J/ψ Production and Elliptic Flow in Relativistic Heavy Ion Collisions

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- Introduction
- J/ψ production mechanisms
- The two-component model
- Nuclear modification factor for J/ψ
- Elliptic flow of J/ψ
- Summary

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Introduction: Signatures of quark-gluon plasma

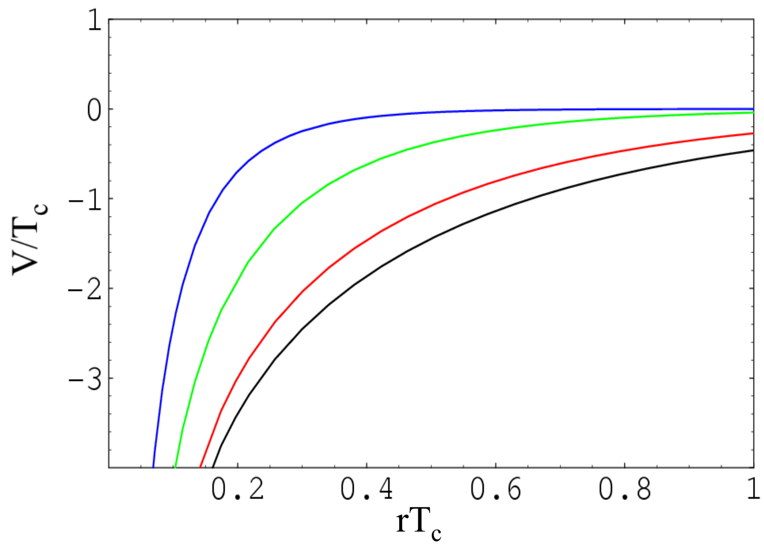
- Dilepton enhancement (Shuryak, 1978)
- Strangeness enhancement (Meuller & Rafelski, 1982)
- J/ψ suppression (Matsui & Satz, 1986)
- Pion interferometry (Pratt; Bertsch, 1986)
- Elliptic flow (Ollitrault, 1992)
- Jet quenching (Gyulassy & Wang, 1992)
- Net baryon and charge fluctuations (Jeon & Koch; Asakawa, Heinz & Muller, 2000)
- Quark number scaling of hadron elliptic flows (Voloshin 2002)
- ……………

J/ψ properties in QGP

▪ Perturbative QCD ➔ screening mass

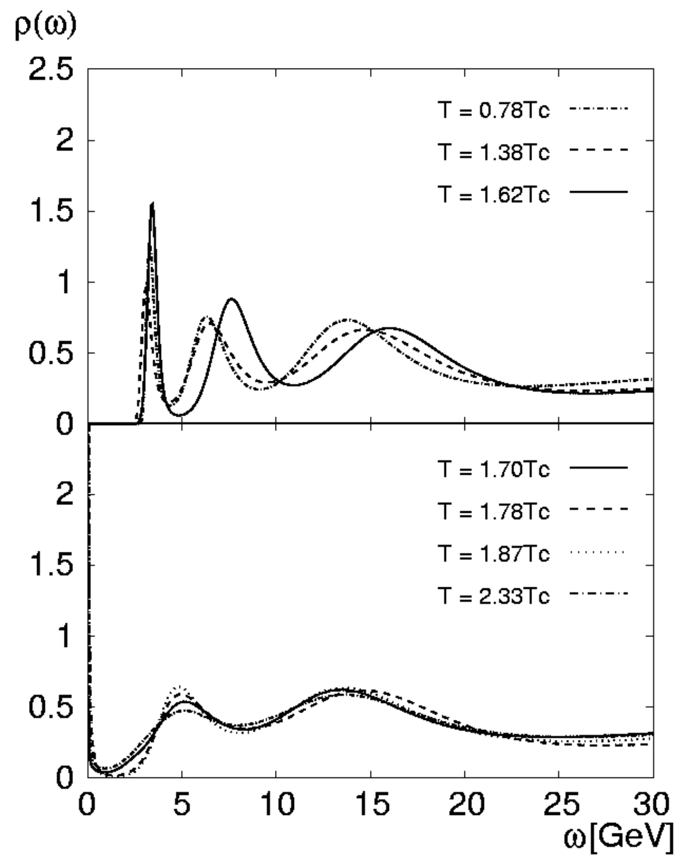
$$V = -\frac{\alpha_s}{r} \longrightarrow V = -\frac{\alpha_s}{r} e^{-r/\lambda_D}$$

$$\lambda_D = \left(\frac{N_c}{3} + \frac{N_f}{6}\right)^{-\frac{1}{2}} (gT)^{-1} \approx \sqrt{\frac{2}{3}} (gT)^{-1}$$



➔J/ψ suppression in HIC (Matsui & Satz)

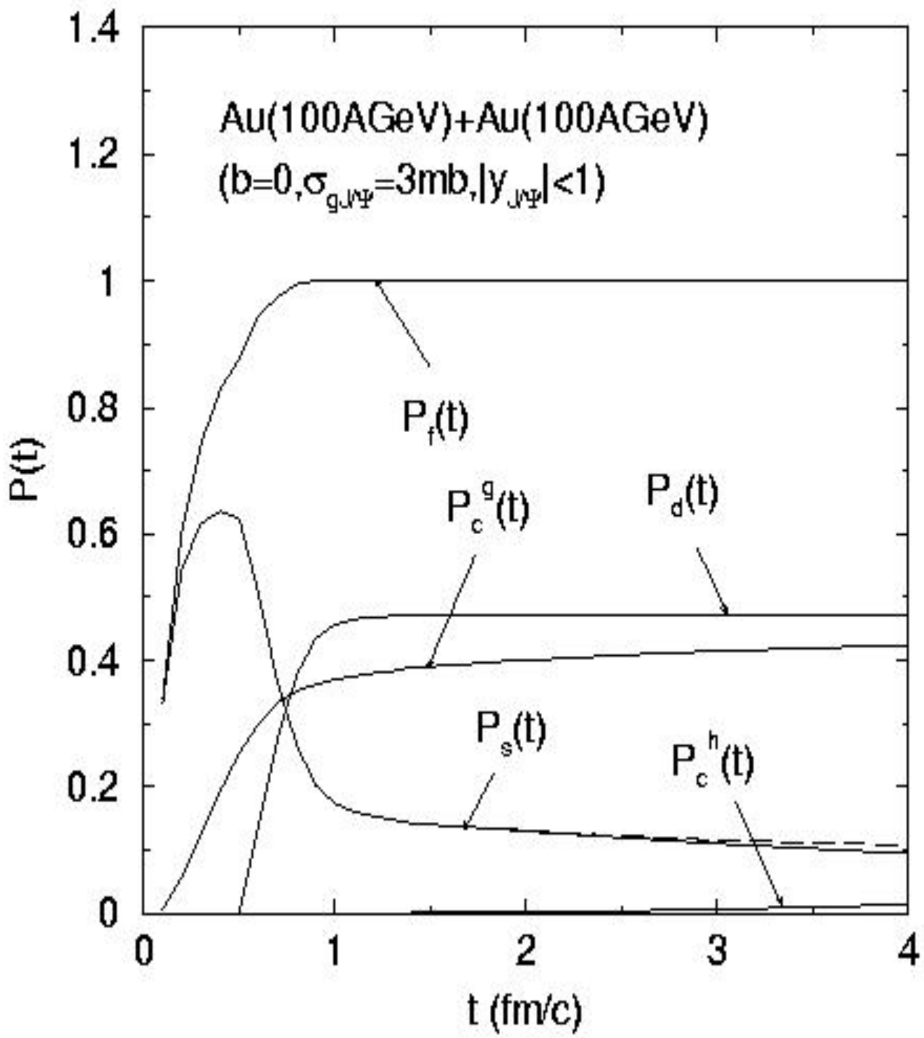
▪ Lattice QCD (Asakawa & Hatuda, Karsch et al.)



➔*J*/ψ survives below 1.62~1.70T_c

J/ψ absorption probability at RHIC

Zhang et al., PRC 62, 054905 (2000)



P_d : Color screening (critical density $n_c \sim 5/fm^3$)

P_c^g : gluons (σ=3 mb)

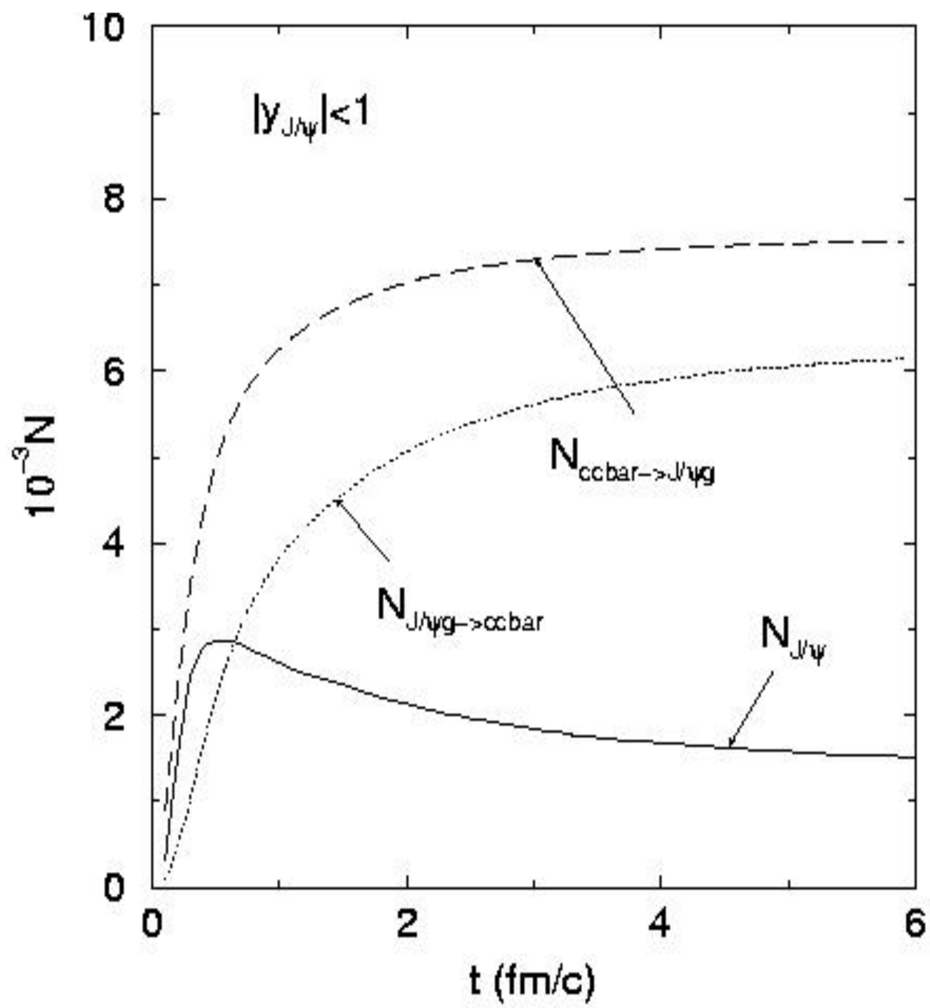
P_c^h : hadrons (σ=3 mb)

P_f : formation

P_s : survival

J/ψ evolution in partonic matter

Zhang et al., PRC 65, 054909 (2002)



- Charm quark mass m_c=1.35 GeV
- Au+Au @ 200A GeV
- Initial $\frac{dN_{c\bar{c}}}{dy}|_{y=0} \approx 1.73$

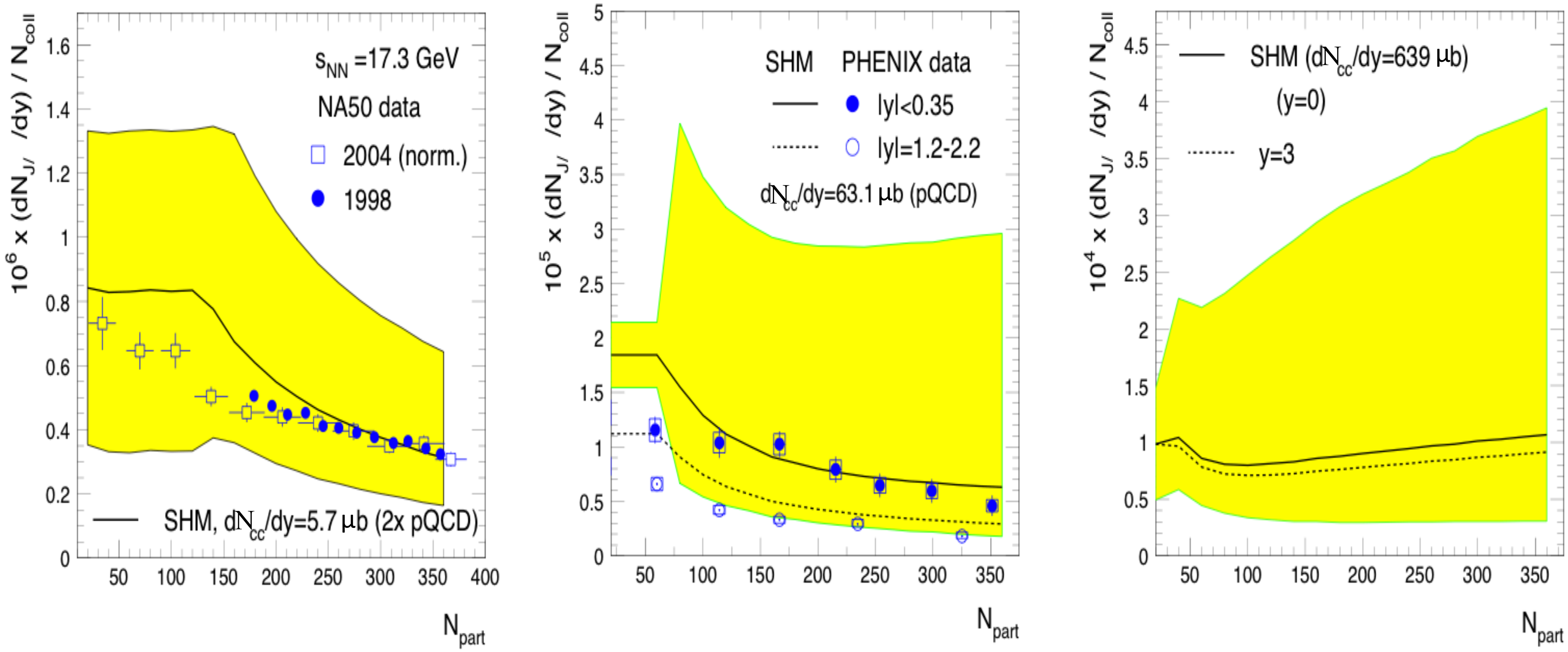
  $\frac{dN_{J/\psi}}{dy}|_{y=0} \approx 0.019$
- Final $\frac{dN_{J/\psi}}{dy}|_{y=0} \approx 0.0014$

$\frac{dN_{J/\psi}}{dy}|_{y=0} \approx 0.0007$ with screening

Statistical hadronization model for J/ψ production

Andronic, Braun-Munzinger, Redlich & Stachel, NPA 789, 334 (2007)

$$N_{J/\psi} = \frac{g}{2p^2}\gamma_c^2 \int_0^\infty \frac{p^2 dp}{e^{\sqrt{m^2+p^2}/T}+1}$$

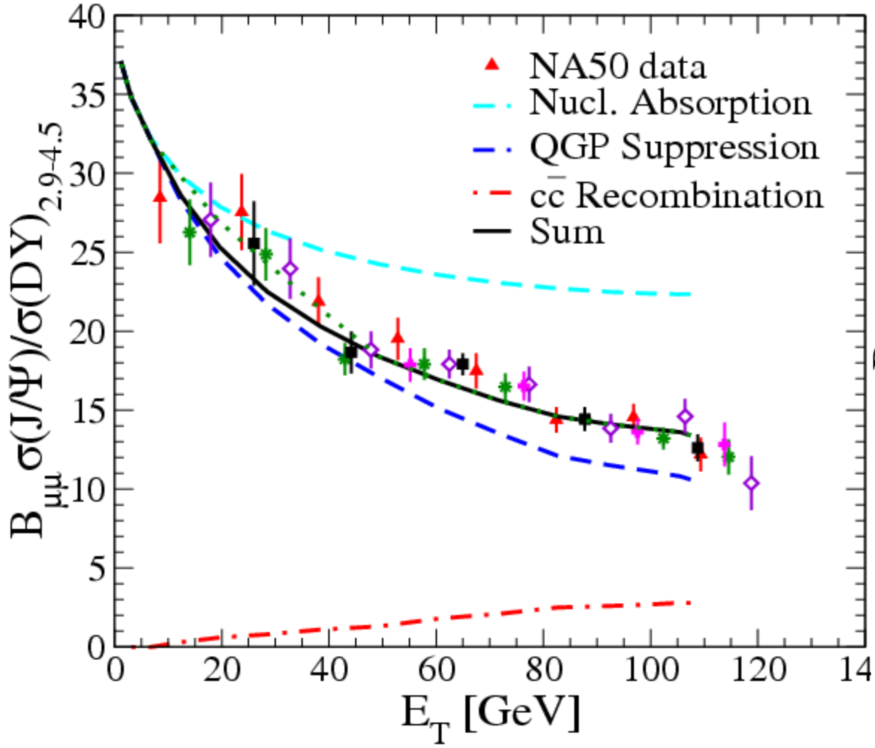


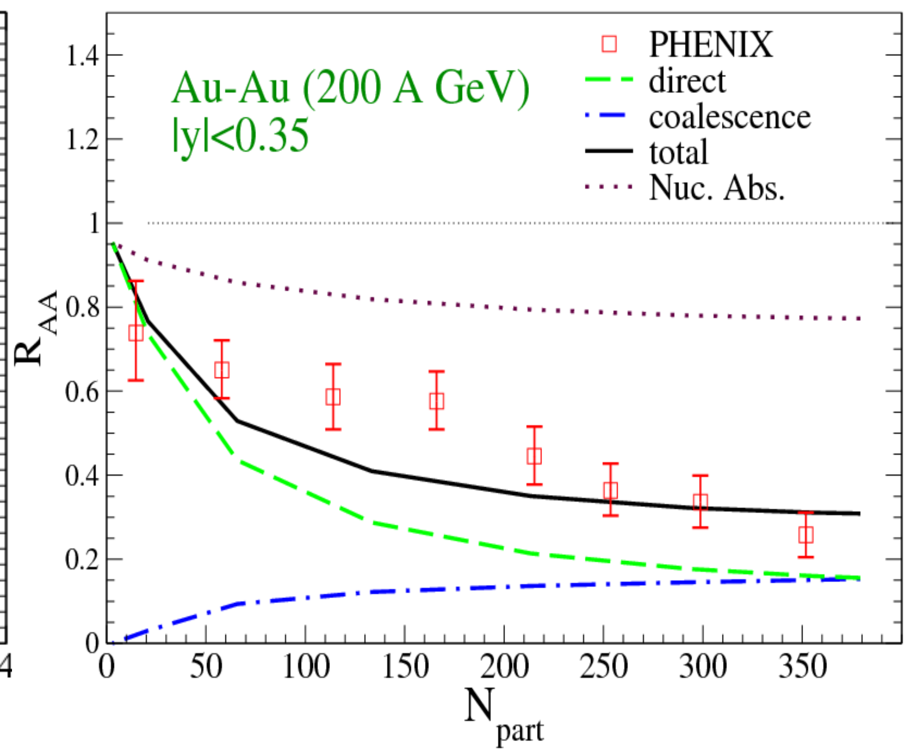
- Results are sensitive to the number of charm quark pairs produced in the collisions.

Two component model for J/ψ production

- Nuclear absorption: J/ψ+N→D+Λ_c; p+A data → σ~ 6 mb
- Absorption and regeneration in QGP: $J/\Psi + g \leftrightarrow c\bar{c}$
- Absorption and regeneration in hadronic matter: $J/\Psi + \pi \leftrightarrow D\bar{D}$

Zhao & Rapp, EPJ 62, 109 (2009)





- Regeneration from coalescence of charm and anticharm quark is non-negligible at RHIC as first pointed out by Thews et al.

The two-component model: directly produced J/ψ

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

- 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

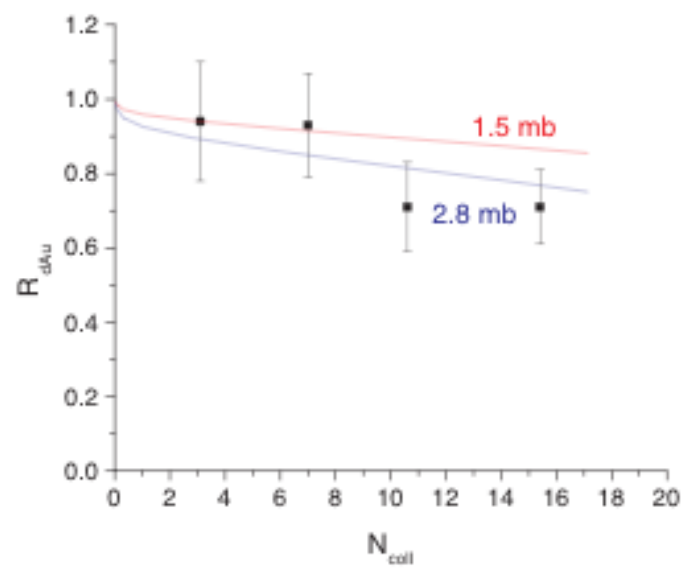
$$\rho(r) = \frac{\rho_0}{1+e^{(r-r_0)/c}}$$

r_0= 6.38 fm, c=0.535 fm for Au

- Nuclear absorption

  - Survival probability

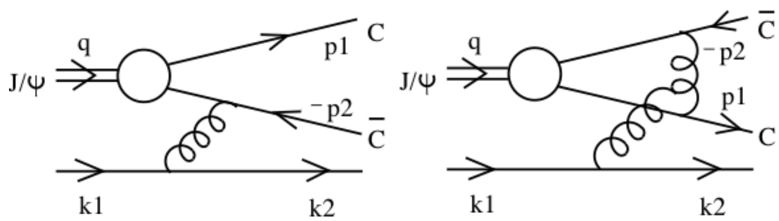
$$S_{nucl}(\vec{b},\vec{s}) = \frac{1}{T_{AB}} \int dz dz' \rho_A(\vec{s},z) \rho_B(\vec{b}-\vec{s},z)$$
$$\times \exp\left\{-(A-1)\int_z^{\infty} dz_A \rho_A(\vec{s},z_A)\sigma_{nuc}\right\}$$
$$\times \exp\left\{-(B-1)\int_z^{\infty} dz_B \rho_B(\vec{s},z_B)\sigma_{nuc}\right\}$$



Thermal dissociation of directly produced J/ψ

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

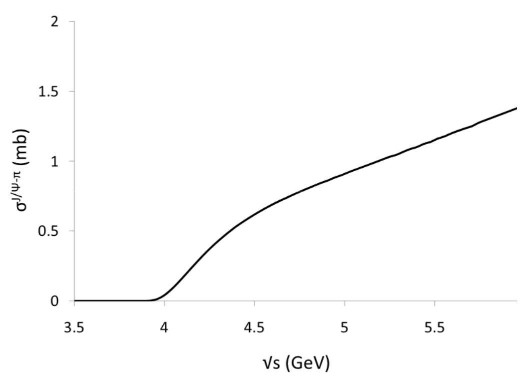
- Dissociation by partons



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

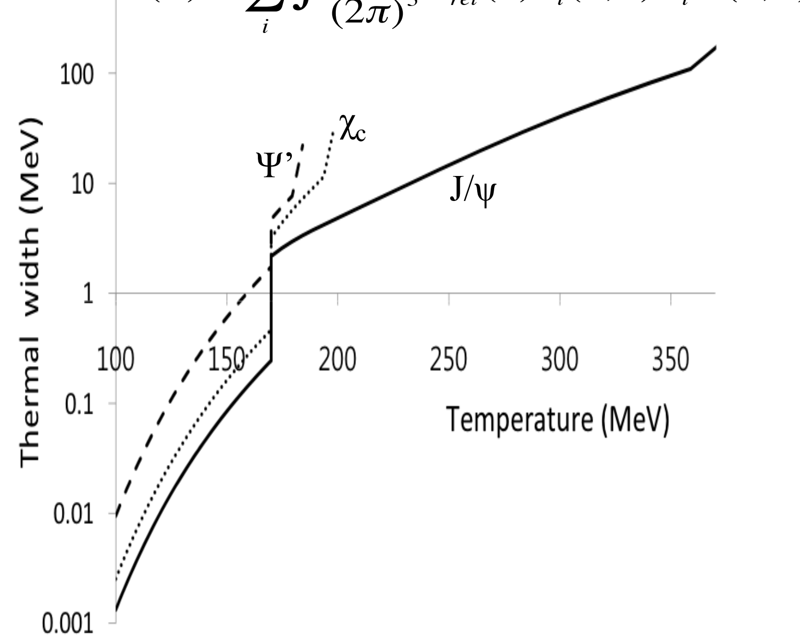
- Dissociation by hadrons

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



- Thermal dissociation width

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



- Thermal dissociate probability

$$S_{th}(\vec{b},\vec{s}) = \exp\left\{-\int_{\tau_0}^{\tau_{cf}} \Gamma(\tau')d\tau'\right\}$$

$$S_{th}(\vec{b},\vec{s}) = 0.67 S_{th}^{J/\psi}(\vec{b},\vec{s}) + 0.25 S_{th}^{\chi_c}(\vec{b},\vec{s}) + 0.08 S_{th}^{\psi'}(\vec{b},\vec{s})$$

The two-component model: regenerated J/ψ

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

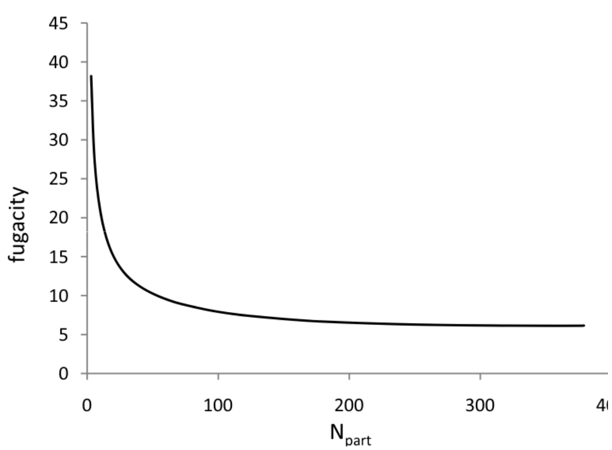
As in statistical model

$$N^{AA}_{reg-J/\psi} = \gamma^2 \left\{ n_{J/\psi} S^{J/\psi}_{th-H} + Br(\chi_c \to J/\psi) n_{\chi_c} S^{\chi_c}_{th-H} + Br(\psi' \to J/\psi) n_{\psi'} S^{\psi'}_{th-H} \right\} VR$$

- Charm fugacity is determined by

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

  - $\sigma^{NN}_{c\bar{c}}$: charm production cross section in NN collision; ~ 63.7 μb at $s^{1/2}$= 200 GeV

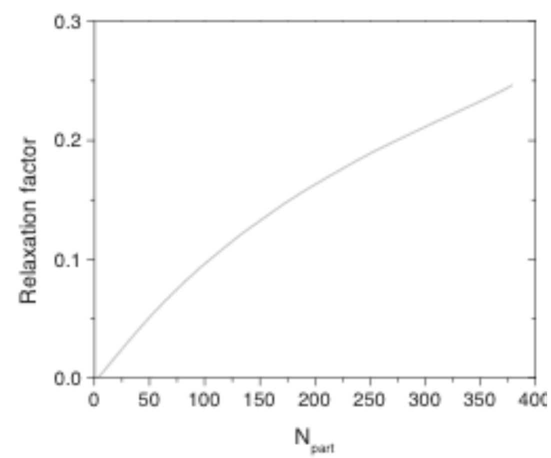


- Charm relaxation factor

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

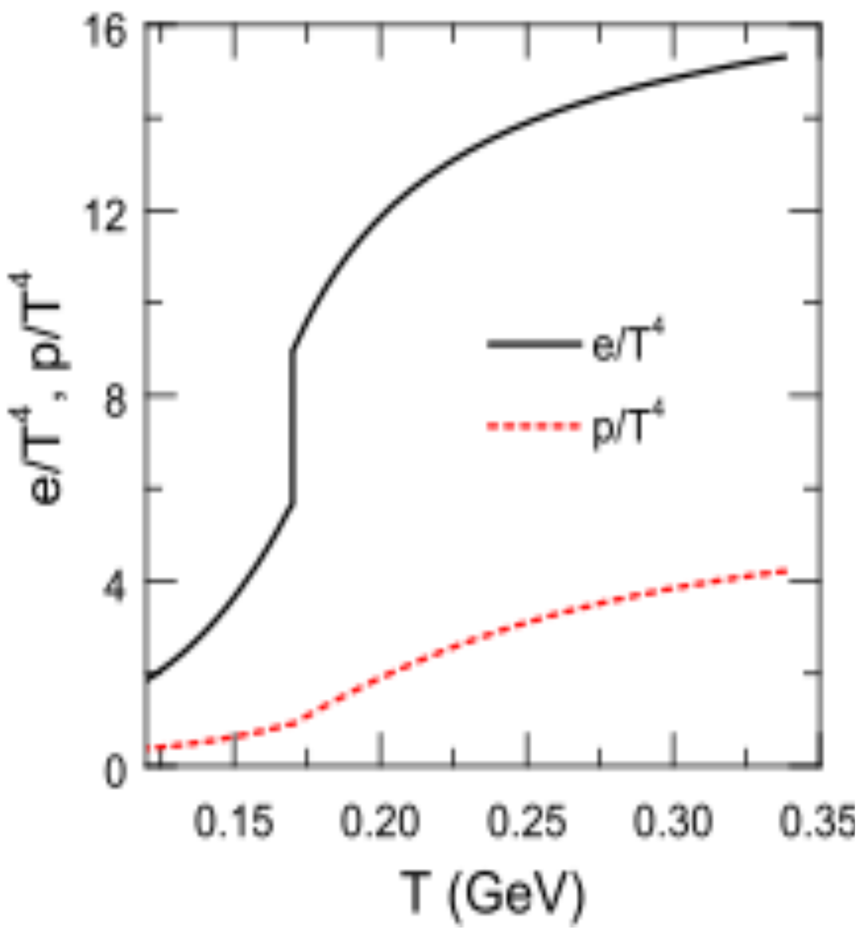
$$\Gamma(T) = \sum_i \int \frac{d^3k}{(2\pi)^3} v_{rel}(k) n_i(k,T) \sigma_i^{diss}(k,T)$$

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



Quasiparticle model for QGP

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



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

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

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

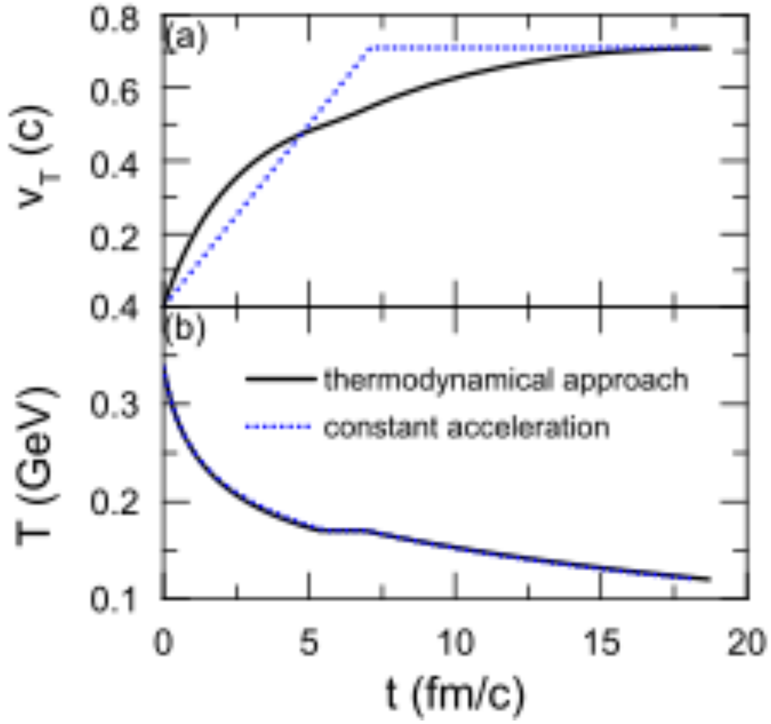
$$m_q^2 = \frac{g^2(T) T^2}{3}$$

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

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

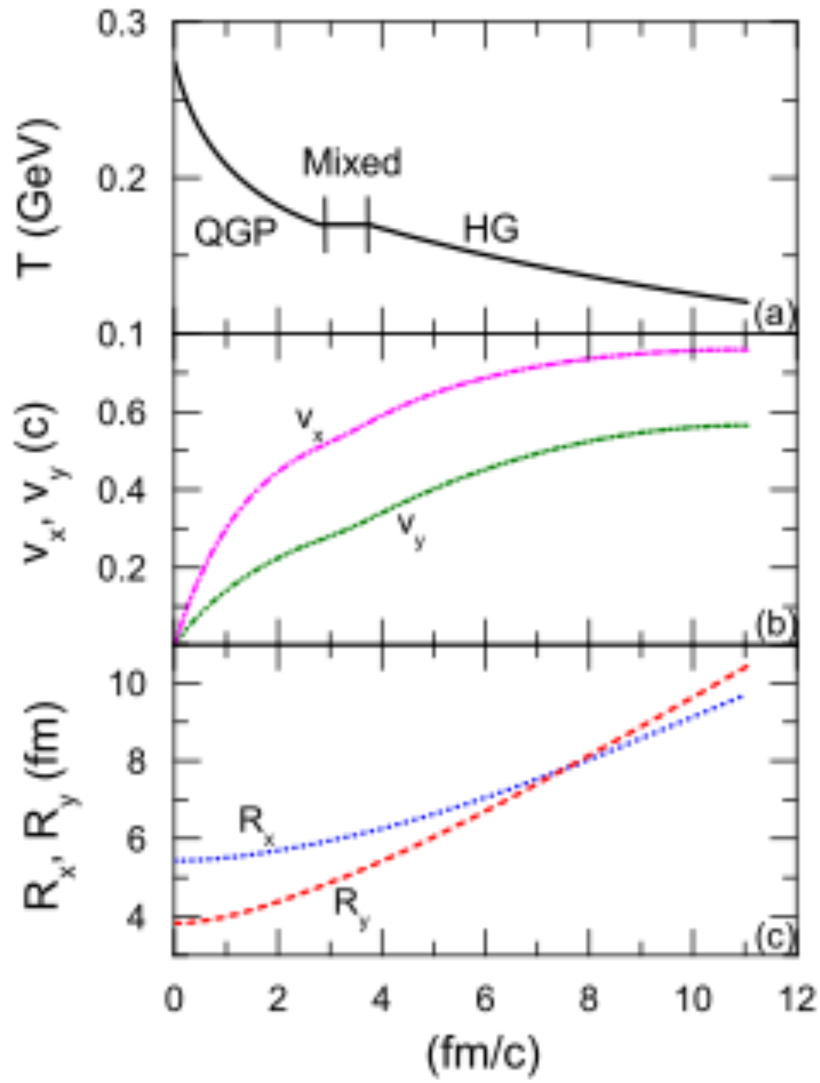
- The model reproduces reasonably the QGP equation of state from LQCD

Fire-cylinder model for relativistic heavy ion collisions



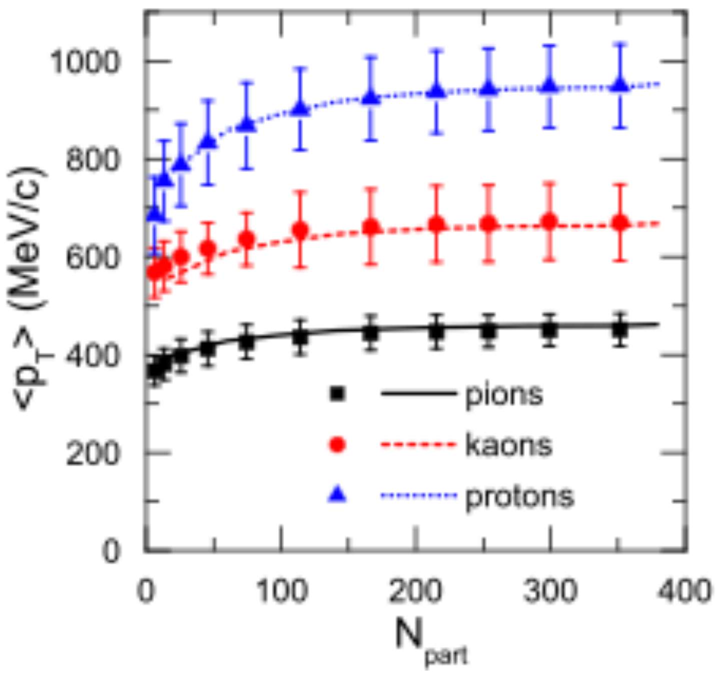
$$a_x = a_T(1 + z\varepsilon), \quad a_y = a_T(1 - z\varepsilon)$$

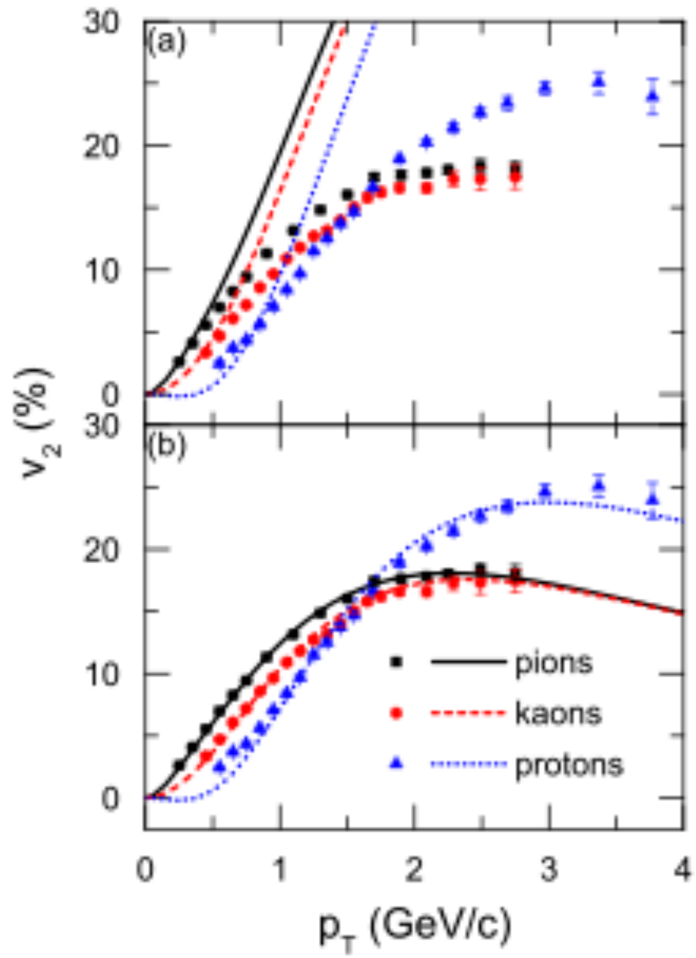
$$a_T = \frac{(p - p_f)A}{M}, \quad \varepsilon = \frac{R_y - R_x}{R_y + R_x}$$



- The acceleration a_T and asymmetry ε can in principle be determined self-consistently from the EOS but are taken as parameters.

Light hadrons mean transverse momentum and elliptic flow





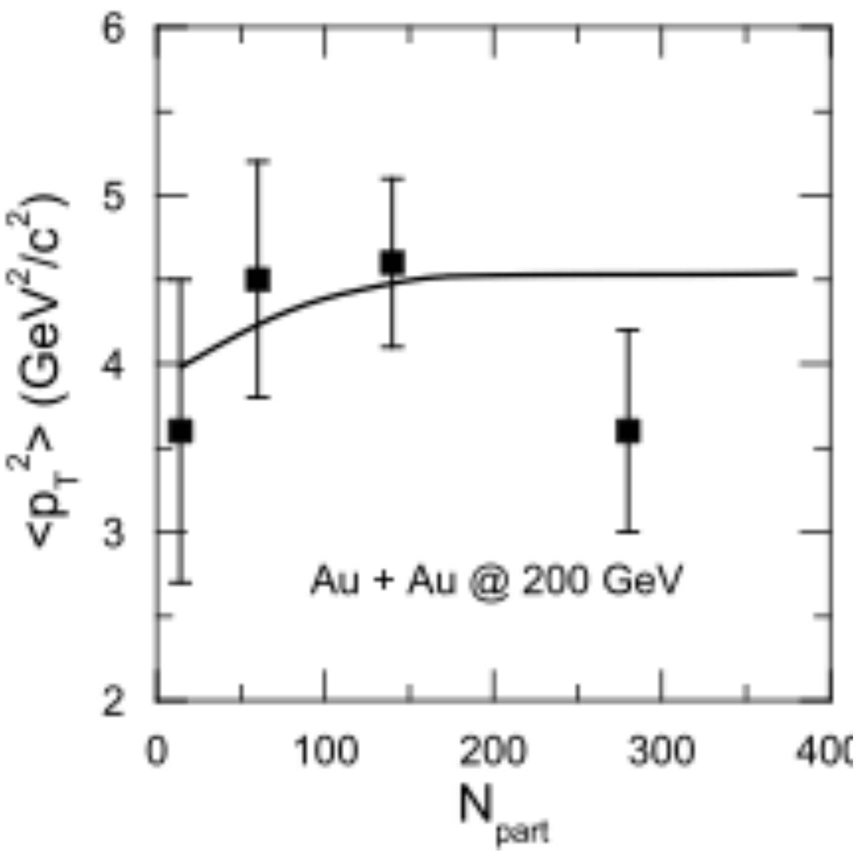
Introduced viscous effect at freeze out T=125 MeV

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

with n= number of quarks in a hadron

- Good description of experimental data

J/ψ average squared transverse momentum



$$\frac{dN}{dydp_T^2} = \frac{1}{2(2\pi)^3}\int_0^{2\pi} d\varphi \int d\sigma \cdot p e^{-p\cdot u/T}$$

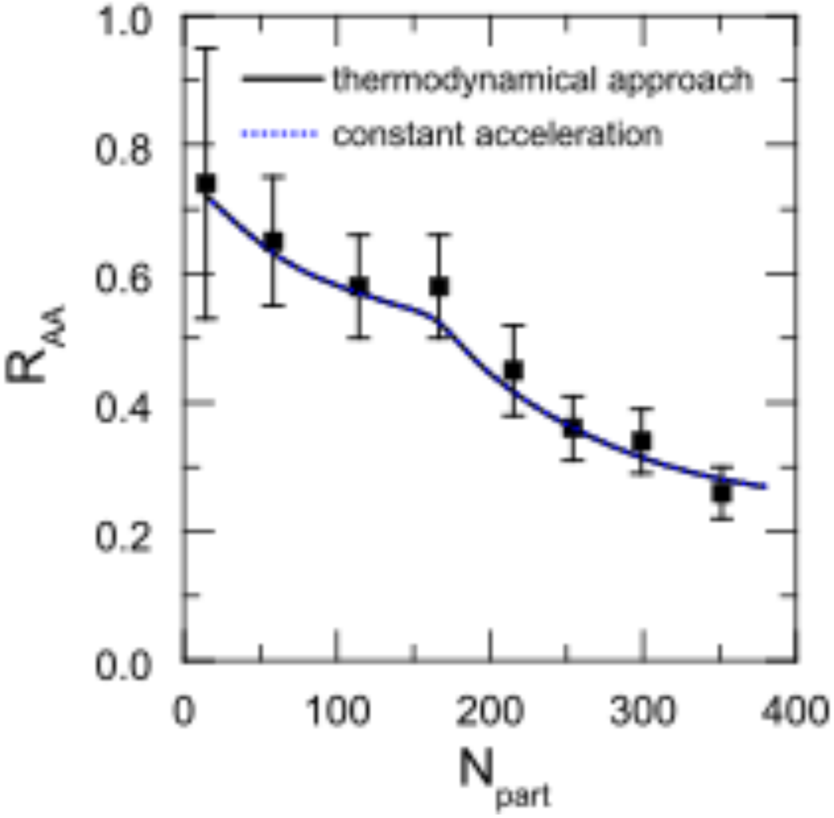
$$\times \frac{\tau m_T}{(2\pi)^2}\int dA_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

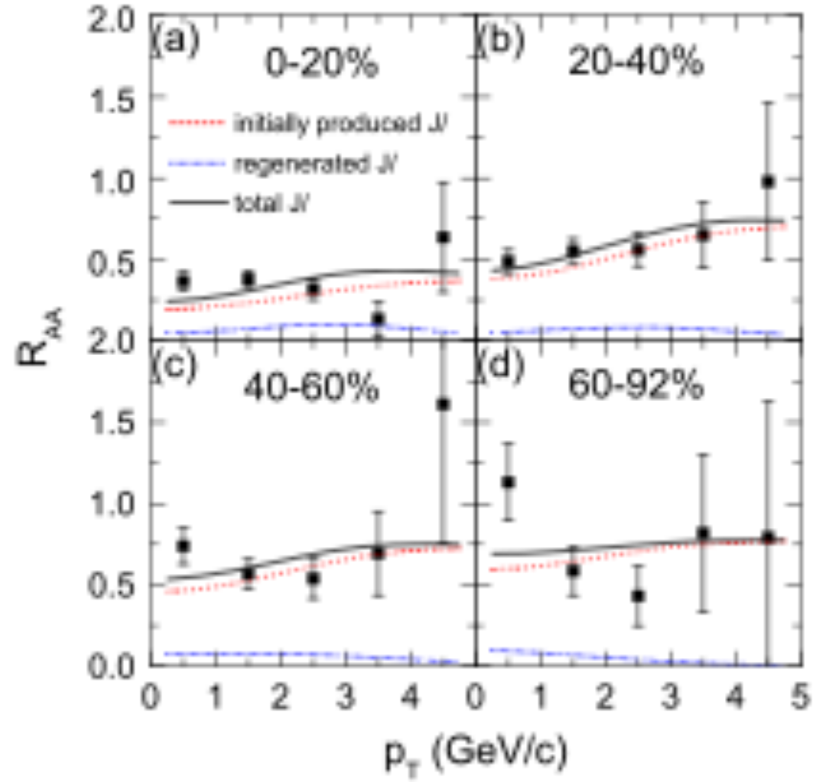
$$\langle p_T^2 \rangle = \frac{\int dp_T^2 p_T^2 (dN/dydp_T^2)}{\int dp_T^2 (dN/dydp_T^2)}$$

- J/ψ freeze out temperature T=175 MeV

- Large value for large N_{part} is due to overestimate of charm quark diffusion

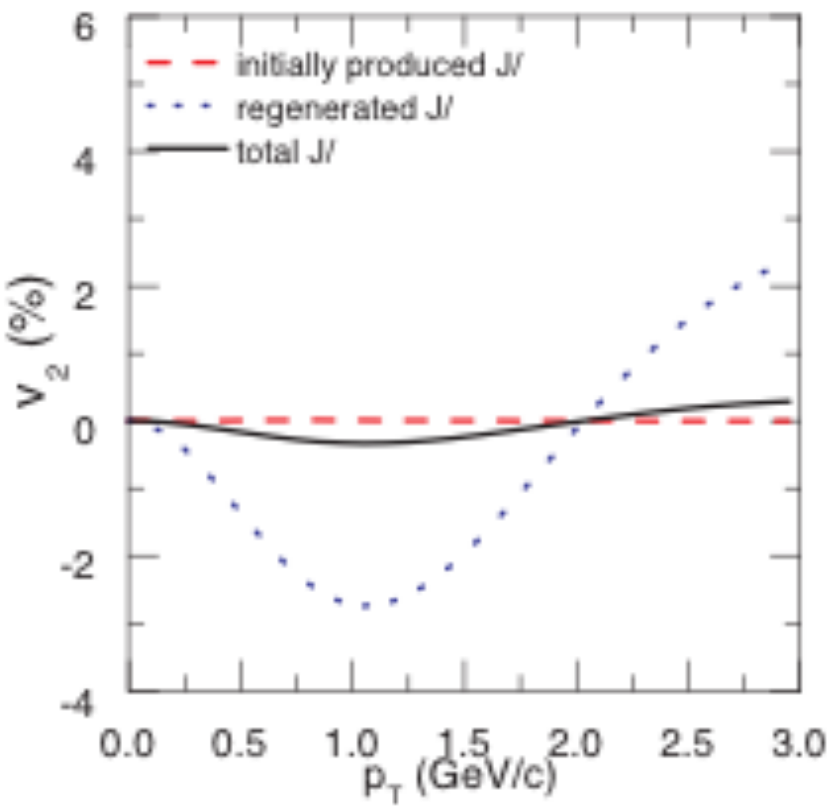
Centrality and transverse momentum dependence of J/ψ nuclear modification factor





- Most J/ψ are survivors from initially produced.
- The kink in R_{AA} is due to different survival probabilities of initially produced J/ψ in high and low regions of the fire-cylinder

J/ψ elliptic flow



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

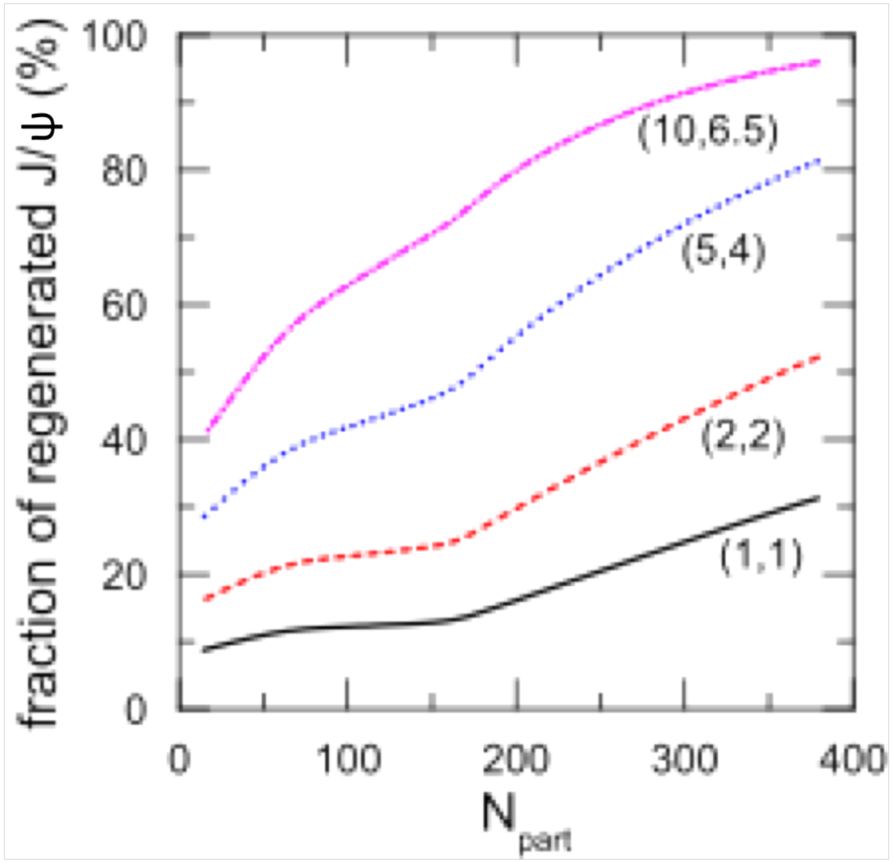
$$= \frac{\int dA_T \cos(2\varphi) I_2(p_T \sinh\rho/T) K_1(m_T \cosh\rho/T)}{\int dA_T I_0(p_T \sinh\rho/T) K_1(m_T \cosh\rho/T)}$$

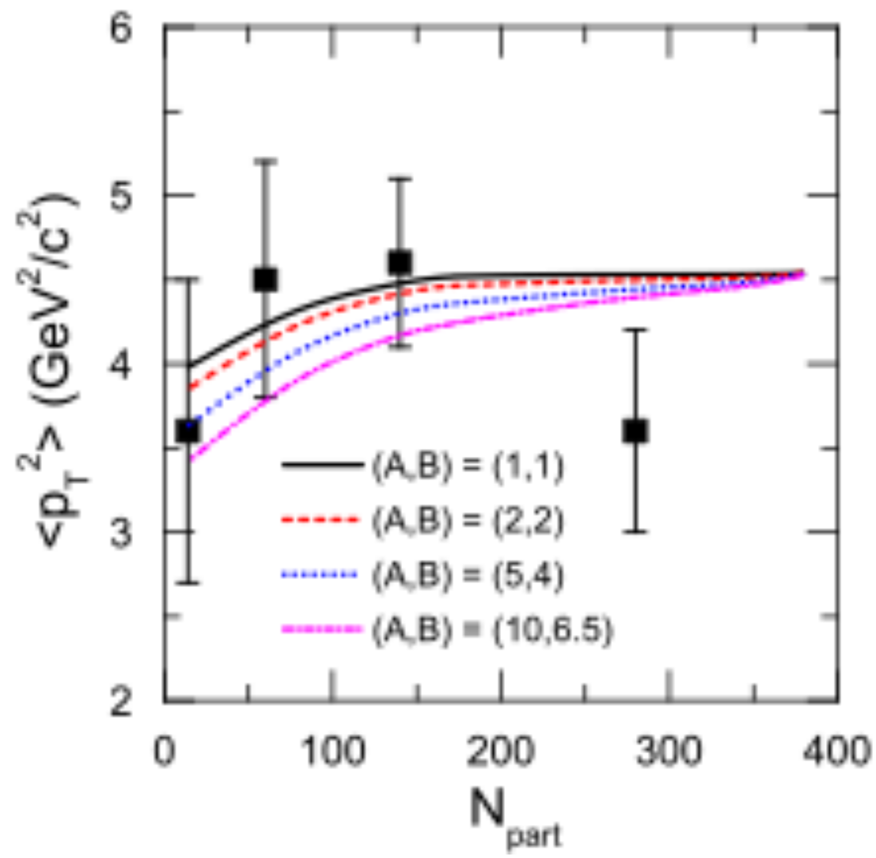
- Initially produced J/ψ have essentially vanishing v_2
- Regenerated J/ψ have large v_2
- Final J/ψ v_2 is small as most are initially produced

Effects of higher-order corrections

$$\sigma'(J/\psi + q(g) \to c + \bar{c} + X) = A\sigma(J/\psi + q(g) \to c + \bar{c} + X)$$

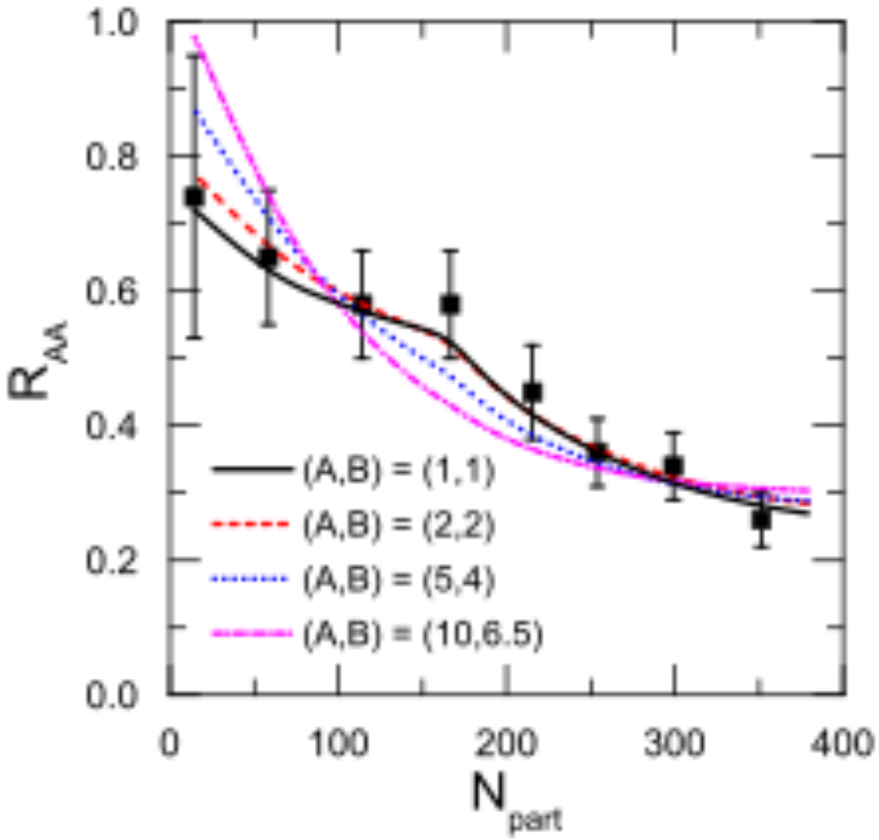
$$\sigma'(c + q(g) \to c + q(g)) = B\sigma(c + q(g) \to c + q(g))$$

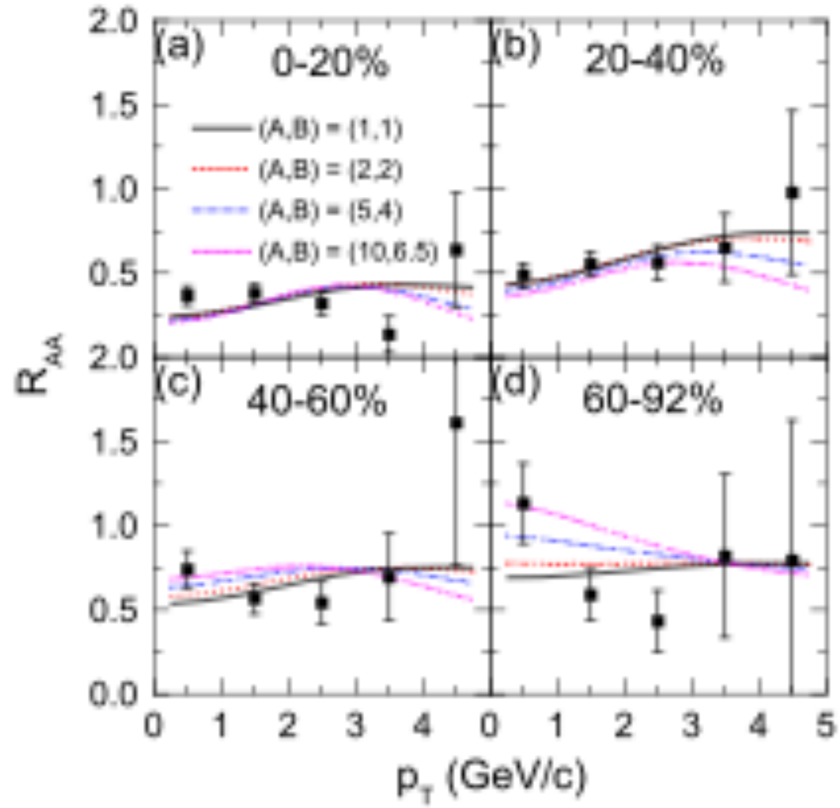




- Higher-order effects are small on J/ψ average squared transverse momentum

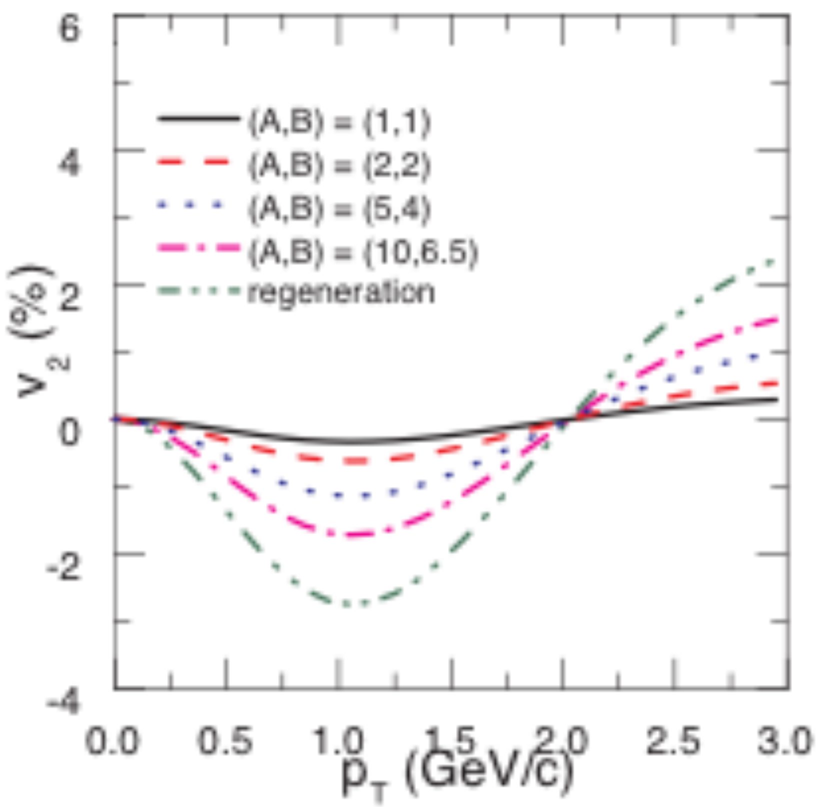
Higher-order effects on J/ψ nuclear modification factor





- Higher-order effects are small on J/ψ nuclear modification factor

Higher-order effects on J/ψ elliptic flow



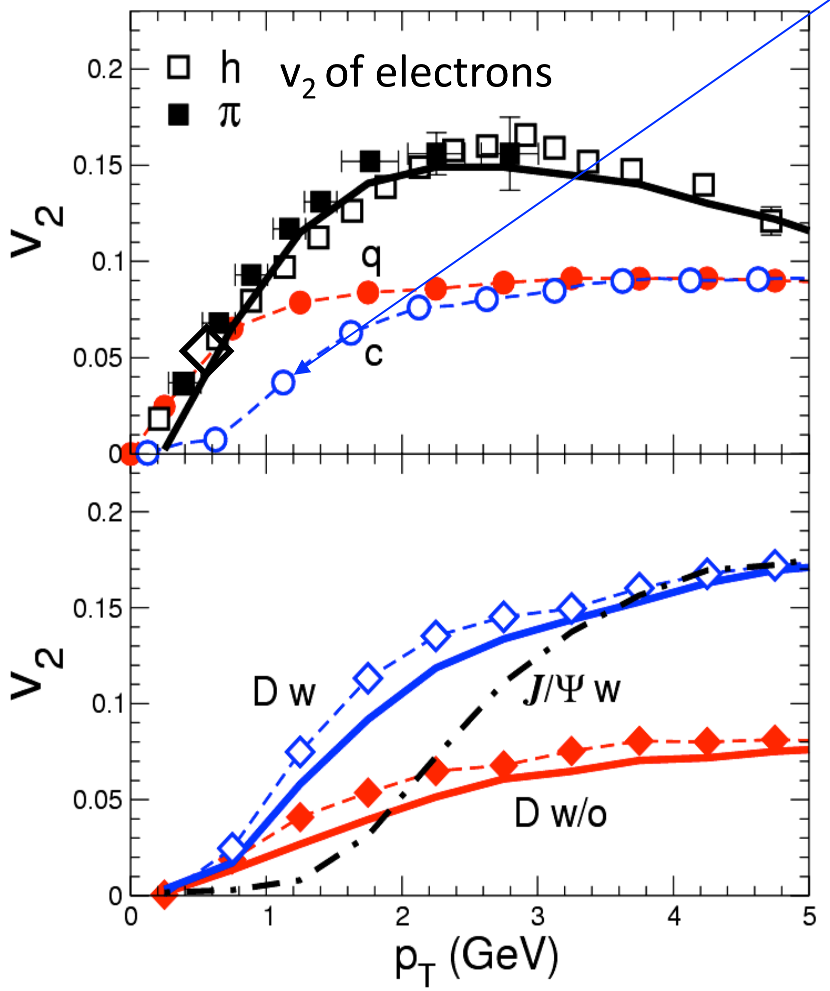
- Higher-order effects on v_2 of J/ψ are large
- v_2 of J/ψ provides information on J/ψ production mechanism in HIC

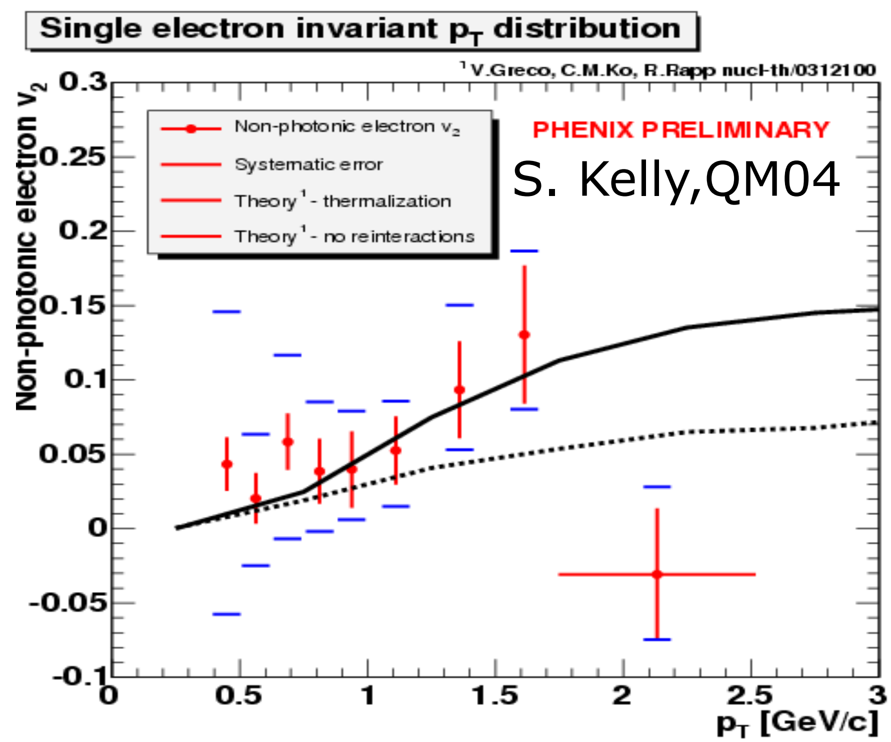
Charmed meson elliptic flow

Greco, Rapp, Ko, PLB595, 202 (04)

Smaller charm v_2 than light quark v_2 at low p_T due to mass effect

Quark coalescence

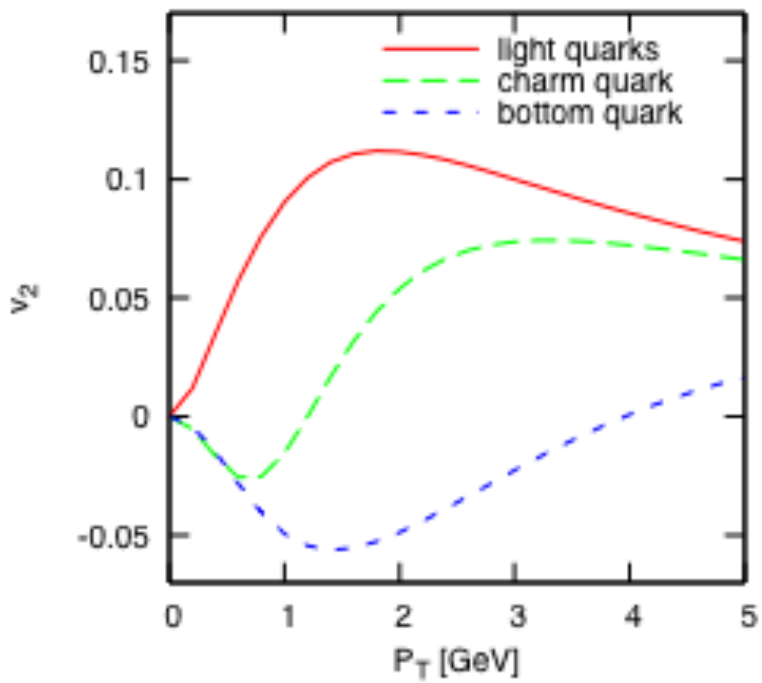


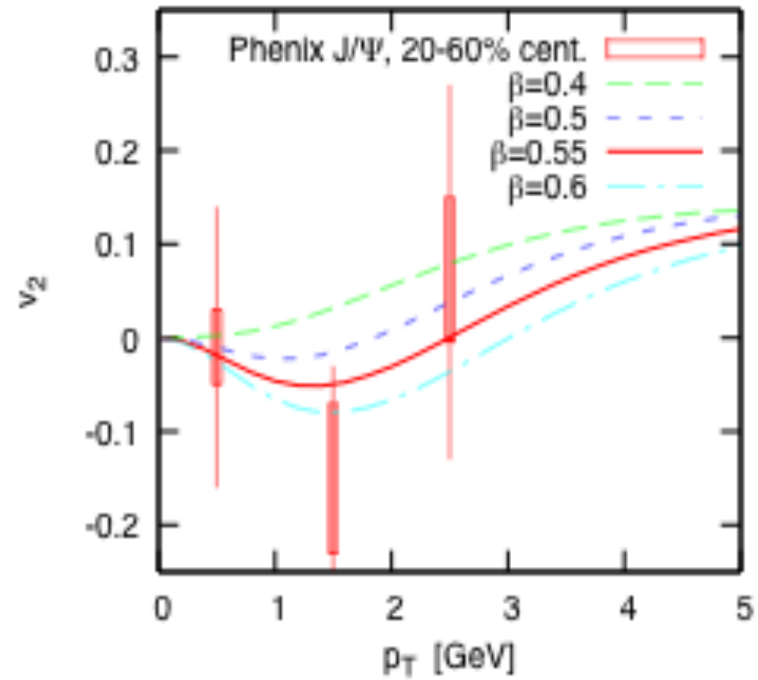


- Data consistent with thermalized charm quarks with similar v_2 as light quarks

J/ψ elliptic flow in the coalescence model

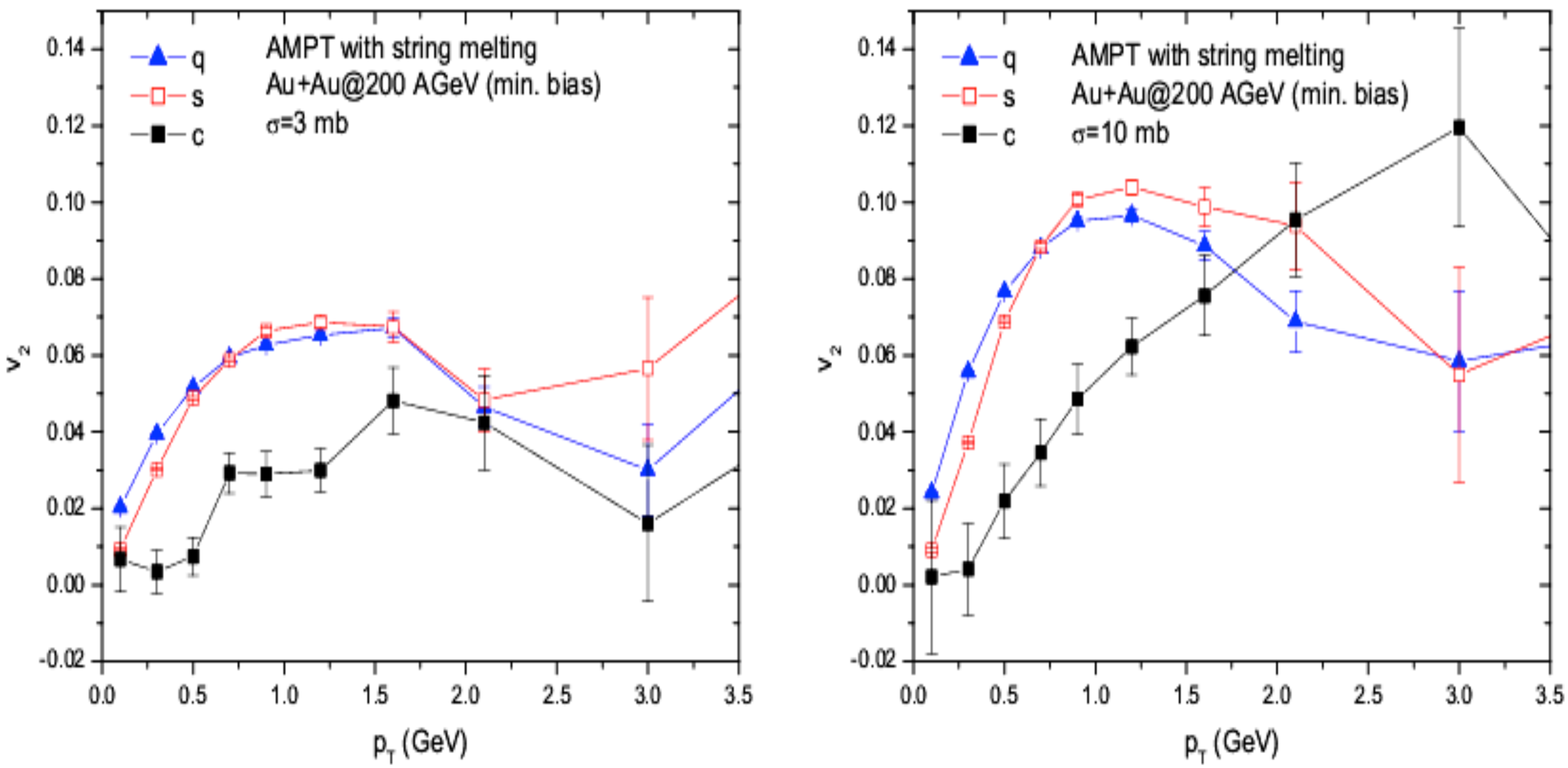
D. Krieg & M. Bleicher, EPJA 39, 1 (2009)





- Negative charm quark v_2 is required to obtain negative J/ψ v_2.
- Resulting non-photonic electron v_2 does not agree with data.

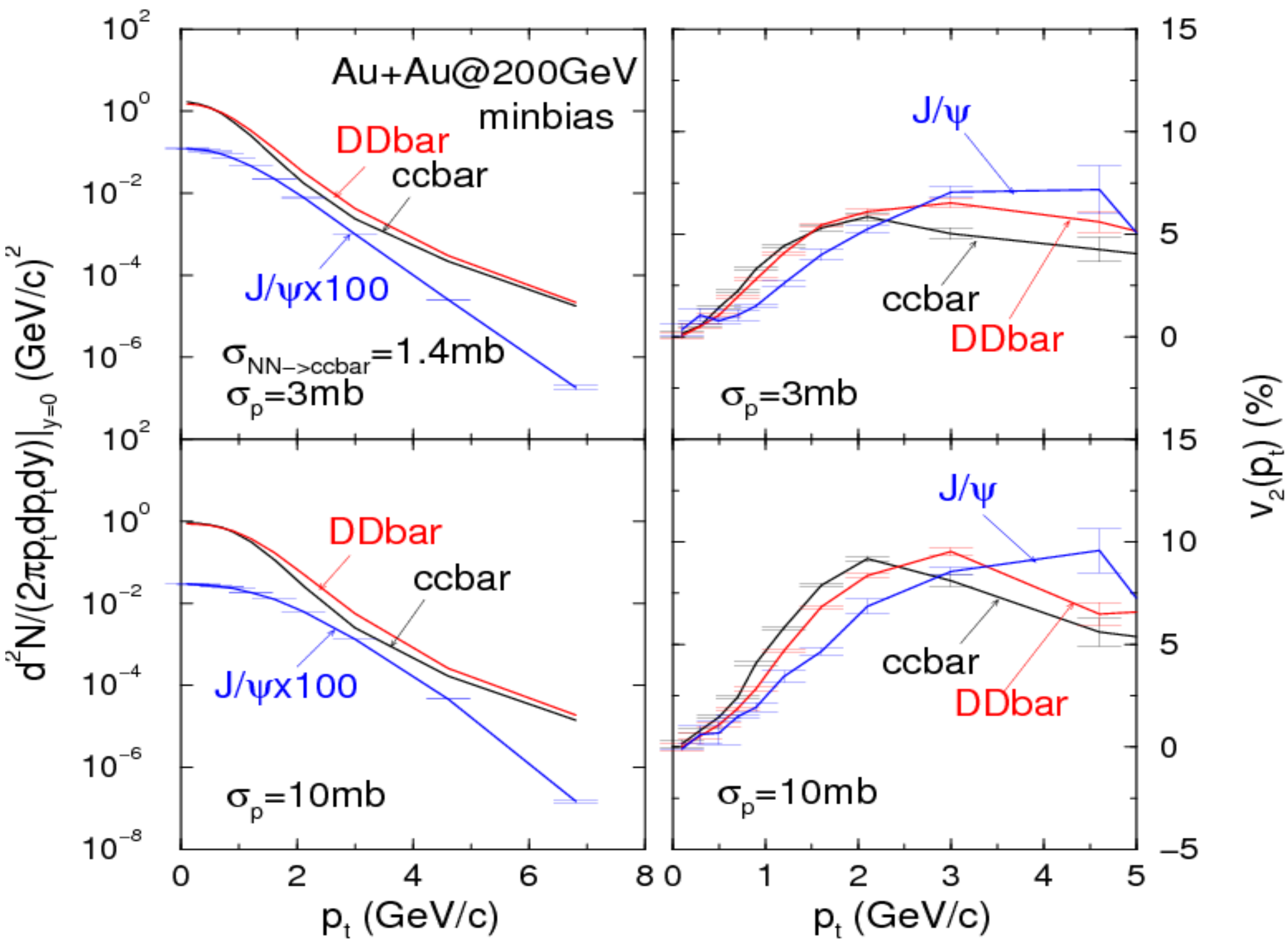
Charm quark elliptic flow from AMPT



- P_T dependence of charm quark v_2 is different from that of light quarks
- At high p_T, charm quark has similar v_2 as light quarks
- Charm elliptic flow is also sensitive to parton cross sections

Charmonium spectra and elliptic flow

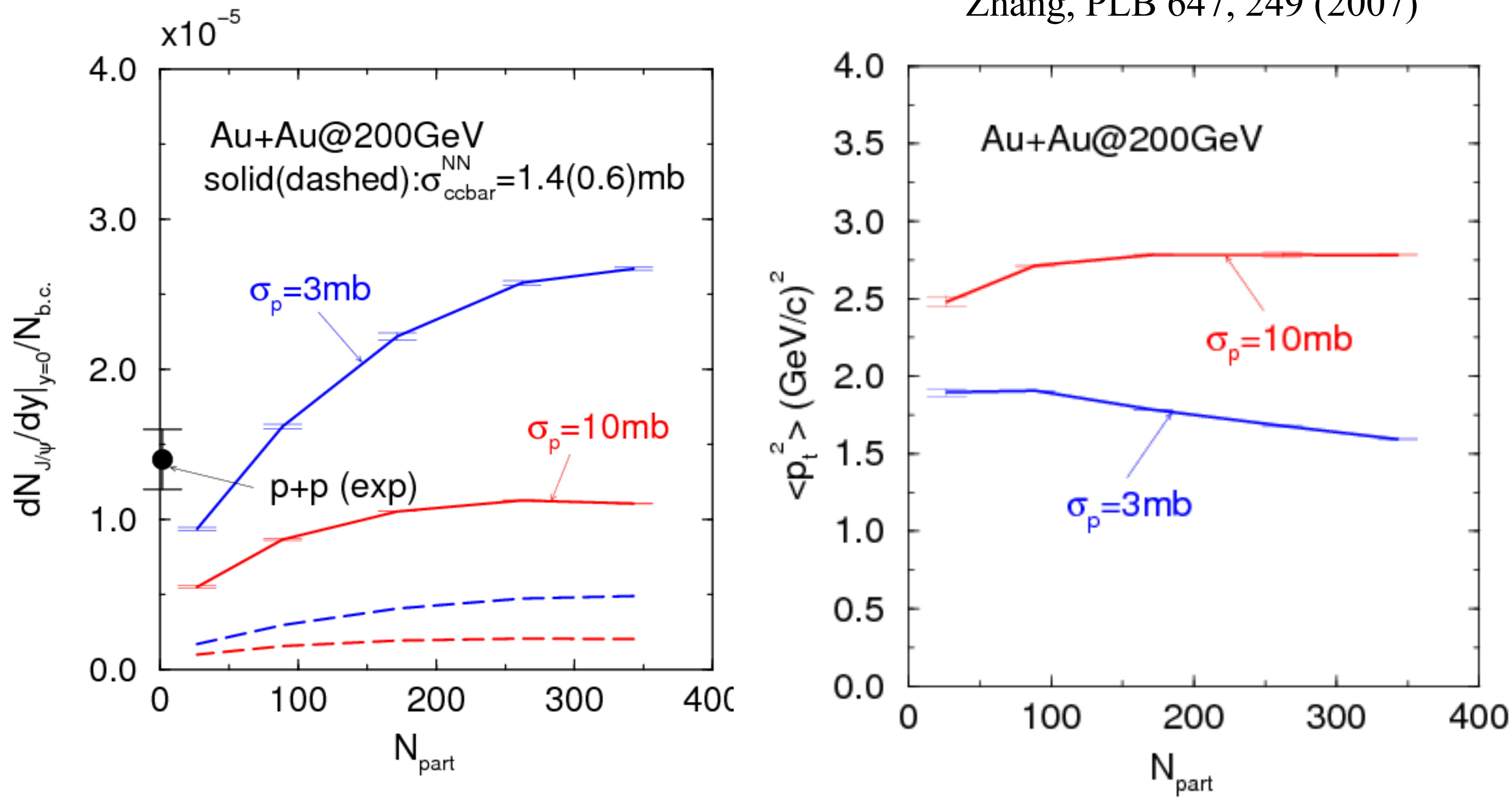
Zhang, PLB 647, 249 (2007)



- AMPT shows that charmonium elliptic flow is appreciable and increases with increasing parton cross sections

J/ψ production from charm quark coalescence

Zhang, PLB 647, 249 (2007)



- In AMPT, large (small) charm quark scattering cross section leads to suppressed (enhanced) yield but larger (smaller) average squared p_t.

Summary

- Both the statistical model, in which all J/ψ are due to regeneration from QGP, and the two-component model, which includes both J/ψ from initial hard scattering and regeneration from QGP, can describe measured $\langle p_T^2 \rangle$ and R_{AA} at RHIC.

- v_2 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.