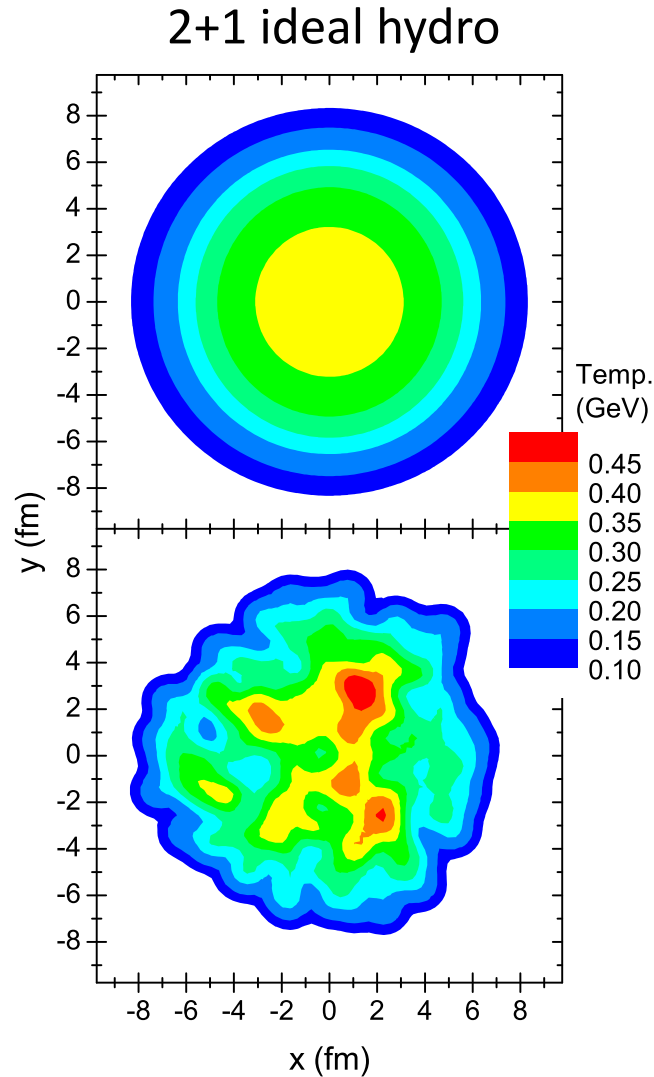ρ=tanh(v_T)=transverse rapidity

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

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

2+1 ideal hydro

Temp. (GeV)

0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10

- R_{AA} of bottomonia is reduced by initial fluctuations in peripheral collisions, and is also reduced at low p_T but enhanced at high p_T

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Summary

- J/ψ survives up to 1.7 T$_c$ and Y(1S) survives up to 4 T$_c$

- Most observed J/ψ and Y(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

- R_{AA} of bottonmonia is reduced by initial fluctuations in peripheral collisions and at low p_T but enhanced at high p_T